Development and Validation of a Seismic Isolation System for Lightweight Residential Construction

by

Huseyin Cilsalar and Michael C. Constantinou

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Preface

MCEER is a national center of excellence dedicated to the discovery and development of new knowledge, tools and technologies that equip communities to become more disaster resilient in the face of earthquakes and other extreme events. MCEER accomplishes this through a system of multidisciplinary, multi-hazard research, in tandem with complimentary education and outreach initiatives.

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The Center derives support from several Federal agencies, including the National Science Foundation, Federal Highway Administration, Department of Energy, Nuclear Regulatory Commission, and the State of New York, foreign governments and private industry.

This report presents a study for the development of a practical low-cost seismic isolation system for lightweight residential construction. The study concludes that single concave rolling isolators cast in high strength concrete with a steel-reinforced plastic rolling ball and a displacement restraint system represent a promising isolation system. A full size isolator suitable for application to typical reinforced concrete houses in Turkey was built and tested. The vertical stiffness, creep characteristics under gravity load and the lateral force-displacement characteristics have been studied. Models for behavior have been developed and validated. These models are useful for response history analysis in commonly available commercial and open source analysis software. A procedure was developed for designing reinforced concrete houses in Turkey equipped with the developed isolator. The validity of the design procedure was investigated in a study of the seismic collapse performance of two-story houses in Turkey following the procedures of FEMA P695. It was shown that houses in Turkey designed by this procedure and equipped with the developed isolation system have acceptable collapse risk, whereas comparable non-isolated houses do not.
ABSTRACT

While seismic isolation has found widespread application ranging from apartment buildings to monumental and essential facilities, only Japan has a significant number of applications of seismic isolation to houses, which after some 5000 applications has reached a halt. The high cost of highly engineered seismic isolation systems is most likely the reason for the lack of applications other than in Japan.

There is an interest to develop practical, simple and reliable seismic isolation system for houses, which can be easily manufactured in most countries without the requirement for advanced technological capability. The work presented in this report concentrates on the development, construction, testing, modeling and validation of an isolator with these characteristics. Moreover, the work concentrates on the development and validation of design procedures for reinforced concrete houses equipped with this isolation system in areas of high seismic hazard in Turkey.

The developed isolator is a single concave rolling isolator cast in fiber and steel-reinforced high strength concrete with a rolling ball made of urethane (Adiprene) in hardness of 95A or 62D and reinforced with a core of steel. The isolator also features a displacement restraint system to prevent collapse of the isolator at large displacements. For applications anywhere in Turkey, the isolator has an ultimate displacement capacity of 650mm after fully engaging the displacement restraint. The isolator was built and tested to determine its properties, including creep and lateral force-displacement characteristics. It was observed that the isolator exhibits significant rolling friction that is practically independent of the hardness of the rolling ball and the conditions of loading and motion. It also exhibits a post-elastic stiffness and an effective yield displacement that are much larger than those predicted by models assuming rigid rolling ball behavior. These properties are desirable and emanate from the viscoelastic behavior of the rolling ball.

Models of behavior of the tested isolator were developed and validated for response history analysis in programs OpenSees and SAP2000. Moreover, an advanced computational mechanics-based model was developed that was capable to predict the observed features of rolling friction, increased stiffness and large yield displacement.

A parametric study of the collapse performance of a range of properties of two-story houses with a range of properties in areas of high seismic hazard in Turkey was performed following the procedures of FEMA P695 with due consideration of the spectral shape and the vertical ground motion effects. It has been shown that houses in Turkey designed by the recommended procedures and using the developed isolator have an acceptable collapse risk described by a probability of collapse that is less than 10% given the occurrence of the 2475-year return period earthquake, whereas comparable non-isolated houses do not.
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R.J. Watson, Inc. of Alden, NY developed the procedure for casting steel-reinforced Adiprene balls for this project. The rolling balls used in this project is a donation of R. J. Watson, Inc.
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Seismic isolation is a mature technology that has found significant application in the seismic protection of important structures, including hospitals, emergency facilities, museums, airport terminals, architecturally and historically significant buildings, data centers, sensitive manufacturing facilities, iconic company headquarters, offshore platforms, liquefied natural gas tanks, and more recently to large residential developments, including high-rise construction (Engineering News-Record, https://www.enr.com/articles/42366-the-10-largest-base-isolated-buildings-in-the-world; Mokha et al, 1996; Clarke et al, 2005; Kani et al, 2006; Wada et al, 2008; Fenz et al, 2011; Whittaker et al, 2014). The technology has no known applications in low-rise residential construction (houses) with the exception of Japan where there is a large number of such applications (Martelli et al, 2014; The Japan Society of Seismic Isolation, JSSI, http://www.jssi.or.jp/english/aboutus/database.html). There are two main reasons for this: (a) perceived high costs with the use of highly engineered seismic isolation systems that are more suitable for important structures, and (b) difficulty in providing effective seismic isolation to light-weight structures with large isolator displacement demands.

The experience of Japan is most interesting to warrant further commentary. As of 2016, Japan (The Japan Society of Seismic Isolation, http://www.jssi.or.jp/english/aboutus/database.html, accessed on 10/31/2018) had approximately 5000 seismically isolated large buildings that include hospitals, office buildings and apartment buildings. The construction rate was approximately 500 isolated buildings every 2 to 3 years. Also as of 2013, Japan had approximately 4700 seismically isolated houses of one to two-story construction. The number of isolated houses remained steady without additional construction until the last reporting in 2016. The isolation system used for the vast majority of houses in Japan is a sliding system consisting of flat sliding bearings and elastomeric springs (House Research Development, http://www.hrd-s.com/pro_base.html, accessed on 10/31/2018). A description of the system, including images, is provided in Wada et al (2008). In this system, the weight of the isolated house is carried by flat sliding bearings whereas restoring force is provided by laminated rubber bearings that act as lateral springs. The system behaves in a manner identical to that of the system tested by Constantinou et al (1991) where the restoring force action was provided by vertically placed helical springs. Variations in the sliding isolation system for houses in Japan have been reported but the number of applications is unknown. Specifically, systems have been developed and tested in which the flat sliding bearings are replaced by bi-directional X-Y flat rail bearings that feature, if needed, uplift restraint (THK, https://www.thk.com/?q=us/node/5223, accessed on 11/03/2018). The behavior of the X-Y-rail bearing bears a similarity to the X-Y uplift-restraining friction pendulum bearing (Roussis and Constantinou, 2006). A further innovation is reported in Kawaguchi et al (2008) in which an X-Y rail system is conically shaped to provide constant restoring force (constant angle of incline) is described.

The details of the Japanese seismic isolation systems for houses reveal complexities in the use of sophisticated hardware (X-Y rail bearings, X-Y conically shaped rail bearings, laminated elastomeric bearings) and/or multiple types of hardware (sliding and elastomeric bearings, and in some applications fluid dampers). The writers of this report perceive these systems as highly
engineered seismic isolation systems with high cost, the use of which cannot be justified for houses. For example, the use of a highly engineered double concave sliding isolator (Fenz and Constantinou, 2006) of a 650mm ultimate displacement capacity as the constructed isolator, would have required two concave steel plates of about the same dimensions (1000mm square) which should be provided with polished stainless steel overlays. If single flat or concave sliding isolators of the same displacement capacity are utilized (Constantinou et al, 2011), they would be of about 1500mm in plan dimensions, and again requiring stainless steel overlays. As such, they are unlikely to be widely implemented to houses in countries of high seismic hazard. This explains the lack of application of seismic isolation to houses, with the exception of Japan. Even in Japan, application of the technology to houses appears to have slowed down or to have stopped. (We speculate that this pause in construction of seismically isolated houses is primarily the result of the high cost of houses in Japan, isolated or non-isolated, so that most buyers opt for the purchase or rent of apartments in large developments, which in Japan continue to utilize seismic isolation and other seismic protective technologies).

The realization that highly engineered seismic isolation systems are unlikely to find implementation to houses due to high costs led researchers to investigate simple methods for seismic isolation. Recently, a doctoral dissertation at Stanford University (Swensen, 2014) investigated light-frame residential construction in the US, including the use of seismic isolation among other options of seismic strengthening. The study concentrated on sliding isolation systems with restoring force and demonstrated the importance of high friction (of the order of 0.20) to achieve manageable displacement demands. The study also demonstrated the significance of restoring force in controlling residual displacements. It was concluded that a strengthened two-story houses equipped with a spherical sliding isolation system with radius of curvature 2000mm and friction of 0.2 to 0.3 would result in small residual displacements, a peak displacement demand of 300mm for areas of high seismicity in California and an acceptable collapse margin per FEMA P695 (FEMA, 2009). A version of the isolation system was also tested on a shake table (Jampole et al, 2016). It may be shown that a system with these characteristics will indeed have small residual displacements per ASCE/SEI 7-16 (ASCE, 2017) (see commentary of ASCE/SEI 7-16 and some details for a simplified interpretation in MCEER report 11-0005, Constantinou et al, 2011). However, the construction of such isolators is complex as they have to be constructed as single or double friction pendulum isolators (Constantinou et al, 2011) and they need to operate at small bearing pressure to achieve high friction. While Swensen (2014) envisions the use of inexpensive materials (e.g., galvanized steel instead of stainless steel for the sliding interface), the cost will still be significant (e.g., forming a spherical surface of sheet steel and forming a contact area with rotational capability) and will likely lack reliability.

Past studies on the behavior of sliding interfaces (MS theses of E. Wolff, 1999 and D. Fenz, 2005 at the University at Buffalo) investigated the friction, wear and frictional heating of high friction materials, including many thermoplastics and carbon/graphite based materials. One of these materials (identified as NF-101) was organic, non-metallic, non-asbestos and used in brakes and clutches. When in contact with stainless steel and up to an average contact pressures of 35MPa it exhibited high friction in the range of 0.35 at the start to 0.25 after five cycles of harmonic motion of small amplitude (25mm) and peak velocity of about 300mm/sec. The drop in friction was due to frictional heating. Use of this promising material would require
consideration of frictional heating, uncertainty in properties and aging (Constantinou et al, 2007; McVitty and Constantinou, 2015) as now regulated in ASCE/SEI 7-16 (ASCE, 2017) which would have resulted in a significant range of friction values (lower and upper bound) to consider in the analysis and design. The likely range based on ASCE/SEI 7-16 would have been about 0.15 to 0.50 when high quality materials are used. When materials such as carbon steel, or galvanized steel, or chrome-plated steel are used for the sliding interfaces, there is potential for corrosion and increase in friction (Constantinou et al, 2007). Moreover, dwell of load has an effect on friction that is dependent on the hardness of the material used and the average pressure. Constantinou et al (2007) observed in tests and provided analytical justification that in order to avoid increases in friction with time in the absence of corrosion, the sliding interface should consists of soft non-metallic materials in contact with polished metals at high enough pressures to cause yielding of the softer material and to significantly expedite creep of the soft material. This suggests that harder materials at low pressures may have large changes in friction over time that need to be determined in prolonged testing observations.

Another recent study reported on shake table testing of a low cost pure frictional isolation system for masonry construction (Nanda et al, 2016). The tests resulted in large residual displacements which were about the same as the peak displacements. Analysis predicted peak and residual displacements that were about half of the observed ones. Nanda et al (2016) did not realize that the reason for the unpredictability of the displacement response is the lack of restoring force as demonstrated decades earlier in tests and analysis by Constantinou et al (1991). Sliding isolation systems cannot be perfectly levelled so always there is a net inclination in one direction. In the tests of Constantinou et al (1991) this angle was determined to be 0.4 degrees. Sliding motion occurs in the direction of inclination and accumulates to large values depending on the duration of the excitation. Results of this study and of another on elastoplastic isolation systems (Tsopelas and Constantinou, 1997) have been instrumental in the establishments of minimum lateral restoring force capability requirements in standards and specifications for bridges that first appeared in AASHTO (AASHTO, 1999) and Eurocode 8, EN1988-2 (European Committee for Standardization, 2005). It is required that isolation system have sufficient restoring force to prevent the accumulation of unpredictable residual displacements, so that purely sliding systems should never be used.

It is evident that sliding isolation systems with restoring force capability are suitable for application in houses but a reliable system will have to be highly engineered in similarity to single, double and triple friction pendulum isolators used for much larger and important structures. The Japanese experience in the use of highly engineered sliding isolation systems for houses is a testament to this observation. However, such systems might not find widespread use in other countries due to their high cost by comparison to the value of the house in which they are installed. The work presented in this report concentrates on the development of a low-cost reliable seismic isolation system for houses with interest in the ability to fabricate the system or most of its components in any location worldwide, with particular emphasis on Turkey where the system should be entirely possible to fabricate.

The work started with investigating various gravity-based seismic isolation systems by determining demands in terms of base shear force and isolator displacement, and residual displacement when applied in areas of high seismic hazard in Turkey. The investigated systems
were rolling systems as the authors considered them to be more reliable than sliding systems in terms of the friction force dependency on hysteretic or frictional heating and in terms of long-term changes due to effects of corrosion and load dwell. Single and double concave (or spherical) and conical rolling systems were investigated. The double spherical and conical systems were eliminated from consideration as being more costly (need two curved surfaces) without offering any advantage in size (unlike sliding systems for which there a size reduction in double and triple configurations). Analyses were then performed for locations of high seismic hazard in Turkey to determine isolator displacement demands and base shear force for various combinations of isolation system parameters with due consideration for the vertical ground motion effects. The study concluded that single concave rolling isolators can be configured to provide lesser isolator displacements and base shear force than comparable single conical isolators at the expense of larger residual displacements.

A full-size single concave rolling isolator was built in high strength fiber and steel-reinforced concrete with rolling balls made of urethane (Adiprene) of varying hardness and with some reinforced with steel cores. The isolator also featured a displacement restraint that was activated at displacement exceeding about 560mm. Tests were conducted to determine the vertical and lateral force-displacement characteristics of the isolator under dynamic conditions, including its behavior when the displacement restraint was engaged. Models of the isolator’s behavior have been developed in programs OpenSees (McKenna, 1997) and SAP2000 (Computers and Structures, 2018), and validated using the test data. The testing revealed a behavior characterized by (a) a desirably high rolling friction coefficient of about 0.10, (b) a post-elastic stiffness about two to three times larger than the stiffness predicted by theory when assuming a rigid rolling ball, and (c) an effective yield displacement that is large and about 25mm. These features of behavior emanate from the viscoelastic properties of the rolling ball, which continually changes shape during motion. The large effective yield displacement is desirable as it results in smaller residual displacements. We developed a preliminary computational mechanics-based model for the isolator in program LS-DYNA (LS-DYNA, 2012), capable of predicting the observed creep behavior under vertical load and the observed complex lateral force-displacement relation, including the observed rolling friction, high stiffness and large effective yield displacement. The model utilized the simplest model of viscoelastic behavior. The model was developed just to demonstrate the origin of the observed behavior and not as means of predicting its behavior in lieu of testing. The behavior of the isolator needs to be established by testing.

Based on the observations in the tests, the upper and lower bounds of properties of the developed isolator were established. This isolator is envisioned for use in houses in areas of high seismic hazard in Turkey. It features a single size and geometric configuration and two options based on the hardness of the Adiprene rolling ball. The ball is reinforced with a steel core, which increases the vertical stiffness and ensures a capability to carry load even in case Adiprene deteriorates due to some unforeseen effect or is damaged by fire. Moreover, a simple design philosophy for reinforced concrete houses in Turkey isolated with this isolation system has been presented.

Based on the established properties of the isolator, a parametric study of the collapse performance of a range of two-story houses isolated with the developed isolator and designed
by the developed procedures in areas of seismic hazard in Turkey was performed. It is shown that the collapse performance of the seismically isolated houses meet the criteria of ASCE/SEI 7-16 (ASCE, 2017) for acceptable collapse risk whereas non-isolated comparable houses do not. The acceptable collapse risk is a probability of collapse of 10% in the maximum considered earthquake (defined as the one with 2475 years return period). Moreover, it was shown by limited representative analyses that the seismically isolated houses have lower probabilities of developing damage to their structural and non-structural systems, and to their contents for all seismic intensity levels up to the maximum considered earthquake.
SECTION 2
STUDY OF CANDIDATE ISOLATORS

2.1 Introduction

Four systems are considered as candidates for the residential isolation system. All are rolling systems in which a deformable reinforced rubber ball is used. The systems differ in the geometry of the surfaces to roll on. Two are conical systems, one being a single and the other being a double conical system. The other two are concave systems, one being a single and the other being a double concave system. The difference between the single and the double concave or conical systems is simply in the restoring force which is less for the single systems than that of the same geometry double systems.

Figure 2-1 illustrates the single and double concave systems and Figure 2-2 illustrates the single and double conical rolling systems. The systems consist of concave or conically shaped plates with a rolling ball sandwiched between the plates. In the single configurations, one of the two plates is flat. In the double configurations, the two plates have identical geometries. The plates are cast in concrete reinforced with fibers and steel and the ball is made of urethane and could feature a reinforcing steel core. The hardness of the urethane and reinforcement of the ball (steel core) are used to control its deflection in order to achieve (a) acceptable pressure on concrete, (b) acceptable vertical deformation and (c) predictable and sufficiently high rolling friction. The ball radius is \( r \). Under compressive load \( W \), as shown in Figures 2-1 and 2-2, the ball deforms to a shape that resembles an ellipsoid with a vertical semi-axis \( r' \) and horizontal semi-axes larger than \( r \).

Each conical plate consists of a conical part of slope \( \phi \) which meshes at the center with a spherical concave part of radius of curvature \( R \). The spherically shaped part has diameter \( 2D_o \). For the single and double concave rolling systems each concave plate is spherically shaped with radius of curvature \( R \) as shown in Figure 2-1.

Figure 2-1 Geometry of Single and Double Concave Rolling Isolator
2.2 Behavior and Modeling

The considered isolators are presumed to have the same behavior in compression, which is controlled by the deformation of the rolling ball. The isolators differ in behavior in the lateral direction under combined vertical and lateral loads. The results presented on the behavior of these isolators are based on theories that consider the rolling ball to be rigid. Accordingly, the behavior resembles frictional behavior with a very small effective yield displacement and with stiffness that is entirely determined by geometry. In reality, the rolling ball is deformable and that should give rise to additional stiffness due to the additional work needed to deform the rolling ball. The deformability of the rolling ball will also give rise to rolling friction. The models presented here will later be modified using the test observations.

Double Concave Rolling Isolator

The behavior of the double concave rolling isolator (Figure 2-2) is identical to the behavior of the double concave sliding isolator (Fenz and Constantinou, 2006) provided that the rolling ball inertia forces are negligible. Accordingly, the relationship between the lateral force, \( F \), to the lateral displacement of the top plate with respect to the bottom plate, \( u \), is given by the following equation when the angles of rotation are small or equivalently the displacement \( u \) is small by comparison to the radius \( R \) (generally valid for \( u \) less than about 0.6\( R \)). Note that the \( \text{sign}(\dot{u}) \) is used to account for the friction force being in the direction opposing motion.

\[
F = \frac{W}{2R_{eff}} u + \mu W \text{sign}(\dot{u})
\]  

In Equation (2-1) \( R_{eff} \) is the effective radius given by

\[
R_{eff} = R - r'
\]  

Quantity \( \mu W \) is the effective rolling friction force with the coefficient of friction \( \mu \) to be determined by testing and expected to be a function of the load \( W \) and stiffness of the rolling

---

**Figure 2-2 Geometry of Single and Double Conical Rolling Isolator**
ball. Note that Equation (2-1) is valid when the two surfaces are of equal radius of curvature. In this case, the displacement of the center of the rubber ball is equal to \( u/2 \). Note that detailed mechanics of the double concave rolling isolator have been presented by Wang (2005) which lead to Equations (2-1) and (2-2) when \( u \) is small be comparison to \( R_{eff} \) (typically when \( u<0.6R_{eff} \)). The work of Wang is for a one-directional isolator using a cylindrical roller but the analysis is readily applicable for the case of the ball rolling system in one-directional analysis.

Single Concave Rolling Isolator

The mechanics of the single concave rolling isolator (Figure 2-1) differ from those of the single concave sliding isolator as actually there is rolling on two surfaces of which one is flat and one is concave. Wang (2005) considered rolling isolators that combined concave and conical surfaces. When a concave surface is combined with a flat surface (which is a conical surface with zero angle of inclination) as in Figure 2-1, the force-displacement relation is given by

\[
F = \frac{W}{4R_{eff}} u + \mu W \text{sign}(\dot{u})
\]  

(2-3)

In this equation \( R_{eff} \) is given by Equation (2-2).

Double Conical Rolling Isolator

The mechanics of the single and double conical rolling isolator have been investigated by many researchers. The first experimental investigation of the double conical isolator was reported by Kasalanati et al (1997) and many treatises followed of which the most interesting are those of Harvey et al (2014), Wang (2005) and Wang et al (2017). The work of Wang et al (2017) is an extension of the earlier work of Lee et al (2007) on the single conical isolator with a cylindrical rigid roller.

The single and double conical rolling isolators in the aforementioned works do not directly apply for the isolators shown in Figure 2-2 which contain an initial concave part that meshes with a conical part. This case was first treated in Cui et al (2012). However, the results slightly differ from the results of the works of Wang et al (2017) and Lee et al (2007) for the force-displacement relationship when motion occurs in the conical part. The correct form is the one in the works of Wang et al (2017) and Lee et al (2007), although the two formulations are identical when the slope \( \phi \) is small so that \( \sin(\phi) \approx \phi \). Herein the presented results were derived from the more complete presentation of Wang (2005) and Wang et al (2017) after some adjustment to account for the existence of both spherical and conical parts per Figure 2-2.

The force-displacement relationships for the double conical rolling isolator per Figure 2-2 are

\[
F = \frac{Wu}{2R_{eff}} + \mu W \text{sign}(\dot{u}) \quad u \leq 2D_o
\]  

(2-4)
\[ F = \frac{W \sin 2\phi}{2} \text{sign}(u) + \mu W \text{sign}(\dot{u}) \quad \text{for} \quad u > 2D_o \quad (2-5) \]

For compatibility in the slopes of the conical isolator with a spherical portion, the following condition must exist:

\[ D_o = R_{\text{eff}} \sin \phi \quad (2-6) \]

Accordingly, the restoring force when \( u = 2D_o \) is predicted by Equation (2-4) to be \( W \sin \phi \), whereas it is predicted by Equation (2-5) to be \( W \sin \phi \cos \phi \). The difference is insignificant given that angle \( \phi \) is small and typically about 0.1 rad.

The restoring force for the double conical rolling isolator when \( u > 2D_o \) in Cui et al (2012) was reported as \( W \sin \phi \) instead of \( W \sin(2\phi)/2 \) per Equation (2-5). Equation (2-5) is correct but the difference is insignificant for small values of slope \( \phi \) (typically 0.2 rad or less) for which \( \sin \phi \sim \sin(2\phi)/2 \sim \phi \).

**Single Conical Rolling Isolator**

For the case of the single conical rolling isolator of Figure (2-2), the force-displacement relationship is given by

\[ F = \frac{W u}{4R_{\text{eff}}} + \mu W \text{sign}(\dot{u}) \quad \text{for} \quad u \leq 2D_o \quad (2-7) \]

\[ F = \frac{W \sin \phi}{2} \text{sign}(u) + \mu W \text{sign}(\dot{u}) \quad \text{for} \quad u > 2D_o \quad (2-8) \]

For compatibility in the slopes of the conical isolator with a spherical portion, Equation (2-6) applies. The restoring force when \( u = 2D_o \) is predicted by both Equations (2-7) and (2-8) after use of (2-6) to be \( W \sin(\phi)/2 = WD_o/2R_{\text{eff}} \).

Representative force-displacement loops for the four considered isolators are presented in Figure 2-3. These loops for the normalized lateral force \( F/W \) vs the lateral top plate displacement \( u \) were generated for the geometries shown in Figure 2-3 and assuming that under load the deformed rubber ball has a vertical semi-axis radius \( r = 100 \text{mm} \).
<table>
<thead>
<tr>
<th>System</th>
<th>Configuration for Displacement Capacity of Over 500mm</th>
<th>Parameters</th>
<th>Force-displacement Loop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Concave Rolling</td>
<td><img src="image1" alt="Diagram" /></td>
<td>$R_{eff}=2000\text{mm}$ $\mu=0.05$</td>
<td><img src="image2" alt="Graph" /></td>
</tr>
<tr>
<td>Double Concave Rolling</td>
<td><img src="image3" alt="Diagram" /></td>
<td>$R_{eff}=2000\text{mm}$ $\mu=0.05$</td>
<td><img src="image4" alt="Graph" /></td>
</tr>
<tr>
<td>Single Conical Rolling</td>
<td><img src="image5" alt="Diagram" /></td>
<td>$R_{eff}=375\text{mm}$ $\phi=0.2\text{rad}$ $D_0=75\text{mm}$ $\mu=0.05$</td>
<td><img src="image6" alt="Graph" /></td>
</tr>
<tr>
<td>Double Conical Rolling</td>
<td><img src="image7" alt="Diagram" /></td>
<td>$R_{eff}=750\text{mm}$ $\phi=0.1\text{rad}$ $D_0=75\text{mm}$ $\mu=0.05$</td>
<td><img src="image8" alt="Graph" /></td>
</tr>
</tbody>
</table>

**Figure 2-3** Representative Geometries and Force-displacement Loops of Rolling Isolators
2.3 Isolator Model for Numerical Analysis

The force-displacement relationships predicted for the conical isolators by Equations (2-2) and (2-4) to (2-8) apply for the case of rigid rolling balls. The use of a deformable rolling ball results in smooth transition between the two stages of deformation when the displacement \( u \) is less and more than \( 2D_o \). This behavior may be reproduced by approximating the restoring force, \( F_r \), in Equations (2-4) and (2-5) for the double conical rolling isolator as follows:

\[
F_r \approx \frac{W \sin \phi}{2} \left( \frac{u}{2D_o} \right) \left( 1 + \left| \frac{u}{2D_o} \right|^{\alpha\frac{1}{\alpha}} \right) \tag{2-9}
\]

Similarly for the single conical rolling isolator, the restoring force, \( F_r \), in Equations (2-7) and (2-8) is approximated as follows:

\[
F_r \approx \frac{W \sin \phi}{2} \left( \frac{u}{2D_o} \right) \left( 1 + \left| \frac{u}{2D_o} \right|^{\alpha\frac{1}{\alpha}} \right) \tag{2-10}
\]

In Equations (2-9) and (2-10) \( \alpha \) is a dimensionless parameter that determines the smoothness of the transition between the two stages of displacement \( u \) being less and more than \( 2D_o \). The effect of parameter \( \alpha \) is seen in Figure 2-4 where the restoring force component of force \( F \) (force given by Equations (2-9) and (2-10) that exclude friction) normalized by \( W \sin \phi / 2 \) or \( W \sin 2\phi / 2 \), for the single and double conical systems, respectively, is presented for various values of the parameter. The value of \( \alpha = 14 \) was selected to best represent smooth behavior. The force-displacement loops of Figure 2-3 have been constructed using the smooth model for the restoring force based on the approximation of Equation (2-9) and using \( \alpha = 14 \).
In modeling the friction force $\mu W\text{sign}(\dot{u})$, $\text{sign}(\dot{u})$ is represented by parameter $Z$ described by the following equation (Mokha et al., 1993):

$$\dot{Z} = \frac{1}{Y}(\dot{u} - 0.1|Z|^2 - 0.9|\dot{u}|Z|Z|)$$  \hspace{1cm} (2-11)

In Equation (2-11), $Y$ is a yield displacement in the visco-plastic representation of friction in this model. An appropriate value for the yield displacement is 1mm or less. Herein the value $Y=1\text{mm}$ is used.

Extension of the model to bi-directional motion with displacement components $u_x$ and $u_y$ and with due consideration for the vertical ground acceleration effect is straightforward based on the model of Mokha et al. (1993) with some additional details in Cilsalar and Constantinou (2017). In the following equations, $F_x$ and $F_y$ are the components of the force acting in the horizontal direction at the top plate of the isolator in the $x$ and $y$ directions, $u_x$ and $u_y$ are the displacement of the top plate with respect to the bottom plate in the two orthogonal directions and $\ddot{u}_{gv}$ is the vertical ground acceleration. Also, $Z_x$ and $Z_y$ are parameters to smoothly approximate the direction cosines of the vector of instantaneous velocity of the top plate with respect to the bottom plate. They are used to represent the components of the friction force in the two orthogonal directions (Mokha et al., 1993). In all equations that follow $\bar{W}$ is the vertical load on the isolator with the vertical ground acceleration effect included.
\[
\bar{W} = W(1 + \frac{\ddot{g}}{g}) 
\]  
\hspace{1cm} (2-12)

Double Concave Rolling Isolator

\[
F_x = \frac{\bar{W}}{2R_{\text{eff}}} u_x + \mu \bar{W} Z_x 
\]  
\hspace{1cm} (2-13)

\[
F_y = \frac{\bar{W}}{2R_{\text{eff}}} u_y + \mu \bar{W} Z_y 
\]  
\hspace{1cm} (2-14)

Single Concave Rolling Isolator

\[
F_x = \frac{\bar{W}}{4R_{\text{eff}}} u_x + \mu \bar{W} Z_x 
\]  
\hspace{1cm} (2-15)

\[
F_y = \frac{\bar{W}}{4R_{\text{eff}}} u_y + \mu \bar{W} Z_y 
\]  
\hspace{1cm} (2-16)

Double Conical Rolling Isolator

\[
F_x = \frac{\bar{W} \sin 2\phi}{2} \left( \frac{u_x}{2D_0} \right) \frac{1}{1 + \left( \frac{u_x}{2D_0} \right)^{2\alpha}} + \mu \bar{W} Z_x 
\]  
\hspace{1cm} (2-17)

\[
F_y = \frac{\bar{W} \sin 2\phi}{2} \left( \frac{u_y}{2D_0} \right) \frac{1}{1 + \left( \frac{u_y}{2D_0} \right)^{2\alpha}} + \mu \bar{W} Z_y 
\]  
\hspace{1cm} (2-18)

Single Conical Rolling Isolator

\[
F_x = \frac{\bar{W} \sin \phi}{2} \left( \frac{u_x}{2D_0} \right) \frac{1}{1 + \left( \frac{u_x}{2D_0} \right)^{2\alpha}} + \mu \bar{W} Z_x 
\]  
\hspace{1cm} (2-19)
Equations (2-15) to (2-18) are valid provided that parameters $D_0$, $R_{\text{eff}}$ and $\phi$ satisfy Equation (2-6), that is, $D_0 = R_{\text{eff}} \sin \phi$.

Parameters $Z_x$ and $Z_y$ are given by the following equations (Park et al., 1985; Mokha et al., 1993):

\[
\dot{Z}_x = \frac{1}{Y} \left( \dot{u}_x - 0.1\dot{u}_y Z_x Z_y - 0.9|\dot{u}_y| Z_y - 0.1\dot{u}_x Z_x^2 - 0.9|\dot{u}_x| Z_x \right)
\]

(2-21)

\[
\dot{Z}_y = \frac{1}{Y} \left( \dot{u}_y - 0.1\dot{u}_x Z_x Z_y - 0.9|\dot{u}_x| Z_x - 0.1\dot{u}_y Z_y^2 - 0.9|\dot{u}_y| Z_y \right)
\]

(2-22)

### 2.4 Selection and Scaling of Ground Motions for Response History Analysis

Analyses were performed to estimate the isolator displacement demands for two locations in Turkey. The first is in Istanbul and the second is in Van. The two locations were selected as being in areas of high seismicity in Turkey on the basis of a draft of the new Turkish Seismic Design Code (TBDY, 2016; Akkar et al., 2017). The new code defines four levels of earthquakes: (a) the Maximum Credible Earthquake or DD-1 level with a 2% of probability of exceedance in 50 years (2475-year return period), (b) the Design Basis Earthquake or DD-2 level with a 10% of probability of exceedance in 50 years (475-year return period), (c) the DD-3 level with a 50% of probability of exceedance in 50 years (72-year return period) and (d) the DD4 level with a 68% of probability of exceedance in 50 years (43-year return period).

Websites ([http://www.deprem.gov.tr/belgeler2016/tbdy.pdf](http://www.deprem.gov.tr/belgeler2016/tbdy.pdf), [https://testtdth.afad.gov.tr/](https://testtdth.afad.gov.tr/); accessed in November 2017) provide information on the seismic parameters for each of these earthquake levels for locations in Turkey based on their coordinates and the soil shear wave velocity. Response spectra in the horizontal and vertical directions are provided. The horizontal spectra are geometric mean spectra and their parameters are defined in the same manner as the parameters defining the shape of the response spectra in ASCE/SEI 7-16 (ASCE, 2017). The vertical response spectra are related to the horizontal response spectra through the use of the vertical to horizontal spectral ratio as function of period.

The site in Istanbul is located at latitude of 41.105° and longitude of 28.784°. It is located at a distance of about 23km from the nearest fault. The site in Van is located at latitude of 38.459° and longitude of 43.344°. It is located at a distance of about 15km from the nearest fault. Figure 2-5 presents the Maximum Credible Earthquake (2475-year return period) 5%-damped horizontal and vertical response spectra for the two sites for a soil type ZD with a shear wave in the upper 30m of soil of 180 to 360m/sec. Important parameters of the horizontal spectra and ground motions of the two locations are the spectral acceleration value at period of 1sec, $S_{D1}$,
the peak ground acceleration, PGA, and the peak ground velocity, PGV. They are (a) for the Istanbul site, $S_{D1}=0.767g$, PGA=0.546g, PGV=341mm/sec and (b) for the Van site, $S_{D1}=0.716g$, PGA=0.487g, PGV=279mm/sec. Both sites are characterized as far-field. On the basis of the spectra in Figure 2-5, the two sites have very close response spectra so that only the site at Istanbul is further considered, assuming that results obtained for the Istanbul site are applicable to the Van site. In general, the response spectra in Figure 2-5 for Istanbul may be considered representative of far-conditions in areas of strong seismicity in Turkey.

![Horizontal, 5% damped][Vertical, 5% damped]

**Figure 2-5 Horizontal (geometric mean) and Vertical Response Spectra at Considered Sites for 2475-Year Return Period Earthquake**

Seven recorded motions were selected for scaling to represent the target horizontal geometric mean spectrum for the Istanbul site in Figure 2-5. The procedure followed the steps below. Note that the scaling does not involve spectral matching and that the same scale factor is used for all three components of each seed motion. That is original ratio of vertical to horizontal spectral values in each seed motion remains the same in the scaled motion.

1) Select seven triplets of recorded ground motion acceleration histories having Magnitude > 6.7 and closest distance of the recording site to the rupture surface ($R_{rup}$) > 10km.

2) Select scale factors for each selected motion such that the average of the scaled geometric mean of the horizontal components closely matches the target spectrum by minimizing the mean square error. The same scale factor is used for both horizontal components of each selected motion. A minimum scale factor of 1.0 and maximum scale factor of 4.0 are used as constraints to limit unrealistically large modification of ground motion records.

3) Compare the average geometric mean spectrum of the scaled motions to the target horizontal spectrum and make adjustments as needed for best matching by multiplying
the factors determined in step 2 by a single factor. The scale factor for each motion is the product of the scale factor from step 2 and the single factor determined in step 3.

4) Compare the average vertical spectrum of the scaled motions to the target vertical spectrum. Use the same scale factor for horizontal and vertical components.

5) Check that horizontal components of the scaled motions satisfy the criteria of Chapter 17 of the ASCE/SEI 7-16 (ASCE, 2017).

The selected ground motions were obtained from the PEER Ground Motion Database (NGA West 2: https://ngawest2.berkeley.edu/; accessed on 01-Nov-2017). Note that the NGA West 2 website is the database for shallow crustal earthquakes in active tectonic regimes worldwide.

The selected ground motions, their characteristics, the scale factors and the values of PGA, PGV and peak ground displacement (PGD) of the scaled motions are presented in Table 2-1. The scale factors used for each ground motions are also presented.

Figure 2-6 compares the average of the geometric mean (geomean) horizontal spectra of the scaled motions, the average vertical spectrum of the scaled motions and the target spectra. The figure demonstrates good matching of the horizontal scaled spectrum to the target spectrum. However, the average vertical spectrum of the scaled motions is substantially conservative for periods larger than about 0.5 sec (by factor of about 2). The vertical component scale factors were not reduced to produce a closer match of the average spectrum to the target spectrum in order to preserve the characteristics of the recorded motions.
Table 2-1 Selected Ground Motions and Scale Factors for Istanbul Site

<table>
<thead>
<tr>
<th>No.</th>
<th>Event</th>
<th>Year</th>
<th>Station</th>
<th>M</th>
<th>$R_{rup}$ (km)</th>
<th>$V_{s30}$ (m/s)</th>
<th>Scale factor</th>
<th>PGA  (g)</th>
<th>PGV   (cm/s)</th>
<th>PGD   (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>68</td>
<td>San Fernando</td>
<td>1971</td>
<td>LA – Hollywood Store FF</td>
<td>6.61</td>
<td>22.77</td>
<td>314.46</td>
<td>4.10</td>
<td>0.92</td>
<td>89.00</td>
<td>65.22</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.80</td>
<td>69.41</td>
<td>52.77</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.67</td>
<td>21.14</td>
<td>16.38</td>
</tr>
<tr>
<td>169</td>
<td>Imperial Valley-06</td>
<td>1979</td>
<td>Delta</td>
<td>6.53</td>
<td>22.03</td>
<td>242.05</td>
<td>2.60</td>
<td>0.61</td>
<td>68.41</td>
<td>38.19</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.91</td>
<td>85.75</td>
<td>52.44</td>
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<td></td>
<td></td>
<td>0.37</td>
<td>39.71</td>
<td>23.68</td>
</tr>
<tr>
<td>174</td>
<td>Imperial Valley-06</td>
<td>1979</td>
<td>El Centro Array #11</td>
<td>6.53</td>
<td>12.56</td>
<td>196.25</td>
<td>2.46</td>
<td>0.90</td>
<td>88.56</td>
<td>61.69</td>
</tr>
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<td></td>
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<td>0.93</td>
<td>109.68</td>
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<td></td>
<td></td>
<td>0.35</td>
<td>28.51</td>
<td>17.74</td>
</tr>
<tr>
<td>721</td>
<td>Superstition Hills-02</td>
<td>1987</td>
<td>El Centro Imp. Co. Cent</td>
<td>6.54</td>
<td>18.20</td>
<td>192.05</td>
<td>2.85</td>
<td>1.02</td>
<td>136.93</td>
<td>54.91</td>
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<td></td>
<td>0.74</td>
<td>119.05</td>
<td>62.27</td>
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<td></td>
<td></td>
<td></td>
<td>0.36</td>
<td>23.50</td>
<td>13.74</td>
</tr>
<tr>
<td>767</td>
<td>Loma Prieta</td>
<td>1989</td>
<td>Gilroy Array #3</td>
<td>6.93</td>
<td>12.82</td>
<td>349.85</td>
<td>2.22</td>
<td>1.24</td>
<td>80.56</td>
<td>24.05</td>
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<td>100.80</td>
<td>53.49</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.76</td>
<td>34.73</td>
<td>15.61</td>
</tr>
<tr>
<td>960</td>
<td>Northridge-01</td>
<td>1994</td>
<td>Canyon Country – W Lost Canyon</td>
<td>6.69</td>
<td>12.44</td>
<td>325.6</td>
<td>2.35</td>
<td>0.95</td>
<td>104.25</td>
<td>26.46</td>
</tr>
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<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>1.11</td>
<td>96.60</td>
<td>34.23</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.71</td>
<td>43.55</td>
<td>12.56</td>
</tr>
<tr>
<td>1602</td>
<td>Duzce, Turkey</td>
<td>1999</td>
<td>Bolu</td>
<td>7.14</td>
<td>12.04</td>
<td>293.57</td>
<td>1.51</td>
<td>1.12</td>
<td>84.42</td>
<td>38.62</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.22</td>
<td>99.43</td>
<td>19.76</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.30</td>
<td>35.42</td>
<td>21.07</td>
</tr>
</tbody>
</table>

PGA, PGV and PGD values are for scaled motions; third row values of PGA, PGV and PGD are for vertical component.
No. is per PEER Ground Motion Database.
2.5 Development of Analysis Tools and Verification

An analysis program was developed in program MATLAB (MATLAB, 2017) based on Equations (2-12) to (2-22) for the analysis of a rigid seismically isolated block. The interest in developing the MATLAB code was for being able to perform parametric studies to obtain displacement and shear force demands and be able to quickly obtain and process results, including the effect of the vertical ground motion (the seismic excitation consisted of the seven scaled triplets of ground acceleration in Table 2-1). The block was symmetrically configured so that torsion was not considered in the analysis.
Moreover, an element was developed and implemented in program OpenSees (McKenna, 1997) to represent the behavior of conical rolling isolators, whereas existing elements in OpenSees were used to model the behavior of concave rolling isolators as they behave in a manner identical to the single friction pendulum isolator. With these elements, program OpenSees can be used for response history analysis of buildings equipped with concave and conical rolling isolators. The developed element is depicted in Figure 2-7. It consists of two nodes that can be connected to any structural element. Between the two nodes, six springs are used to represent the translational and rotational behavior in the axial, two shear, torsion and two rotational bending directions. The location of the shear elements is at the midpoint between the two nodes. The stiffness of the torsional and two rotational springs should be specified by the user to have very small values (actual values are essentially zero) using any uniaxial material in program OpenSees. The axial spring should be defined by the user using the elastic uniaxial material element with zero tensile stiffness and the appropriate compression stiffness. The force-displacement relationship of the springs in the two shear directions is based on numerical solution of Equations (2-17), (2-18), (2-21) and (2-22) for the double conical rolling isolator and Equations (2-19) to (2-22) for the single conical rolling isolator. In these equations, $\bar{W}$ is the axial force in the vertical spring of the element. Accordingly, the element can account for fluctuating vertical load due to overturning moment effects and due to the vertical ground motion effects. Also, the element is capable of capturing P-\(\Delta\) effects when large displacement analysis is activated. Note that the coefficient of friction $\mu$ in Equations (2-13) to (2-22) can be described as a function of velocity and other effects as determined by testing. The version of the model verified and used in the studies reported in this section is based on an assumed constant value for the coefficient of friction.

![Figure 2-7 Representation of Element in Program OpenSees for Conical Rolling Isolators](image)

Figure 2-7 Representation of Element in Program OpenSees for Conical Rolling Isolators

Table 2-2 presents a description of the parameters of the model and the input values used in representing the behavior of the single conical rolling isolator depicted in Figure 2-3.
## Table 2-2 Parameters and Values in OpenSees Model of Sample Single Conical Rolling Isolator

<table>
<thead>
<tr>
<th>User Input Parameters</th>
<th>Data type</th>
<th>Description (value used in analysis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element tag</td>
<td>Integer</td>
<td>Unique element tag that defines the element number of isolator in the model</td>
</tr>
<tr>
<td>Node tag 1</td>
<td>Integer</td>
<td>Unique tag for Node 1 in global coordinates</td>
</tr>
<tr>
<td>Node tag 2</td>
<td>Integer</td>
<td>Unique tag for Node 2 in global coordinates</td>
</tr>
<tr>
<td>μ</td>
<td>Double</td>
<td>Constant friction coefficient (0.05 or 0.10)</td>
</tr>
<tr>
<td>Do</td>
<td>Double</td>
<td>Calculated internally as $D_o = R_{eff} \sin(\phi)$</td>
</tr>
<tr>
<td>$R_{eff}$</td>
<td>Double</td>
<td>Effective radius of spherical part (375mm)</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Double</td>
<td>Slope of conical part (0.2rad)</td>
</tr>
<tr>
<td>$k_{in}$</td>
<td>Double</td>
<td>Initial stiffness in visco-plastic representation of friction. Use value $\frac{\mu W}{Y}$ where $Y$ is the yield displacement in Equations (2-20) and (2-21). Use $Y=1\text{mm}$ or less. ($Y=1\text{mm}$)</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Double</td>
<td>Smoothness in force response in transition from spherical to conical part. Suggested value 14. (14)</td>
</tr>
<tr>
<td>Material tag 1</td>
<td>Integer</td>
<td>Unique material tag for axial spring</td>
</tr>
<tr>
<td>Material tag 2</td>
<td>Integer</td>
<td>Unique material tag for torsional spring</td>
</tr>
<tr>
<td>Material tag 3</td>
<td>Integer</td>
<td>Unique material tag for rotational spring in direction 2</td>
</tr>
<tr>
<td>Material tag 4</td>
<td>Integer</td>
<td>Unique material tag for rotational spring in direction 3</td>
</tr>
<tr>
<td>x</td>
<td>3x1 vector double</td>
<td>Vector that defines orientation of isolator in x local coordinates ($[1 0 0]^T$)</td>
</tr>
<tr>
<td>y</td>
<td>3x1 vector double</td>
<td>Vector that defines orientation of isolator in y local coordinates ($[0 1 0]^T$)</td>
</tr>
<tr>
<td>Shear Distance</td>
<td>Double</td>
<td>Parameter that defines the shear location of isolator as fraction of length (between 0 and 1, 0.5 for mid-point) (0.5)</td>
</tr>
<tr>
<td>Rayleigh</td>
<td>Integer</td>
<td>Parameter to account for isolator in construction of damping matrix (Rayleigh damping). 1 for accounting, 0 for neglecting. (0)</td>
</tr>
<tr>
<td>Mass</td>
<td>Double</td>
<td>Mass of isolator. If mass is assigned, two nodes are assigned half of the mass as lumped mass. (0)</td>
</tr>
<tr>
<td>Maximum iteration</td>
<td>Integer</td>
<td>Number of maximum iterations for convergence in friction model. (100)</td>
</tr>
<tr>
<td>Tolerance</td>
<td>Double</td>
<td>Tolerance for convergence. (1.0e^{-12})</td>
</tr>
</tbody>
</table>

The developed OpenSees model was verified by comparing force-displacement loops and isolator displacement histories obtained in the analysis of a rigid block on four single conical isolators to the same quantities obtained from the direct integration of the equations of motion in the MATLAB program. For the analysis, three-component motions were used from Table 2-1, as scaled to represent the response spectrum of the Istanbul site. Results are presented in Figures 2-8 to 2-11 for two of these motions (stations El Centro Array #11 and El Centro Imp. 21.
Co. Cent) and for single conical rolling isolators with parameters $R_{eff}=375\text{mm}$, $D_o=75\text{mm}$, $\phi=0.2\text{rad}$ and $\mu=0.05$ or $0.10$. Force-displacement loops (force normalized by weight $W$) and isolator displacement histories in the X and Y horizontal directions are presented and compared. The results obtained by the OpenSees model are identical to those obtained by direct integration of the equations of motion in MATLAB.

$\phi=0.2\text{ rad}, R_{eff}=375\text{ mm}, D_o=75\text{mm}, \mu=0.05$

![Comparison of Normalized Force-displacement Loops and Displacement Histories Obtained for Scaled El Centro Array #11 Motion for Single Conical System with $\mu=0.05$ (with vertical input)](image)

Figure 2-8 Comparison of Normalized Force-displacement Loops and Displacement Histories Obtained for Scaled El Centro Array #11 Motion for Single Conical System with $\mu=0.05$ (with vertical input)
Figure 2-9 Comparison of Normalized Force-displacement Loops and Displacement Histories Obtained for Scaled El Centro Array #11 Motion for Single Conical System with $\mu=0.10$ (with vertical input)
Figure 2-10 Comparison of Normalized Force-displacement Loops and Displacement Histories Obtained for Scaled El Centro Imp. Co. Cent Motion for Single Conical System with $\mu=0.05$ (with vertical input)
Furthermore, for verification of the OpenSees isolator model and the MATLAB analysis program, the results of the analyses in Figures 2-8 to 2-11 were compared to results obtained in program SAP2000 (Computers and Structures, 2018) in the case of only horizontal excitation as the vertical ground motion effects could not be properly considered in the single conical isolator.
model in SAP2000. The representation of the rigid block with four single conical isolators in SAP2000 consisted of four very stiff beams supported by four flat sliding bearings representing the frictional behavior of the isolation system. Additionally, four bilinear elastic springs were located at the flat sliding bearing locations to represent the horizontal restoring force of the isolators as given by Equation (2-10) for the considered single conical rolling isolators (Equation (2-9) applies for the double conical rolling isolator). The vertical stiffness of these springs was assigned a zero value so that the weight of the block was entirely carried by the flat sliding bearings so that the frictional force was correctly modelled. The horizontal stiffness was represented with the MultiLinear Plastic link element of SAP2000. The force-displacement relationship of this element can be described by users. The element was assigned to have elastic behavior up to a displacement equal to $2D_o=2R_{eff}\sin(\phi)$ and a force (“yield force”) equal to $W\sin(\phi)/2$. Beyond the displacement limit of $2D_o$, the force remained constant at the “yield value”. That is, in the model in SAP2000 the behavior sharply changes from elastic to one of constant force as shown in Figure 2-4 for the case of $\alpha=100$. The model does not account for the effect of the fluctuating vertical load on the restoring force. Accordingly, the vertical ground motion was not included in the analyses that are presented next. Results in Figures 2-12 to 2-15 compare force-displacement loops and displacement histories as computed in SAP2000, OpenSees and MATLAB. The results obtained by the three different methods of analysis are nearly identical, thus completing the verification of the OpenSees element of the MATLAB code.
Figure 2-12 Comparison of Normalized Force-displacement Loops and Displacement Histories Obtained for Scaled El Centro Array #11 Motion for Single Conical System with $\mu=0.05$ (without vertical input)
Figure 2-13 Comparison of Normalized Force-displacement Loops and Displacement Histories Obtained for Scaled El Centro Array #11 Motion for Single Conical System with $\mu=0.10$ (without vertical input)
Figure 2-14 Comparison of Normalized Force-displacement Loops and Displacement Histories Obtained for Scaled El Centro Imp. Co. Cent Motion for Single Conical System with $\mu=0.05$ (without vertical input)
Figure 2-15 Comparison of Normalized Force-displacement Loops and Displacement Histories obtained for Scaled El Centro Imp. Co. Cent Motion for Single Conical System with $\mu=0.10$ (without vertical input)
2.6 Analysis to Determine Displacement Demands and Base Shear Forces

Response history analysis was conducted with the rigid block model in MATLAB to compute displacements and base shear forces using the scaled motions of Table 2-1 for the Istanbul site for a) a single conical rolling system with parameters: $\phi=0.2\text{ rad}, R_{\text{eff}}=375\text{ mm}, D_o=75\text{ mm}$ and $\mu=0.05$ or $\mu=0.10$, and b) a single concave rolling system with parameters: $R_{\text{eff}}=1000\text{ mm}$ or $1750\text{ mm}$ and $\mu=0.05$ or $\mu=0.10$.

All three components of ground motions were used in the analysis. Peak resultant isolator displacement and base shear force results are presented in Tables 2-3 to 2-6. Residual displacements are also presented. Note that some residual displacement develops in the conical rolling system because of the existence of the spherical part of the isolator.

Table 2-3 Analysis Results for Single Conical Rolling System with $\phi=0.2\text{ rad}, R_{\text{eff}}=375\text{ mm}, D_o=75\text{ mm}, \mu=0.05$

<table>
<thead>
<tr>
<th>Ground Motion Number</th>
<th>Resultant Displacement (mm)</th>
<th>Resultant Base Shear/W</th>
<th>Resultant Residual Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>68</td>
<td>1162.6</td>
<td>0.21</td>
<td>0.4</td>
</tr>
<tr>
<td>169</td>
<td>608.3</td>
<td>0.20</td>
<td>6.1</td>
</tr>
<tr>
<td>174</td>
<td>732.6</td>
<td>0.23</td>
<td>4.2</td>
</tr>
<tr>
<td>721</td>
<td>828.7</td>
<td>0.24</td>
<td>10.8</td>
</tr>
<tr>
<td>767</td>
<td>621.0</td>
<td>0.23</td>
<td>2.4</td>
</tr>
<tr>
<td>960</td>
<td>509.7</td>
<td>0.24</td>
<td>7.0</td>
</tr>
<tr>
<td>1602</td>
<td>481.5</td>
<td>0.22</td>
<td>2.3</td>
</tr>
<tr>
<td>Average</td>
<td>706.4</td>
<td>0.22</td>
<td>4.7</td>
</tr>
</tbody>
</table>

Table 2-4 Analysis Results for Single Conical Rolling System with $\phi=0.2\text{ rad}, R_{\text{eff}}=375\text{ mm}, D_o=75\text{ mm}, \mu=0.10$

<table>
<thead>
<tr>
<th>Ground Motion Number</th>
<th>Resultant Displacement (mm)</th>
<th>Resultant Base Shear/W</th>
<th>Resultant Residual Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>68</td>
<td>592.1</td>
<td>0.24</td>
<td>6.9</td>
</tr>
<tr>
<td>169</td>
<td>393.7</td>
<td>0.21</td>
<td>18.4</td>
</tr>
<tr>
<td>174</td>
<td>533.8</td>
<td>0.27</td>
<td>3.3</td>
</tr>
<tr>
<td>721</td>
<td>768.7</td>
<td>0.31</td>
<td>6.0</td>
</tr>
<tr>
<td>767</td>
<td>503.1</td>
<td>0.27</td>
<td>2.8</td>
</tr>
<tr>
<td>960</td>
<td>382.6</td>
<td>0.33</td>
<td>2.7</td>
</tr>
<tr>
<td>1602</td>
<td>350.0</td>
<td>0.26</td>
<td>0.8</td>
</tr>
<tr>
<td>Average</td>
<td>503.5</td>
<td>0.27</td>
<td>5.9</td>
</tr>
</tbody>
</table>
Table 2-5 Analysis Results for Single Concave Rolling System with $R_{eff}=1000$ mm and $R_{eff}=1750$ mm, $\mu=0.05$

<table>
<thead>
<tr>
<th>Ground Motion Number</th>
<th>$R_{eff}=1000$ mm</th>
<th>$R_{eff}=1750$ mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Resultant Displacement (mm)</td>
<td>Resultant Base Shear/W</td>
</tr>
<tr>
<td>68</td>
<td>1200.5</td>
<td>0.36</td>
</tr>
<tr>
<td>169</td>
<td>479.1</td>
<td>0.18</td>
</tr>
<tr>
<td>174</td>
<td>565.4</td>
<td>0.20</td>
</tr>
<tr>
<td>721</td>
<td>802.9</td>
<td>0.28</td>
</tr>
<tr>
<td>767</td>
<td>472.5</td>
<td>0.21</td>
</tr>
<tr>
<td>960</td>
<td>431.7</td>
<td>0.16</td>
</tr>
<tr>
<td>1602</td>
<td>306.2</td>
<td>0.12</td>
</tr>
<tr>
<td>Average</td>
<td>608.3</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Table 2-6 Analysis Results for Single Concave Rolling System with $R_{eff}=1000$ mm and $R_{eff}=1750$ mm, $\mu=0.10$

<table>
<thead>
<tr>
<th>Ground Motion Number</th>
<th>$R_{eff}=1000$ mm</th>
<th>$R_{eff}=1750$ mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Resultant Displacement (mm)</td>
<td>Resultant Base Shear/W</td>
</tr>
<tr>
<td>68</td>
<td>536.8</td>
<td>0.26</td>
</tr>
<tr>
<td>169</td>
<td>341.8</td>
<td>0.18</td>
</tr>
<tr>
<td>174</td>
<td>436.1</td>
<td>0.25</td>
</tr>
<tr>
<td>721</td>
<td>672.6</td>
<td>0.31</td>
</tr>
<tr>
<td>767</td>
<td>396.9</td>
<td>0.26</td>
</tr>
<tr>
<td>960</td>
<td>354.1</td>
<td>0.20</td>
</tr>
<tr>
<td>1602</td>
<td>231.8</td>
<td>0.17</td>
</tr>
<tr>
<td>Average</td>
<td>424.3</td>
<td>0.23</td>
</tr>
</tbody>
</table>
SECTION 3
DESCRIPTION AND PROPERTIES OF TESTED ISOLATOR

3.1 Introduction

Several alternate rolling isolator configurations and properties were presented and investigated in Section 2. Based on the results of the analysis, including dynamic response history analysis for determining isolator displacements, base shear and residual displacements, a selection was made for the single concave rolling isolator having a radius of curvature equal to 1850mm, a concave depression diameter equal to 700mm and a rolling ball of 254mm diameter. The decision to select the single rolling configuration was based on cost considerations as one of the two plates needed would be flat and easily cast in concrete. Moreover, the single rolling configuration offers lower stiffness but has the same displacement capacity as a double rolling configuration for the same plan dimensions. The decision to select the concave shape rather than the conical shape was based on the results of analysis in Section 2 which are summarized in Table 3-1. Evidently, the concave configuration offers lower isolator displacements and base shear force at the expense of larger residual displacements. Isolator residual displacements that do not accumulate do not affect performance and are just a serviceability issue.

Table 3-1 Summary of Dynamic Analysis Results for Istanbul Location in 2475-Year Return Period Earthquake

<table>
<thead>
<tr>
<th>Friction Coefficient</th>
<th>Single Conical Rolling System $\phi=0.2$rad, $R_{eff}=375$ mm, $D_o=75$mm</th>
<th>Single Concave Rolling System $R_{eff}=1750$ mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Isolator Disp. (mm)</td>
<td>Base Shear /Weight</td>
</tr>
<tr>
<td>0.05</td>
<td>706</td>
<td>0.22</td>
</tr>
<tr>
<td>0.10</td>
<td>504</td>
<td>0.27</td>
</tr>
</tbody>
</table>

The analysis results in Table 3-1 were based on the assumption that the rolling ball is rigid. In reality, the rolling ball will deform under vertical load resulting in rolling friction that depends on the vertical load and higher stiffness than predicted by the theory in Section 2. Moreover, it will be demonstrated in this section that the deformability of the rolling ball results in a large effective yield displacement. These conditions result in essentially nil residual displacements. Accordingly, the results in Table 3-1 are slightly conservative in terms of displacements but slightly un-conservative in terms of the base shear force. This observation further supports the decision to concentrate on the concave system which resulted in the least base shear force.

3.2 Description and Construction of Isolator

The isolator built for testing is full size with a displacement capacity of about 550mm when it first engages its displacement restraint system and an ultimate displacement capacity of about 650mm. The displacement capacity depends on the location of the restraint system, the stiffness
of the rolling ball (hardness of material and use of reinforcement) and the vertical load as it affects the ball deformation.

The isolator was made out of high strength concrete. It featured a displacement restraint in the form of square 50mm steel tubing, 400mm long, connected to the top and bottom plates using shear lugs embedded in the concrete plates. The tubing was only placed in one direction (that of testing). A complete multi-directional displacement restraint should be in the form of a ring or in the form of an octagon (the form built is that of an octagon with only two sides installed). The restraint system was connected to the shear lugs at two different locations (affecting the gap size). Figures 3-1 and 3-2 shows sections and plans of the bearing parts. Figure 3-2 shows the geometry of a shear lug. Figure 3-4 shows a three-dimensional representation of the built isolator.

![Figure 3-1 Section and Plan of Bottom Concave Plate of Built Isolator](image-url)
Figure 3-2 Section and Plan of Top Flat Plate of Built Isolator

Figure 3-3 Typical Shear Lug and Connection Detail for Bottom Concave Plate
The top and bottom plates were cast in Ultra High Performance Concrete (UHPC) in order to achieve high compressive strength and to be able to sustain high contact stresses in repeated testing. Ingredients of the UHPC were cement, sand, slag, silica fume, high range water reducing admixture (HRWRA), fibers, and water. The exact composition and method of preparation was based on Ranade et al (2013) and Ragalwar et al (2016). A compressive strength of 100MPa was aimed and it was required to have very low water to cement ratio to reach the desired strength. This made it necessary to use HRWRA and reduce the water to cement ratio to 0.33. As a result, the hydration temperature of the concrete was significantly higher than that of conventional mixtures. The addition of fibers reduced any damaging effect of high temperature during the early stage of hydration in addition to improving the strength. Nevertheless, nominal steel reinforcement was added primarily to be able to sustain the forces at
the shear lugs and for lifting and transporting the parts. This reinforcement was in the form of 75mm x 75mm grid deformed 4.5mm diameter wire mesh. Figure 3-5 shows the mold of the bottom concave plate after pouring concrete. The shear lugs and steel mesh reinforcement are on top of a solid foam convex shape used to provide the desired concave surface. The use of the solid foam convex shape facilitated the shaping of the concave surface of the bearing but could not be repeatedly used as it was damaged during removal. Steel forms should be used for mass production.

When concrete was cast, 50mm cube specimens were also cast from the same mixture in order to test for their strength. Table 3-2 presents values of the cube strength obtained after 7, 14 and 28 days. After 28 days, the concrete average strength was 120 MPa.

**Table 3-2 Strength of Concrete Cube Specimens**

<table>
<thead>
<tr>
<th>Day</th>
<th>Number Tested</th>
<th>Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>1</td>
<td>82</td>
</tr>
<tr>
<td>14</td>
<td>1</td>
<td>89</td>
</tr>
<tr>
<td>28</td>
<td>3</td>
<td>117,120,125</td>
</tr>
</tbody>
</table>
The rolling balls were cast in urethane (Adiprene) either solid or with a steel core reinforcement. The core was solid steel sphere of 127mm diameter. Table 3-3 presents information on the hardness of the material and geometry of the balls. Figure 3-6 shows images of the four balls.

### Table 3-3 Rolling Ball Geometry and Material Hardness

<table>
<thead>
<tr>
<th>Hardness</th>
<th>Configuration</th>
<th>Ball Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shore 95A</td>
<td>Solid</td>
<td>245</td>
</tr>
<tr>
<td></td>
<td>127 mm Steel Core</td>
<td>245</td>
</tr>
<tr>
<td>Shore 62D</td>
<td>Solid</td>
<td>245</td>
</tr>
<tr>
<td></td>
<td>127 mm Steel Core</td>
<td>245</td>
</tr>
</tbody>
</table>

**Figure 3-6 Images of Rolling Balls**

Figures 3-7 and 3-8 show views of one isolator in the bearing testing machine. In Figure 3-8 the rolling ball is shown pressing against the displacement restraints.

**Figure 3-7 View of Isolator in Bearing Testing Machine (Case of Solid 95A Ball)**
3.3 Testing Equipment

The isolator was tested in combined compression and shear in the small bearing test machine at the University at Buffalo. Figure 3-9 shows a schematic of the machine and Figure 3-10 a view of the machine during testing of a bearing for this project. This machine is capable of 150mm lateral displacement amplitude (limited to 125mm in cyclic dynamic testing for safety reasons), 50mm vertical displacement amplitude, vertical load of up to 310kN and horizontal load of up to 245kN. The machine is capable of dynamic testing with peak velocities in the conducted tests reaching 235mm/sec.

![Figure 3-9 Schematic of Bearing Testing Machine at the University at Buffalo (units: mm)](image_url)
The rolling balls were first tested in compression to determine their stiffness and to study their creep characteristics. Figure 3-11 shows a view of a rolling ball in the equipment used for the compression testing. The equipment is a MTS Axial-Torsion machine with a compression capacity of 445kN.
3.4 Behavior in Compression

Each rolling ball was subjected to vertical load of 133.5kN over a period of 5 minutes and then again over one hour while the vertical displacement was continuously measured. Moreover, tests with load dwell of six hours (maximum permitted in one day of continuous testing based on laboratory rules) were conducted only for the two rolling balls with steel cores as being the two recommended for application. Following the sustained compression, three cycles of force were applied so the force varied between 89kN and 178kN with frequency of 0.025 Hz. This enabled the measurement of the vertical stiffness. Figures 3-12 to 3-21 present the recorded histories of vertical force and displacement, force-displacement curves and the measured values of stiffness for each of the tests. The reported values of stiffness include the initial stiffness useful in calculating the elastic deformation and the vertical stiffness determined in the cyclic tests and useful in dynamic analysis calculations.

![Figure 3-12 Histories of Vertical Force and Vertical Displacement and Force-displacement Curve in Compression of 95A Solid Ball in Test with Five Minute Load Dwell](image-url)
Figure 3-13 Histories of Vertical Force and Vertical Displacement and Force-displacement Curve in Compression of 95A Solid Ball in Test with One Hour Load Dwell
Figure 3-14 Histories of Vertical Force and Vertical Displacement and Force-displacement Curve in Compression of 95A Ball with Steel Core in Test with Five Minute Load Dwell
Figure 3-15 Histories of Vertical Force and Vertical Displacement and Force-displacement Curve in Compression of 95A Ball with Solid Core in Test with One Hour Load Dwell

Vertical Stiffness = 11.5 kN/mm
Initial Stiffness = 3.2 kN/mm
Figure 3-16 Histories of Vertical Force and Vertical Displacement and Force-displacement Curve in Compression of 62D Solid Ball in Test with Five Minute Load Dwell

Vertical Stiffness = 16.7 kN/mm
Initial Stiffness = 6.4 kN/mm
Figure 3-17 Histories of Vertical Force and Vertical Displacement and Force-displacement Curve in Compression of 62D Solid Ball in Test with One Hour Load Dwell
Figure 3-18 Histories of Vertical Force and Vertical Displacement and Force-displacement Curve in Compression of 62D Ball with Steel Core in Test with Five Minute Load Dwell
Figure 3-19 Histories of Vertical Force and Vertical Displacement and Force-displacement Curve in Compression of 62D Ball with Steel Core in Test with One Hour Load Dwell
Figure 3-20 Histories of Vertical Force and Vertical Displacement and Force-displacement Curve in Compression of 95A Ball with Steel Core in Test with Six Hour Load Dwell

Vertical Stiffness=12.3 kN/mm
Initial Stiffness=3.2 kN/mm
Table 3-4 presents results on the vertical and initial stiffness, where it is evident that the vertical stiffness is larger in the tests with longer load dwell. The difference is due to differences in the shape of the rolling balls that resulted from additional creep in the longer load dwell tests. Based on the small difference in the measured values of the vertical stiffness between the cases of one and six hour load dwell (differences of 1 to 6%), creep is essentially complete after about one hour.

The data in Figures 3-12 to 3-21 are useful in estimating the creep displacement as portion of the elastic displacement. Based on the data for the six-hour load dwell tests and also utilizing information on the elastic displacement from the other tests, we estimated the creep displacement to be:
1) For the 95A rolling with steel core at load of 133.5kN, 46% of the elastic displacement. 
2) For the 62D rolling with steel core at load of 133.5kN, 73% of the elastic displacement.

These values of creep displacement are consistent with published data on creep of Adiprene in du Pont (1976).

### Table 3-4 Stiffness of Rolling Balls at Load of 133.5kN

<table>
<thead>
<tr>
<th>Rolling Ball</th>
<th>Five Minute Load Dwell Test</th>
<th>One Hour Load Dwell Test</th>
<th>Six Hour Load Dwell Test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial Stiffness (kN/mm)</td>
<td>Vertical Stiffness (kN/mm)</td>
<td>Initial Stiffness (kN/mm)</td>
</tr>
<tr>
<td>95A Hardness Solid</td>
<td>2.8</td>
<td>6.8</td>
<td>2.8</td>
</tr>
<tr>
<td>95A Hardness with Steel Core</td>
<td>3.2</td>
<td>10.2</td>
<td>3.2</td>
</tr>
<tr>
<td>62D Hardness Solid</td>
<td>6.4</td>
<td>16.7</td>
<td>6.4</td>
</tr>
<tr>
<td>62D Hardness with Steel Core</td>
<td>5.9</td>
<td>21.8</td>
<td>5.9</td>
</tr>
</tbody>
</table>

### 3.5 Behavior in Combined Compression and Shear

The bearing with four different rolling balls was tested in combined compression and imposed lateral motion under the conditions presented in Table 3-5. Figure 3-22 shows a sample of the history of vertical load and measured vertical displacement in a test with specified load of 133.5kN at frequency of 0.01Hz. Figure 3-23 presents the histories of the imposed lateral displacement in each of the tests at three different frequencies. The displacement amplitude was 125mm (test machine capacity was 150mm but a smaller value was specified for safety). Note that the vertical load was maintained on the bearing for about seven minutes prior to initiating the lateral motion so that most creep effects were essentially completed. Also, each test consisted of 2.5 cycles at the specified frequency.

During testing the following quantities were measured: time, horizontal actuator displacement and force, and the force and displacement of the two vertical actuators. There was no direct measurement of the force transmitted through the tested bearing. While the bearing was supported by a load cell, the cell was not functional. The shear force transmitted through the tested bearing was obtained from the measured horizontal and vertical actuator forces as follows and with reference to Figure 3-24, which shows the bearing testing machine in a state of deformation. The quantities measured are the horizontal actuator displacement \( u_h \), the horizontal actuator force \( F_h \), the vertical actuator forces \( F_v \), and \( F_{vn} \), and the vertical actuator displacement \( u_v \) (the two vertical actuators move in unison so that they have the same displacement). As a result of these motions, the horizontal and vertical actuators continually change inclinations as shown in Figure 3-24.
### Table 3-5 Test Matrix for Combined Compression and Shear Tests

<table>
<thead>
<tr>
<th>Rolling Ball</th>
<th>Vertical Load (kN)</th>
<th>Frequency (Hz)</th>
<th>Amplitude (mm)</th>
<th>Peak Velocity (mm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness 95A</td>
<td>133.5</td>
<td>0.01, 0.1, 0.3</td>
<td>125</td>
<td>8, 79, 236</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hardness 95A with steel core</td>
<td>22</td>
<td>0.01</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>133.5</td>
<td>0.01, 0.1, 0.3</td>
<td>125</td>
<td>8, 79, 236</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>0.01</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>Hardness 62D</td>
<td>22</td>
<td>0.01</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>133.5</td>
<td>0.01, 0.1, 0.3</td>
<td>125</td>
<td>8, 79, 236</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>0.01</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>Hardness 62D with steel core</td>
<td>22</td>
<td>0.01</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>133.5</td>
<td>0.01, 0.1, 0.3</td>
<td>125</td>
<td>8, 79, 236</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>0.01</td>
<td></td>
<td>8</td>
</tr>
</tbody>
</table>

**Figure 3-22 History of Vertical Load and Vertical Displacement in Test with 95A Solid Ball, Load of 133.5kN and Frequency of 0.01Hz**

Vertical Displacement (mm) vs. Time (sec)

Vertical Load (kN) vs. Time (sec)
Test at \( f=0.01 \text{Hz} \)

Test at \( f=0.1 \text{Hz} \)

Test at \( f=0.3 \text{Hz} \)

Figure 3-23 Histories of Horizontal Displacement in Tests at Various Frequencies
Based on equilibrium and with reference to Figure 3-24, the force $V$ transmitted through the tested bearing and the vertical force on the tested bearing $P$ are given by

$$V = F_h \cos(\theta_h) - F_{vs} \sin(\theta_s) - F_{vn} \sin(\theta_n) \tag{3-1}$$

$$P = F_{vs} \cos(\theta_s) + F_{vn} \cos(\theta_n) - F_h \sin(\theta_h) \tag{3-2}$$

where $\theta_s$, $\theta_n$, and $\theta_h$ are the angles of inclinations

$$\theta_s = \sin^{-1} \left( \frac{u_h}{L_s'} \right) \tag{3-3}$$

$$\theta_n = \sin^{-1} \left( \frac{u_h}{L_n'} \right) \tag{3-4}$$

$$\theta_h = \sin^{-1} \left( \frac{u_v}{L_h'} \right) \tag{3-5}$$

In these equations, $L_s'$ and $L_n'$ are the instantaneous lengths between the pivot points of the two vertical actuators and $L_h'$ is the instantaneous length of the horizontal actuator between the pivot points. These lengths vary on the basis of the following equations:

$$L_s' = L_o - u_{vs} \tag{3-6}$$

$$L_n' = L_o - u_{vn} \tag{3-7}$$

$$L_h' = L_{h0} + u_h \tag{3-8}$$

In these equations $L_o$ and $L_{h0}$ are the starting values of the vertical and horizontal actuator lengths between the pivot points. Equation (3-1) does not include the inertia force of the moving
loading beam of the test machine. This force was too small to have an effect owing to the small accelerations of the moving beam. The peak acceleration during dynamic testing at 0.3Hz is less than 0.05g, leading to an inertia force of less than 0.7kN. Note that the imposed lateral displacement (see Figure 3-23) included a slow motion towards the displacement amplitude from where the dynamic motion started. This avoids the generation of high accelerations when dynamic sinusoidal motion starts from the position of zero displacement.

Representative force-displacement loops for the tested bearing are presented in Figures 3-25 to 3-28 for the case of the 133.5kN load at frequency of 0.1Hz in the four cases of rolling balls. The force is normalized by the instantaneous vertical force. A complete set of loops for all tests is presented in Appendix A.
The loops in these figures and in Appendix A demonstrate small effects of frequency, vertical load and type of rolling ball (representing different vertical stiffness and contact areas) on the rolling friction. However, there are important effects of the type of rolling ball and of frequency on the tangent stiffness of the bearings. For the normalized loops as shown in Figures 3-25 to 3-28 the theoretical value of the normalized tangent stiffness is derived from Equation (2-3) as

\[ \frac{K}{W} = 1/(4R_{\text{eff}}) \]

where \( R_{\text{eff}} \) is the effective radius calculated as the actual radius of curvature (=1850mm) minus half of the height of the deformed rolling ball. If the ball is rigid, the height is 254mm for which \( R_{\text{eff}} = 1723 \)mm. Each of Figures 3-25 to 3-28 includes a red line to denote the actual tangent stiffness. The ratio of the stiffness obtained from the slopes of the red lines in these figures to the theoretical stiffness is the Stiffness Modification Factor, \( S_m \), which is reported in Table 3-6.
Table 3-6 Stiffness Modification Values

<table>
<thead>
<tr>
<th>Rolling Ball</th>
<th>Vertical Load (kN)</th>
<th>Frequency (Hz)</th>
<th>Stiffness Modification Factor $S_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>95A Solid</td>
<td>133.5</td>
<td>0.01</td>
<td>2.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.10</td>
<td>2.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.30</td>
<td>3.65</td>
</tr>
<tr>
<td>95A with Steel Core</td>
<td>200.0</td>
<td>0.01</td>
<td>2.45</td>
</tr>
<tr>
<td>62D Solid</td>
<td>133.5</td>
<td>0.01</td>
<td>2.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.10</td>
<td>1.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.30</td>
<td>2.95</td>
</tr>
<tr>
<td>62D with Steel Core</td>
<td>200.0</td>
<td>0.01</td>
<td>1.65</td>
</tr>
</tbody>
</table>

Values of the rolling friction coefficient were also obtained for each test and cycle of test as the average zero displacement normalized force intercept in the normalized loops of Appendix A. Values are presented in Table 3-7. The results show that the coefficient of rolling friction is effectively independent of the frequency of motion and that it slightly increases as the vertical load is increased. For the case of the 62D ball with or without steel core, the friction values are about 0.09 for load of 133.5kN and about 0.12 for load of 200kN, with a nominal value of friction for all loads up to 200kN of 0.10.
### Table 3-7 Rolling Friction Values

<table>
<thead>
<tr>
<th>Rolling Ball</th>
<th>Vertical Load (kN)</th>
<th>Frequency (Hz)</th>
<th>Friction Coefficient (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>95A Solid</td>
<td>133.5</td>
<td>0.01</td>
<td>8.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.10</td>
<td>9.70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.30</td>
<td>9.80</td>
</tr>
<tr>
<td>200.0</td>
<td>0.01</td>
<td>9.80</td>
<td></td>
</tr>
<tr>
<td>95A with Steel Core</td>
<td>133.5</td>
<td>0.01</td>
<td>7.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.10</td>
<td>8.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.30</td>
<td>8.50</td>
</tr>
<tr>
<td>200.0</td>
<td>0.01</td>
<td>9.00</td>
<td></td>
</tr>
<tr>
<td>62D Solid</td>
<td>133.5</td>
<td>0.01</td>
<td>8.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.10</td>
<td>8.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.30</td>
<td>8.40</td>
</tr>
<tr>
<td>200.0</td>
<td>0.01</td>
<td>12.0</td>
<td></td>
</tr>
<tr>
<td>62D with Steel Core</td>
<td>133.5</td>
<td>0.01</td>
<td>8.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.10</td>
<td>8.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.30</td>
<td>8.70</td>
</tr>
<tr>
<td>200.0</td>
<td>0.01</td>
<td>12.0</td>
<td></td>
</tr>
</tbody>
</table>

### 3.6 Behavior when Engaging the Displacement Restraint

Testing at large displacements exceeding about 500mm in order to engage the displacement restraint was not possible in the available bearing testing machine which was limited to displacements of 250mm if only one-directional motion was used or 125mm if cyclic motion was used (actual are 300mm and 150mm, respectively, but lesser displacements could be used for safety). Instead, the bearing was “pre-deformed” by moving the top plate forward and the bottom plate backwards in the testing machine as seen in the images of Figure 3-29. The first image shows the bearing prior to inserting the rolling ball. In the second image, the ball (95A solid) has been inserted and the vertical load of 133.5kN has been applied while the horizontal actuator maintained the position of the bearing. Thereafter, motion was applied until the displacement restraint was fully engaged and it was resisting with large lateral force, followed by motion in the opposite direction to complete one loop.

Two configurations of the displacement restraint were used in testing. The first is as shown in Figures 3-1 to 3-4. In this configuration, there is a gap of 50mm between the side of the displacement restraint (tube) and the edge of the concave surface (referred to as (50mm gap” configuration). In the second configuration, the gap has been eliminated by using two square tubes instead of one (referred to as “zero gap” configuration). Figure 3-30 shows sections of the bearing with the two gap configurations of the displacement restraint system and Figure 3-31 shows a bearing tested in the zero gap displacement restraint configuration.

Testing was conducted at vertical load of 133.5kN and using the four rolling balls, for a total of eight tests. Figures 3-32 and 3-33 present the recorded vertical load and vertical displacement histories, and the force-displacement loops in the tests with solid 95A ball in the tests of the
50mm and zero gap configurations. A complete set of results is presented in Appendix B. The figures present the force-displacement loops as recorded (starting at zero displacement) and then again shifted by adding the displacement at which the bearing was pre-deformed at the start of each test. These shifted loops are then compared to the loops recorded in the cyclic testing of the same bearing when the tests started in the un-deformed position when there was no restraint. It may be seen that the loops of the two tests, with and without the restraint, are in good agreement, providing thus validity to the test results with the restraint.

The results in Figures 3-32 and 3-33 and in Appendix B show that the bearing with the 50mm gap restraint configuration has a displacement capacity at initiation of stiffening of about 560mm when the 95A ball is used (solid or with steel core) and about 580mm when the 62D ball is used (solid or with steel core). When the zero gap restraint configuration is used, the displacement capacities at initiation of stiffening reduce to about 450mm and 475mm in the 95A and 62D ball cases, respectively. The increased displacement capacity when the stiffer 62D ball is used is due to the fact that the ball has less lateral expansion on the application of the vertical load and thus more space to roll towards the restraint. Table 3-8 provides a summary of capacities and stiffness for the tested bearings. The ultimate displacement capacity of the bearings was not determined in the tests. It was apparent in the tests that the bearings would continue resisting motion with increasing force after engagement of the displacement restraint until failure of the rolling ball or of the restraint. It appeared impossible for the ball to rise and roll-over the restraining tubes. Based on the geometry of the balls under deformation, there is capacity for the bearing to deform beyond the stiffening limits in Table 3-8 that exceeds 50mm. Given the information obtained in these tests, the displacement restraint configuration with 50mm gap provides the largest displacement capacity and is thus preferred.
Figure 3-29 Pre-deformed Bearing with Displacement Restraints (50mm Gap Configuration) in Testing Machine
Figure 3-30 Drawings of “50mm Gap” (top) and “Zero Gap” (bottom) Displacement Restraint Configurations

Figure 3-31 View of Bearing with 95A Solid Ball in Test with Zero Gap Displacement Restraint Configuration
Figure 3-32 Recorded Histories of Vertical Load and Vertical Displacement and Loops in Test of Bearing with 95A Solid Ball and 50mm Gap Displacement Restraint

95A Solid, W=133.5 kN, 50 mm Gap
Figure 3-33 Recorded Histories of Vertical Load and Vertical Displacement and Loops in Test of Bearing with 95A Solid Ball and Zero Gap Displacement Restraint
Table 3-8 Displacement Capacities and Stiffness of Tested Single Concave Rolling Bearing for Vertical Load of 133.5kN

<table>
<thead>
<tr>
<th>Rolling Ball</th>
<th>Displacement Restraint Configuration</th>
<th>Displacement at Initiation of Stiffening (mm)</th>
<th>Stiffness in Stiffening Regime (kN/mm)</th>
<th>Minimum Additional Displacement Capacity in Stiffening Regime (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>95A</td>
<td>50mm Gap</td>
<td>557</td>
<td>0.50</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>Zero Gap</td>
<td>445</td>
<td>0.53</td>
<td>34</td>
</tr>
<tr>
<td>95A with Steel Core</td>
<td>50mm Gap</td>
<td>561</td>
<td>0.45</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>Zero Gap</td>
<td>452</td>
<td>0.52</td>
<td>30</td>
</tr>
<tr>
<td>62D</td>
<td>50mm Gap</td>
<td>582</td>
<td>0.69</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Zero Gap</td>
<td>477</td>
<td>0.72</td>
<td>21</td>
</tr>
<tr>
<td>62D with Steel Core</td>
<td>50mm Gap</td>
<td>583</td>
<td>0.70</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Zero Gap</td>
<td>474</td>
<td>0.73</td>
<td>19</td>
</tr>
</tbody>
</table>
SECTION 4
DEVELOPMENT AND VALIDATION OF ANALYSIS MODELS FOR SINGLE CONCAVE ROLLING ISOLATOR

4.1 Introduction

Section 2 presented mathematical models to represent the behavior of candidate isolators, including the selected Single Concave Rolling Isolator. The models were based on a number of assumptions that need to be modified based on the test results presented in Section 3. Specifically, the models of Section 2 are based on the assumption of rigid rolling ball, which leads to a stiffness that is entirely dependent on geometry. In reality as seen in the test data of Section 3 the rolling ball is deformable, which leads to higher stiffness and larger effective yield displacement. Accordingly, the model of Section 2 for the Single Concave Rolling Isolator is revised to better represent the observed behavior of the tested isolators. Two classes of models are developed:

1) A phenomenological model which is a modification of the models presented in Section 2. The model includes stiffening behavior when the displacement restraint is engaged. This model has been implemented in computer program OpenSees (McKenna, 1997) and is used later for fragility analysis of isolated buildings. The model in its simpler version without stiffening behavior may be easily used in computer program SAP2000 (Computers and Structure, 2018) for the analysis of seismically isolated structures. Examples are presented for the use of the model in program SAP2000.

2) A mechanics-based model developed in computer program LS-DYNA (LS-DYNA, 2012). The model requires a three-dimensional representation of the isolator and its parameters are basic mechanical properties of the material used for the rolling ball. It can correctly capture creep and its effects on the final shape of the rolling ball, which itself controls the post-elastic stiffness, effective rolling friction and the shape of the hysteresis loop. The utility of this model is in explaining the observed behavior and not as means of predicting its behavior in lieu of testing. It is computational very expensive to justify its use in the dynamic analysis of isolated structures.

4.2 Phenomenological Model

The model is identical to the one in Section 2 with modifications to account for the observed increase in stiffness depending on the stiffness of the rolling ball. The basic equations to describe the behavior of the model are given by Equations (2-12), (2-15), (2-16), (2-21) and (2-22) where the equations used to describe the horizontal forces (Equations 2-15 and 2-16) are modified as follows, in which \( S_m \) is the experimentally obtained stiffness modification factor presented in Table 3-6.

\[
F_x = S_m \frac{\bar{W}}{4R_{eff}} u_x + \mu \bar{W} Z_x
\] (4-1)
The coefficient of rolling friction in these equations is as determined experimentally and is reported in Table 3.7. Values of this coefficient range between 0.08 and 0.12 depending on the speed of motion, and on the stiffness of the rolling ball and the load applied, that is, depending on the amount of deformation of the rolling ball. The range is narrow given the range of stiffness of the tested balls (see Table 3-4 and vertical deformation data in the graphs of Appendix A) to warrant modeling the load dependency on the friction coefficient. Variability in friction and that of other parameters can be and should be accounted for in bounding analysis following the paradigm in McVitty and Constantinou (2015) and the formality of ASCE/SEI 7-16 (ASCE, 2017).

The model described by Equations (2-12), (2-21), (2-22), (4-1) and (4-2) accounts for the behavior of the isolators prior to engaging the displacement restraint. The restraint is designed to engage at a displacement larger than the average displacement demand in the Maximum Considered Earthquake. Accordingly, it is not required to be modelled when simplified and response history analysis are conducted for determining displacements and forces for design. The displacement restraint is intended for reducing the probability of collapse (Kitayama and Constantinou, 2018) as studied later in this report. Therefore, a model of stiffening behavior is developed and implemented in program OpenSees which is used for fragility analysis for determining probabilities of collapse and other performance indicators.

For modeling stiffening behavior, Equations (4-1) and (4-2) are modified to include an additional force as follows. It is assumed that the rolling ball engages the displacement restraint at a displacement $u_{stop}$ which was determined experimentally and is presented in Table 3-8 (as the displacement at initiation of stiffening). Note that this displacement is the distance the rolling ball can travel from its initial position to the restraint, which depends on the initial deformation of the ball. The force exerted by the restraint is given by the following equation provided that the resultant displacement $u = \sqrt{u_x^2 + u_y^2}$ is larger than $u_{stop}$. Quantity $k_{stiff}$ is the restraint stiffness determined experimentally and presented in Table 3-8 (as the stiffness in the stiffening regime).

$$F_{restrainer} = k_{stiff} (|u| - u_{stop})$$

(4-3)

The components of force exerted by the restraint in the two orthogonal directions are given by the following equations provided that the resultant displacement $u = \sqrt{u_x^2 + u_y^2}$ is larger than $u_{stop}$.

$$F_{restrainer_x} = \frac{k_{stiff} (|u| - u_{stop})(u_x - u_{stopx})}{\sqrt{(u_x - u_{stopx})^2 + (u_y - u_{stopy})^2}}$$

(4-4)
\[ F_{\text{restrained}} = \frac{k_{\text{stiff}}(|u| - u_{\text{stop}})(u_y - u_{\text{stopy}})}{\sqrt{(u_x - u_{\text{stopx}})^2 + (u_y - u_{\text{stopy}})^2}} \]  

(4-5)

In Equations (4-4) and (4-5), \( u_{\text{stopx}} \) and \( u_{\text{stopy}} \) are the components of \( u_{\text{stop}} \) in the x and y directions at the last instant at which the displacement restraint was engaged. That is, the values of \( u_{\text{stopx}} \) and \( u_{\text{stopy}} \) change every time the displacement restraint is engaged although their vectorial sum remains equal to \( u_{\text{stop}} \).

The total forces in the two orthogonal directions are given by following equations based on Equations (4-1) and (4-2) after adding the components in (4-4) and (4-5) and correcting for the effect of the bearing stiffness prior to engaging the restraint. Equations (4-6) and (4-7) are valid provided that quantity \(|u| - u_{\text{stop}}\) is positive. If it is negative, the restraint force is set equal to zero.

\[ F_x = S_m \frac{\bar{W}}{4R_{\text{eff}}} u_x + \mu \bar{W}Z_x + \frac{(k_{\text{stiff}} - S_m \frac{\bar{W}}{4R_{\text{eff}}})(|u| - u_{\text{stop}})(u_x - u_{\text{stopx}})}{\sqrt{(u_x - u_{\text{stopx}})^2 + (u_y - u_{\text{stopy}})^2}} \]  

(4-6)

\[ F_y = S_m \frac{\bar{W}}{4R_{\text{eff}}} u_y + \mu \bar{W}Z_y + \frac{(k_{\text{stiff}} - S_m \frac{\bar{W}}{4R_{\text{eff}}})(|u| - u_{\text{stop}})(u_y - u_{\text{stopy}})}{\sqrt{(u_x - u_{\text{stopx}})^2 + (u_y - u_{\text{stopy}})^2}} \]  

(4-7)

Note that in Equations (4-4) to (4-7) the components of force from the restraint are treated as spring forces so that the direction vectors are determined from the displacement components. The restraint actually provides a force that is hysteretic in nature as seen in the force-displacement loops of Appendix B. This behavior is still captured in the model of Equations (4-6) and (4-7) through the second term of Equations (4-6) and (4-7) in the form of friction.

### 4.2.1 Implementation of Phenomenological Model in OpenSees

The procedure for implementation of the phenomenological model in program OpenSees is essentially the same as that presented in Section 2. The element consists of the six-spring representation shown in Figure 2-7. The springs in the vertical and the three rotational directions are based on user’s definition of spring materials. Any of the materials that are available in OpenSees library can be used for these springs, and force response is determined according to the provided force-displacement relations. Typically, the vertical spring is treated as linear elastic with a linear viscous element in parallel to represent the correct stiffness and effective damping in the vertical direction. The rotational springs intend to capture the very low resistance of the isolator to rotation. They are typically assigned linear elastic behavior with very small stiffness, which could also be specified as zero.
For the two horizontal directions, Equations (4-1) to (4-7), (2-20) and (2-21) have been implemented in the program to account for the hysteretic behavior of the isolator. Engagement with the restraint and use of Equations (4-6) and (4-7) is controlled by conditional statements when the resultant isolator displacement is larger than \( u_{\text{stop}} \).

Input information that needs to be defined by the user of this element is presented in Table 4-1. Units are “Newton” for force and “meter” for displacement and length. Recommended values of the model parameters are presented in Table 4-2 based on the observed behavior of the tested isolators and the results in Tables 3-6 to 3-8. The recommended values friction are based on the test results at the highest velocity and for load of 133.5kN. The values of friction for higher loads are larger than those of Table 4-2 by 15% to 35% (see Table 3-7). The recommended values of the stiffness modification factor \( S_m \) are also based on the test data at the highest velocity. The values of the stiffness when engaging the displacement restraint are for slow speed conditions as those are expected when engaging the restraint. Table 4-2 also includes values of vertical storage stiffness and the related loss tangent or loss factor \( \tan \delta \) to be used in modeling the behavior of the isolator in the vertical direction (ASTM, 1994). The values of stiffness are those in Table 3-4 when measured following one-hour load dwell for the cases of the two balls without a steel core and following six-hour load dwell for the two balls with steel cores. The values of \( \tan \delta \) are based on the observed visco-elastic behavior in Figures 3-13 to 3-21. Note that the effective damping in the vertical direction is equal to \( \tan \delta/2 \).
Table 4-1 Parameters of Single Concave Rolling Isolator Model in OpenSees

<table>
<thead>
<tr>
<th>User Input Parameters</th>
<th>Data type</th>
<th>Description (sample value used in analysis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element tag</td>
<td>Integer</td>
<td>Unique element tag that defines element number of isolator in the model</td>
</tr>
<tr>
<td>Node tag 1</td>
<td>Integer</td>
<td>Unique tag for Node 1 in global coordinates</td>
</tr>
<tr>
<td>Node tag 2</td>
<td>Integer</td>
<td>Unique tag for Node 2 in global coordinates</td>
</tr>
<tr>
<td>( \mu )</td>
<td>Double</td>
<td>Constant friction coefficient</td>
</tr>
<tr>
<td>( R_{\text{eff}} )</td>
<td>Double</td>
<td>Effective radius of spherical part</td>
</tr>
<tr>
<td>Material tag 1</td>
<td>Integer</td>
<td>Unique material tag for axial spring</td>
</tr>
<tr>
<td>Material tag 2</td>
<td>Integer</td>
<td>Unique material tag for torsional spring</td>
</tr>
<tr>
<td>Material tag 3</td>
<td>Integer</td>
<td>Unique material tag for rotational spring in direction 2</td>
</tr>
<tr>
<td>Material tag 4</td>
<td>Integer</td>
<td>Unique material tag for rotational spring in direction 3</td>
</tr>
<tr>
<td>( x )</td>
<td>3x1 vector double</td>
<td>Vector that defines orientation of isolator in x local coordinates ( (0 \ 0 \ 1)^T )</td>
</tr>
<tr>
<td>( y )</td>
<td>3x1 vector double</td>
<td>Vector that defines orientation of isolator in y local coordinates ( (1 \ 0 \ 0)^T )</td>
</tr>
<tr>
<td>Shear Distance</td>
<td>Double</td>
<td>Parameter defines shear location of isolator as fraction of length (between 0 and 1, 0.5 for mid-point) (0.5)</td>
</tr>
<tr>
<td>Rayleigh</td>
<td>Integer</td>
<td>Parameter to account for isolator in construction of damping matrix (Rayleigh damping). 1 for accounting, 0 for neglecting. (0)</td>
</tr>
<tr>
<td>Mass</td>
<td>Double</td>
<td>Mass of isolator. If mass is assigned, two nodes are each assigned half as lumped mass. (0)</td>
</tr>
<tr>
<td>Maximum iteration</td>
<td>Integer</td>
<td>Number of maximum iterations for convergence in friction model. (100)</td>
</tr>
<tr>
<td>Tolerance</td>
<td>Double</td>
<td>Tolerance for convergence. (1.0e-12)</td>
</tr>
<tr>
<td>( S_m ) factor</td>
<td>Double</td>
<td>Stiffness modification factor per Table 4-2; stiffness is calculated as ( S_m W/(4R_{\text{eff}}) )</td>
</tr>
<tr>
<td>Yield displacement</td>
<td>Double</td>
<td>Yield displacement per Table 4-2</td>
</tr>
<tr>
<td>( K_{\text{stiff}} )</td>
<td>Double</td>
<td>Stiffness of isolator in stiffening regime per Table 4-2</td>
</tr>
<tr>
<td>Max Displacement</td>
<td>Double</td>
<td>Displacement at initiation of stiffening ( (u_{\text{stop}}) ) per Table 4-2</td>
</tr>
</tbody>
</table>
Table 4-2 Values of Parameters Describing Behavior of Single Concave Rolling Isolator for use in Dynamic Analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Type of Rolling Ball</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>95A Solid</td>
</tr>
<tr>
<td></td>
<td></td>
<td>95A with Steel Core</td>
</tr>
<tr>
<td></td>
<td></td>
<td>62D Solid</td>
</tr>
<tr>
<td></td>
<td></td>
<td>62D with Steel Core</td>
</tr>
<tr>
<td>Coefficient of Rolling Friction</td>
<td>μ</td>
<td>0.100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.085</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.085</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.085</td>
</tr>
<tr>
<td>Stiffness Modification Factor</td>
<td>S_m</td>
<td>3.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.95</td>
</tr>
<tr>
<td>Yield Displacement</td>
<td>Y (m)</td>
<td>0.025</td>
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<td>0.025</td>
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<td></td>
<td></td>
<td>0.020</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.020</td>
</tr>
<tr>
<td>Stiffness when Engaging Displacement</td>
<td>k_stiff (kN/m)</td>
<td>500</td>
</tr>
<tr>
<td>Restraint</td>
<td></td>
<td>500</td>
</tr>
<tr>
<td></td>
<td></td>
<td>700</td>
</tr>
<tr>
<td></td>
<td></td>
<td>700</td>
</tr>
<tr>
<td>Displacement at Initiation of</td>
<td>u_stop (m)</td>
<td>0.56</td>
</tr>
<tr>
<td>Stiffening (Max displacement)</td>
<td></td>
<td>0.56</td>
</tr>
<tr>
<td>for Case of 50mm Gap</td>
<td></td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.58</td>
</tr>
<tr>
<td>Vertical Storage Stiffness</td>
<td>K_v (kN/m)</td>
<td>8200</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12200</td>
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<tr>
<td></td>
<td></td>
<td>19800</td>
</tr>
<tr>
<td></td>
<td></td>
<td>27000</td>
</tr>
<tr>
<td>Loss Tangent or Loss Factor</td>
<td>tanδ</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.14</td>
</tr>
</tbody>
</table>

Values of friction coefficient and stiffness modification factor are for high-speed conditions. See Tables 3-6 and 3-7 for values at slow-speed conditions.

4.2.2 Implementation of Phenomenological Model in SAP2000

The single friction pendulum isolator element was used for modeling the single concave rolling isolator in program SAP2000 (Computers and Structure, 2018). Friction was modeled as constant with friction coefficient \( \mu \) at low and large velocities of motion being the same and equal to the values in Table 3-7. The radius of curvature of the element was specified as equal to \( 4R_{eff}/S_m \) to correctly capture the post-elastic stiffness observed in the tests. The element makes use of the elastic stiffness \( K_\epsilon \) which was calculated through the use of the following equation in which \( W \) is the gravity load on the bearing and \( Y \) is an effective yield displacement of the isolator. The yield displacement was obtained by inspection of the unloading and reloading branches of the recorded force-displacement loops in Section 3 and is reported in Table 4-2.

\[
K_\epsilon = \frac{\mu W}{Y} 
\]  

(4-8)

4.2.3 Verification and Validation of Phenomenological Model in OpenSees and SAP2000

The model of Equations (2-12), (2-21), (2-22) and (4-1) to (4-7) was first implemented in a computer program developed in MATLAB (MATLAB ,2017) to compute the response of a rigid mass subjected to ground seismic excitation along the lines of a similar program described in Section 2. This program could also be used to obtain force-displacement loops for prescribed one-directional motion for use in comparing results obtained by programs OpenSees and
SAP2000, and also to compare computational and experimental results. Figures 4-1 to 4-4 present comparisons of experimental and computational results using the phenomenological model for four cases of tests under load W=133.5kN, amplitude of displacement equal to 125mm and frequency of 0.01Hz. The four cases correspond to the four rolling balls used in the testing. The model parameters for the friction coefficient and the stiffness modification factor used are those determined in the tests and reported in Tables 3-6 and 3-7. Figures 4-5 to 4-8 present comparison of results for the same conditions but for the frequency being 0.3Hz. The parameters used in the analytical models for Figures 4-5 to 4-8 were those of Table 4-2. The vertical stiffness in the OpenSees and SAP2000 models was set to be very high (and much larger than the values reported in Table 4-2). The value of the vertical stiffness does not affect the lateral behavior when the vertical load is constant as in the simulated results in Figures 4-1 to 4-8. Also, note that the results in Figure 4-1 to 4-8 are for displacements prior to engaging the displacement restraint.

![Figure 4-1 Comparison of Experimental and Computational Results for Test with 95A Solid Ball under Load of 133.5kN and Frequency of 0.01Hz](image)

**95A Solid, W=133.5 kN, f=0.01 Hz**

\[ \mu = 0.085, \quad S_m = 2.10 \]
Figure 4-2 Comparison of Experimental and Computational Results for Test with 95A Ball with Steel Core under Load of 133.5kN and Frequency of 0.01Hz

Figure 4-3 Comparison of Experimental and Computational Results for Test with 62D Solid Ball under Load of 133.5kN and Frequency of 0.01Hz
Figure 4-4 Comparison of Experimental and Computational Results for Test with 62D Ball with Steel Core under Load of 133.5kN and Frequency of 0.01Hz

Figure 4-5 Comparison of Experimental and Computational Results for Test with 95A Solid Ball under Load of 133.5kN and Frequency of 0.3Hz
Figure 4-6 Comparison of Experimental and Computational Results for Test with 95A Ball with Steel Core under Load of 133.5 kN and Frequency of 0.3 Hz

\[ \mu = 0.085, S_m = 2.30 \]

Figure 4-7 Comparison of Experimental and Computational Results for Test with 62D Solid Ball under Load of 133.5 kN and Frequency of 0.3 Hz

\[ \mu = 0.085, S_m = 2.95 \]
The results in Figures 4-1 to 4-8 provide verification of the OpenSees model as it produces results that are identical to those obtained by the independently developed solution in MATLAB. The results obtained with the SAP2000 model are close to those obtained by the other two computational solutions but for the sharpness of the transition between elastic and inelastic domains. This is controlled for the OpenSees and MATLAB models by the parameters selected for Equations (2-21) and (2-22)-the same equations are utilized in the SAP2000 model. The SAP2000 model parameters could not be adjusted to produce a smoother transition. Nevertheless, the results of the three computational solutions are in good agreement but not as smooth in transition as the experimental results.

In terms of validation of the model, the figures provide evidence of the validity of the phenomenological model in terms of its ability to capture the strength and post-elastic stiffness and generally the shape of the hysteresis loop but not all details that result from the changing shape of the rolling ball. These effects are better captured by the advanced mechanics-based model that is described later in this report. We note that the model requires a detailed finite element representation of the rolling ball.

Figures 4-9 to 4-12 present comparisons of isolator displacement histories and force-displacement loops obtained in response history analysis of a rigid block subjected to two of the scaled motions developed for response history analysis in Table 2-1 of Section 2: (a) Motion LA-Hollywood, and (b) Motion Bolu. The block is supported by isolators, each of which carries a gravity load of 133.5kN. The results in Figures 4-9 and 4-11 are for bi-directional excitation without the vertical ground motion, whereas the results in Figures 4-10 and 4-12 include the effect of the vertical ground motion. The results are for the case of the rolling 62D
solid ball. The results obtained by MATLAB, OpenSees and SAP2000 are essentially the same. Note that in obtaining these results, the models in OpenSees and SAP2000 included a very stiff vertical spring so that the results can be compared to the MATLAB solution, which is based on a rigid body with infinite vertical stiffness. The results in Figures 4-9 to 4-12 have certain features that require discussion:

1) There is no residual displacement whereas results obtained with the preliminary model in Section 2 show residual displacements (See Table 2-6). This difference is the result of the much larger yield displacement of the isolators (20mm or 25mm), whereas in Section 2 the model utilized of a very small value of the yield displacement (1mm). The large yield displacement results from the deformation of the rolling ball—the ball was assumed rigid in the modeling of Section 2. Studies in Katsaras et al (2008) have demonstrated this effect of the yield displacement on the calculated residual displacement. The subject is further discussed in the Commentary of ASCE/SEI 7-16 (ASCE, 2017) in relation to the design of seismically isolated buildings. Moreover, the additional stiffness provided by the deforming rolling ball must have contributed to the elimination of the residual displacements.

2) The displacement histories when motion is supposed to cease show some low amplitude and high frequency oscillations that continue forever. This is more pronounced in the SAP2000 solution as seen clearly in Figure 4-11. This is a manifestation of the model as there is no damping when the amplitude of motion is less than the yield displacement. The same kind of oscillations also existed in the results presented in Section 2 but the yield displacement was too small for the oscillations to be visible in the graphs. Note that the model used in the analysis consisted of a rigid block and no global damping was assigned to avoid affecting the isolator displacement (Sarlis and Constantinou, 2011). In dynamic analysis of buildings, a global damping matrix is constructed that eliminates this annoyance.

3) The results in Figures 4-9 to 4-11 do not include any displacement restraint effects. The effects of the displacement restraint are investigated next.
Figure 4-9 Comparison of Displacement Histories and Normalized Force-displacement Loops Obtained for LA-Hollywood Motion for Single Concave Rolling System with 62D Solid Ball (without vertical ground motion)
Figure 4-10 Comparison of Displacement Histories and Normalized Force-displacement Loops Obtained for LA-Hollywood Motion for Single Concave Rolling System with 62D Solid Ball (with vertical ground motion)
Figure 4-11 Comparison of Displacement Histories and Normalized Force-displacement Loops Obtained for Bolu Motion for Single Concave Rolling System with 62D Solid Ball (without vertical ground motion)
Figure 4-12 Comparison of Displacement Histories and Normalized Force-displacement Loops Obtained for Bolu Motion for Single Concave Rolling System with 62D Solid Ball (with vertical ground motion)
The behavior of the computational models in MATLAB and OpenSees was investigated when stiffening behavior was introduced at large displacement amplitudes. First, an attempt to validate the models was made by comparing computational results to adjusted experimental results (shifted in displacement per procedures described in Section 3). Figures 4-13 and 4-14 present computational force-displacement loops for large amplitude motion for the cases of the 95A solid ball and the 62D solid ball using the experimentally identified parameters which are presented in Table 4-2. The displacement restraint is placed with a 50mm gap as discussed in Section 3. The graphs contain the recorded force-displacement loops in the tests that engaged the displacement restraint after shifting to a displacement of 483 mm per results in Section 3 and Appendix B. The computational loops are in good agreement with the shifted experimental loops.

**Figure 4-13** Comparison of Computational and Shifted Experimental Loops in Test that Engage the Displacement Restraint for 95A Solid Ball and 50mm Gap

**Figure 4-14** Comparison of Computational and Shifted Experimental Loops in Test that Engage the Displacement Restraint for 62D Solid Ball and 50mm Gap
The dynamic response of the rigid body subjected to the LA-Hollywood motion with vertical component have been re-calculated in the case of the 95A ball with steel core for which the displacements are large enough to engage the displacement restraint. Results are presented in Figure 4-15. The parameters used are those of Table 4-2 for the case of the 50mm gap in placing the displacement restraint. The results of the MATLAB and OpenSees models are identical, providing thus verification for the OpenSees model. The results also demonstrate the effect of the displacement restraint.

Figure 4-15 Comparison of Displacement Histories and Normalized Force-displacement Loops Obtained for LA-Hollywood Motion for Single Concave Rolling System with 95A Ball with Steel Core and Displacement Restraint Placed with 50mm Gap (with vertical ground motion)
To demonstrate the effects of the vertical stiffness, the analysis for which results were presented in Figure 4-15 was repeated but with the OpenSees model including a finite vertical stiffness and the related damping from Table 4-2. Based on the supported weight of 133.5kN, the vertical stiffness of 19800kN/m and $\tan \delta = 0.14$ per Table 4-2, the vertical period and corresponding damping ratio are, respectively, 0.16sec and 0.07. Figure 4-16 presents the results where they are compared to the OpenSees solution when assuming vertically rigid behavior. There is a very small difference between the results of the two cases.

![Graphs showing displacement history and force-displacement loops](image)

**Figure 4-16** Comparison of Displacement Histories and Normalized Force-displacement Loops Obtained for LA-Hollywood Motion for Single Concave Rolling System with 95A Ball with Steel Core and Displacement Restraint Placed with 50mm Gap (with vertical ground motion) when Considering Vertical Isolator Flexibility
4.3 Mechanics-Based Finite Element Model

A complete three-dimensional finite element representation of the tested single concave rolling isolator was developed in program LS-DYNA (2012). The model is shown in Figure 4-17. In this model the top flat and bottom concave plates are modelled as linear elastic material, the restrainer tubes as steel elastic material and the rolling ball as linear viscoelastic material. The use of a viscoelastic model for the rolling ball material is needed to capture the observed behavior under combined vertical load and lateral deformation. The concave plate is fixed at its bottom and the top plate is subject to prescribed histories of vertical load and lateral displacement without rotation.

![Figure 4-17 Model of Tested Single Concave Rolling Bearing in LS-DYNA](image)

Quadrilateral finite elements were used for the top and bottom plates and for the restrainer tubes. Tetrahedron finite elements were used for the rolling ball. The tetrahedron elements better captured the behavior of the rolling ball under large deformation and accordingly the model better predicted the observed behavior. All finite elements used were 8-noded elements.

The contact between the rolling ball and the top plate and bottom plates, and the rolling ball and the restrainer tubes was defined using the “AUTOMATIC_SURFACE_TO_SURFACE” contact definition in LS-DYNA. Nodes on the two plates were assumed to be master nodes and the rolling ball was forced to follow the motion of each plate without penetration but with separation (uplift) if needed for equilibrium. Sliding friction at the contact of the ball with the plates and tubes was modelled using Coulomb friction with friction coefficient of 0.5.

The contact between the steel restrainer tubes and the concrete plates was defined using the “TIED.NODES_TO_SURFACE” contact definition of LS-DYNA. In this definition, the nodes on the top of the upper restrainers are tied to the top plate’s surface and the nodes underneath the lower restrainers are tied to bottom plate’s surface so that the restrainers follow the motion imposed by the plates without any slippage or penetration.

The top and bottom concrete plates were modelled using the “ELASTIC” material definition of LS-DYNA with modulus of elasticity E=45GPa and Poisson ratio ν=0.2. The steel tubes were modelled using the same definition with E=200GPa and ν=0.3. The rolling ball material was
modelled using the “KELVIN-MAXWELL_VISCOELASTIC,” Material 061, Maxwell option in LS-DYNA. The element is described by the following parameters: (a) the short-term shear modulus $G_0$, (b) the long-term shear modulus $G_\infty$, (c) the decay constant, $\beta$ (d) the bulk modulus $K$ and (e) the material density. This is one of the simplest models of viscoelastic behavior. In this model the shear behavior of the material is described by the Maxwell model in which the shear relaxation modulus is given by Equation (4-9), whereas the volumetric behavior is elastic.

$$G(t) = G_\infty + (G_0 - G_\infty) e^{\beta t}$$

(4-9)

Values of the parameters used in the analysis for material with hardness 95A are presented in Table 4-3. Of the values in this table, the density ($1100$kg/m$^3$) and the long-term shear modulus ($G_\infty = 7$MPa) were based on data reported in Du Pont (1976). The value of the bulk modulus ($K = 2500$MPa) was based on Fishman and Machmer (1994) who measured the bulk modulus of Adiprene of 70A and 90A hardness. The short-term shear modulus and the decay constant values were determined by parametric studies that provided an acceptable prediction of hysteretic behavior in the combined compression and shear tests under quasi-static conditions. However, the set of parameters in Table 4-3 resulted in a computational solution in which the elastic displacements were over-estimated and creep was completed faster than actually observed in the tests. Particularly, a much better prediction of the observed creep behavior was predicted when using the values of parameters in Table 4-3 but for the decay constant being much less than 0.07sec$^{-1}$ (e.g., 0.01sec$^{-1}$ instead of 0.07sec$^{-1}$). Also, the computational model became numerically unstable when the conditions of loading were high speed dynamic.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m$^3$)</td>
<td>1100.0</td>
</tr>
<tr>
<td>Long-Term Shear Modulus $G_\infty$ (MPa)</td>
<td>7.0</td>
</tr>
<tr>
<td>Short-term Shear Modulus $G_0$ (MPa)</td>
<td>13.0</td>
</tr>
<tr>
<td>Decay constant $\beta$ (sec$^{-1}$)</td>
<td>0.07</td>
</tr>
<tr>
<td>Bulk modulus $K$ (MPa)</td>
<td>2500.0</td>
</tr>
</tbody>
</table>

Analyses were conducted for the case of the solid rolling ball with material of hardness 95A as it resulted the largest vertical deformation under load.

4.3.1 Results of Analysis in Compression

The behavior of the solid ball of 95A hardness was simulated in the tests in compression with load dwell of five minutes. The test results have been presented in Figure 3-12. In this test the load was applied over the specified duration and then the ball was subjected to cyclic force so that the force-displacement loops in the vertical direction could be obtained and used to measure
the vertical stiffness. Figure 4-18 presents the simulated results where they are compared to the experimental results. Results are presented for the values of parameters in Table 4-3 but with two different values of the decay parameter: 0.01 sec\(^{-1}\) and 0.07 sec\(^{-1}\). It may be seen that the elastic and creep displacements in the test are not predicted well when \(\beta=0.07\) sec\(^{-1}\) is used but the hysteretic behavior during the cyclic portion of the test is reproduced. Specifically, creep concludes in a time interval that is much shorter than that observed in the tests. In a second analysis with \(\beta=0.01\) sec\(^{-1}\) the elastic and creep displacements are better predicted but the calculated loops in the cyclic portion of the test exhibit little hysteresis in contrast to the observed behavior.

The results demonstrate the capability of the model to predict behavior. It is conceivable that improvements in the prediction accuracy can made when a more advanced material model for the ball material is used and the selection of the material properties is based on appropriate material testing.

Figure 4-18 Comparison of Experimental and Simulated Histories of Vertical Force and Vertical Displacement and Force-displacement Curve in Compression of 95A Solid Ball in Test with Five-Minute Load Dwell
4.3.2 Results of Analysis in Combined Compression and Lateral Deformation

Tests with combined vertical load and lateral cyclic motion for the case of the 95A solid rolling ball were simulated under quasi-static conditions and the results are compared to test results in Figure 4-19 for the case of 0.01Hz frequency of testing. In this test a very slow motion was imposed to move the isolator to the maximum displacement, which was then followed by three cycles of harmonic motion at 0.01Hz frequency. This is a case when the displacement restraint was not engaged. The analysis utilized the values of parameters in Table 4-3. The computational model shows capability of reasonably represent the instantaneous stiffness (but for the initial ascending branch of the loop), hysteresis, smoothness of transition from loading to unloading and the effective large yield displacement. The lower stiffness seen in the ascending branch of the first loop is due to the much lower speed of motion in the analysis. The computational model is more sensitive to the effects of the speed than actually observed. Attempts to simulate the behavior for the same test but under high-speed conditions resulted in numerically unstable solutions.

![Figure 4-19 Comparison of Experimental and Simulated Histories of Vertical Displacement and Horizontal Force-Displacement Loop for Case of 95A Solid Ball at 133.5kN Load and 0.01 Hz Frequency](image)

Furthermore, an experiment was simulated for the isolator with the 95A solid ball and displacement restraints placed with a 50mm gap. A load of 133.5kN was applied with slow lateral cyclic motion of one and half cycle as shown in Figure 4-20. Note that the displacement history is sinusoidal so that at zero time there is a non-zero velocity. The displacement amplitude was 590mm, which was sufficiently large to engage the restraint. Figure 4-21 shows a simulated view of the isolator at displacement of 590mm where the deformation of the rolling ball due to the vertical compressive load and the lateral forces from the restraints is apparent.
Figure 4-20 Histories of Vertical Load and Lateral Displacement in Simulation of Test of Isolator with 95A Solid Ball and Displacement Restraint Placed at 50mm Gap
Figure 4-21 Simulated View of Isolator at Displacement of 590mm

Figure 4-22 presents the calculated lateral force-displacement loop. Superimposed to the computational loop is the recorded loop obtained in testing (see Figure 3-32) after shifting to account for the initially deformed configuration used in the test. There is reasonable agreement between the computational and the shifted experimental loops. Note that the computational loop in the ascending branch of the first cycle shows higher stiffness than the computational loop in Figure 4-19 as a result of the higher velocity at initiation of motion.

![Graph showing horizontal force vs. displacement](image)

Figure 4-22 Computational and Shifted Experimental Force-displacement Loops of Isolator with 95A Solid Ball and Displacement Restraints Placed with a 50mm Gap for Load of 133.5kN and 590mm Peak Displacement
SECTION 5
ANALYSIS OF STRUCTURES WITH SINGLE CONCAVE ROLLING ISOLATORS AND CALCULATION OF DISPLACEMENT DEMAND AND BASE SHEAR FORCE

5.1 Introduction
Section 2 presented results of analysis for calculating the isolator displacement demands and base shear force in structures with a number of candidate isolators, including the selected single concave rolling isolator. The results were based on assumptions on the behavior of the isolators that did not account for the effects of the additional stiffness experienced due to the change of shape of the rolling ball and the large effective yield displacement, although the values of friction used were in the correct range. The analysis is repeated in this section using the validated phenomenological model for the single concave rolling isolator presented in Section 4, with due consideration for uncertainties in the properties of the isolators.

Only the cases of the rolling balls with a steel core are considered further in this study. The use of the steel core is important in ensuring a fail-safe operation of the isolator in its lifetime. While urethane (Adiprene) has been in use for decades for load-carrying rotational elements in disk bridge bearings and isolators (e.g., Disktron Bearings, R.J. Watson, Inc., https://www.rjwatson.com/) it is conceivable that a ball of this material without reinforcement under load over time in unconfined conditions may develop some form of undesirable problem, the worst of which is disintegration or destruction in a fire. Even so, the top flat plate will come into contact with the concave plate below and the behavior will be that of a frictional interface consisting of concrete materials. That is, the isolator does not collapse. Moreover, the use of the reinforcing steel core of 127mm diameter will maintain the integrity of the isolator even when the Adiprene completely disintegrates with its behavior being then closer to the theoretical behavior presented in Section 2 due to the rigidity of the steel rolling ball but with uncertain friction and stiffness due to the expected high contact stresses, crashing of concrete and the creation of grooves as observed in Kasalanati et al (1997). That is, the isolator will still be functional but with unknown properties.

5.2 Properties of Isolator
It is presumed that a manufacturer of isolators will be producing one type of single concave rolling isolator in terms of concrete material properties, dimensions and geometry. It will be demonstrated in this section and later in this report that the tested isolator dimensions are sufficient for most applications of residential construction in Turkey. The only variable is the type of ball: 95A or 62D hardness Adiprene ball of 254mm diameter with a 127mm steel reinforcing core. It is presumed that either or both types of rolling ball may be used in the same building. Moreover, the displacement restraint will be placed with a gap of 50mm as it provides a larger displacement capacity. The data presented in Table 4-2 may be regarded as representative nominal properties for this isolator.
When considering the bounding values of properties following the formality in ASCE/SEI 7-16 (ASCE, 2017) and the paradigm in McVitty and Constantinou (2015), we have the following comments:

1) The values of rolling friction were marginally affected by the speed of testing (see Table 3-7). This is due to the fact that rolling friction is not the result of frictional contact (and thus resulting in significant sliding interface heating—see Constantinou et al, 2007). Rather the friction is part of the normalized shear force needed to keep the deformed ball rolling (normalization by the vertical load). Since there is work done in deforming the rolling ball, there is heating but the temperature is small due to the large volume of the ball that is heated. This is similar to the heating of high damping elastomeric isolators in which the energy dissipated causes a small increase in the temperature (Constantinou et al, 2007).

2) The shear force also includes a restoring force part, which has two components, one due to the rise in height of the bearing on lateral deformation and an additional component due to the deformation of the rolling ball. The restoring force is accounted for in the model of Equations (4-1) and (4-2) by their first term, which includes the Stiffness Modification Factor $S_m$. The additional stiffness accounted for by this factor is due to the rolling ball deformation. Based on the test data of Table 3-6, the stiffness is essentially independent of the speed of testing for the two considered cases of rolling balls with steel core, with factor $S_m$ being in the range of 2.30 to 2.95. However, the model of Equations (4-1) and (4-2) implies that the additional stiffness is proportional to the instantaneous vertical load, while the tests data in Table 3-7 suggest that for the two considered cases of 95A and 62D balls with steel core the stiffness modification factor reduces by 10% to 20% when the load is increased. This leads to the decision not to further increase the stiffness modification factor beyond the upper limits in Table 4-2 for accounting for uncertainty.

3) Hysteretic heating is not an important consideration in the determination of the rolling friction. Rather important is the additional stiffness as a result of the ball deformation. Accordingly, the nominal friction is selected as 0.085 for both types of rolling balls and the Stiffness Modification Factor $S_m$ is presumed to be in the range of 2.3 for the 95A rolling ball to 3.0 for the 62A rolling ball, both with steel core.

4) Uncertainty in the properties of ±15% of the nominal values is also assumed, except for the upper bound limit on the stiffness modification factor.

5) Aging is not considered in adjusting the friction and Stiffness Modification Factor as the data in Table 4-2 demonstrate that increases in hardness of the material used in the ball either have no effect or have mixed effects that do not follow a systematic trend. Note that aging will result in increases in the hardness of the material which are expected to be small by comparison to the difference in hardness between 95A and 62D (correspond to approximately a two-fold increase in the modulus of elasticity—Du Pont, 1976).
Based on the above considerations, Tables 5-1 to 5-3 have been prepared to include the nominal, lower bound and upper bound values of properties of the bearings with 95A and 62D rolling balls with steel core.

Analyses are performed for the cases of the lower bound properties for the 95A ball with steel core and the upper bound properties for the 62D ball with steel core. These two cases should provide the bounds on isolator displacement demand and base shear force.

**Table 5-1 Nominal Values of Properties of Single Concave Rolling Isolator**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Type of Rolling Ball</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>95A with Steel Core</td>
</tr>
<tr>
<td>Coefficient of Rolling Friction</td>
<td>$\mu$</td>
<td>0.085</td>
</tr>
<tr>
<td>Stiffness Modification Factor</td>
<td>$S_m$</td>
<td>2.30</td>
</tr>
<tr>
<td>Yield Displacement</td>
<td>$Y$ (m)</td>
<td>0.025</td>
</tr>
<tr>
<td>Stiffness when Engaging Displacement Restraint</td>
<td>$k_{stiff}$ (kN/m)</td>
<td>500</td>
</tr>
<tr>
<td>Displacement at Initiation of Stiffening for Case of 50mm Gap</td>
<td>$u_{stop}$ (m)</td>
<td>0.56</td>
</tr>
<tr>
<td>Vertical Storage Stiffness</td>
<td>$K_v$ (kN/m)</td>
<td>12300</td>
</tr>
<tr>
<td>Loss Tangent or Loss Factor</td>
<td>$\tan \delta$</td>
<td>0.14</td>
</tr>
</tbody>
</table>

**Table 5-2 Lower Bound Values of Properties of Single Concave Rolling Isolator**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Type of Rolling Ball</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>95A with Steel Core</td>
</tr>
<tr>
<td>Coefficient of Rolling Friction</td>
<td>$\mu$</td>
<td>0.072</td>
</tr>
<tr>
<td>Stiffness Modification Factor</td>
<td>$S_m$</td>
<td>1.96</td>
</tr>
<tr>
<td>Yield Displacement</td>
<td>$Y$ (m)</td>
<td>0.025</td>
</tr>
<tr>
<td>Stiffness when Engaging Displacement Restraint</td>
<td>$k_{stiff}$ (kN/m)</td>
<td>425</td>
</tr>
<tr>
<td>Displacement at Initiation of Stiffening for Case of 50mm Gap</td>
<td>$u_{stop}$ (m)</td>
<td>0.56</td>
</tr>
<tr>
<td>Vertical Storage Stiffness</td>
<td>$K_v$ (kN/m)</td>
<td>10455</td>
</tr>
<tr>
<td>Vertical Loss Tangent or Loss Factor</td>
<td>$\tan \delta$</td>
<td>0.12</td>
</tr>
</tbody>
</table>
Table 5-3 Upper Bound Values of Properties of Single Concave Rolling Isolator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Type of Rolling Ball</th>
<th>95A with Steel Core</th>
<th>62D with Steel Core</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of Rolling Friction</td>
<td>( \mu )</td>
<td>0.098</td>
<td>0.098</td>
<td></td>
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<tr>
<td>Stiffness Modification Factor</td>
<td>( S_m )</td>
<td>2.65</td>
<td>3.00</td>
<td></td>
</tr>
<tr>
<td>Yield Displacement</td>
<td>( Y ) (m)</td>
<td>0.025</td>
<td>0.020</td>
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<tr>
<td>Stiffness when Engaging Displacement Restraint</td>
<td>( k_{stiff} ) (kN/m)</td>
<td>575</td>
<td>805</td>
<td></td>
</tr>
<tr>
<td>Displacement at Initiation of Stiffening for Case of 50mm Gap</td>
<td>( u_{stop} ) (m)</td>
<td>0.56</td>
<td>0.56</td>
<td></td>
</tr>
<tr>
<td>Vertical Storage Stiffness</td>
<td>( K_v ) (kN/m)</td>
<td>14145</td>
<td>31050</td>
<td></td>
</tr>
<tr>
<td>Vertical Loss Tangent or Loss Factor</td>
<td>( \tan \delta )</td>
<td>0.14</td>
<td>0.14</td>
<td></td>
</tr>
</tbody>
</table>

5.3 Results of Analysis

Analysis was performed for a rigid block subjected to the seven triplets of scaled motions of Table 2-1. The block was modelled in MATLAB (2017) as described in Section 2 but using the revised Equations (2-12), (2-21), (2-22), (4-1) and (4-2) without the displacement restraint effect. The vertical flexibility of the isolators was ignored as the results in Section 4, Figure 4-16 show that the vertical stiffness is sufficiently large to produce essentially the same results as when vertical rigidity is assumed.

Results are presented in Tables 5-4 and 5-5 in terms of the resultant isolator displacement, the resultant base shear, the base shear in the two orthogonal directions and the residual isolator displacement. Note that the shear forces in the two orthogonal directions are used for design. The results in Table 5-4 for the lower bound conditions show an average displacement within the displacement capacity of the isolators prior to initiation of stiffening, which is 560mm. It may be noted that the calculated displacements in the lower bound case are larger than or about the same as those calculated in Section 2 (see Tables 2-5 and 2-6). This is primarily the result of the large effective yield displacement. This also affected the residual displacements which are now insignificant. The results for the upper bound case show that buildings need to be designed for a base shear force equal to 0.28 times the weight in each principal direction (this includes the effect of the vertical earthquake) prior to any reduction for ductile behavior.
Table 5-4 Analysis Results for Case of 95A Ball with Steel Core in Lower Bound Properties

<table>
<thead>
<tr>
<th>Ground Motion Number</th>
<th>Resultant Displacement (mm)</th>
<th>Resultant Base Shear/W</th>
<th>X-Direction Base Shear/W</th>
<th>Y-Direction Base Shear/W</th>
<th>Resultant Residual Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>68</td>
<td>806.6</td>
<td>0.34</td>
<td>0.34</td>
<td>0.15</td>
<td>2.6</td>
</tr>
<tr>
<td>169</td>
<td>438.7</td>
<td>0.21</td>
<td>0.20</td>
<td>0.15</td>
<td>6.9</td>
</tr>
<tr>
<td>174</td>
<td>560.7</td>
<td>0.27</td>
<td>0.21</td>
<td>0.16</td>
<td>5.2</td>
</tr>
<tr>
<td>721</td>
<td>798.8</td>
<td>0.34</td>
<td>0.21</td>
<td>0.31</td>
<td>15.6</td>
</tr>
<tr>
<td>767</td>
<td>449.7</td>
<td>0.27</td>
<td>0.14</td>
<td>0.27</td>
<td>3.9</td>
</tr>
<tr>
<td>960</td>
<td>448.9</td>
<td>0.20</td>
<td>0.19</td>
<td>0.16</td>
<td>3.8</td>
</tr>
<tr>
<td>1602</td>
<td>317.2</td>
<td>0.16</td>
<td>0.15</td>
<td>0.14</td>
<td>3.1</td>
</tr>
<tr>
<td>Average</td>
<td>545.8</td>
<td>0.25</td>
<td>0.21</td>
<td>0.19</td>
<td>5.9</td>
</tr>
</tbody>
</table>

Table 5-5 Analysis Results for Case of 62D Ball with Steel Core in Upper Bound Properties

<table>
<thead>
<tr>
<th>Ground Motion Number</th>
<th>Resultant Displacement (mm)</th>
<th>Resultant Base Shear/W</th>
<th>X-Direction Base Shear/W</th>
<th>Y-Direction Base Shear/W</th>
<th>Resultant Residual Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>68</td>
<td>485.6</td>
<td>0.33</td>
<td>0.33</td>
<td>0.18</td>
<td>2.2</td>
</tr>
<tr>
<td>169</td>
<td>381.7</td>
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<td>0.21</td>
<td>0.25</td>
<td>8.4</td>
</tr>
<tr>
<td>174</td>
<td>505.6</td>
<td>0.38</td>
<td>0.30</td>
<td>0.23</td>
<td>1.9</td>
</tr>
<tr>
<td>721</td>
<td>882.8</td>
<td>0.49</td>
<td>0.30</td>
<td>0.48</td>
<td>5.3</td>
</tr>
<tr>
<td>767</td>
<td>443.8</td>
<td>0.40</td>
<td>0.16</td>
<td>0.40</td>
<td>3.9</td>
</tr>
<tr>
<td>960</td>
<td>435.8</td>
<td>0.33</td>
<td>0.33</td>
<td>0.23</td>
<td>2.9</td>
</tr>
<tr>
<td>1602</td>
<td>294.1</td>
<td>0.23</td>
<td>0.22</td>
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<td>2.6</td>
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<tr>
<td>Average</td>
<td>489.9</td>
<td>0.34</td>
<td>0.26</td>
<td>0.28</td>
<td>3.9</td>
</tr>
</tbody>
</table>
SECTION 6
PARAMETRIC STUDY OF PERFORMANCE OF SEISMICALLY
ISOLATED RESIDENTIAL STRUCTURES

6.1 Introduction

This section presents a parametric study of the performance of an archetypical residential
building isolated with the studied isolation system when located in areas of high seismic hazard
in Turkey. The isolation system consist of isolators with the geometric characteristics of the
tested isolators with a 50mm gap in placing the displacement restraint as shown in Figure 6-1.
It is a single concave rolling isolator with a 254mm rolling urethane (Adiprene) ball of 95A or
62D hardness and a 127mm steel core.

The building considered is a two-story construction with weight, stiffness and strength
consistent with those of typical residential construction in Turkey designed for high seismic
hazard. Appendix C presents a detailed description of a representative two-story residential
building in Turkey from where information on stiffness and strength is extracted. The
parametric study then considers a range of parameters that account for variability in stiffness
and strength of the building, and in the mechanical properties of the isolators.

A simple approach for the design of residential construction with this isolation system in Turkey
was developed. It applies for structures in areas of the highest seismic hazard in Turkey but for
near-fault conditions, for which the approach has not been evaluated.

The design approach is based on the following steps:
1) Designing the superstructure as being non-isolated cast-in-situ reinforced concrete structure for an elastic shear force corresponding to an acceleration of 1g. The structural system is one of high ductility level with $R$ factor in the range of 6 to 8 depending on the design approach to consider the seismic loadings resisted by frames, structural walls or a combination of the two, per provisions of the Turkish Seismic Design Code (TBDY, 2016).

2) Utilizing isolators of the geometry shown in Figure 6-1 and of the properties presented in Table 6-1 below for all locations in Turkey except for locations in close proximity to active faults (near-fault conditions).

Note that the design approach requires ductile detailing of the structure. This is important in achieving acceptable collapse performance based on information in the studies of Kitayama and Constantinou (2018a, 2018b and 2019b) and Shao et al (2017). Studies presented below confirm that structures designed by this approach have indeed acceptable collapse performance and overall improved performance by comparison to non-isolated comparable structures.

### 6.1.1 General Description of Building Model and Ground Motions

The archetypical building of Appendix C was represented for a parametric performance evaluation in the two-dimensional shear type representation shown in Figure 6-2. The properties of the isolation system considered in the parametric study are those of Tables 5-2 and 5-3 for the upper and lower bound values. They are summarized in Table 6-1 below. Twenty isolators are needed to carry the total seismic weight of 2600kN, with each isolator carrying an average of 130kN. The values for the vertical stiffness and the stiffness when engaging the displacement restraint in Table 6-1 are for the entire isolation system which are those of Tables 5-2 and 5-3 multiplied by the number of isolators (20). Note that the parameters in Table 6-1 apply for the 95A isolators with a steel core, although the parameters for the 62D with steel core isolators are essentially the same (only important difference is the stiffness modification factor).

The bounding values in Table 6-1 were used instead of using the lower bound values for the case of isolators of 95A ball with steel core and the upper bound values for the case of the isolators of 62D ball with steel core as done in the analysis of Section 5. The two cases differ in the set of values used in the upper bound analysis which now has a smaller stiffness modification factor (2.65 instead of 3.0) than the analysis of Section 5. The smaller stiffness modification factor actually leads to larger isolator displacement demands and an increased probability of collapse. It will be evident in the results to be presented that the highest probabilities of collapse occur for the case of lower bound properties and, therefore, the upper bound values used are not important for the collapse performance evaluation. Simply the bounding analysis performed in Section 5 may be regarded as conservative but appropriate for the simple design procedure followed.
Figure 6-2 Model of Two-story Building for Parametric Study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Bounds of Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of Rolling Friction</td>
<td>$\mu$</td>
<td>0.098 0.072</td>
</tr>
<tr>
<td>Effective Radius</td>
<td>$R_{eff}$ (m)</td>
<td>1.75 1.75</td>
</tr>
<tr>
<td>Stiffness Modification Factor</td>
<td>$S_m$</td>
<td>2.65 1.96</td>
</tr>
<tr>
<td>Yield Displacement</td>
<td>$Y$ (m)</td>
<td>0.025 0.025</td>
</tr>
<tr>
<td>Stiffness when Engaging Displacement Restraint</td>
<td>$k_{stiff}$ (kN/m)</td>
<td>11500 8500</td>
</tr>
<tr>
<td>Displacement at Initiation of Stiffening</td>
<td>$u_{stop}$ (m)</td>
<td>0.56 0.56</td>
</tr>
<tr>
<td>Ultimate Displacement</td>
<td>$u_{ult}$ (m)</td>
<td>0.65 0.65</td>
</tr>
<tr>
<td>Vertical Storage Stiffness</td>
<td>$K_v$ (kN/m)</td>
<td>282900 209100</td>
</tr>
<tr>
<td>Loss Tangent or Loss Factor</td>
<td>$\tan\delta$</td>
<td>0.14 0.12</td>
</tr>
<tr>
<td>Total Seismic Weight</td>
<td>$W$ (kN)</td>
<td>2600 2600</td>
</tr>
</tbody>
</table>
The ultimate displacement capacity of the isolators is listed in Table 6-1 as 0.65m. This is 10% larger than the value of 0.59m based on experimental evidence in Section 3. All tests were terminated when the shear force reached 35kN in isolators carrying a load of 133.5kN (0.25 of supported load). It was evident by the absence of any damage to the rolling balls in these tests that the isolators are capable of sustaining larger force. It is presumed that the force exceeds 0.45 times the supported weight (that is, larger than the largest considered strength of the superstructure in the parametric study). Therefore, the isolators cannot fail and they are presumed to behave with the same high stiffness $K_{\text{stiff}}$ for displacements beyond 0.59m and up to the ultimate limit of 0.65m.

The properties of the superstructure were as shown in Figure 6-2 with the following range of values. Note that the figure shows the non-deteriorated backbone curve for the story shear force-drift relation. More details on the assumed behavior are provided later in this section.

1) Elastic stiffness of first story $K_{e1}=1.5K_{e2}$ or $1.75K_{e2}$ or $2.0K_{e2}$ (3 cases).

2) Elastic stiffness of second story $K_{e2}$ such that the fundamental period of the superstructure when fixed to the ground $T_{\text{FIXED}}= 0.20$ or 0.25 or 0.30 second, depending on the structural system (3 cases).

3) First story shear strength $Q_1=0.35W_S$ or $Q_1=0.40W_S$ or $Q_1=0.45W_S$, where $W_S$ is the weight of the superstructure $W_1+W_2=1800kN$, depending on the structural system (1 case).

4) Second story shear strength $Q_2=0.5Q_1$ or $0.6Q_1$ or $0.7Q_1$ (3 cases).

5) Values of other parameters are fixed and presented below.

Nominal values of the model parameters were determined based on the example building presented in Appendix C. They are (rounded figures): $Q_1=0.35(W_1+W_2)$, $Q_2=0.6Q_1$, $T_{\text{FIXED}}= 0.25$ second and $K_{e1}=1.75K_{e2}$. The pushover curves shown in Appendix C reliably predict the elastic stiffness and yield strength ($Q_1$ and $Q_2$ in Figure 6-1) but not the post-elastic behavior which depends on the assumptions made on the behavior of plastic hinges. Accordingly, the post-elastic to elastic stiffness ratio is set at 0.03 so that the capping strength does not significantly differ from the yield strength. The range of values assumed for other properties intends to capture variability in the nominal properties. Note that the nominal base shear strength is selected as $Q_1=0.35(W_1+W_2)$ on the basis of the following considerations. It is the base shear force for the design for a stiff building in the highest seismicity areas of Turkey (elastic shear force for 1g acceleration and a structural behavior factor $R=8$ for a cast-in-situ reinforced concrete building of high ductility level; TBDY, 2016) multiplied by factor 2.75 to account for over-strength.

Note that the approach recommended for design of residential construction with this isolation system in Turkey is to design the superstructure as being non-isolated for an elastic shear force corresponding to an acceleration of 1g and then implement the isolation system of Figure 6-1. It is presumed that the structure is a cast-in-situ reinforced concrete building with a structural system of high ductility level for which the $R$ factor is in the range of 6 to 8 depending on the
design approach to consider the seismic loadings resisted by frames, structural walls or a combination of the two. These range of values for the $R$ factor corresponds to the range of first story shear strength $Q_1=0.35W_S$ to $0.45W_S$, where $W_S$ is the weight of the superstructure.

The property values presented above result in a total of 54 system property combinations for analysis (27 sets of structural system parameters and 2 sets of isolation system parameters). Each of these configurations was subjected to the far-field suite of ground motions from FEMA P695 (FEMA, 2009). Table 6-2 lists these motions and their characteristics. The vertical components of two ground motion sets (Superstition Hills in Poe Road Station and Cape Mendocino in Rio Dell Overpass Station) were not available. These two motions were removed from the suite and a total of 20 ground motion sets were used, forming a total of 40 pairs of combined horizontal and vertical ground motion histories for use in the analysis.

The sites where the far-field ground motions were recorded are located at distance greater than or equal to 10 km from the fault rupture, the source is either strike-slip or thrust and the soil conditions are soft rock or stiff soil, defined as class C and D soil types. PGA, PGV and PGD in Table 6-2 are, respectively, the Peak Ground Acceleration, the Peak Ground Velocity and the Peak Ground Displacement.

Figures 6-3 and 6-4 present the 5%-damped acceleration response spectra for the horizontal and vertical ground motions, respectively. There are 40 spectra of horizontal components and 20 spectra of vertical components. Also shown are the average spectra for each direction and values of the effective period of the analyzed isolated structure in the horizontal and vertical directions. The vertical ground motion spectra include strong spectra components at the vertical period of the isolated model structure. Based on the data in Table 6-1, the isolated structure has a period in the vertical direction of 0.19 to 0.22 sec and a damping ratio of 0.06 to 0.07. The isolated structure will experience vertical acceleration that can exceed 1g, which will cause general uplift of the isolators. Therefore, we need to consider the uplift behavior in the analysis and assessment of performance of the isolated structure.
Table 6-2 Earthquake Events and Station Data for Far-Field Record Set of FEMA (2009)

<table>
<thead>
<tr>
<th>ID No. per FEMA (2009)</th>
<th>Earthquake</th>
<th>Recording Station</th>
<th>Site Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M  Year</td>
<td>Name</td>
<td>Site Class</td>
</tr>
<tr>
<td>1</td>
<td>6.7 1994</td>
<td>Northridge</td>
<td>Beverly Hills - Mulhol</td>
</tr>
<tr>
<td>2</td>
<td>6.7 1994</td>
<td>Northridge</td>
<td>Canyon Country-WLC</td>
</tr>
<tr>
<td>3</td>
<td>7.1 1999</td>
<td>Duzce, Turkey</td>
<td>Bolu</td>
</tr>
<tr>
<td>4</td>
<td>7.1 1999</td>
<td>Hector Mine</td>
<td>Hector</td>
</tr>
<tr>
<td>5</td>
<td>6.5 1979</td>
<td>Imperial Valley</td>
<td>Delta</td>
</tr>
<tr>
<td>6</td>
<td>6.5 1979</td>
<td>Imperial Valley</td>
<td>El Centro Array #11</td>
</tr>
<tr>
<td>7</td>
<td>6.9 1995</td>
<td>Kobe, Japan</td>
<td>Nishi-Akashi</td>
</tr>
<tr>
<td>8</td>
<td>6.9 1995</td>
<td>Kobe, Japan</td>
<td>Shin-Osaka</td>
</tr>
<tr>
<td>9</td>
<td>7.5 1999</td>
<td>Kocaeli, Turkey</td>
<td>Duzce</td>
</tr>
<tr>
<td>10</td>
<td>7.5 1999</td>
<td>Kocaeli, Turkey</td>
<td>Arcelik</td>
</tr>
<tr>
<td>11</td>
<td>7.3 1992</td>
<td>Landers</td>
<td>Yermo Fire Station</td>
</tr>
<tr>
<td>12</td>
<td>7.3 1992</td>
<td>Landers</td>
<td>Coolwater</td>
</tr>
<tr>
<td>13</td>
<td>6.9 1989</td>
<td>Loma Prieta</td>
<td>Capitolia</td>
</tr>
<tr>
<td>14</td>
<td>6.9 1989</td>
<td>Loma Prieta</td>
<td>Gilroy Array #3</td>
</tr>
<tr>
<td>15</td>
<td>7.4 1990</td>
<td>Manjil, Iran</td>
<td>Abbar</td>
</tr>
<tr>
<td>16</td>
<td>6.5 1987</td>
<td>Superstition Hills</td>
<td>El Centro Imp. Co.</td>
</tr>
<tr>
<td>19</td>
<td>7.6 1999</td>
<td>Chi-Chi, Taiwan</td>
<td>CHY101</td>
</tr>
<tr>
<td>20</td>
<td>7.6 1999</td>
<td>Chi-Chi, Taiwan</td>
<td>TCU045</td>
</tr>
<tr>
<td>21</td>
<td>6.6 1971</td>
<td>San Fernando</td>
<td>LA - Hollywood Stor</td>
</tr>
<tr>
<td>22</td>
<td>6.5 1976</td>
<td>Friuli, Italy</td>
<td>Tolmezzo</td>
</tr>
<tr>
<td>Earthquake Name</td>
<td>Recording Station</td>
<td>Values shown are in two horizontal directions, then vertical. Units g, m/sec, m</td>
<td></td>
</tr>
<tr>
<td>-----------------</td>
<td>---------------------</td>
<td>--------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Northridge</td>
<td>Beverly Hills - Mulhol</td>
<td>0.42 0.52 0.32 0.59 0.63 0.20 0.13 0.11 0.03</td>
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</tr>
<tr>
<td>Northridge</td>
<td>Canyon Country- WLC</td>
<td>0.41 0.48 0.30 0.43 0.45 0.19 0.12 0.12 0.05</td>
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</tr>
<tr>
<td>Duzce, Turkey</td>
<td>Bolu</td>
<td>0.73 0.82 0.20 0.56 0.62 0.23 0.23 0.13 0.14</td>
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</tr>
<tr>
<td>Hector Mine</td>
<td>Hector</td>
<td>0.27 0.34 0.15 0.28 0.42 0.12 0.23 0.14 0.08</td>
<td></td>
</tr>
<tr>
<td>Imperial Valley</td>
<td>Delta</td>
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<td></td>
</tr>
<tr>
<td>Imperial Valley</td>
<td>El Centro Array #11</td>
<td>0.36 0.38 0.38 0.35 0.42 0.45 0.16 0.19 0.21</td>
<td></td>
</tr>
<tr>
<td>Kobe, Japan</td>
<td>Nishi-Akashi</td>
<td>0.51 0.50 0.39 0.37 0.37 0.25 0.10 0.11 0.05</td>
<td></td>
</tr>
<tr>
<td>Kobe, Japan</td>
<td>Shin-Osaka</td>
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<td></td>
</tr>
<tr>
<td>Kocaeli, Turkey</td>
<td>Duzce</td>
<td>0.31 0.36 0.21 0.59 0.46 0.21 0.44 0.18 0.14</td>
<td></td>
</tr>
<tr>
<td>Kocaeli, Turkey</td>
<td>Arcelik</td>
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<td></td>
</tr>
<tr>
<td>Landers</td>
<td>Yermo Fire Station</td>
<td>0.24 0.15 0.14 0.51 0.30 0.13 0.44 0.25 0.05</td>
<td></td>
</tr>
<tr>
<td>Landers</td>
<td>Coolwater</td>
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</tr>
<tr>
<td>Loma Prieta</td>
<td>Capitola</td>
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<td></td>
</tr>
<tr>
<td>Loma Prieta</td>
<td>Gilroy Array #3</td>
<td>0.56 0.34 0.34 0.36 0.45 0.45 0.08 0.19 0.24</td>
<td></td>
</tr>
<tr>
<td>Manjil, Iran</td>
<td>Abbar</td>
<td>0.51 0.50 0.54 0.42 0.52 0.42 0.15 0.21 0.26</td>
<td></td>
</tr>
<tr>
<td>Superstition Hills</td>
<td>El Centro Imp. Co.</td>
<td>0.36 0.26 0.13 0.46 0.41 0.08 0.18 0.20 0.05</td>
<td></td>
</tr>
<tr>
<td>Chi-Chi, Taiwan</td>
<td>CHY101</td>
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<td></td>
</tr>
<tr>
<td>Chi-Chi, Taiwan</td>
<td>TCU045</td>
<td>0.47 0.51 0.36 0.37 0.39 0.21 0.51 0.14 0.21</td>
<td></td>
</tr>
<tr>
<td>San Fernando</td>
<td>LA - Hollywood Stor</td>
<td>0.21 0.17 0.16 0.19 0.15 0.05 0.12 0.06 0.04</td>
<td></td>
</tr>
<tr>
<td>Friuli, Italy</td>
<td>Tolmezzo</td>
<td>0.35 0.31 0.28 0.22 0.31 0.10 0.04 0.05 0.03</td>
<td></td>
</tr>
</tbody>
</table>
Figure 6-3 Acceleration Response Spectra of Horizontal Components of Ground Motions

Figure 6-4 Acceleration Response Spectra of Vertical Components of Ground Motions
6.1.2 Detailed Description of Model for Superstructure Behavior

The superstructure behavior in terms of the non-deteriorated backbone story shear force-story drift curves is depicted in Figure 6-1. The model is based on Ibarra et al (2005) and Ibarra and Chowdhury (2006). A version of the model with deteriorating peak-oriented hysteretic behavior is adopted for the study. The deteriorating behavior is important in assessing performance under highly inelastic conditions. Table 6-3 presents values of the model parameters. Note that quantity $\delta_{ui}$ is a model parameter as seen in the backbone curve of Figure 6-1. It is not the ultimate drift at which collapse of a story occurs. Rather, the drift at which collapse occurs is defined as that for which the story shear force drops to 0.8 of the capping strength $Q_C$ (Ibarra et al, 2005; Perus and Fajfar, 2007; FEMA, 2009).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Structural System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural Behavior Factor</td>
<td>$R$</td>
<td>8</td>
</tr>
<tr>
<td>Base Shear Yield Strength</td>
<td>$Q_1$</td>
<td>$0.35W_S$</td>
</tr>
<tr>
<td>Second Story Yield Strength</td>
<td>$Q_2$</td>
<td>$Q_2$: 0.5$Q_1$ or 0.6$Q_1$ or 0.7$Q_1$</td>
</tr>
<tr>
<td>First Story Elastic Stiffness</td>
<td>$K_{e1}$</td>
<td>$K_{e1}$: 1.5$K_{e2}$ or 1.75$K_{e2}$ or 2.0$K_{e2}$</td>
</tr>
<tr>
<td>Second Story Elastic Stiffness</td>
<td>$K_{e2}$</td>
<td>Such that $T_{\text{FIXED}}$ is as below</td>
</tr>
<tr>
<td>Elastic Fixed Base Period</td>
<td>$T_{\text{FIXED}}$ (sec)</td>
<td>0.30</td>
</tr>
<tr>
<td>Post-elastic to Elastic Stiffness Ratio</td>
<td>$\alpha_i$</td>
<td>0.03</td>
</tr>
<tr>
<td>Yield Drift</td>
<td>$\delta_{yi}$</td>
<td>$Q_i/K_{ei}$</td>
</tr>
<tr>
<td>Capping Drift</td>
<td>$\delta_{ci}$</td>
<td>$0.015h_i$, $0.010h_i$, $0.007h_i$</td>
</tr>
<tr>
<td>Ultimate Drift</td>
<td>$\delta_{ui}$</td>
<td>$0.10h_i$, $0.07h_i$, $0.05h_i$</td>
</tr>
<tr>
<td>Deterioration Parameter</td>
<td>$\lambda$</td>
<td>4.0</td>
</tr>
<tr>
<td>Story Drift at Collapse$^1$</td>
<td></td>
<td>$0.032h_i$, $0.022h_i$, $0.016h_i$</td>
</tr>
<tr>
<td>Story Drift at Onset of Damage</td>
<td></td>
<td>$0.005h_i$, $0.004h_i$, $0.003h_i$</td>
</tr>
<tr>
<td>Floor Acceleration at Onset of Damage (g)</td>
<td></td>
<td>0.3</td>
</tr>
</tbody>
</table>

$W_S=W_1+W_2=1800kN; h_i=$story height=2900mm; $i=1$ first story; $i=2$ second story

$^1$: Calculated for backbone curve when strength drops to 80% of capping strength

The selection of the model parameters was based on the pushover curves of the sample building in Appendix C and information in Ibarra et al (2005), Perus and Fajfar (2007) and Akkar et al (2005). This information allowed for the selection of the parameters in the case of the moment frame with $R=8$. The capping and ultimate displacement parameters for the other two cases of $R=6$ and 7 were selected such that the ratio of the displacement to the yield displacement remained about the same as for the case of $R=8$ (in effect these displacements were reduced by the square of the ratio of period of the considered case to the period for the case of $R=8$). Figure 6-5 presents the first story shear force-story drift backbone curves of two cases in Table
6-1, \( R=8 \) and 6, that is, \( Q_1 \) strength equal to 0.35\( W_S \) and 0.45\( W_S \), when also \( Q_2=0.6Q_1 \) and \( K_{e1}=1.75K_{e2} \). Note that collapse is defined when the story shear strength reduces to 80% of the capping strength at a story drift ratio between 1.6% and 3.2%.

Table 6-3 includes additional information: (a) a deterioration parameter as described below, (b) the story drift at collapse, defined as the drift when the story strength drops to 80% of the capping strength, and (c) the story drift and peak floor acceleration at the onset of damage. The latter are used in the assessment of performance in low intensity earthquakes and are based on past experience (Elenas and Meskouris, 2001; Akkar et al, 2005; FEMA, 2012a; Furukama et al, 2013; Soroushian et al, 2015a; Ryu and Reinhorn, 2017).

![Figure 6-5 First Story Non-deteriorated Backbone Curves for Cases of \( R=8 \) and 6 in Table 6-4 (when \( Q_2=0.6Q_1 \) and \( K_{e1}=1.75K_{e2} \)](image)

The model of the isolated structure was represented in program OpenSees (McKenna, 1997) by three nodes, one at the base and one at each of the two floor levels. Masses were lumped at these nodes and rotations were constrained. The force-displacement relationships at each story were represented by link elements that developed forces in the vertical and horizontal directions. The elastic vertical stiffness of each story was calculated based on the example of Appendix C and used for all cases studied. The shear force-displacement relationship at each story in the horizontal direction was represented using the Modified Ibarra-Medina-Krawinkler deterioration model with peak oriented hysteretic behavior (ModMIKPeakOriented in OpenSees). Figure 6-6 illustrates the general form of the force-displacement relation of this element. Note that in the simplified form used in this study (see Figure 6-1) displacements \( u_r \)
and $u_u$ are equal to $\delta_u$ in Figure 6-1. The post-capping version of the model with deteriorating behavior has been used. This model has the following parameters to describe its behavior:

1) Parameters to describe the backbone curve, which may be different in the positive and negative directions: elastic stiffness, yield strength ($F_y$ in Figure 6-6), strain hardening ratio, displacement at capping ($u_p$ in Figure 6-6), post-capping displacement ($u_{pc}$ in Figure 6-6), residual strength ratio ($F_u$ in Figure 6-6 divided by $F_y$) and ultimate displacement ($u_u$ in Figure 6-6).

2) Parameters $\lambda$ to describe cyclic deterioration of yield strength, capping strength, reloading stiffness, and unloading stiffness.

3) Parameters $c$ to describe the rate of deterioration for each of the parameters in item 2 above.

![Diagram of modified Ibarra-Medina-Krawinkler force-displacement loops](image)

**Figure 6-6 Modified Ibarra-Medina-Krawinkler Force-displacement Loops of Element ModMIKPeakOriented in OpenSees**

The cyclic deterioration model is expressed by Equations (6-1) and (6-2).

$$\beta_i = \left(\frac{E_i}{E_t - \sum E_j}\right)^c$$

(6-1)

$$F_{i+} = (1-\beta_{s,i})F_{i-1} \quad \text{and} \quad F_{i-} = (1-\beta_{s,i})F_{i-1}$$

(6-2)

In excursion $i$ deterioration is described by parameter $\beta_i$ where $E_i$ is the hysteretic energy dissipated in excursion $i$, $\sum E_j$ is the total energy dissipated in previous cycles and $E_t$ energy dissipation capacity, which is given by $E_t = \gamma F_y \delta_y$. Parameter $c$ is controls the deterioration rate.
When the total energy dissipated in previous cycles becomes equal to the total energy dissipation capacity of the system (i.e., \(E_t=\sum E_j\)), collapse occurs and resisting force drops to zero.

Forces \(F_i^{+/-}\) and \(F_i^{-/-}\) are the deteriorated yield strengths after and before excursion i, respectively. Parameter \(\beta_{s,i}\) is calculated using Equation (6-1) each time the inelastic force-displacement curve crosses the horizontal axis, that is, when there is reversal in the force direction.

Parameter \(c\) has values in the range of 1.0 and 2.0 (Rahman and Krawinkler, 1993). Haselton and Deierlein (2007) and Ibarra and Krawinkler (2005) used a value of unity in modeling reinforced concrete and steel elements. The value of unity is also in this study. Parameter \(\lambda\) is typically obtained in model calibration using experimental results. Data for steel elements have been reported in Lignos and Krawinkler (2011) and for reinforced concrete elements in Haselton and Deierlein (2007). There is little information on system behavior as used in this work. Recently, Yenidogan et al (2018) represented the overall response of a four-story reinforced concrete full-scale model using the “ModMIKPeakOriented” element in OpenSees. The calibrated values of parameter \(\lambda\) were 3.0 when shear walls were used and 4.0 when moment frames were used, whereas the value of parameter \(c\) was unity. Accordingly, parameter \(\lambda\) was selected in the range of 3 to 4 as presented in Table 6-3. Parameter \(c\) was set equal to unity.

Examples of the cyclic behavior of the model are presented in Figures 6-7 and 6-8. The figures show the first story (base) shear force-first story drift loops obtained by the model of the parameters in Table 6-1 in two cases: (a) moment frame per Table 6-3 when \(Q_2=0.6Q_1\) and \(K_{e1}=1.75K_{e2}\) (Fig. 6-7) and (b) solid shear walls case per Table 6-4 when \(Q_2=0.6Q_1\) and \(K_{e1}=1.75K_{e2}\) (Fig. 6-8). In these examples the model of Figure 6-2 without the isolation system and when fixed to the ground was analyzed using the horizontal component of motion 1994 Northridge, Beverly Hills-Mulhol from the set of motions for far-field in Table 6-2. The ground motion was applied as originally recorded without any scaling. Note that in these examples the calculated drift did not reach the drift limit identified in the figures, so that collapse did not occur, although it is close in the case of the example of Figure 6-7.

We have commented earlier in this report on the significance of the vertical ground motion in conjunction with the vertical acceleration response spectra in Figure 6-4. Specifically, the motions used in the fragility analysis and scaled up in the incremental dynamic analysis achieve at some level of scaling spectral acceleration values in the vertical direction that exceed 1g at period of about 0.2sec, which is the vertical period of the isolated structure. This will lead to isolator uplift. Allowing for uplift required to (a) specify the vertical spring of stiffness \(K_v\) shown in Figure 6-2 as a compression-only spring, and (b) modify the vertical damping element shown in Figure 6-2 (a linear viscous element of constant \(C\) such that the damping ratio in the vertical direction is \(\tan\delta/2\)) is removed when uplift occurs. This was accomplished by setting the damping constant equal to zero when uplift is detected first.
Figure 6-7 Base Shear Force-First Story Drift of System with Moment Frame (R=8), \(Q_2=0.6Q_1\) and \(K_{e1}=1.75K_{e2}\) per Table 6-4 in Analysis with Ground Motion 1994 Northridge, Beverly Hills-Mulhol (Non-isolated)

Figure 6-8 Base Shear Force-First Story Drift of System with Solid Shear Walls (R=6), \(Q_2=0.6Q_1\) and \(K_{e1}=1.75K_{e2}\) per Table 6-4 in Analysis with Ground Motion 1994 Northridge, Beverly Hills-Mulhol (Non-isolated)
Figures 6-9 and 6-10 present results of an example of analysis of the isolated structure under conditions of uplift. We considered the model of Figure 6-2 with the isolation system properties for upper bound conditions in Table 6-1. The vertical period and corresponding damping ratio of the isolated structure are 0.19sec and 0.07, respectively. The superstructure has the properties of the structural walls system in Table 6-3 with $T_{\text{FIXED}}=0.20\text{sec}$, $K_{e1}=1.5K_{e2}$ and assumed to behave elastically so that results in two different analysis programs could be compared. The ground motion is the one recorded in the Northridge earthquake, station Beverly Hills – Mulhol per Table 6-2. The first horizontal component (PGA=0.42g) together with the vertical component were used. The two components were scaled by a factor of 1.5, leading to a peak horizontal ground acceleration of 0.63g and a peak vertical ground acceleration of 0.48g. The vertical ground motion 5%-damped spectral acceleration at the vertical period of 0.20sec of the scaled motion is 1.66g so that isolator uplift occurred. For the verification of results a model was also developed in program SAP2000 (Computers and Structures, 2018) with the same characteristics for the isolation system as in the OpenSees model and with the superstructure represented as elastic since the deteriorating behavior shown for the OpenSees model in Figure 6-8 could not be modelled.

| Superstructure $T_{\text{FIXED}}=0.20\text{sec}$, elastic with $K_{e1}=1.5K_{e2}$. Upper bound isolator properties. |

Figure 6-9 presents histories of the vertical displacement and force of the isolation system as predicted by the two programs. There is isolator uplift for several instances with the maximum uplift displacement predicted to be 1mm (it was 20mm when the ground motion was scaled up by factor of two instead of 1.5). Figure 6-10 presents loops of the base shear force versus the isolator horizontal displacement and of the vertical isolator force versus the isolator vertical displacement. The results obtained by the two programs are very close except that the loops in the horizontal direction have some small differences. These differences are due to differences in the isolator model in the two programs. Specifically, the Friction Pendulum element was used to represent the isolator in program SAP2000 with appropriate parameters but for the smoothness of the transition from elastic to inelastic regimes (see Section 4 for comparisons of models in various programs). Note that both the SAP2000 and OpenSees models predict a small tensile force, which originates in the vertical damping element of the isolation system. This
force is gradually removed (instead of instantaneously removed) upon uplift, resulting in a small tensile force.

The effects of the vertical acceleration are evident in the modification of the base shear-horizontal displacement loops and in the substantial compressive force on the isolation system. To demonstrate the difference, we note that the peak base-shear force is equal to 0.31W when considering vertical ground motion effects in this example. Without the vertical ground motion effect considered, the base-shear force is 0.21W at a maximum isolator displacement of 300mm. That is, the vertical ground motion in this analysis resulted in a lower isolator displacement and a larger base shear force. Figure 6-11 presents the calculated base shear versus the isolator displacement loop when the vertical ground motion is disregarded.

Superstructure $T_{\text{FIXED}}=0.20\text{sec}$, elastic with $K_{e1}=1.5K_{e2}$. Upper bound isolator properties.

Figure 6-10 Loops of Vertical Isolator Force vs Displacement and Base Shear Force vs Isolator Horizontal Displacement in Analyses with Beverly Hills – Mulhol Horizontal-Vertical Ground Motion Scaled by Factor 1.5 (with vertical ground motion)

The increase in the base-shear force and to a lesser extent the reduction in isolator displacement when the vertical ground motion is considered in this example are important in assessing performance and demonstrates the need to include the vertical ground motion and, importantly, the vertical flexibility of the isolation system. Without accounting for the vertical flexibility of the isolation system, uplift does not occur as the peak vertical structure acceleration is 0.48g instead of 1.66g.
Superstructure $T_{\text{FIXED}}=0.20\text{sec}$, elastic with $K_{e1}=1.5K_{e2}$. Upper bound isolator properties.

![Graph showing vertical isolator force vs displacement and base shear force vs isolator horizontal displacement](image)

**Figure 6-11** Loops of Vertical Isolator Force vs Displacement and Base Shear Force vs Isolator Horizontal Displacement in Analyses with Beverly Hills – Mulhol Horizontal Ground Motion Only Scaled by Factor 1.5 (without vertical ground motion)

### 6.2 Results of Collapse Performance Evaluation for Representative Site in Istanbul

The analysis followed the FEMA P-695 (FEMA, 2009) procedures except for the correction for spectral shape effects (Baker and Cornell, 2005; 2006), which were computed based on the direct procedure described in Haselton et al (2011) and also used in Kitayama and Constantinou (2018a, 2018b). Collapse was defined as any of the following events, whichever occurs first:

1) The story drift at either of the two stories reaches the limit for which the strength of the story falls below 80% of the capping strength.

2) The isolator displacement reaches the limit of 0.65m.

3) There is numerical divergence in the analysis.

4) The uplift displacement of the isolation system reaches a certain failure limit. We analyzed two cases: (a) one without any failure limit on the uplift displacement and (b) one with a 30mm failure limit on the uplift displacement.

The median collapse spectral acceleration at the fundamental period $\tilde{S}_{\text{Col,adj}}(T_1)$, with due consideration for the spectral shape effects, is provided by Equation (6-3) in which factors $c_0$ and $c_1$ were obtained by regression analysis of the Incremental Dynamic Analysis (IDA) data. Appendix D presents details of the procedure and the results of the regression analysis.
\( \bar{S}_{a_{\text{Col,adj}}} (T_1) \) (units g) = \exp [c_0 + c_1 \bar{e}(T_1)] \quad (6-3)

The median collapse capacity, \( \bar{S}_{a_{\text{Col}}} (T_1) \), without due consideration for the spectral shape effects (as directly obtained from the IDA results) and the dispersion coefficient due to the record-to-record variability (as obtained from the IDA results), \( \beta_{\text{RTR}} \), were also computed. The spectral shape factor \( SSF \), the collapse margin ratio \( CMR \) and the adjusted collapse margin ratio \( ACMR \), all per FEMA (2009), are given by:

\[
SSF = \frac{\bar{S}_{a_{\text{Col,adj}}} (T_1)}{\bar{S}_{a_{\text{Col}}} (T_1)} \quad (6-4)
\]
\[
CMR = \frac{\bar{S}_{a_{\text{Col}}} (T_1)}{S_{a_{\text{MCE}}} (T_1)} \quad (6-5)
\]
\[
ACMR = \frac{\bar{S}_{a_{\text{Col,adj}}} (T_1)}{S_{a_{\text{MCE}}} (T_1)} \quad (6-6)
\]

In Equations (6-5) and (6-6), \( S_{a_{\text{MCE}}} (T_1) \) is the Maximum Considered Earthquake (MCE) (2475 year return period earthquake) spectral acceleration at the fundamental period \( T_1 \) (or \( T_{\text{eff}} \) for isolated structures). The total system uncertainty \( \beta_{\text{TOT}} \) is given by Equation (6-7) where each component of uncertainty is related to a quality rating as described in FEMA (2009).

\[
\beta_{\text{TOT}} = \sqrt{\beta^2_{\text{RTR}} + \beta^2_{\text{DR}} + \beta^2_{\text{TD}} + \beta^2_{\text{MDL}}} \quad (6-7)
\]

In Equation (6-7) \( \beta_{\text{DR}} \) is the design requirements-related collapse uncertainty, \( \beta_{\text{TD}} \) is the test data-related collapse uncertainty and \( \beta_{\text{MDL}} \) is the modeling-related collapse uncertainty. The following quality ratings and related uncertainties were used: good with \( \beta_{\text{MDL}}=0.2 \) for modeling; good with \( \beta_{\text{TD}}=0.2 \) for test data and superior with \( \beta_{\text{DR}}=0.1 \) for design following FEMA, 2009 examples for isolated and non-isolated ductile reinforced concrete structures.

The conditional probability of collapse caused by the MCE or \( P_{\text{COL,MCE}} \), is given by:

\[
P_{\text{COL,MCE}} = \int_0^1 \frac{1}{s \beta_{\text{TOT}} \sqrt{2\pi}} \exp \left\{ - \frac{(\ln s - \text{ACMR})^2}{2\beta^2_{\text{TOT}}} \right\} ds \quad (6-8)
\]

Appendix E presents fragility curves as computed in the IDA and after correction for the spectral shape effects. In addition, Appendix E presents the results of the regression analysis to determine the median spectral acceleration at collapse with due consideration for the spectral shape effects.

The calculation of the \( CMR \), the \( ACMR \) and probabilities of collapse depend on the values of the spectral acceleration at the period of the structure in the Maximum Considered Earthquake, \( S_{a_{\text{MCE}}} (T_1) \). The MCE is the 2475-year return period earthquake based on the new Turkish Seismic Design Code where it is termed the Maximum Credible Earthquake (TBDY, 2016;
Akkar et al., 2017). For the study reported in this subsection, the specific site considered for the performance evaluation is on the Western part of Istanbul (European site) at a location of coordinates with latitude of 41.105° and longitude of 28.784°. The MCE spectra for this site have been presented in Figure 2-5. The spectral acceleration values $S_{\text{MCE}}(T_1)$ at this location are 1.35g for the non-isolated structures of period 0.2 to 0.3sec and 0.245g for all isolated structures with period $T_{\text{eff}}=3.13$sec.

Other important parameters of the site considered for the performance evaluation relate to the correction for spectral shape effects as described in Appendix D. This analysis requires prediction of the mean spectrum and standard deviation at the magnitude $M$ and distance $R$ corresponding to the 2475-year return period at the selected site and for the fundamental period $T_1$. This prediction requires de-aggregation of the ground motion hazard and use of an appropriate prediction model for the ground motion. For this site the controlling magnitude $M=7$ for the non-isolated structures and 7.3 for the isolates structures, and distance $R=21$km. In addition, the value of the target epsilon $\bar{\varepsilon}_0(T_1)$ is needed (see Appendix D for details) for the calculation of the SSF. The value of this parameter was selected equal to 2.0 for all periods of interest based on analysis and data presented in Appendix D. In addition, we considered a value of $\bar{\varepsilon}_0(T_1)$ equal to 1.5 in the discussion of the results of the fragility analysis.

Results on the probabilities of collapse in the MCE are presented in Tables 6-4 to 6-8. The results in these tables are based on an expected or target value for epsilon $\bar{\varepsilon}_0(T_1)$ equal to 2.0. Of these tables, Table 6-4 presents the results for the non-isolated structure in which the vertical ground motion effects have not been considered as they could not be accounted for in the model of analysis. We note that the vertical ground motion effects on the collapse assessment of non-isolated structures may be under certain conditions important (Harrington and Liel, 2016). These conditions do not apply for the analyzed structure so that the vertical ground motions effects are expected to be minor for the non-isolated structure.

Tables 6-5 to 6-8 present results for the isolated structure for the following cases: (a) Lower bound and upper bound properties of the isolation system per Table 6-1, and (b) collapse criteria that do not include a limit value on the isolator uplift displacement and criteria that include a limit of 30mm on isolator uplift displacement. The results presented are the CMR, SSF, ACMR, dispersion coefficients and probabilities of collapse in the MCE computed by using the record-to-record ($\beta_{RTR}$) and the total ($\beta_{TOT}$) uncertainties.

The results for the non-isolated building show probabilities of collapse in the MCE that are generally unacceptable with values in the range of about 13% to 25%. Acceptable values per requirements of ASCE 7-16 (ASCE, 2017) are 10% for residential construction.

The results for the isolated buildings show probabilities of collapse that are generally less than the limit of 10%. Specifically, when isolator uplift is disregarded in the definition of collapse, the probabilities of collapse are small and generally less than 4%. When considering that an isolator uplift displacement of 30mm or more causes failure, the probabilities of collapse increase but still are acceptable and generally less than 5%. A 30mm uplift displacement is considered acceptable as it cannot cause dislodgement of the isolator parts, which are enclosed in the 50mm tall restrainer ring (see Figure 6-1).
The results in Tables 6-4 to 6-8 show significant improvements in the probability of collapse given the MCE for the isolated structures, which reduce from unacceptable high values for the non-isolated structures to values well below the acceptable limit of 10% for the isolated structures. However, the results in these tables also show that this improvement largely depends on the correction for spectral shape effects, without which the probabilities of collapse in the MCE would have been also unacceptable for the isolated structures (yet less than those for the non-isolated structures). The value of the average (or target) epsilon \( \bar{\varepsilon}_0 = 2 \) used in the analysis (see Appendix D for details) has an important effect in accounting for the spectral shape effects. While the value of \( \bar{\varepsilon}_0 = 2 \) is appropriate for the location considered in Turkey based on published information reported in Appendix D, we investigated the effect of the target epsilon by lowering the value to \( \bar{\varepsilon}_0 = 1.5 \). Tables 6-9 and 6-10 present results for the non-isolated structure and for the isolated structure in the lower bound condition with an isolator uplift limit of 30mm considered as causing collapse when \( \bar{\varepsilon}_0 = 1.5 \). The considered case for the isolated structure resulted in the largest probabilities of collapse among all considered cases in Tables 6-5 to 6-8. The results in Tables 6-9 and 6-10, which should be compared to those of Tables 6-4 and 6-7, respectively, show that values of the SSF reduce and values of the probabilities of collapse increase when \( \bar{\varepsilon}_0 = 1.5 \). The values of the probability of collapse are now significantly larger than the acceptable limit for the non-isolated structure but are still acceptable for the isolated structure.
### Table 6-4 Results of Analysis of Non-isolated Buildings (without vertical ground motion, $\bar{\varepsilon}_0=2$)

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<th>$K_{\varepsilon_1}/K_{\varepsilon_2}$</th>
<th>CMR</th>
<th>ACMR</th>
<th>SSF</th>
<th>$\beta_{RTR}$</th>
<th>$\beta_{TOT}$</th>
<th>Probability of Collapse in MCE without Spectral Shape Effects (%)</th>
<th>Probability of Collapse in MCE with Spectral Shape Effects (%)</th>
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<td>$\beta_{TOT}$</td>
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<td>$\beta_{TOT}$</td>
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Table 6-7 Results of Analysis of Isolated Buildings, Case of Lower Bound Properties, 30mm Isolator Uplift Failure Criterion (with vertical ground motion, $\bar{\varepsilon}_0=2$)

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Table 6-8 Results of Analysis of Isolated Buildings, Case of Upper Bound Properties, 30mm Isolator Uplift Failure Criterion (with vertical ground motion, $\bar{e}_o=2$)

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Table 6-10 Results of Analysis of Isolated Buildings, Case of Lower Bound Properties, 30mm Isolator Uplift Failure Criterion (with vertical ground motion, $\bar{e}_0=1.5$)

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6.3 Evaluation of Collapse Performance of Isolated Structure at Location of Higher Seismic Hazard

The collapse fragility analysis in the preceding subsection demonstrated that isolated residential structures designed by the procedure described in the Introduction of this section have acceptable probabilities of collapse in the Maximum Credible Earthquake (2475-year return period), whereas comparable non-isolated structures have unacceptably high probabilities of collapse. The results are valid for a particular location in Turkey with the assessment of collapse performance based on the following information:

1) The 2475-year return period spectrum (termed the Maximum Credible Earthquake) of the new Turkish Seismic Design Code (TBDY, 2016; Akkar et al, 2017) at a specific location in the Istanbul area. The important parameter of this spectrum for the studied isolated structures was the spectral acceleration at the effective period $T_{eff}=3.13$ sec, $S_a(T_{eff})=0.245g$. This value of the spectral acceleration was used in conjunction with the results of Incremental Dynamic Analysis (IDA) to compute the collapse margin ratio $CMR$.

2) The expected epsilon and mean spectra and spectral standard deviation at the considered location (see analysis and data in Appendix D). This information was used to obtain the spectral shape factor $SSF$ and the adjusted collapse margin ratio $ACMR$.

The results for the isolated structures presented in Tables 6-5 to 6-8 apply for the location with $S_a(T_{eff})=0.245g$, expected epsilon value $\bar{\varepsilon}_0(T_1)=2$ and the mean spectrum and standard deviation for the considered site as described in Appendix D.

The results in Tables 6-5 to 6-8 may be adjusted for another location without the need to repeat the IDA. Simply the results on the $CMR$ may be adjusted for the new value of $S_a(T_{eff})$ which can be readily obtained from the design standard (in this case the TBDY, 2016). However, the results for the $ACMR$ and the $SSF$ require availability of data from de-aggregation of the ground motion hazard and then regression analysis. Most important parameter affecting the results for the $ACMR$ and the $SSF$ is the expected epsilon $\bar{\varepsilon}_0(T_1)$.

We have re-computed the results on the collapse performance of the isolated structure for a location of higher seismic hazard in the Istanbul area. The design of the superstructure and isolation system remained unchanged. The new location is East of Istanbul (Asian site) at a location of coordinates with latitude of $40.9^\circ$ and longitude of $29.2^\circ$. The spectral acceleration value at this location is $S_a(MCE)(T_{eff})=0.297g$ for the isolated structure with period $T_{eff}=3.13$ sec. The seismic intensity as measured by the value of $S_a(T_{eff})$ is 21% higher at the new location. The median spectra and standard deviation for this site are presented in Appendix D where the controlling parameters are magnitude $M=7.3$ and distance $R=16km$. The value of expected epsilon $\bar{\varepsilon}_0(T_1)=2$ based on published information reviewed in Appendix D.

Results are presented in Table 6-11 for the case that resulted in the highest probabilities of collapse (case of lower bound properties, 30mm isolator uplift failure criterion). The results of this table should be compared to the results in Table 6-7 that apply for the lower seismic intensity location. The probabilities of collapse have increased but still are acceptable.
Table 6-11 Results of Analysis of Isolated Buildings, Case of Lower Bound Properties, 30mm Isolator Uplift Failure Criterion, Location of Higher Seismic Intensity (with vertical ground motion, $\bar{\epsilon}_0=2$)

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<th>SSF</th>
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6.4 Evaluation of Performance Other than Collapse

The results presented in the preceding subsection demonstrated that isolated residential structures designed by the procedures described in the Introduction of this section and with the isolation system of Figure 6-1, which has the properties of Table 6-1, have acceptable probabilities of collapse in areas of high seismic hazard in Turkey, typified in the analysis by sites in the Marmara region of Turkey not in close proximity to active faults. These probabilities of collapse are generally below 10% given the occurrence of the 2475-year return period earthquake (or MCE). In contrast, non-isolated comparable in design structures had generally unacceptably high probabilities of collapse which for certain systems and locations far exceeded 10% given the MCE.

The isolation system is also expected to offer additional advantages, which include reduction of the probability of damage given seismic action of increasing intensity up to the MCE. In assessing performance other than collapse performance, we considered the probability of exceeding certain values of the peak floor acceleration and the peak story drift. Floor acceleration and story drift are indicators of damage to structural and non-structural elements and to building contents. The story drift ratio is used as index of structural damage. It is also related to damage to non-structural components that run vertically. The peak floor acceleration is related to damage of non-structural components attached to floors such as suspended ceilings, lighting fixtures, caster-supported furniture, unsecured furniture, sprinklers, mechanical, electrical and plumbing systems, and building contents (FEMA P-58, FEMA, 2012a; Elenas and Meskouris, 2001; FEMA E-74, FEMA, 2012b; Furukawa et al, 2013; Soroushian et al, 2015a and 2015b; Ryu and Reinhorn, 2017). In general, a peak floor acceleration of 0.3g denotes very low or no damage. A maximum story drift ratio of 0.5% denotes the onset of damage for mechanical, electrical and plumbing systems and content damage and loss of use.

We performed analysis and present results for one representative system: case of R=8, $T_{\text{FIXED}}=0.3$ sec, $Q_2=0.6Q_1$, and $K_{e1}=1.75K_{e2}$. The behavior of the structural system was presented in Figures 6-5 and 6-7 in terms of the first story shear force-drift relation. Note that a story drift ratio of 0.5% corresponds to a drift of 14.5mm, which for this system is just less than one third of the capping drift. By comparison, the drift at collapse (see Table 6-5) is 93mm. The analysis followed the approach used for the collapse performance evaluation with criteria for terminating the analysis being the same as those used for collapse with the addition of one more criterion: either the peak floor acceleration (first or second floor, not the base) exceeding 0.3g, or the peak story drift ratio exceeding 0.5%. When isolated, the criteria for uplift included the 30mm uplift displacement limit. For the isolated structure, the vertical ground motion was included in the analysis. The analysis showed that the limits of 0.5% drift ratio or 0.3g peak floor acceleration were reached prior to “collapse” by exceeding the isolator uplift limit of 30mm or any other collapse criterion.

Results are presented in Figures 6-12 and 6-13 for the probability of exceeding the floor acceleration limit of 0.3g and the story drift ratio of 0.5%, respectively, as function of the seismic intensity. The seismic intensity is measured by the spectral acceleration at the fundamental period normalized by the spectral acceleration at the same period in the MCE. The Eastern site was considered for the normalization, for which $S_{aMCE}(T_{\text{eff}})=0.297g$ and $S_{aMCE}(T_1)=1.86g$. There was no correction for spectral shape effects in the results of these
figures, which applies for the analysis of collapse. When spectral shape effects need to be correctly accounted for, a much more complex analysis is needed as implemented in Kitayama and Constantinou (2018a, 2019b) for isolated structures. The approach followed by Kitayama and Constantinou (2018a, 2019a) was to construct conditional spectra for increasing seismic intensities characterized by return period of 43 to 10000 years (10 intensities), select 40 ground motions to represent each intensity and then perform analysis with these 400 motions.

Figure 6-12 Probability of Exceeding Floor Peak Acceleration of 0.3g for Systems with R=8, T_{\text{FIXED}}=0.3sec, Q_2=0.6Q_1 and K_{e1}=1.75K_{e2} at Site with S_{a\text{MCE}}(T_{\text{eff}})=0.297g and S_{a\text{MCE}}(T_1)=1.86g

Figure 6-13 Probability of Exceeding Story Drift Ratio of 0.5% for Systems with R=8, T_{\text{FIXED}}=0.3sec, Q_2=0.6Q_1 and K_{e1}=1.75K_{e2} at Site with S_{a\text{MCE}}(T_{\text{eff}})=0.297g and S_{a\text{MCE}}(T_1)=1.86g
The fragility curves in Figures 6-12 and 6-13 show significantly higher probabilities of exceeding the limits of drift and acceleration in the non-isolated than in the isolated structure for all seismic intensity levels. To better show the differences, probabilities of exceeding the limits of drift and acceleration have been computed and are presented in Table 6-12 for seismic intensities of 0.25MCE, 0.5MCE and 0.67MCE (denotes the design earthquake per ASCE/SEI 7-16 standard, ASCE, 2017). Evidently, the probabilities of developing some form of minor damage to the structural and non-structural systems, and to the contents of isolated building are much lower than those for the comparable non-isolated building.

Table 6-12 Probability of Exceeding Peak Floor Acceleration of 0.3g or Peak Story Drift Ratio of 0.5% as Function of Seismic Intensity Measured as Portion of MCE (Systems with R=8, T\textsubscript{FIXED}=0.3sec, Q\textsubscript{2}=0.6Q\textsubscript{1} and K\textsubscript{e1}=1.75K\textsubscript{e2} at Site with S\textsubscript{aMCE}(T\textsubscript{eff})=0.297g and S\textsubscript{aMCE}(T\textsubscript{1})=1.86g)

<table>
<thead>
<tr>
<th>System</th>
<th>Seismic Intensity</th>
<th>Peak Floor Acceleration Exceeding 0.3g</th>
<th>Peak Story Drift Ratio Exceeding 0.5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-isolated</td>
<td>0.25MCE</td>
<td>100%</td>
<td>4.34%</td>
</tr>
<tr>
<td></td>
<td>0.5MCE</td>
<td>100%</td>
<td>83.43%</td>
</tr>
<tr>
<td></td>
<td>0.67MCE</td>
<td>100%</td>
<td>98.34%</td>
</tr>
<tr>
<td>Isolated</td>
<td>0.25MCE</td>
<td>12.72%</td>
<td>0.02%</td>
</tr>
<tr>
<td></td>
<td>0.5MCE</td>
<td>49.35%</td>
<td>4.53%</td>
</tr>
<tr>
<td></td>
<td>0.67MCE</td>
<td>68.07%</td>
<td>18.06%</td>
</tr>
</tbody>
</table>
SECTION 7
SUMMARY AND CONCLUSIONS

This report started with a discussion on the widespread and worldwide implementation of seismic isolation to structures ranging from apartment buildings to monumental and essential structures but with a very limited number of applications to houses. Exception is Japan where after the construction of about 5000 seismically isolated houses, the application to houses appears to have halted. The main reason for the lack of applications or the selective and limited application of seismic isolation to houses is primarily the perception of high cost of the isolation system. This is true when highly engineered seismic isolators suitable for important structures are used for houses.

The Japanese construction industry has developed and implemented several seismic isolation systems for houses that are all highly engineered sliding systems characterized by strong restoring force, low to medium friction and in some additional capability to dissipate energy by use of dampers. These systems are costly and cannot be widely implemented. Even in the United States efforts have been made to develop simpler and less expensive systems for applications in houses. The recent efforts of Swensen (2014) and Jampole et al (2016) resulted in the conclusion that spherically shaped high friction sliding systems are most appropriate for application in California, and they have tested a full-scale version of a house with such a system. However, for all practical purposes the system is identical to the single friction pendulum system, which in order to be reliably produced requires details that are costly and result in low to medium rather than high friction. With this in mind, the work in the report concentrated on the development of a practical, simple and reliable seismic isolation system for houses, which can be easily produced in most countries without the requirement for advanced technological capability.

Based on the experience of past works, the work concentrated on gravity based rolling systems that are spherically and conically shaped. The concentration on rolling rather than sliding systems was the result of considerations for the higher reliability of rolling friction and for the lesser effect of heating on the rolling friction. A review of past works was performed and the behavior of single and double rolling spherically and conically shaped systems was summarized. This behavior was based on the use of a single rigid rolling ball. The results demonstrated that double spherical or conical systems (consisting of two spherical or conical surfaces) do not offer any advantage in terms of size by comparison to displacement capacity. Actually single systems, consisting of one flat and one shaped surface, are more economical to construct. Analyses were then conducted to compare isolator displacement demands and base shear forces of isolated houses located in areas of high seismic hazard in Turkey. The results demonstrated that use of single spherically shaped rolling systems resulted in the least peak isolator displacements and peak base-shear forces but at the expense of residual displacements, which were insignificant in the case of the studied conical system. The single spherical rolling system was found to be most promising and was selected for construction and testing.

A full-size single concave rolling isolator was built in high strength fiber and steel-reinforced concrete with four different rolling balls made of urethane (Adiprene) in hardness of 95A and
Two of the balls featured steel cores for reinforcement. The four balls provided a wide range of stiffness for the rolling ball. Just the difference between the 95A and 62D hardness provides a more than two-fold increase in stiffness. The isolator also featured a displacement restraint that activated at displacement exceeding 560mm. Tests were conducted to determine the vertical and lateral force-displacement characteristics of the isolator under dynamic conditions, including creep behavior under sustained load and its behavior when the displacement restraint was engaged. Models of the isolator’s behavior have been developed in programs OpenSees (McKenna, 1997) and SAP2000 (Computers and Structures, 2018), and validated using the test data. The testing revealed a behavior characterized by (a) rolling friction coefficient of about 0.10, (b) a post-elastic stiffness about two to three times larger than the stiffness predicted by theory when assuming a rigid rolling ball, and (c) an effective yield displacement that is large and about 25mm. These features of behavior emanate from the viscoelastic properties of the rolling ball, which continually changes shape during motion. The large effective yield displacement is desirable as it results in smaller residual displacements.

We also developed a preliminary computational mechanics-based model for the isolator in program LS-DYNA (LS-DYNA, 2012), capable of predicting the observed creep behavior under vertical load and the observed complex lateral force-displacement relation, including the observed rolling friction, high stiffness and large effective yield displacement. The model required a detailed finite element representation of the isolator. The model utilized the simplest model of viscoelastic behavior. It was developed just to demonstrate the origin of the observed behavior and not as means of predicting its behavior in lieu of testing or for use in response history analysis. The behavior of the isolator needs to be established by testing.

Based on the observations in the tests, the upper and lower bounds of properties of the developed isolator have been established. A simple design philosophy for reinforced concrete houses in Turkey isolated with this isolation system has then been developed. In this design philosophy houses are designed everywhere in Turkey using an elastic lateral force corresponding to an acceleration of 1g and then procedures for analysis and detailing based on the currently applicable codes for non-isolated buildings are followed. The house is equipped with the isolation system having the dimensions of the tested isolator, which has a 0.65m ultimate displacement capacity when the displacement restraint is fully engaged. Rolling balls reinforced with a steel core are recommended for use as they provide higher vertical stiffness and also provide for a fail-safe isolator in case of an unanticipated deterioration of the Adiprene part of the ball over the lifetime of the house or damage in a fire.

Based on the established properties of the isolator, a parametric study of the collapse performance of a range of properties of two-story houses in areas of seismic hazard in Turkey was performed following the procedures of FEMA P695 (FEMA, 2009) with due consideration of the spectral shape and the vertical ground motion effects. The latter effects are very important as the vertical ground motion is magnified in the isolation system due to the flexibility of the system in the vertical direction. It was shown that the seismically isolated houses have acceptable collapse risk per criteria of ASCE/SEI 7-16 (ASCE, 2017), whereas non-isolated comparable houses do not. The acceptable collapse risk was defined as a 10% probability of collapse in the Maximum Considered Earthquake (defined as the one with 2475 years return period). Moreover, it was shown by limited representative analyses that the
seismically isolated houses have lower probabilities of developing damage to their structural and non-structural systems, and to their contents for all seismic intensity levels up to the Maximum Considered Earthquake.

The performed collapse performance analysis could be further extended in future studies to (a) consider actual houses rather than generic representations as done in this work, (b) consider more locations in Turkey, (c) consider near-fault locations, and (d) investigate other design strategies than the simple one used so far. Moreover, a rigorous performance evaluation by computing the probability of developing damage including collapse over the lifetime of houses is recommended. This requires that rigorous seismic hazard analysis be performed for a number of locations, conditional spectra are constructed for several earthquake return periods, and hundreds of motions are selected and scaled for nonlinear response history analysis (Kitayama and Constantinou, 2018a, 2019a).

The developed isolator could be further tested over its entire range of displacement capacity and high velocities, and to failure when the displacement restraint is fully engaged. This requires the use of an isolator test machine capable of over 650mm displacement amplitude. In this work, testing was limited to amplitudes of 125mm of cyclic dynamic motion while pre-deforming the isolator to 0, 380 and 480mm of initial deformation. Also in this work, testing with the displacement restraint engaged was terminated when the lateral force exceeded 0.25 times the vertical load in order to avoid damage to the isolator and the test machine.

Moreover, other materials instead of Adiprene may be utilized and this could be investigated. Materials that are stiff, resistant to the environment, resistant to aging and with low creep are of interest. Such materials are readily available and used in many industrial applications, including some used as protective cover for natural rubber isolators.


was last accessed on November 2017. (Final version of the seismic code is available in following website: http://www.resmigazete.gov.tr/eskiler/2018/03/20180318M1-2-1.pdf; last accessed on November 2018). (In Turkish)


APPENDIX A

EXPERIMENTAL RESULTS WITHOUT ENGAGEMENT OF DISPLACEMENT RERAINT

95A Solid, W=133.5 kN, f=0.01Hz

Figure A-1 History of Vertical Displacement and Force, Recorded Horizontal Force-Displacement Loop, and Horizontal/Vertical Force-Displacement Loop for Case of 95A Solid Ball at 133.5kN Load and 0.01 Hz Frequency
Figure A-2 History of Vertical Displacement and Force, Recorded Horizontal Force-Displacement Loop, and Horizontal/Vertical Force-Displacement Loop of 95A Solid Ball at 133.5kN Load and 0.1 Hz Frequency
Figure A-3 History of Vertical Displacement and Force, Recorded Horizontal Force-Displacement Loop, and Horizontal/Vertical Force-Displacement Loop of 95A Solid Ball at 133.5kN Load and 0.3 Hz Frequency
Figure A-4 History of Vertical Displacement and Force, Recorded Horizontal Force-Displacement Loop, and Horizontal/Vertical Force-Displacement Loop of 95A with Steel Core at 133.5kN Load and 0.01 Hz Frequency
Figure A-5 History of Vertical Displacement and Force, Recorded Horizontal Force-Displacement Loop, and Horizontal/Vertical Force-Displacement Loop of 95A with Steel Core at 133.5kN Load and 0.1 Hz Frequency
Figure A-6 History of Vertical Displacement and Force, Recorded Horizontal Force-Displacement Loop, and Horizontal/Vertical Force-Displacement Loop of 95A with Steel Core at 133.5kN Load and 0.3 Hz Frequency
Figure A-7 History of Vertical Displacement and Force, Recorded Horizontal Force-Displacement Loop, and Horizontal/Vertical Force-Displacement Loop of 62D Solid Ball at 133.5kN Load and 0.01 Hz Frequency
Figure A-8 History of Vertical Displacement and Force, Recorded Horizontal Force-Displacement Loop, and Horizontal/Vertical Force-Displacement Loop of 62D Solid Ball at 133.5kN Load and 0.1 Hz Frequency
Figure A-9 History of Vertical Displacement and Force, Recorded Horizontal Force-Displacement Loop, and Horizontal/Vertical Force-Displacement Loop of 62D Solid Ball at 133.5kN Load and 0.3 Hz Frequency
Figure A-10 History of Vertical Displacement and Force, Recorded Horizontal Force-Displacement Loop, and Horizontal/Vertical Force-Displacement Loop of 62D with Steel Core at 133.5kN Load and 0.01 Hz Frequency
Figure A-11 History of Vertical Displacement and Force, Recorded Horizontal Force-Displacement Loop, and Horizontal/Vertical Force-Displacement Loop of 62D with Steel Core at 133.5 kN Load and 0.1 Hz Frequency
62D with Steel Core, $W=133.5$ kN, $f=0.3$ Hz

Figure A-12 History of Vertical Displacement and Force, Recorded Horizontal Force-Displacement Loop, and Horizontal/Vertical Force-Displacement Loop of 62D with Steel Core at 133.5kN Load and 0.3 Hz Frequency
Figure A-13 History of Vertical Displacement and Force, Recorded Horizontal Force-Displacement Loop, and Horizontal/Vertical Force-Displacement Loop of 95A Solid Ball at 200kN Load and 0.01 Hz Frequency
Figure A-14 History of Vertical Displacement and Force, Recorded Horizontal Force-Displacement Loop, and Horizontal/Vertical Force-Displacement Loop of 95A with Steel Core at 200kN Load and 0.01 Hz Frequency
Figure A-15 History of Vertical Displacement and Force, Recorded Horizontal Force-Displacement Loop, and Horizontal/Vertical Force-Displacement Loop of 62D Solid Ball at 200kN Load and 0.01 Hz Frequency
Figure A-16 History of Vertical Displacement and Force, Recorded Horizontal Force-Displacement Loop, and Horizontal/Vertical Force-Displacement Loop of 62 with Steel Core at 200kN Load and 0.01 Hz Frequency
APPENDIX B
EXPERIMENTAL RESULTS WITH ENGAGEMENT OF DISPLACEMENT RESTRAINT

95A Solid, W=133.5 kN, 50 mm Gap

Figure B-1 Recorded Histories of Vertical Load and Vertical Displacement and Loops in Test of Bearing with 95A Solid Ball and 50mm Gap Displacement Restraint
95A with Steel Core, $W=133.5$ kN, 50 mm Gap

Figure B-2 Recorded Histories of Vertical Load and Vertical Displacement and Loops in Test of Bearing with 95A with Steel Core and 50mm Gap Displacement Restraint
Figure B-3 Recorded Histories of Vertical Load and Vertical Displacement and Loops in Test of Bearing with 62D Solid Ball and 50mm Gap Displacement Restraint
Recorded Histories of Vertical Load and Vertical Displacement and Loops in Test of Bearing with 62D with Steel Core and 50 mm Gap Displacement Restraint
Figure B-5 Recorded Histories of Vertical Load and Vertical Displacement and Loops in Test of Bearing with 95A Solid Ball and Zero Gap Displacement Restraint
95A with Steel Core, W=133.5 kN, Zero Gap

Figure B-6 Recorded Histories of Vertical Load and Vertical Displacement and Loops in Test of Bearing with 95A with Steel Core and Zero Gap Displacement Restraint
Figure B-7 Recorded Histories of Vertical Load and Vertical Displacement and Loops in Test of Bearing with 62D Solid Ball and Zero Gap Displacement Restraint
Figure B-8 Recorded Histories of Vertical Load and Vertical Displacement and Loops in Test of Bearing with 62D with Steel Core and Zero Gap Displacement Restraint
APPENDIX C
DESCRIPTION AND BEHAVIOR OF A SAMPLE RESIDENTIAL BUILDING IN TURKEY

C.1. Introduction

Low-rise residential structures in Turkey typically are cast-in-situ reinforced concrete constructions with brick walls. The structural system is moment frame or shear walls or a combination of the two. While options exist for detailing with nominal or high ductility levels (TBDY, 2016), this work only considers constructions detailed for high ductility level.

The example building is a typical two-story construction designed for an area of high seismic intensity and detailed for high ductility level (Tapan, 2017). The building has been designed following the 2007 version of Turkish Seismic Code (TSDC, 2007) for Zone 1 and site class Z3 for which the spectral acceleration is 1.0g in the range of 0.15 to 0.6sec period. The building period is in this range so that the lateral force for the design prior to application of the Structural Behavior Factor $R$ (per Turkish Code) is equal to the seismic weight.

C.2. Building Description

Figures C-1 to C-4 present side views of the sample building. Each floor has an area of approximately 100 square meters. The height of stories (mid-floor to mid-floor) is 2900mm. The roof is sloped and is covered with tiles. Figures C-5 to C-11 present details of the reinforced concrete beams, columns and slabs of the building. The compressive strength of concrete is 25MPa. The yield strength of the reinforcing steel bars is 420MPa.

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**Figure C-1 Building East Side View**
Figure C-2 Building West Side View

Figure C-3 Building North Side View
Figure C-4 Building South Side View
Figure  C-5 Details of Columns at both Stories (units: cm)
Figure C-6 Details of Beams and Slabs at First Floor (units: cm)
Figure C-7 Details of Beams and Slabs at Second Floor (units: cm)
Figure C-8 Longitudinal Reinforcement Details of Columns at First Story (units: cm)

Figure C-9 Longitudinal Reinforcement Details of Columns at Second Story (units: cm)
Figure C-10 Reinforcement Details of Beam at First Floor
C.3. Building Design Parameters

The design parameters for the building are summarized in Table C-1. The dynamic characteristics of the building (periods and mode shapes) were determined in the original building analysis and design (Tapan, 2017).
Table C-1 Sample Building Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number Stories</td>
<td>2</td>
</tr>
<tr>
<td>Number of Columns</td>
<td>14</td>
</tr>
<tr>
<td>Structural Behavior Factor $R$</td>
<td>8</td>
</tr>
<tr>
<td>Building Importance Factor</td>
<td>1</td>
</tr>
<tr>
<td>Spectral Acceleration in Period Range $T_A$ to $T_B$ (g)</td>
<td>1.0</td>
</tr>
<tr>
<td>Spectrum Characteristic Periods ($T_A/T_B$, sec) (per 2007 Turkish Code)</td>
<td>0.15/0.60 sec</td>
</tr>
<tr>
<td>Concrete Strength (MPa)</td>
<td>25</td>
</tr>
<tr>
<td>Steel Yield Strength (MPa)</td>
<td>420</td>
</tr>
<tr>
<td>Plan Eccentricity (%)</td>
<td>5.3</td>
</tr>
<tr>
<td>Period of Structure in Two Orthogonal Directions (sec)</td>
<td>0.22/0.21</td>
</tr>
<tr>
<td>1st Mode Shape (1st/2nd floor)</td>
<td>1/1.98</td>
</tr>
<tr>
<td>Story Height (1st/2nd floor, m)</td>
<td>2.9/2.9</td>
</tr>
<tr>
<td>Floor Dead Load (1st/2nd floor, kN)</td>
<td>1016.9/752.0</td>
</tr>
<tr>
<td>Floor Live Load (1st/2nd floor, kN)</td>
<td>147.2/147.2</td>
</tr>
<tr>
<td>Floor Seismic Weight (1st/2nd floor, dead plus 0.3 of live load, kN)</td>
<td>1061.1/796.2</td>
</tr>
<tr>
<td>Total Seismic Weight (kN)</td>
<td>1857.3</td>
</tr>
<tr>
<td>Seismic Force for Design in X and Y Directions (1st/2nd floor, kN)</td>
<td>91.5/140.7</td>
</tr>
<tr>
<td>Base Shear Force (kN)</td>
<td>232.2</td>
</tr>
</tbody>
</table>

C.4. Building Behavior

The building was modelled in program SAP2000 (Computers and Structures, 2018) in order to perform nonlinear static analysis and obtain information on the story elastic stiffness, strength and post-elastic stiffness. The modelling was two-dimensional with all frames concentrated in the plane of the two-dimensional representation and interconnected by rigid floors. Any eccentricities have thus been ignored.

The beams were assumed to extend on straight lines neglecting any offsets. For example, beams KZ11 and KZ10 which connect to column SZ05 were modelled without the discontinuity seen in Figures C-5 to C-7. Slabs were modelled using rigid diaphragm constraints for the nodes at each floor level. The columns were assumed fixed to the footings/ground.

The end of all beams and columns were assigned as possible plastic hinge locations. Rigid offsets were also defined at each joint. The moment-rotation relationship assumed at plastic hinges is shown in Figure C-12. The yield rotation and yield moment values (point B in Figure C-12) were calculated based on the section dimensions, material properties and reinforcement ratio. The capping strength and rotation (point C in Figure C-12), the residual strength (point D) and the ultimate rotation capacity (point E) were modelled using the ASCE/SEI 41-13 plastic hinge definition (ASCE, 2013), which is available as an option in program SAP2000. However, the results presented below for the shear force-drift relationships should be considered valid up the yield point of the structure, whereas there is uncertainty on the post-elastic behavior.
The building was analyzed and pushover curves were constructed for lateral loads distributed in accordance with procedures in FEMA P-695 (FEMA, 2009). The building period was determined to be 0.24 sec, which is slightly more than the values of 0.21 and 0.22 sec reported by Tapan (2017).

Pushover curves are presented in Figures C-13 to C-15. Results in these curves demonstrate a base shear strength of 0.35 times the seismic weight, a second story shear strength equal to 0.60 times the first story shear strength, and a first story elastic shear stiffness equal to 1.75 times the second story shear stiffness. The post-elastic to elastic stiffness ratio in these curves is very low and close to 0.015. This is the result of the plastic hinge behavior assumed.
Figure C-14 Second Story Shear Force-Second Story Drift Curve

Figure C-15 First Story Shear Force-First Story Drift Curve
APPENDIX D
PROCEDURE FOR CALCULATING THE MEDIAN COLLAPSE SPECTRAL ACCELERATION WHEN CONSIDERING SPECTRAL SHAPE EFFECTS

The procedure is based on Haselton et al (2011) and is described below in steps based on the presentation in Kitayama and Constantinou (2018a; 2018b):

1) Perform a de-aggregation of the ground motion hazard for the considered site and obtain the expected epsilon $\bar{\varepsilon}_0(T_1)$, magnitude $M$, and distance $R$ based on the spectral period of interest and the earthquake return period. The return period of 2475 years (corresponding to a probability of exceedance of 2% in 50 years) is used. The periods of interest are $T_1=0.2$, 0.25 and 0.3 sec for the non-isolated structures and $T_1= T_{eff}=3.13$ sec for the isolated structures. The latter is the effective period of the isolated structure in the lower bound condition at the isolator displacement when stiffening initiates.

2) Perform Incremental Dynamic Analysis (IDA) (Vamvatsikos and Cornell, 2002) using the 40 ground motions pairs (horizontal and vertical) of Table 6-2 to obtain the collapse capacity in terms of the spectral acceleration at the fundamental period $T_1$ at collapse for each ground motion, $S_{a_{col},j}(T_1)$ ($T_{eff}$ in case of base-isolated structures and $j$ is the identification number for the ground motions; $j$ = 1 to 40).

3) Calculate epsilon at $T_1$, $\varepsilon(T_1)$ for the $j^{th}$ ground motion (horizontal component) ($j$=1 to 40), defined as the number of standard deviations by which the natural logarithm of $S_{a_j}(T_1)$, $\ln[S_{a_j}(T_1)]$, differs from the mean predicted $\ln[S_{a}(T_1)]$ for a given magnitude and distance (Baker, 2011):

$$\varepsilon_j(T_1)=\frac{\ln[S_{a_j}(T_1)]-\mu_{\ln[S_{a}]}}{\sigma_{\ln[S_{a}]}}$$  \hspace{1cm} (D-1)

In Equation (D-1), $\mu_{\ln[S_{a}]}(M,R,T_1)$ is the predicted mean of $\ln[S_{a}(T_1)]$ at a given magnitude $M$, distance $R$ and period $T_1$, and $\sigma_{\ln[S_{a}]}(T_1)$ is the predicted standard deviation of $\ln[S_{a}(T_1)]$ at a given $M$, $R$ and $T_1$. Quantity $\ln[S_{a_j}(T_1)]$ in Equation (D-1) is the natural logarithm of the spectral acceleration at $T_1$ of each of 40 original (before scaling) horizontal components of the ground motions.

4) Obtain the $\mu_{\ln[S_{a}]}(M,R,T_1)$ and $\sigma_{\ln[S_{a}]}(T_1)$ using a ground motion prediction model.

5) Perform a linear regression analysis between $\ln[S_{a_{col},j}(T_1)]$ and $\varepsilon(T_1)$ and determine parameters $c_0$ and $c_1$ based on the following equation:

$$\ln[S_{a_{col}}(T_1)]=c_0+c_1 \cdot \varepsilon(T_1)$$  \hspace{1cm} (D-2)

The relationship between the $\ln[S_{a_{col}}(T_1)]$ and $\varepsilon(T_1)$ has a statistically defensible trend and is acceptable when the $p$-value (Neter et al, 1996) is less than 0.05 (FEMA, 2009). The values of “$p$” were calculated for each analyzed system was found to be less than
0.008 for non-isolated structures and even smaller for the isolated structures. Accordingly, the presented results based on Equation (D-2) are statistically correct.

6) Replace \( \alpha(T_1) \) with \( \bar{\epsilon}_0(T_1) \) in Equation (D-2) and solve to obtain the adjusted mean collapse capacity, \( \bar{S}_{a_{col,adj}}(T_1) \):

\[
\bar{S}_{a_{col,adj}}(T_1) \text{ (units g)} = \exp[c_0 + c_1 \bar{\epsilon}_0(T_1)] \quad (D-3)
\]

7) The record-to-record dispersion coefficient, \( \beta_{RTR} \), is calculated as the standard deviation of the natural logarithm of \( S_{a_{col}}(T_1) \) of the 40 motions (horizontal component) without any further adjustment. Note that Haselton et al (2011) described a procedure for further reduction of the dispersion using the residuals of the regression analysis but the effect was not considered as other studies (Kitayama and Constantinou, 2018a) found the effect to be insignificant.

Values of the expected (or target) epsilon \( \bar{\epsilon}_0(T_1) \), magnitude \( M \) and distance \( R \) for return period of 2475 years used in the analysis are presented in Table D-1. The data were obtained from published studies of de-aggregation of the seismic hazard for the Marmara region of Turkey by Erdik et al (2008) and for the eastern site (latitude 40.9°, longitude 29.2°) by Odabasi (2016).

### Table D-1 Values of \( \bar{\epsilon}_0(T_1) \), \( M \) and \( R \) for Considered Sites and Earthquake of 2475-Years Return Period

<table>
<thead>
<tr>
<th>Structure</th>
<th>( \bar{\epsilon}_0(T_1) )</th>
<th>( M )</th>
<th>( R ) (km) for Eastern Site</th>
<th>( R ) (km) for Western Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolated ((T_1=T_{eff}=3.13\text{sec}))</td>
<td>2.0</td>
<td>7.3</td>
<td>16.0</td>
<td>21.0</td>
</tr>
<tr>
<td>Non-isolated ((T_1=0.2-0.3\text{sec}))</td>
<td>2.0</td>
<td>7.0</td>
<td>16.0</td>
<td>21.0</td>
</tr>
<tr>
<td>Eastern Site: Latitude 40.9°, Longitude 29.2°</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Western Site: Latitude 41.105°, Longitude 28.784°</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Using the ground motion prediction model for Turkey of Kale et al (2015), the median 5%-damped horizontal response spectra and their standard deviation for the isolated and non-isolated structures were constructed and are presented in Figures D-1 and D-2 for the two considered sites. It should be noted that the model of Kale et al (2015) makes use of the Joyner-Boore distance (Joyner and Boore, 1981), \( R_{JB} \), which differs from the rupture distance \( R_{rup} \) (which is more commonly used in de-aggregation studies). The study of Odabaşı (2015) used the rupture distance \( R_{rup} \) but this is not clear in the study of Erdik et al (2008). In general, \( R_{rup}>R_{JB} \) and the difference diminishes as the distance increases. The value reported in Table D-1 is the rupture distance. We used this value in the construction of the median spectra using the model of Kale et al (2015). We also varied the value and re-computed the spectra and the resulting correction for spectral shape effects (factor \( SSF \)). The effect of distance on factor \( SSF \) was minor. Rather, the value of the expected \( \bar{\epsilon}_0(T_1) \) was significant on the calculation of the \( SSF \) as demonstrated in Section 6. That is, while there is some uncertainty on the value of \( R \) in Table D-1, the effect on the computed \( SSF \) is minor. In addition, the soil conditions assumed for
both sites corresponded to a shear wave velocity $V_{S30}=270\text{m/sec}$. This is consistent with soil type ZD assumed for the construction of the uniform hazard spectra for the 2475-year return period earthquake based on the draft of the new Turkish Seismic Design Code (TBDY, 2016; Akkar et al, 2017).

Results of the analysis in the form of graphs of the fragility curve or probability of collapse versus the intensity of the ground motion (horizontal spectral acceleration $S_a(T)$) without and with the spectral shape effects, and graphs of the regression analysis to determine the parameters of Equation (D-2) are presented in Appendix E for each analyzed case.

![Figure D-1 Predicted Mean Spectra and Standard Deviation for Eastern Site](image-url)
Finally and for completeness, the uniform hazard spectra of the two considered sites for the 2475-year return period earthquake are presented. The spectra for the western site are based on the draft of the new Turkish Seismic Design Code (TBDY, 2016; https://testtdth.afad.gov.tr/; accessed in November 2017) and are presented in Figure D-3. The spectra for the eastern site are based on the new Turkish Seismic code, were obtained from https://tdth.afad.gov.tr/ (accessed in November 2018) and are presented in Figure D-4.
Figure D-3 Uniform Hazard Spectra for Western Site Based on draft of the New Turkish Seismic Design Code (Latitude 41.105°, Longitude 28.784°, Soil ZD)
Figure D-4 Uniform Hazard Spectra for Eastern Site Based on the New Turkish Seismic Design Code (Latitude 40.9°, Longitude 29.2°, Soil ZD)
APPENDIX E
RESULTS OF FRAGILITY ANALYSIS AND REGRESSION ANALYSIS
FOR CORRECTING SPECTRAL SHAPE EFFECTS

E.1. Results for western site with latitude 41.105°, longitude 28.784°, $\bar{X}(T_1) = 2.0$

\[ T_1 = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.50, \quad Q_2/Q_1 = 0.5, \quad R=8, \quad \text{Non-isolated} \]
(without vertical ground motion)
$T_1 = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00$, $Q_2/Q_1 = 0.5$, $R = 8$, Non-isolated
(without vertical ground motion)

$T_1 = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50$, $Q_2/Q_1 = 0.6$, $R = 8$, Non-isolated
(without vertical ground motion)
$T_1 = 0.30 \text{ sec}, K_{e_1}/K_{e_2} = 1.75, Q_2/Q_1 = 0.6, R=8$, Non-isolated
(without vertical ground motion)
$T_1 = 0.30$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.7$, $R=8$, Non-isolated
(without vertical ground motion)

$T_1 = 0.30$ sec, $K_{e1}/K_{e2} = 1.75$, $Q_2/Q_1 = 0.7$, $R=8$, Non-isolated
(without vertical ground motion)
$T_1 = 0.30$ sec, $K_{e1}/K_{e2} = 2.00$, $Q_2/Q_1 = 0.7$, $R = 8$, Non-isolated (without vertical ground motion)

$T_1 = 0.25$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.5$, $R = 7$, Non-isolated (without vertical ground motion)
$T_1 = 0.25$ sec, $K_{e1}/K_{e2} = 1.75$, $Q_2/Q_1 = 0.5$, $R = 7$, Non-isolated
(without vertical ground motion)

$T_1 = 0.25$ sec, $K_{e1}/K_{e2} = 2.00$, $Q_2/Q_1 = 0.5$, $R = 7$, Non-isolated
(without vertical ground motion)
$T_1 = 0.25$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.6$, $R = 7$, Non-isolated (without vertical ground motion)
$T_1 = 0.25 \text{ sec, } K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.6, R = 7, \text{ Non-isolated}$

(without vertical ground motion)

$T_1 = 0.25 \text{ sec, } K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.7, R = 7, \text{ Non-isolated}$

(without vertical ground motion)
$T_1 = 0.25 \text{ sec, } K_{\alpha_1}/K_{\alpha_2} = 1.75, Q_2/Q_1 = 0.7, R = 7, \text{ Non-isolated}

\text{(without vertical ground motion)}$
$T_1 = 0.20$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.5$, $R = 6$, Non-isolated
(without vertical ground motion)
$T_1 = 0.20$ sec, $K_{e1}/K_{e2} = 2.00$, $Q_2/Q_1 = 0.5$, $R = 6$, Non-isolated (without vertical ground motion)

$S_a(T_1)/g$

$S_{a\text{COL}} = 1.520g$
$\rho_{\text{RTR}} = 0.386$
$S_{a\text{COL}} = 2.004g$

Empirical
- w/o SSE
- w/ SSE

$T_1 = 0.20$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.6$, $R = 6$, Non-isolated (without vertical ground motion)

$S_a(T_1)/g$

$S_{a\text{COL}} = 1.490g$
$\rho_{\text{RTR}} = 0.415$
$S_{a\text{COL}} = 1.966g$

Empirical
- w/o SSE
- w/ SSE
\( T_1 = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_2}{Q_1} = 0.6, R = 6, \) Non-isolated

(without vertical ground motion)

\[ S_{acol} = 1.520g \]
\[ \beta_{RTR} = 0.411 \]
\[ S_{acol} = 2.034g \]

\( T_1 = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, \frac{Q_2}{Q_1} = 0.6, R = 6, \) Non-isolated

(without vertical ground motion)

\[ S_{acol} = 1.590g \]
\[ \beta_{RTR} = 0.414 \]
\[ S_{acol} = 2.085g \]
$T_1 = 0.20\text{ sec}, K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.7, R = 6$, Non-isolated
(without vertical ground motion)

$$S_{a_{COL}} = 1.460g, \quad \beta_{RTE} = 0.388$$

$T_1 = 0.20\text{ sec}$

$S_{a_{MCE}}(T_1) = 1.350g$

$\epsilon_0 = 2.0$

Empirical

- w/o SSE
- w/ SSE

$\ln[S_{a_{COL}}(T_1)] = 0.1632 + 0.2361(\epsilon(T_1))$

$T_1 = 0.20\text{ sec}, K_{e1}/K_{e2} = 1.75, Q_2/Q_1 = 0.7, R = 6$, Non-isolated
(without vertical ground motion)

$$S_{a_{COL}} = 1.490g, \quad \beta_{RTE} = 0.386$$

$T_1 = 0.20\text{ sec}$

$S_{a_{MCE}}(T_1) = 1.350g$

$\epsilon_0 = 2.0$

Empirical

- w/o SSE
- w/ SSE

$\ln[S_{a_{COL}}(T_1)] = 0.1792 + 0.2328(\epsilon(T_1))$
$T_1 = 0.20 \text{ sec, } K_{e1}/K_{e2} = 2.00, \frac{Q_2}{Q_1} = 0.7, R = 6$, Non-isolated
(without vertical ground motion)

$T_1 = 0.20 \text{ sec, } S_{sCOL} = 1.520g, \beta_{RTR} = 0.392$
$S_{sMCF} = 1.350g$

$\epsilon_0 = 2.0$

$\ln[S_{sCOL}^a(T_1)] = 0.1901 + 0.2341(\epsilon(T_1))$

$T_{fixed} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.50, \frac{Q_2}{Q_1} = 0.5, R = 8$, Isolated
(without vertical ground motion)

$S_{sCOL} = 0.380g, \beta_{RTR} = 0.224$
$S_{sMCF} = 0.245g$

$\epsilon_0 = 2.0$

$\ln[S_{sCOL}^a(T_{eff})] = -1.0282 + 0.1458(\epsilon(T_{eff}))$
\[ T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.75, \frac{Q_2}{Q_1} = 0.5, R = 8, \text{ Isolated} \]

(without vertical ground motion)

\[ S_{a_{\text{COL}}} = 0.380g \]
\[ \beta_{RTR} = 0.223 \]

\[ S_{a_{\text{COL}}} = 0.479g \]

\[ T_{\text{eff}} = 3.13 \text{ sec} \]
\[ S_{a_{\text{MCE}}}(T_{\text{eff}}) = 0.245g \]

Lower Bound

- Empirical
- w/o SSE
- w/ SSE

\[ \epsilon_0 = 2.0 \]

\[ \ln[S_{a_{\text{COL}}}(T_{\text{eff}})] = -1.0267 + 0.1454\epsilon(T_{\text{eff}}) \]

Lower Bound

\[ \ln[S_{a_{\text{COL}}}(T_{\text{eff}})] = -1.0259 + 0.1452\epsilon(T_{\text{eff}}) \]

Lower Bound
$T_{\text{fixed}} = 0.30 \text{ sec}, K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.6, R = 8$, Isolated
(without vertical ground motion)

$S_{a\text{COL}} = 0.380g$
$\beta_{\text{RTR}} = 0.224$
$S_{a\text{COL}} = 0.479g$

$T_{\text{eff}} = 3.13 \text{ sec}$
$S_{\text{AMCE}(T_{\text{eff}})} = 0.245g$

Lower Bound

$\bar{c}_0 = 2.0$

Empirical

w/o SSE

w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0295 + 0.1466\epsilon(T_{\text{eff}})$

Lower Bound

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0297 + 0.1479\epsilon(T_{\text{eff}})$

Lower Bound
$T_{\text{fixed}} = 0.30$ sec, $K_{e1}/K_{e2} = 2.00$, $Q_2/Q_1 = 0.6$, $R = 8$, Isolated
(without vertical ground motion)
\[ T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_2}{Q_1} = 0.7, R = 8, \text{ Isolated} \]
(without vertical ground motion)

\[ S_{a\text{COL}} = 0.380g \]
\[ \beta_{RTR} = 0.224 \]
\[ S_{a\text{COL}} = 0.479g \]
\[ T_{\text{eff}} = 3.13 \text{ sec} \]
\[ S_{a\text{MCE}}(T_{\text{eff}}) = 0.245g \]
Lower Bound

- **Empirical**
- w/o SSE
- w/ SSE

\[ \epsilon_0 = 2.0 \]

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0286 + 0.1462\epsilon(T_{\text{eff}}) \]

\[ T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, \frac{Q_2}{Q_1} = 0.7, R = 8, \text{ Isolated} \]
(without vertical ground motion)

\[ S_{a\text{COL}} = 0.380g \]
\[ \beta_{RTR} = 0.223 \]
\[ S_{a\text{COL}} = 0.479g \]
\[ T_{\text{eff}} = 3.13 \text{ sec} \]
\[ S_{a\text{MCE}}(T_{\text{eff}}) = 0.245g \]
Lower Bound

- **Empirical**
- w/o SSE
- w/ SSE

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0278 + 0.1455\epsilon(T_{\text{eff}}) \]
$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.50, \frac{Q_2}{Q_1} = 0.5, R = 7$, Isolated
(without vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$
$S_{a\text{COL}}(T_{\text{eff}}) = 0.245g$
$Lower \ Bound$

$\varphi = 2.0$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0369 + 0.1436\epsilon(T_{\text{eff}})$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0354 + 0.1433\epsilon(T_{\text{eff}})$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0354 + 0.1433\epsilon(T_{\text{eff}})$

Lower Bound

Empirical
w/o SSE
w/ SSE

$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.75, \frac{Q_2}{Q_1} = 0.5, R = 7$, Isolated
(without vertical ground motion)
$T_{\text{fixed}} = 0.25 \text{ sec}, \quad K_{e1}/K_{e2} = 2.00, \quad Q_2/Q_1 = 0.5, \quad R = 7$, Isolated
(without vertical ground motion)

$S_{a\text{COL}} = 0.380g$
$\beta_{\text{RTR}} = 0.221$
$S_{a\text{COL}} = 0.473g$
$T_{\text{eff}} = 3.13 \text{ sec}$
$S_{a\text{MEC}}(T_{\text{eff}}) = 0.245g$
Lower Bound

$\epsilon_0 = 2.0$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0354 + 0.1430 \epsilon(T_{\text{eff}})$

$T_{\text{fixed}} = 0.25 \text{ sec}, \quad K_{e1}/K_{e2} = 1.50, \quad Q_2/Q_1 = 0.6, \quad R = 7$, Isolated
(without vertical ground motion)

$S_{a\text{COL}} = 0.380g$
$\beta_{\text{RTR}} = 0.222$
$S_{a\text{COL}} = 0.472g$
$T_{\text{eff}} = 3.13 \text{ sec}$
$S_{a\text{MEC}}(T_{\text{eff}}) = 0.245g$
Lower Bound

$\epsilon(T_{\text{eff}})$
\[ T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_2}{Q_1} = 0.6, R = 7, \text{ Isolated} \]

(without vertical ground motion)

\[ S_{a\text{COL}} = 0.380g \]
\[ \beta_{RTR} = 0.221 \]
\[ S_{a\text{COL}} = 0.472g \]
\[ T_{\text{eff}} = 3.13 \text{ sec} \]
\[ S_{a\text{MCER}(T_{\text{eff}})} = 0.245g \]

Lower Bound

\[ \tau_0 = 2.0 \]

Empirical
- w/o SSE
- w/ SSE

\[ \ln[S_{a\text{COL}(T_{\text{eff}})}] = -1.0366 + 0.1434 \epsilon(T_{\text{eff}}) \]

Lower Bound

\[ \ln[S_{a\text{COL}(T_{\text{eff}})}] = -1.0357 + 0.1428 \epsilon(T_{\text{eff}}) \]

Lower Bound
$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, \frac{Q_2}{Q_1} = 0.7, R = 7, \text{ Isolated}$

(without vertical ground motion)
$T_{\text{fixed}} = 0.25 \text{ sec}, K_{e_1}/K_{e_2} = 2.00, Q_2/Q_1 = 0.7, R = 7$, Isolated
(without vertical ground motion)

- $S_{a\text{COL}} = 0.380g$
- $\beta_{\text{RTR}} = 0.221$
- $S_{a\text{COL}} = 0.472g$
- $T_{\text{eff}} = 3.13 \text{ sec}$
- $S_{\text{AMCA}(T_{\text{eff}})} = 0.245g$

Lower Bound

- Empirical
- w/o SSE
- w/ SSE

$T_{\text{fixed}} = 0.20 \text{ sec}, K_{e_1}/K_{e_2} = 1.50, Q_2/Q_1 = 0.5, R = 6$, Isolated
(without vertical ground motion)

- $S_{a\text{COL}} = 0.370g$
- $\beta_{\text{RTR}} = 0.229$
- $S_{a\text{COL}} = 0.465g$
- $T_{\text{eff}} = 3.13 \text{ sec}$
- $S_{\text{AMCA}(T_{\text{eff}})} = 0.245g$

Lower Bound

- Empirical
- w/o SSE
- w/ SSE
\[ T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_{2}}{Q_{1}} = 0.5, R = 6, \text{ Isolated} \]

(without vertical ground motion)
$T_{\text{fixed}} = 0.20\ \text{sec}, \frac{K_{e_1}}{K_{e_2}} = 1.50, \frac{Q_2}{Q_1} = 0.6, R = 6, \text{Isolated}$

(without vertical ground motion)

$S_{\text{a COL}} = 0.370g$

$S_{\text{RTR}} = 0.219$

$S_{\text{a COL}} = 0.466g$

$T_{\text{eff}} = 3.13\ \text{sec}$

$S_{\text{AMCE}}(T_{\text{eff}}) = 0.245g$

$e_0 = 2.0$

$\ln[S_{\text{a COL}}(T_{\text{eff}})] = -1.0459 + 0.149\epsilon(T_{\text{eff}})$

$\ln[S_{\text{a COL}}(T_{\text{eff}})] = -1.0467 + 0.1415\epsilon(T_{\text{eff}})$

Empirical

w/o SSE

w/ SSE

Lower Bound
$T_{\text{fixed}} = 0.20 \text{ sec, } K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.6, R = 6, \text{ Isolated}$

(without vertical ground motion)

$S_{a\text{COL}} = 0.370g$
$S_{a\text{LRT}} = 0.222$
$S_{a\text{COL}} = 0.466g$
$S_{a\text{MCE}} = 0.245g$
$T_{\text{eff}} = 3.13 \text{ sec}$

Lower Bound

Empirical

w/o SSE

w/ SSE

$\epsilon_0 = 2.0$

$S_{a(T_{\text{eff}})}g$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0463 + 0.1407\epsilon(T_{\text{eff}})$

Lower Bound

$S_{a(T_{\text{eff}})}g$

$\epsilon(T_{\text{eff}})$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0486 + 0.1424\epsilon(T_{\text{eff}})$

Lower Bound
$T_{\text{fixed}} = 0.20 \text{ sec, } K_{e_1}/K_{e_2} = 1.75, Q_2/Q_1 = 0.7, R = 6, \text{ Isolated}$

(without vertical ground motion)
$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.5, R = 8$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)
$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e_1}/K_{e_2} = 1.75, Q_2/Q_1 = 0.5, R=8$, Isolated, Failure due to 30 mm Uplift

(with vertical ground motion)
with vertical ground motion)

\[ T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 2.00, Q_2/Q_1 = 0.50, R = 8 \text{, Isolated, Failure due to 30 mm Uplift} \]

\[ \text{(with vertical ground motion)} \]

\[ T_{\text{eff}} = 3.13 \text{ sec}, S_{a\text{COL}} = 0.350 \text{g}, \beta_{\text{RTN}} = 0.399 \]

\[ S_{a\text{COL}} = 0.576 \text{g}, S_{\text{AMCE}}(T_{\text{eff}}) = 0.245 \text{g} \]

\[ \varepsilon_0 = 2.0 \]

\[ \text{Empirical} \]

\[ \text{w/o SSE} \]

\[ \text{w/ SSE} \]

\[ \text{Lower Bound} \]

\[ \text{Upper Bound} \]
$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.6, R = 8$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$S_{a\text{COL}} = 0.350g$
$\beta_{RTH} = 0.399$

$S_{a\text{COL}} = 0.573g$
$T_{\text{eff}} = 3.13 \text{ sec}$
$S_{a\text{MC}}(T_{\text{eff}}) = 0.245g$

Lower Bound

$\varepsilon_0 = 2.0$

Empirical
w/o SSE
w/ SSE

$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.6, R = 8$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$S_{a\text{COL}} = 0.360g$
$\beta_{RTH} = 0.436$

$S_{a\text{COL}} = 0.632g$
$T_{\text{eff}} = 3.13 \text{ sec}$
$S_{a\text{MC}}(T_{\text{eff}}) = 0.245g$

Upper Bound

$\varepsilon_0 = 2.0$

Empirical
w/o SSE
w/ SSE
$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.75, Q_2/Q_1 = 0.6, R=8$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

![Graph with empirical data and lower and upper bounds]

$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.75, Q_2/Q_1 = 0.6, R=8$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

![Graph with empirical data and lower and upper bounds]
$T_{\text{fixed}} = 0.30 \text{ sec}, K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.6, R = 8$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{\text{a}(T_{\text{eff}})} = 0.575g$

$S_{\text{a}(T_{\text{eff}})} = 0.350g$

$\beta_{\text{RTH}} = 0.398$

Empirical

w/o SSE

w/ SSE

$\epsilon_0 = 2.0$

$\ln[S_{\text{a}(T_{\text{eff}})}] = -1.2190 + 0.3331 \epsilon(T_{\text{eff}})$

Lower Bound

Upper Bound

$\ln[S_{\text{a}(T_{\text{eff}})}] = -1.1512 + 0.3495 \epsilon(T_{\text{eff}})$

$\epsilon_0 = 2.0$
$T_{\text{fixed}} = 0.30 \text{ sec}$, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.7$, $R = 8$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

\[ \text{Probability of Collapse} \]

\[ S_{a\left(T_{\text{eff}}\right)} g \]

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.2277 + 0.3357 \epsilon(T_{\text{eff}}) \]

\[ \epsilon(T_{\text{eff}}) \]

\[ \ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.1595 + 0.3497 \epsilon(T_{\text{eff}}) \]

\[ \epsilon(T_{\text{eff}}) \]
$T_{fixed} = 0.30$ sec, $K_{e1}/K_{e2} = 1.75$, $Q_{2}/Q_{1} = 0.7$, $R=8$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$T_{eff} = 3.13$ sec, $S_{a_{COL}} = 0.574$g, $S_{a_{MCE}}(T_{eff}) = 0.245$g

$\epsilon = 2.0$

$\beta_{RTH} = 0.398$

Empirical: w/o SSE, w/ SSE

$\ln[S_{a_{COL}}(T_{eff})] = -1.2231 + 0.3336 \epsilon (T_{eff})$

$S_{a_{COL}}(T_{eff})g$

$\ln[S_{a_{COL}}(T_{eff})]$

$\epsilon (T_{eff})$

$T_{eff} = 3.13$ sec, $S_{a_{COL}} = 0.370$g, $S_{a_{MCE}}(T_{eff}) = 0.245$g

$\beta_{RTH} = 0.438$

Empirical: w/o SSE, w/ SSE

$\ln[S_{a_{COL}}(T_{eff})] = -1.1550 + 0.3495 \epsilon (T_{eff})$

$S_{a_{COL}}(T_{eff})g$

$\ln[S_{a_{COL}}(T_{eff})]$

$\epsilon (T_{eff})$
$T_{\text{fixed}} = 0.30$ sec, $K_{e1}/K_{e2} = 2.00$, $Q_2/Q_1 = 0.7$, $R = 8$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$S_{a_{COL}} = 0.350g$, $\beta_{RTH} = 0.400$
$S_{a_{COL}} = 0.575g$, $T_{\text{eff}} = 3.13$ sec
$S_{a_{MCE}}(T_{\text{eff}}) = 0.245g$

$\epsilon_0 = 2.0$

$\ln|S_{a_{COL}}(T_{\text{eff}})| = -1.2236 + 0.3351 \epsilon(T_{\text{eff}})$

$T_{\text{fixed}} = 0.30$ sec, $K_{e1}/K_{e2} = 2.00$, $Q_2/Q_1 = 0.7$, $R = 8$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$S_{a_{COL}} = 0.370g$, $\beta_{RTH} = 0.439$
$S_{a_{COL}} = 0.636g$, $T_{\text{eff}} = 3.13$ sec
$S_{a_{MCE}}(T_{\text{eff}}) = 0.245g$

$\epsilon_0 = 2.0$

$\ln|S_{a_{COL}}(T_{\text{eff}})| = -1.1518 + 0.3495 \epsilon(T_{\text{eff}})$
$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, Q_2/Q_1 = 0.5, R = 7$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{a\text{COL}} = 0.350g$

$\beta_{RTH} = 0.395$

$S_{a\text{COL}} = 0.584g$

$S_{\text{AMCE}}(T_{\text{eff}}) = 0.245g$

Lower Bound

$\varepsilon_0 = 2.0$

Empirical
- w/o SSE
- w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.2304 + 0.3292T_{\text{eff}}$

Upper Bound

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1634 + 0.3454\varepsilon(T_{\text{eff}})$

$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, Q_2/Q_1 = 0.5, R = 7$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{a\text{COL}} = 0.360g$

$\beta_{RTH} = 0.431$

$S_{a\text{COL}} = 0.623g$

$S_{\text{AMCE}}(T_{\text{eff}}) = 0.245g$

Upper Bound

$\varepsilon_0 = 2.0$

Empirical
- w/o SSE
- w/ SSE
$T_{\text{fixed}} = 0.25$ sec, $K_{e1}/K_{e2} = 1.75$, $Q_2/Q_1 = 0.5$, $R=7$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

![Graph 1](image1)

$T_{\text{fixed}} = 0.25$ sec, $K_{e1}/K_{e2} = 1.75$, $Q_2/Q_1 = 0.5$, $R=7$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

![Graph 2](image2)
$T_{\text{fixed}} = 0.25 \text{ sec, } K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.5, R=7$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)
$T_{\text{fixed}} = 0.25$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.6$, $R = 7$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

\begin{align*}
S_{a\text{COL}} = & 0.350g \\
\beta_{RTH} = & 0.395 \\
S_{a\text{COL}} = & 0.584g \\
T_{\text{eff}} = & 3.13$ sec \\
S_{\text{AMCE}}(T_{\text{eff}}) = & 0.245g
\end{align*}

Lower Bound

$(\text{Empirical})$

w/o SSE

w/ SSE

$T_{\text{fixed}} = 0.25$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.6$, $R = 7$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

\begin{align*}
S_{a\text{COL}} = & 0.360g \\
\beta_{RTH} = & 0.431 \\
S_{a\text{COL}} = & 0.619g \\
T_{\text{eff}} = & 3.13$ sec \\
S_{\text{AMCE}}(T_{\text{eff}}) = & 0.245g
\end{align*}

Upper Bound

$(\text{Empirical})$

w/o SSE

w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.2318 + 0.3296 \epsilon(T_{\text{eff}})$$$

\begin{align*}
\ln[S_{a\text{COL}}(T_{\text{eff}})] = & -1.1676 + 0.3442 \epsilon(T_{\text{eff}})
\end{align*}
$T_{\text{fixed}} = 0.25 \text{ sec, } K_{e_1}/K_{e_2} = 1.75, \frac{Q_2}{Q_1} = 0.6, R = 7$, Isolated, Failure due to 30 mm Uplift

(with vertical ground motion)
$T_{\text{fixed}} = 0.25$ sec, $K_{e1}/K_{e2} = 2.00$, $Q_2/Q_1 = 0.6$, R=7, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

$S_{a\text{COL}} = 0.340g$
$\beta_{RTN} = 0.395$
$S_{a\text{COL}} = 0.586g$
$T_{\text{eff}} = 3.13$ sec.
$S_{\text{AMCE}}(T_{\text{eff}}) = 0.245g$
Lower Bound

$\varepsilon_0 = 2.0$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.2302 + 0.3302\varepsilon(T_{\text{eff}})$

$T_{\text{fixed}} = 0.25$ sec, $K_{e1}/K_{e2} = 2.00$, $Q_2/Q_1 = 0.6$, R=7, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

$S_{a\text{COL}} = 0.360g$
$\beta_{RTN} = 0.433$
$S_{a\text{COL}} = 0.627g$
$T_{\text{eff}} = 3.13$ sec.
$S_{\text{AMCE}}(T_{\text{eff}}) = 0.245g$
Upper Bound

$\varepsilon_0 = 2.0$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1614 + 0.3473\varepsilon(T_{\text{eff}})$
$T_{\text{fixed}} = 0.25 \text{ sec}, \ \frac{K_{e_1}}{K_{e_2}} = 1.50, \ \frac{Q_2}{Q_1} = 0.7, \ R = 7, \ \text{Isolated, Failure due to 30 mm Uplift}$

(with vertical ground motion)

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$T_{\text{fixed}} = 0.25 \text{ sec}, \ \frac{K_{e_1}}{K_{e_2}} = 1.50, \ \frac{Q_2}{Q_1} = 0.7, \ R = 7, \ \text{Isolated, Failure due to 30 mm Uplift}$

(with vertical ground motion)
$T_{fixed} = 0.25 \text{ sec, } K_{e_1}/K_{e_2} = 1.75, Q_2/Q_1 = 0.7, R = 7$, Isolated, Failure due to 30 mm Uplift

(with vertical ground motion)

$T_{eff} = 3.13 \text{ sec, } S_{a,\text{COL}} = 0.350 g$

$S_{a,\text{COL}} = 0.585 g$

$S_{a,\text{MCE}}(T_{eff}) = 0.245 g$

Lower Bound

$\varepsilon = 2.0$

Empirical

w/o SSE

w/ SSE

$T_{fixed} = 0.25 \text{ sec, } K_{e_1}/K_{e_2} = 1.75, Q_2/Q_1 = 0.7, R = 7$, Isolated, Failure due to 30 mm Uplift

(with vertical ground motion)

$T_{eff} = 3.13 \text{ sec, } S_{a,\text{COL}} = 0.360 g$

$S_{a,\text{COL}} = 0.618 g$

$S_{a,\text{MCE}}(T_{eff}) = 0.245 g$

Upper Bound

$\varepsilon = 2.0$

Empirical

w/o SSE

w/ SSE

$\ln[S_{a,\text{COL}}(T_{eff})] = -1.2317 + 0.3299 \epsilon(T_{eff})$

$\ln[S_{a,\text{COL}}(T_{eff})] = -1.1701 + 0.3445 \epsilon(T_{eff})$

Lower Bound

Upper Bound
$T_{\text{fixed}} = 0.25$ sec, $K_{e1}/K_{e2} = 2.00$, $Q_2/Q_1 = 0.7$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

Empirical
\[ \text{w/o SSE} \]
\[ \text{w/ SSE} \]

\[ S_{a\text{COL}} = 0.350g \]
\[ \beta_{RTH} = 0.395 \]
\[ S_{a\text{COL}} = 0.586g \]
\[ T_{\text{eff}} = 3.13 \text{ sec} \]
\[ S_{\text{AMCE}}(T_{\text{eff}}) = 0.245g \]

Lower Bound

\[ \epsilon_0 = 2.0 \]

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.2308 + 0.3305\epsilon(T_{\text{eff}}) \]

Lower Bound

\[ \text{Upper Bound} \]

\[ S_{a\text{COL}} = 0.360g \]
\[ \beta_{RTH} = 0.433 \]
\[ S_{a\text{COL}} = 0.624g \]
\[ T_{\text{eff}} = 3.13 \text{ sec} \]
\[ S_{\text{AMCE}}(T_{\text{eff}}) = 0.245g \]

\[ \epsilon_0 = 2.0 \]

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1648 + 0.3466\epsilon(T_{\text{eff}}) \]

Upper Bound
$T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, Q_2/Q_1 = 0.5, R = 6$, Isolated, Failure due to 30 mm Uplift

(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}, S_{\text{aCOL}}(T_{\text{eff}}) = 0.557g$

$S_{\text{aMCE}}(T_{\text{eff}}) = 0.245g$

$\epsilon_0 = 2.0$

Empirical

- w/o SSE
- w/ SSE

$\ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.2360 + 0.3256(\epsilon(T_{\text{eff}}))$

$\ln[S_{\text{aMCE}}(T_{\text{eff}})] = -1.1850 + 0.3413(\epsilon(T_{\text{eff}}))$

Upper Bound

Lower Bound
$T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.75, \frac{Q_2}{Q_1} = 0.5, R = 6$, isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

$S_{a\text{COL}} = 0.340g$

$\frac{\gamma_{RTN}}{\gamma_{RTN}} = 0.392$

$S_{a\text{COL}} = 0.557g$

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{\text{MCE}}(T_{\text{eff}}) = 0.245g$

Lower Bound

$\varepsilon_0 = 2.0$

Empirical

w/o SSE

w/ SSE

$\ln[\ln(S_{a\text{COL}}(T_{\text{eff}}))] = -1.2355 + 0.3255 \varepsilon(T_{\text{eff}})$

$\ln[\ln(S_{a\text{COL}}(T_{\text{eff}}))] = -1.1629 + 0.3415 \varepsilon(T_{\text{eff}})$

Upper Bound

Lower Bound
$T_{fixed} = 0.20$ sec, $K_{e1}/K_{e2} = 2.00$, $Q_2/Q_1 = 0.5$, $R = 6$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

$S_{a\text{COL}} = 0.340g$
$\gamma = 0.392$

$S_{a\text{COL}} = 0.557g$
$T_{eff} = 3.13$ sec
$S_{a\text{MCE}}(T_{eff}) = 0.245g$
Lower Bound

$\epsilon_0 = 2.0$

$T_{fixed} = 0.20$ sec, $K_{e1}/K_{e2} = 2.00$, $Q_2/Q_1 = 0.5$, $R = 6$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

$S_{a\text{COL}} = 0.370g$
$\gamma = 0.433$

$S_{a\text{COL}} = 0.621g$
$T_{eff} = 3.13$ sec
$S_{a\text{MCE}}(T_{eff}) = 0.245g$
Upper Bound

$\epsilon_0 = 2.0$
$T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, Q_2/Q_1 = 0.6, R=6$, Isolated, Failure due to 30 mm Uplift

(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$, $S_{a\text{COL}} = 0.340g$, $\beta_{RTH} = 0.390$

Lower Bound

$T_{\text{eff}} = 3.13 \text{ sec}$, $S_{a\text{COL}} = 0.557g$

Empirical

$T_{\text{eff}} = 3.13 \text{ sec}$, $S_{a\text{COL}} = 0.245g$

$e_0 = 2.0$

$\ln[\ln(S_{a\text{COL}}(T_{\text{eff}}))] = -1.2369 + 0.3256e(T_{\text{eff}})$

Lower Bound

$\ln[\ln(S_{a\text{COL}}(T_{\text{eff}}))] = -1.1719 + 0.3423e(T_{\text{eff}})$

Upper Bound
$T_{\text{fixed}} = 0.20 \text{ sec}, K_{e1}/K_{e2} = 1.75, Q_2/Q_1 = 0.6, R = 6$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

- $S_a(T_{\text{eff}})g$
  - $S_{a,\text{COL}} = 0.340g$
  - $S_{a,\text{COL}} = 0.557g$
  - $S_{a,\text{MCE}}(T_{\text{eff}}) = 0.245g$
  - $T_{\text{eff}} = 3.13 \text{ sec}$

- Lower Bound
  - $\epsilon_0 = 2.0$

- Empirical
- w/o SSE
- w/ SSE

$log[S_{a,\text{COL}}(T_{\text{eff}})] = -1.2371 + 0.3256\epsilon(T_{\text{eff}})$

$T_{\text{fixed}} = 0.20 \text{ sec}, K_{e1}/K_{e2} = 1.75, Q_2/Q_1 = 0.6, R = 6$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

- $S_a(T_{\text{eff}})g$
  - $S_{a,\text{COL}} = 0.370g$
  - $S_{a,\text{COL}} = 0.619g$

- Upper Bound
  - $\epsilon_0 = 2.0$

- Empirical
- w/o SSE
- w/ SSE

$log[S_{a,\text{COL}}(T_{\text{eff}})] = -1.1671 + 0.3437\epsilon(T_{\text{eff}})$
$T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, \frac{Q_2}{Q_1} = 0.6, R = 6$, Isolated, Failure due to 30 mm Uplift

(with vertical ground motion)
$T_{\text{fixed}} = 0.20$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.7$, $R = 6$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

- $S_{\text{a,COL}} = 0.340$g
- $\gamma_{RTH} = 0.390$
- $S_{\text{a,COL}} = 0.557$g
- $T_{\text{eff}} = 3.13$ sec
- $S_{\text{MCE}}(T_{\text{eff}}) = 0.245$g

Lower Bound

- Empirical
- w/o SSE
- w/ SSE

$\epsilon_0 = 2.0$

$\ln[S_{\text{a,COL}}(T_{\text{eff}})] = -1.2369 + 0.3257\epsilon(T_{\text{eff}})$

$T_{\text{fixed}} = 0.20$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.7$, $R = 6$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

- $S_{\text{a,COL}} = 0.360$g
- $\gamma_{RTH} = 0.426$
- $S_{\text{a,COL}} = 0.604$g
- $T_{\text{eff}} = 3.13$ sec
- $S_{\text{MCE}}(T_{\text{eff}}) = 0.245$g

Upper Bound

$\ln[S_{\text{a,COL}}(T_{\text{eff}})] = -1.1785 + 0.3368\epsilon(T_{\text{eff}})$
$T_{\text{fixed}} = 0.20 \text{ sec}, \quad K_{e1}/K_{e2} = 1.75, \quad Q_2/Q_1 = 0.7, \quad R = 6$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{a\text{COL}} = 0.340g$

$S_{a\text{COL}} = 0.557g$

$\beta_{\text{RTH}} = 0.390$

$S_{a\text{COL}} = 0.607g$

$\beta_{\text{RTH}} = 0.428$

$S_{a\text{COL}} = 0.370g$

$S_{a\text{COL}} = 0.245g$

Lower Bound

Empirical

w/o SSE

w/ SSE

$\varepsilon = 2.0$

$\varepsilon = 2.0$

$\text{Empirical}$

w/o SSE

w/ SSE

$\text{Upper Bound}$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.2372 + 0.325\varepsilon(T_{\text{eff}})$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1743 + 0.337\varepsilon(T_{\text{eff}})$

Lower Bound

Upper Bound
$T_{\text{fixed}} = 0.20 \text{ sec, } K_{e_1}/K_{e_2} = 2.00, Q_2/Q_1 = 0.7, R = 6, \text{ isolated, Failure due to 30 mm Uplift}$

(with vertical ground motion)
$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.50, \frac{Q_2}{Q_1} = 0.5, R = 8, \text{ Isolated, Failure due to Uplift not Considered}$

(with vertical ground motion)

![Graph showing probability of collapse vs. $S_a(T_{\text{eff}})$]

$S_{aCOL} = 0.360g, \beta_R = 0.269$

$S_{aCOL} = 0.513g, T_{\text{eff}} = 3.13 \text{ sec, } S_{aMCE}(T_{\text{eff}}) = 0.245g$

Lower Bound

Empirical
- w/o SSE
- w/ SSE

![Graph showing $\ln[S_{aCOL}(T_{\text{eff}})]$ vs. $\epsilon(T_{\text{eff}})$]

$\ln[S_{aCOL}(T_{\text{eff}})] = -1.0879 + 0.2101\epsilon(T_{\text{eff}})$

Lower Bound

$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.50, \frac{Q_2}{Q_1} = 0.5, R = 8, \text{ Isolated, Failure due to Uplift not Considered}$

(with vertical ground motion)

![Graph showing probability of collapse vs. $S_a(T_{\text{eff}})$]

$S_{aCOL} = 0.380g, \beta_R = 0.334$

$S_{aCOL} = 0.574g, T_{\text{eff}} = 3.13 \text{ sec, } S_{aMCE}(T_{\text{eff}}) = 0.245g$

Upper Bound

Empirical
- w/o SSE
- w/ SSE

![Graph showing $\ln[S_{aCOL}(T_{\text{eff}})]$ vs. $\epsilon(T_{\text{eff}})$]

$\ln[S_{aCOL}(T_{\text{eff}})] = -1.0539 + 0.2497\epsilon(T_{\text{eff}})$

Upper Bound
$T_{\text{fixed}} = 0.30 \text{ sec}, K_{e1}/K_{e2} = 1.75, Q_{e2}/Q_{e1} = 0.5, R = 8$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}, S_{a\text{MCE}}(T_{\text{eff}}) = 0.245\text{g}$

Lower Bound

Empirical

$\varepsilon_0 = 2.0$

$S_{a\text{COL}} = 0.360\text{g}$

$\beta_{RTH} = 0.266$

$S_{a\text{COL}} = 0.513\text{g}$

$\varepsilon_0 = 2.0$

$S_{a\text{COL}} = 0.380\text{g}$

$\beta_{RTH} = 0.332$

$S_{a\text{COL}} = 0.576\text{g}$

$\varepsilon_0 = 2.0$

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$T_{\text{fixed}}=0.30\text{ sec, } K_{e1}/K_{e2}=2.00, Q_2/Q_1=0.5, R=8$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

$T_{\text{eff}}=3.13\text{ sec, } S_{a\text{COL}}=0.360g, \beta_{RTH}=0.266$

Lower Bound

Empirical
- w/o SSE
- w/ SSE

$\varepsilon_0=2.0$

$\ln[S_{a\text{COL}}(T_{\text{eff}})]=1.0814+0.2056\varepsilon(T_{\text{eff}})$

Lower Bound

Empirical
- w/o SSE
- w/ SSE

$\varepsilon_0=2.0$

$\ln[S_{a\text{COL}}(T_{\text{eff}})]=1.0447+0.2484\varepsilon(T_{\text{eff}})$

Upper Bound
$T_{\text{fixed}} = 0.30$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.6$, $R = 8$, Isolated, Failure due to Uplift not Considered

(with vertical ground motion)

$S_{\text{aCOL}} = 0.360g$
$\beta_{HTN} = 0.271$

$S_{\text{aCOL}} = 0.510g$
$T_{\text{eff}} = 3.13$ sec
$S_{\text{aMCE}}(T_{\text{eff}}) = 0.245g$

Lower Bound
$\epsilon_0 = 2.0$

Empirical
- w/o SSE
- w/ SSE

$\ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.0925 + 0.2098(\epsilon_{T_{\text{eff}}})$

$\ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.0573 + 0.2526(\epsilon_{T_{\text{eff}}})$

(with vertical ground motion)

$S_{\text{aCOL}} = 0.380g$
$\beta_{HTN} = 0.335$

$S_{\text{aCOL}} = 0.576g$
$T_{\text{eff}} = 3.13$ sec
$S_{\text{aMCE}}(T_{\text{eff}}) = 0.245g$

Upper Bound
$\epsilon_0 = 2.0$

Empirical
- w/o SSE
- w/ SSE

$\ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.0925 + 0.2098(\epsilon_{T_{\text{eff}}})$

$\ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.0573 + 0.2526(\epsilon_{T_{\text{eff}}})$
$T_{\text{fixed}} = 0.30 \text{ sec, } \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_2}{Q_1} = 0.6, R = 8$, Isolated, Failure due to Uplift not Considered

(with vertical ground motion)
$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 2.00, Q_z/Q_1 = 0.6, R=8$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec, } S_{a(\text{COL})} = 0.511g, \beta_{RTN} = 0.266$

$S_{a(\text{COL})} = 0.360g$

$\varepsilon_0 = 2.0$

Empirical

$\text{w/o SSE}$

$\text{w/ SSE}$

$\ln[S_{a(\text{COL})}(T_{\text{eff}})] = -1.0844 + 0.2070\varepsilon(T_{\text{eff}})$

Lower Bound

$\ln[S_{a(\text{COL})}(T_{\text{eff}})] = -1.0466 + 0.2500\varepsilon(T_{\text{eff}})$

Upper Bound
$T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, Q_2/Q_1 = 0.7, R = 8$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

[Graph 1]

[Graph 2]

$T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, Q_2/Q_1 = 0.7, R = 8$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

[Graph 3]

[Graph 4]
$T_{fixed} = 0.30 \text{ sec, } K_{e1} / K_{e2} = 1.75, Q_2 / Q_1 = 0.7, R = 8$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

$S_{aCOL} = 0.360g$
$
\beta_{RTN} = 0.276$

$S_{aCOL} = 0.510g$
$T_{eff} = 3.13 \text{ sec}$
$S_{aMCE(T_{eff})} = 0.245g$

Lower Bound

Empirical
w/o SSE
w/ SSE

$\epsilon_0 = 2.0$

$\ln[S_{aCOL(T_{eff})}] = -1.0929 + 0.2096 \epsilon(T_{eff})$

$S_{a(T_{eff})} g$
$\epsilon(T_{eff})$

$T_{fixed} = 0.30 \text{ sec, } K_{e1} / K_{e2} = 1.75, Q_2 / Q_1 = 0.7, R = 8$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

$S_{aCOL} = 0.380g$

$\beta_{RTN} = 0.337$

$S_{aCOL} = 0.578g$
$T_{eff} = 3.13 \text{ sec}$
$S_{aMCE(T_{eff})} = 0.245g$

Upper Bound

Empirical
w/o SSE
w/ SSE

$\epsilon_0 = 2.0$

$\ln[S_{aCOL(T_{eff})}] = -1.0536 + 0.2540 \epsilon(T_{eff})$

$S_{a(T_{eff})} g$
$\epsilon(T_{eff})$
$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e_1}/K_{e_2} = 2.00, Q_2/Q_1 = 0.7, R = 8$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

![Graph showing probability of collapse vs. $S_a(T_{\text{eff}})g$](image)

$T_{\text{eff}} = 3.13 \text{ sec, } S_{\text{aCOL}} = 0.510g, S_{\text{aMCE}}(T_{\text{eff}}) = 0.245g$

Lower Bound

Empirical
- w/o SSE
- w/ SSE

$\varepsilon_0 = 2.0$

$\ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.0907 + 0.2088(\varepsilon(T_{\text{eff}}))$

Lower Bound

(with vertical ground motion)

$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e_1}/K_{e_2} = 2.00, Q_2/Q_1 = 0.7, R = 8$, Isolated, Failure due to Uplift not Considered

![Graph showing probability of collapse vs. $S_a(T_{\text{eff}})g$](image)

$S_{\text{aCOL}} = 0.380g, S_{\text{aMCE}}(T_{\text{eff}}) = 0.245g$

Upper Bound

Empirical
- w/o SSE
- w/ SSE

$\varepsilon_0 = 2.0$

$\ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.0488 + 0.2511(\varepsilon(T_{\text{eff}}))$

Upper Bound
$T_{\text{fixed}} = 0.25$ sec, $K_{\text{e1}}/K_{\text{e2}} = 1.50$, $Q_2/Q_1 = 0.5$, $R = 7$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

- $S_{a,\text{COL}}^{\text{LH}} = 0.350g$
- $R_{\text{H1H}} = 0.271$
- $S_{a,\text{COL}}^{\text{MC}} = 0.504g$
- $T_{\text{eff}} = 3.13$ sec
- $S_{a,\text{MC}}^{\text{MC}}(T_{\text{eff}}) = 0.245g$

Lower Bound

- Empirical
- w/o SSE
- w/ SSE

$\ln |S_{a,\text{COL}}(T_{\text{eff}})| = -1.1031 + 0.2086\epsilon(T_{\text{eff}})$

Lower Bound

- $T_{\text{fixed}} = 0.25$ sec, $K_{\text{e1}}/K_{\text{e2}} = 1.50$, $Q_2/Q_1 = 0.5$, $R = 7$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

- $S_{a,\text{COL}}^{\text{MC}} = 0.370g$
- $R_{\text{H1H}} = 0.337$
- $S_{a,\text{COL}}^{\text{MC}} = 0.568g$
- $T_{\text{eff}} = 3.13$ sec
- $S_{a,\text{MC}}^{\text{MC}}(T_{\text{eff}}) = 0.245g$

Upper Bound

- Empirical
- w/o SSE
- w/ SSE

$\ln |S_{a,\text{COL}}(T_{\text{eff}})| = -1.0680 + 0.2512\epsilon(T_{\text{eff}})$

Upper Bound
$T_{\text{fixed}} = 0.25$ sec, $K_{e1}/K_{e2} = 1.75$, $Q_{p}/Q_{s} = 0.5$, $R = 7$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

\begin{align*}
S_{adc} &= 0.350 g \\
\beta_{RTN} &= 0.270 \\
S_{aCOL} &= 0.504 g \\
T_{eff} &= 3.13 \text{ sec} \\
S_{AMCE}(T_{eff}) &= 0.245 g
\end{align*}

Lower Bound

Empirical
- w/o SSE
- w/ SSE

\begin{align*}
\ln[S_{aCOL}(T_{eff})] &= -1.1010 + 0.2077 (\epsilon(T_{eff}))
\end{align*}

\begin{align*}
\ln[S_{aCOL}(T_{eff})] &= -1.0842 + 0.2515 (\epsilon(T_{eff}))
\end{align*}

$T_{\text{fixed}} = 0.25$ sec, $K_{e1}/K_{e2} = 1.75$, $Q_{p}/Q_{s} = 0.5$, $R = 7$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

\begin{align*}
S_{aCOL} &= 0.370 g \\
\beta_{RTN} &= 0.337 \\
S_{adc} &= 0.570 g \\
T_{eff} &= 3.13 \text{ sec} \\
S_{AMCE}(T_{eff}) &= 0.245 g
\end{align*}

Upper Bound

Empirical
- w/o SSE
- w/ SSE
$T_{\text{fixed}} = 0.25$ sec, $K_{e1}/K_{e2} = 2.00$, $Q_2/Q_1 = 0.5$, $R = 7$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

[Diagram showing probability of collapse vs. $S_a(T_{\text{eff}})$ and $\ln[S_a(T_{\text{eff}})]$ vs. $\epsilon(T_{\text{eff}})$ with empirical data and bounds.]

$T_{\text{eff}} = 3.13$ sec, $S_{a,\text{COL}} = 0.504g$, $\beta_{RTH} = 0.269$

$S_{a,\text{COL}} = 0.350g$

Lower Bound

Empirical
- w/o SSE
- w/ SSE

$\epsilon_0 = 2.0$

$\ln[S_a(T_{\text{eff}})] = 1.0993 + 0.2071\epsilon(T_{\text{eff}})$

Lower Bound

$S_{a,\text{COL}} = 0.370g$

$\beta_{RTH} = 0.335$

Upper Bound

Empirical
- w/o SSE
- w/ SSE

$\epsilon_0 = 2.0$

$\ln[S_a(T_{\text{eff}})] = -1.0601 + 0.2525\epsilon(T_{\text{eff}})$

Upper Bound
$T_{\text{fixed}} = 0.25 \text{ sec}, K_{e1}/K_{e2} = 1.50, Q_{z}/Q_{x} = 0.6, R=7, \text{ Isolated, Failure due to Uplift not Considered}$

(with vertical ground motion)

$S_{a\text{COL}} = 0.350g$
$\beta_{RTH} = 0.273$

$S_{a\text{COL}} = 0.504g$

$T_{\text{eff}} = 3.13 \text{ sec}$
$S_{a\text{MCE}}(T_{\text{eff}}) = 0.245g$

Lower Bound

$\epsilon_{0} = 2.0$

Empirical
- w/o SSE
- w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1070 + 0.2109(\epsilon(T_{\text{eff}}))$

Lower Bound

$T_{\text{fixed}} = 0.25 \text{ sec}, K_{e1}/K_{e2} = 1.50, Q_{z}/Q_{x} = 0.6, R=7, \text{ Isolated, Failure due to Uplift not Considered}$

(with vertical ground motion)

$S_{a\text{COL}} = 0.370g$
$\beta_{RTH} = 0.344$

$S_{a\text{COL}} = 0.569g$

$T_{\text{eff}} = 3.13 \text{ sec}$
$S_{a\text{MCE}}(T_{\text{eff}}) = 0.245g$

Upper Bound

$\epsilon_{0} = 2.0$

Empirical
- w/o SSE
- w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0799 + 0.2580(\epsilon(T_{\text{eff}}))$

Upper Bound

249
$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_2}{Q_1} = 0.6, R=7$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}, S_{\text{aC}} = 0.350g, \beta_{\text{cum}} = 0.270$

$S_{\text{aC}} = 0.502g, S_{\text{aMCE}}(T_{\text{eff}}) = 0.245g$

Lower Bound

$\sigma = 2.0$

Empirical
w/o SSE
w/ SSE

$\ln[S_{\text{aC}}(T_{\text{eff}})] = -1.1031 + 0.2074\epsilon(T_{\text{eff}})$

Lower Bound

Empirical
w/o SSE
w/ SSE

$\ln[S_{\text{aC}}(T_{\text{eff}})] = -1.0725 + 0.2556\epsilon(T_{\text{eff}})$

Upper Bound

$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_2}{Q_1} = 0.6, R=7$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)
\( T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{\text{eff}}}{K_{\text{ref}}} = 2.00, Q_2/Q_1 = 0.6, R = 7 \), Isolated, Failure due to Uplift not Considered

(with vertical ground motion)

\( T_{\text{eff}} = 3.13 \text{ sec}, S_{\text{aCOL}}(T_{\text{eff}}) = 0.350g \)

\( \beta_{\text{RTH}} = 0.269 \)

\( S_{\text{aCOL}} = 0.503g \)

Lower Bound

\( \varepsilon_0 = 2.0 \)

\( \ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.0116 + 0.2071\varepsilon(T_{\text{eff}}) \)

Upper Bound

\( \ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.0668 + 0.2547\varepsilon(T_{\text{eff}}) \)
$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, \frac{Q_2}{Q_1} = 0.7, R = 7$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)
$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.75, Q_2/Q_1 = 0.7, R = 7$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$, $S_{\text{aCOL}} = 0.350g$, $\beta_{\text{RTH}} = 0.273$

$S_{\text{aCOL}} = 0.504g$

$S_{\text{aMOE}}(T_{\text{eff}}) = 0.245g$

Lower Bound

Empirical
- w/o SSE
- w/ SSE

$\varepsilon_0 = 2.0$

$\ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.1075 + 0.2113\epsilon(T_{\text{eff}})$

$\ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.0833 + 0.2596\epsilon(T_{\text{eff}})$

Upper Bound

$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.75, Q_2/Q_1 = 0.7, R = 7$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$, $S_{\text{aCOL}} = 0.360g$, $\beta_{\text{RTH}} = 0.343$

$S_{\text{aCOL}} = 0.569g$

$S_{\text{aMOE}}(T_{\text{eff}}) = 0.245g$

Empirical
- w/o SSE
- w/ SSE

$\varepsilon_0 = 2.0$
$T_{\text{fixed}} = 0.25 \text{ sec, } K_{e1}/K_{e2} = 2.00, Q_Z/Q_1 = 0.7, R = 7$, Isolated. Failure due to Uplift not Considered
(with vertical ground motion)

![Probability of Collapse vs $S_a(T_{\text{eff}})$](image1)

![Log of $S_a(T_{\text{eff}})$ vs $\epsilon(T_{\text{eff}})$](image2)

$T_{\text{fixed}} = 0.25 \text{ sec, } K_{e1}/K_{e2} = 2.00, Q_Z/Q_1 = 0.7, R = 7$, Isolated. Failure due to Uplift not Considered
(with vertical ground motion)

![Probability of Collapse vs $S_a(T_{\text{eff}})$](image3)

![Log of $S_a(T_{\text{eff}})$ vs $\epsilon(T_{\text{eff}})$](image4)
T_{\text{fixed}} = 0.20 \text{ sec, } K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.5, R=6, \text{ Isolated, Failure due to Uplift not Considered}

(with vertical ground motion)

\begin{align*}
&\text{Empirical} \quad \text{w/o SSE} \quad \text{w/ SSE} \\
&T_{\text{eff}} = 3.13 \text{ sec, } S_{a\text{COL}} = 0.500g, S_{a\text{MCE}}(T_{\text{eff}}) = 0.245g, \epsilon = 2.0, \text{ Lower Bound}
\end{align*}

\begin{align*}
&\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1136 + 0.2104\epsilon(T_{\text{eff}})
\end{align*}

\begin{align*}
&T_{\text{fixed}} = 0.20 \text{ sec, } K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.5, R=6, \text{ Isolated, Failure due to Uplift not Considered}

&(\text{with vertical ground motion})

\begin{align*}
&\text{Empirical} \quad \text{w/o SSE} \quad \text{w/ SSE} \\
&T_{\text{eff}} = 3.13 \text{ sec, } S_{a\text{COL}} = 0.370g, S_{a\text{MCE}}(T_{\text{eff}}) = 0.245g, \epsilon = 2.0, \text{ Upper Bound}
\end{align*}

\begin{align*}
&\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0749 + 0.2527\epsilon(T_{\text{eff}})
\end{align*}
$T_{\text{fixed}} = 0.20 \text{ sec, } K_{e1}/K_{e2} = 1.75, Q_{2}/Q_{1} = 0.5, R = 6$, Isolated, Failure due to Uplift not Considered

(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec, } S_{a\text{COL}} = 0.350g$

Lower Bound

Empirical

$\epsilon = 2.0$

Empirical

$\epsilon = 3.39$

Upper Bound

Empirical

$\epsilon = 2.0$

Empirical

$\epsilon = 2.0$

Empirical
$T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, Q_2/Q_1 = 0.5, R = 6$, Isolated, Failure due to Uplift not Considered

(with vertical ground motion)
$T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, Q_2/Q_1 = 0.6, R = 6,$ Isolated, Failure due to Uplift not considered.

(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}, S_{a\text{COL}} = 0.350g, T_{\text{eff}} = \frac{3.13}{S_{a\text{COL}}} = 0.245g,$

Lower Bound

Empirical

$\varepsilon_0 = 2.0$

$S_a(T_{\text{eff}})g$

$\varepsilon(T_{\text{eff}})$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1161 + 0.2118 \varepsilon(T_{\text{eff}})$

Lower Bound

$T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, Q_2/Q_1 = 0.6, R = 6,$ Isolated, Failure due to Uplift not considered.

(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}, S_{a\text{COL}} = 0.370g, T_{\text{eff}} = \frac{3.13}{S_{a\text{COL}}} = 0.352g,$

Upper Bound

Empirical

$\varepsilon_0 = 2.0$

$S_a(T_{\text{eff}})g$

$\varepsilon(T_{\text{eff}})$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0961 + 0.2611 \varepsilon(T_{\text{eff}})$

Upper Bound
$T_{\text{fixed}} = 0.20 \text{ sec}, K_{e1}/K_{e2} = 1.75, Q_{1}/Q_{2} = 0.6, R = 6$, Isolated, Failure due to Uplift not Considered

(With vertical ground motion)

$S_a(T_{\text{eff}})g$

Probability of Collapse

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1153 + 0.2115 \epsilon(T_{\text{eff}})$

Lower Bound

Empirical
w/o SSE
w/ SSE

$\epsilon_0 = 2.0$

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{a\text{COL}} = 0.350g$

$\beta_{\text{RHN}} = 0.270$

$S_{a\text{COL}} = 0.500g$

$S_{a\text{MCE}}(T_{\text{eff}}) = 0.245g$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0803 + 0.2558 \epsilon(T_{\text{eff}})$

Upper Bound

Empirical
w/o SSE
w/ SSE

$\epsilon_0 = 2.0$

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{a\text{COL}} = 0.370g$

$\beta_{\text{RHN}} = 0.344$

$S_{a\text{COL}} = 0.566g$

$S_{a\text{MCE}}(T_{\text{eff}}) = 0.245g$
$T_{\text{fixed}} = 0.20 \text{ sec}, K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.6, R = 6$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

$S_{a,\text{COL}} = 0.340g$
$\beta_{RTN} = 0.269$
$S_{a,\text{COL}} = 0.500g$
$T_{\text{eff}} = 3.13 \text{ sec}$
$S_{\text{AMCE}}(T_{\text{eff}}) = 0.245g$

Empirical
- w/o SSE
- w/ SSE

$\ln[S_{a,\text{COL}}(T_{\text{eff}})] = -1.1144 + 0.2106 \epsilon(T_{\text{eff}})$

$T_{\text{fixed}} = 0.20 \text{ sec}, K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.6, R = 6$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

$S_{a,\text{COL}} = 0.370g$
$\beta_{RTN} = 0.342$
$S_{a,\text{COL}} = 0.567g$
$T_{\text{eff}} = 3.13 \text{ sec}$
$S_{\text{AMCE}}(T_{\text{eff}}) = 0.245g$

Empirical
- w/o SSE
- w/ SSE

$\ln[S_{a,\text{COL}}(T_{\text{eff}})] = -1.0734 + 0.2534 \epsilon(T_{\text{eff}})$
$T_{\text{fixed}} = 0.20$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.7$, $R = 6$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

$S_{a\text{COL}} = 0.350g$
$\beta_{RTH} = 0.272$

$S_{a\text{COL}} = 0.501g$

$T_{\text{eff}} = 3.13$ sec
$S_{AMCE}(T_{\text{eff}}) = 0.245g$

Lower Bound

$\epsilon_0 = 2.0$

Empirical
w/o SSE
w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1173 + 0.2126(\epsilon(T_{\text{eff}}))$

Lower Bound

$T_{\text{fixed}} = 0.20$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.7$, $R = 6$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

$S_{a\text{COL}} = 0.370g$
$\beta_{RTH} = 0.356$

$S_{a\text{COL}} = 0.555g$

$T_{\text{eff}} = 3.13$ sec
$S_{AMCE}(T_{\text{eff}}) = 0.245g$

Upper Bound

$\epsilon_0 = 2.0$

Empirical
w/o SSE
w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1080 + 0.2600(\epsilon(T_{\text{eff}}))$

Upper Bound
$T_{\text{fixed}} = 0.20$ sec, $K_{e_1}/K_{e_2} = 1.75$, $Q_2/Q_1 = 0.7$, $R = 6$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

$S_{\text{a}_x}(T_{\text{eff}})g$

Empirical

$S_{\text{a}_x}(T_{\text{eff}})g$

$\beta_{\text{RTN}} = 0.270$

$S_{\text{a}_x}(T_{\text{eff}})g$

$\epsilon_0 = 2.0$

$T_{\text{eff}} = 3.13$ sec

$S_{\text{a}_x}(T_{\text{eff}}) = 0.245g$

Empirical

$S_{\text{a}_x}(T_{\text{eff}})g$

$\beta_{\text{RTN}} = 0.354$

$S_{\text{a}_x}(T_{\text{eff}})g$

$\epsilon_0 = 2.0$

$T_{\text{eff}} = 3.13$ sec

$S_{\text{a}_x}(T_{\text{eff}}) = 0.245g$

Empirical

$\epsilon(T_{\text{eff}})$

Lower Bound

$\ln[S_{\text{a}_x}(T_{\text{eff}})] = 1.1155 + 0.2113 \epsilon(T_{\text{eff}})$

Lower Bound

$\ln[S_{\text{a}_x}(T_{\text{eff}})] = 1.1016 + 0.2578 \epsilon(T_{\text{eff}})$

Upper Bound

262
\( T_{\text{fixed}} = 0.20\) sec, \( K_{e1}/K_{e2} = 2.00 \), \( Q_2/Q_1 = 0.7 \), \( R = 6 \), Isolated, Failure due to Uplift not Considered (with vertical ground motion)
E.2. Results for western site with latitude 41.105°, longitude 28.784° \( \bar{\varepsilon}_0(T_1) = 1.5 \)

\[ T_1 = 0.30 \text{ sec, } K_{e_1}/K_{e_2} = 1.50, \ Q_2/Q_1 = 0.5, \ R = 8, \text{ Non-isolated} \]

(without vertical ground motion)

\[ T_1 = 0.30 \text{ sec, } K_{e_1}/K_{e_2} = 1.75, \ Q_2/Q_1 = 0.5, \ R = 8, \text{ Non-isolated} \]

(without vertical ground motion)
$T_1 = 0.30$ sec, $K_{e1}/K_{e2} = 2.00$, $Q_2/Q_1 = 0.5$, $R = 8$, Non-isolated
(without vertical ground motion)

$T_1 = 0.30$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.6$, $R = 8$, Non-isolated
(without vertical ground motion)
$T_1 = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.75, \frac{Q_2}{Q_1} = 0.6, R = 8, \text{ Non-isolated}$

(Without vertical ground motion)

$T_1 = 0.30 \text{ sec, } K_{e1}/K_{e2} = 2.00, \frac{Q_2}{Q_1} = 0.6, R = 8, \text{ Non-isolated}$

(Without vertical ground motion)
\( T_1 = 0.30 \text{ sec}, K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.7, R = 8, \) Non-isolated
(without vertical ground motion)

\[ S_{s\text{COL}} = 1.690g \]
\[ r_{RTR} = 0.408 \]
\[ S_{s\text{COL}} = 1.890g \]

\( T_1 = 0.30 \text{ sec} \)
\( S_{\text{MCE}}(T_1) = 1.350g \)
\( \epsilon_0 = 1.5 \)

\( \ln(S_{s\text{COL}}(T_1)) = 0.2890 + 0.2321(T_1) \)

\( T_1 = 0.30 \text{ sec}, K_{e1}/K_{e2} = 1.75, Q_2/Q_1 = 0.7, R = 8, \) Non-isolated
(without vertical ground motion)

\[ S_{s\text{COL}} = 1.700g \]
\[ r_{RTR} = 0.406 \]
\[ S_{s\text{COL}} = 1.905g \]

\( T_1 = 0.30 \text{ sec} \)
\( S_{\text{MCE}}(T_1) = 1.350g \)
\( \epsilon_0 = 1.5 \)

\( \ln(S_{s\text{COL}}(T_1)) = 0.3016 + 0.2290(T_1) \)
$T_1 = 0.30 \text{ sec}, K_{e1}/K_{e2} = 2.00, Q_x/Q_1 = 0.7, R = 8$, Non-isolated
(without vertical ground motion)

$T_1 = 0.25 \text{ sec}, K_{e1}/K_{e2} = 1.50, Q_x/Q_1 = 0.5, R = 7$, Non-isolated
(without vertical ground motion)
$T_1 = 0.25$ sec, $K_1/K_2 = 1.75$, $Q_1/Q_2 = 0.5$, $R = 7$, Non-isolated
(without vertical ground motion)

![Graph 1](image1)

$T_1 = 0.25$ sec, $K_1/K_2 = 2.00$, $Q_1/Q_2 = 0.5$, $R = 7$, Non-isolated
(without vertical ground motion)

![Graph 2](image2)
$T_1 = 0.25 \text{ sec, } K_{e_1}/K_{e_2} = 1.50, \ Q_2/Q_1 = 0.6, \ R = 7, \ \text{Non-isolated (without vertical ground motion)}$

$T_1 = 0.25 \text{ sec, } K_{e_1}/K_{e_2} = 1.75, \ Q_2/Q_1 = 0.6, \ R = 7, \ \text{Non-isolated (without vertical ground motion)}$
$T_1 = 0.25$ sec, $K_{e1}/K_{e2} = 2.00$, $Q_2/Q_1 = 0.6$, $R = 7$, Non-isolated
(without vertical ground motion)

$T_1 = 0.25$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.7$, $R = 7$, Non-isolated
(without vertical ground motion)
$T_1 = 0.25 \text{ sec, } K_{e1}/K_{e2} = 1.75, \frac{Q_z}{Q_1} = 0.7, R = 7$, Non-isolated

(without vertical ground motion)

$T_1 = 0.25 \text{ sec, } K_{e1}/K_{e2} = 2.00, \frac{Q_z}{Q_1} = 0.7, R = 7$, Non-isolated

(without vertical ground motion)
\[ T_1 = 0.20 \text{ sec, } \frac{K_{e1}}{K_{e2}} = 1.50, \frac{Q_2}{Q_1} = 0.5, R = 6, \text{ Non-isolated} \]

(without vertical ground motion)

\[ \ln[S_{\text{acol}}(T_1)] = 0.2348 + 0.2590 \epsilon(T_1) \]

\[ \ln[S_{\text{acol}}(T_1)] = 0.2454 + 0.2410 \epsilon(T_1) \]
$T_1 = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, \frac{Q_2}{Q_1} = 0.5, R = 6$, Non-isolated
(without vertical ground motion)

\[ \text{Prob}(\text{Collapse}) \]

\[ S_a(T_1)/g \]

\[ T_1 = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, \frac{Q_2}{Q_1} = 0.6, R = 6$, Non-isolated
(without vertical ground motion)

\[ \text{Prob}(\text{Collapse}) \]

\[ S_a(T_1)/g \]
$T_1 = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_2}{Q_1} = 0.6, R = 6$, Non-isolated
(without vertical ground motion)

![Graph 1](image1)

$T_1 = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, \frac{Q_2}{Q_1} = 0.6, R = 6$, Non-isolated
(without vertical ground motion)

![Graph 2](image2)
$T_1 = 0.20$ sec, $K_e / K_{e2} = 1.50$, $Q_\alpha / Q_e = 0.7$, $R = 6$, Non-isolated (without vertical ground motion)
$T_1 = 0.20 \text{ sec}, K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.7, R = 6, \text{ Non-isolated}$

(without vertical ground motion)

$T_1 = 0.20 \text{ sec}$

$S_{aCOL} = 1.520g$

$\beta_{RTR} = 0.392$

$S_{aMCE}(T_1) = 1.350g$

$\epsilon_0 = 1.5$

Empirical

$\text{w/o SSE}$

$\text{w/ SSE}$

$T_{\text{fixed}} = 0.30 \text{ sec}, K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.5, R = 8, \text{ Isolated}$

(without vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{aCOL} = 0.445g$

$\beta_{RTR} = 0.224$

$S_{aMCE}(T_{\text{eff}}) = 0.245g$

$\epsilon_0 = 1.5$

Empirical

$\text{w/o SSE}$

$\text{w/ SSE}$

Lower Bound

$\text{ln}(S_{aCOL}(T_{\text{eff}})) = 1.0282 + 0.1458\epsilon(T_{\text{eff}})$

Lower Bound
\[ T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_2}{Q_1} = 0.5, \text{ R=8, Isolated} \]

(without vertical ground motion)

\[ S_{a\text{COL}} = 0.380g, \quad \beta_{RTR} = 0.223 \]

\[ S_{a\text{COL}} = 0.445g \]

\[ T_{\text{ef}} = 3.13 \text{ sec} \]

\[ S_{\text{AMCE}(T_{\text{eff}})} = 0.245g \]

Lower Bound

\[ \varepsilon_0 = 1.5 \]

\[ \epsilon(T_{\text{ef}}) \]

\[ \ln[S_{a\text{COL}(T_{\text{eff}})}] = -1.0267 + 0.1454 \epsilon(T_{\text{ef}}) \]

Lower Bound

\[ \epsilon(T_{\text{ef}}) \]

\[ \ln[S_{a\text{COL}(T_{\text{eff}})}] = -1.0259 + 0.1452 \epsilon(T_{\text{ef}}) \]

Lower Bound
$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.6, R = 8, \text{ Isolated}$

(without vertical ground motion)

$S_{a\text{COL}} = 0.380g$

$\beta_{\text{RTR}} = 0.223$

$S_{a\text{COL}} = 0.445g$

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{\text{AMCE}}(T_{\text{eff}}) = 0.245g$

Lower Bound

$e_{\theta} = 1.5$

Empirical

- w/o SSE
- w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0276 + 0.1454\epsilon(T_{\text{eff}})$

Lower Bound

(without vertical ground motion)

$S_{a\text{COL}} = 0.380g$

$\beta_{\text{RTR}} = 0.224$

$S_{a\text{COL}} = 0.445g$

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{\text{AMCE}}(T_{\text{eff}}) = 0.245g$

Lower Bound

$e_{\theta} = 1.5$

Empirical

- w/o SSE
- w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0298 + 0.1469\epsilon(T_{\text{eff}})$

Lower Bound
\( T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_2}{Q_1} = 0.7, R = 8, \text{ Isolated} \)

(without vertical ground motion)

\( T_{\text{eff}} = 3.13 \text{ sec} \)

\( S_{a\text{COL}}(T_{\text{eff}}) = 0.445g \)

\( S_{a\text{COL}}(T_{\text{eff}}) = 0.380g \)

\( \beta_{\text{RTR}} = 0.224 \)

\( \epsilon_0 = 1.5 \)

Empirical

- \( w/o \text{ SSE} \)
- \( w/ \text{ SSE} \)

\( \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0286 + 0.1462 \epsilon(T_{\text{eff}}) \)

Lower Bound

\( \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0278 + 0.1455 \epsilon(T_{\text{eff}}) \)

Lower Bound
\[ T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.50, \frac{Q_2}{Q_1} = 0.5, R = 7, \text{ Isolated} \]

(without vertical ground motion)

\[ S_{a_{\text{COL}}} = 0.380g, \quad \beta_{\text{RTR}} = 0.222 \]

\[ S_{a_{\text{COL}}} = 0.440g \]

\[ T_{\text{eff}} = 3.13 \text{ sec} \]

\[ S_{a_{MCE}}(T_{\text{eff}}) = 0.245g \]

Lower Bound

\( e_0 = 1.5 \)

\[ \text{Empirical} \quad \text{w/o SSE} \quad \text{w/ SSE} \]

\[ \ln[S_{a_{\text{COL}}}(T_{\text{eff}})] = -1.0369 + 0.1436e(T_{\text{eff}}) \]

\( \text{Lower Bound} \)

\[ T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.75, \frac{Q_2}{Q_1} = 0.5, R = 7, \text{ Isolated} \]

(without vertical ground motion)

\[ S_{a_{\text{COL}}} = 0.380g, \quad \beta_{\text{RTR}} = 0.221 \]

\[ S_{a_{\text{COL}}} = 0.440g \]

\[ T_{\text{eff}} = 3.13 \text{ sec} \]

\[ S_{a_{MCE}}(T_{\text{eff}}) = 0.245g \]

Lower Bound

\( e_0 = 1.5 \)

\[ \text{Empirical} \quad \text{w/o SSE} \quad \text{w/ SSE} \]

\[ \ln[S_{a_{\text{COL}}}(T_{\text{eff}})] = -1.0354 + 0.1433e(T_{\text{eff}}) \]

\( \text{Lower Bound} \)
$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, \frac{Q_2}{Q_1} = 0.5, R = 7$, Isolated
(without vertical ground motion)

\begin{align*}
S_{\text{COL}} &= 0.380g \\
\beta_{\text{RTR}} &= 0.221 \\
S_{\text{COL}} &= 0.440g \\
T_{\text{eff}} &= 3.13 \text{ sec} \\
S_{\text{AMCE}}(T_{\text{eff}}) &= 0.245g
\end{align*}

Lower Bound

- **Empirical**
- w/o SSE
- w/ SSE

\begin{align*}
\ln[S_{\text{AMCE}}(T_{\text{eff}})] &= -1.0354 + 0.1430\epsilon(T_{\text{eff}})
\end{align*}

Lower Bound

$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, \frac{Q_2}{Q_1} = 0.6, R = 7$, Isolated
(without vertical ground motion)

\begin{align*}
S_{\text{COL}} &= 0.380g \\
\beta_{\text{RTR}} &= 0.222 \\
S_{\text{COL}} &= 0.440g \\
T_{\text{eff}} &= 3.13 \text{ sec} \\
S_{\text{AMCE}}(T_{\text{eff}}) &= 0.245g
\end{align*}

Lower Bound

- **Empirical**
- w/o SSE
- w/ SSE

\begin{align*}
\ln[S_{\text{AMCE}}(T_{\text{eff}})] &= -1.0373 + 0.1435\epsilon(T_{\text{eff}})
\end{align*}

Lower Bound
$T_{\text{fixed}} = 0.25 \text{ sec}, K_{e1}/K_{a2} = 1.75, Q_2/Q_1 = 0.6, R = 7$, Isolated
(without vertical ground motion)

\begin{align*}
S_{a\text{COL}} &= 0.380g \\
\beta_{\text{RTR}} &= 0.221 \\
S_{a\text{COL}} &= 0.440g \\
T_{\text{eff}} &= 3.13 \text{ sec} \\
S_{a\text{MCE}}(T_{\text{eff}}) &= 0.245g \\
\epsilon_0 &= 1.5
\end{align*}

$T_{\text{fixed}} = 0.25 \text{ sec}, K_{e1}/K_{a2} = 2.00, Q_2/Q_1 = 0.6, R = 7$, Isolated
(without vertical ground motion)

\begin{align*}
\ln[S_{a\text{COL}}(T_{\text{eff}})] &= -1.0366 + 0.1434\epsilon(T_{\text{eff}}) \\
\ln[S_{a\text{COL}}(T_{\text{eff}})] &= -1.0357 + 0.1426\epsilon(T_{\text{eff}})
\end{align*}
\[ T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, \frac{Q_2}{Q_1} = 0.7, R = 7, \text{ Isolated} \]

(without vertical ground motion)
$T_{\text{fixed}} = 0.25 \text{ sec, } K_{e1}/K_{e2} = 2.00, \frac{Q_2}{Q_1} = 0.7, R = 7, \text{ Isolated}$

(without vertical ground motion)

$T_{\text{fixed}} = 0.20 \text{ sec, } K_{e1}/K_{e2} = 1.50, \frac{Q_2}{Q_1} = 0.5, R = 6, \text{ Isolated}$

(without vertical ground motion)
$T_{\text{fixed}} = 0.20\;\text{sec},\; K_{a1}/K_{a2} = 1.75,\; Q_2/Q_1 = 0.5,\; R = 6,\; \text{Isolated (without vertical ground motion)}$

\begin{align*}
S_{a\text{COL}} &= 0.370g \\
S_{a\text{COL}} &= 0.434g \\
T_{\text{eff}} &= 3.13\;\text{sec} \\
S_{\text{AMCE}(T_{\text{eff}})} &= 0.245g
\end{align*}

\begin{align*}
\varepsilon_0 &= 1.5 \\
\beta_{\text{RTR}} &= 0.219
\end{align*}

\begin{align*}
\ln[S_{a\text{COL}}(T_{\text{eff}})] &= -1.0475 + 0.1411\epsilon(T_{\text{eff}}) \\
\ln[S_{a\text{COL}}(T_{\text{eff}})] &= -1.0463 + 0.1408\epsilon(T_{\text{eff}})
\end{align*}

\begin{align*}
\text{Lower Bound} \\
\text{Empirical} \\
w/o\;\text{SSE} \\
w/\;\text{SSE}
\end{align*}
$T_{\text{fixed}} = 0.20\text{ sec}, K_{e_1}/K_{e_2} = 1.50, Q_j/Q_i = 0.6, R = 6, \text{ Isolated}$

(without vertical ground motion)

---

$S_{a_{\text{COL}}} = 0.370g$

$T_{\text{eff}} = 3.13\text{ sec}$

$S_{a_{\text{AMCE}}(T_{\text{eff}})} = 0.245g$

$\varepsilon_0 = 1.5$

---

$\ln(S_{a_{\text{COL}}(T_{\text{eff}})}) = -1.0459 + 0.1409\varepsilon(T_{\text{eff}})$

Lower Bound

---

$S_{a(T_{\text{eff}})g}$

$\varepsilon(T_{\text{eff}})$

Empirical

w/o SSE

w/ SSE

---

288
\[
T_{\text{fixed}} = 0.20 \text{ sec}, \quad K_{e1}/K_{e2} = 2.00, \quad Q_2/Q_1 = 0.6, \quad R = 6, \text{ Isolated (without vertical ground motion)}
\]

\[
\beta_{RTR}^{\text{Hed}} = 0.220
\]

\[
S_{a\text{COL}} = 0.434g
\]

\[
T_{\text{eff}} = 3.13 \text{ sec}
\]

\[
S_{\text{ampl}(T_{\text{eff}})} = 0.245g
\]

Lower Bound

- Empirical
- w/o SSE
- w/ SSE

\[
\varepsilon_0 = 1.5
\]

\[
\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0463 + 0.1407\varepsilon(T_{\text{eff}})
\]

\[
\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0486 + 0.1424\varepsilon(T_{\text{eff}})
\]

Lower Bound
$T_{\text{fixed}} = 0.20 \text{ sec, } K_{e_1}/K_{e_2} = 1.75, \frac{Q_2}{Q_1} = 0.7, \text{ R=6, Isolated}$

(without vertical ground motion)

$S_{a\text{COL}} = 0.370g, \beta_{RTR} = 0.220$

$S_{a\text{COL}} = 0.434g$

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{a\text{MAC}}(T_{\text{eff}}) = 0.245g$

Lower Bound

Empirical

$\varepsilon_0 = 1.5$

$\text{w/o SSE}$

$\text{w/ SSE}$

$x^2$

$S_{a(T_{\text{eff}})g}$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0466 + 0.1415\varepsilon(T_{\text{eff}})$

Lower Bound

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0463 + 0.1407\varepsilon(T_{\text{eff}})$

Lower Bound

$S_{a(T_{\text{eff}})g}$

$\varepsilon(T_{\text{eff}})$

290
$T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{1}}{K_{2}} = 1.50, Q_{2}/Q_{1} = 0.5, R=8$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

![Graph 1]

$T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{1}}{K_{2}} = 1.50, Q_{2}/Q_{1} = 0.5, R=8$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

![Graph 2]
$T_{\text{fixed}} = 0.30$ sec, $K_{e1}/K_{e2} = 1.75$, $Q_2/Q_1 = 0.5$, $R=8$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$T_{\text{eff}} = 3.13$ sec, $S_{\text{aCOL}}(T_{\text{eff}}) = 0.245$g, $\beta_{\text{RTN}} = 0.399$

Lower Bound

Empirical
- w/o SSE
- w/ SSE

$S_{\text{a}}(T_{\text{eff}})g$

Probability of Collapse

$T_{\text{fixed}} = 0.30$ sec, $K_{e1}/K_{e2} = 1.75$, $Q_2/Q_1 = 0.5$, $R=8$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$T_{\text{eff}} = 3.13$ sec, $S_{\text{aCOL}}(T_{\text{eff}}) = 0.245$g, $\beta_{\text{RTN}} = 0.438$

Upper Bound

Empirical
- w/o SSE
- w/ SSE

$S_{\text{a}}(T_{\text{eff}})g$

Probability of Collapse

$\ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.2178 + 0.3330(\epsilon(T_{\text{eff}}))$

Lower Bound

$\ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.1521 + 0.3487(\epsilon(T_{\text{eff}}))$

Upper Bound
$T_{\text{fixed}} = 0.30 \text{ sec}, K_e_1/K_e_2 = 2.00, Q_2/Q_1 = 0.5, R = 8$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$
$S_{a,\text{MCE}}(T_{\text{eff}}) = 0.245g$
$\epsilon_\theta = 1.5$

- Empirical
- w/o SSE
- w/ SSE

$\ln[S_{a,\text{COL}}(T_{\text{eff}})] = -1.2179 + 0.3334\epsilon(T_{\text{eff}})$

$S_{a,\text{COL}} = 0.350g$
$\beta_{RH} = 0.399$

$S_{a,\text{COL}} = 0.488g$

$S_{a,\text{COL}} = 0.370g$
$\beta_{RH} = 0.439$

$S_{a,\text{COL}} = 0.535g$

$S_{a,\text{MCE}}(T_{\text{eff}}) = 0.245g$
$\epsilon(T_{\text{eff}})$

$S_{a,\text{MCE}}(T_{\text{eff}}) = 0.535g$
$\epsilon(T_{\text{eff}})$

$\ln[S_{a,\text{COL}}(T_{\text{eff}})] = -1.1494 + 0.3494\epsilon(T_{\text{eff}})$

$\epsilon_\theta = 1.5$
$T_{\text{fixed}} = 0.30 \text{ sec}, K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.6, R = 8, \text{ Isolated, Failure due to 30 mm Uplift}$

(with vertical ground motion)

1. **Graph 1:**
   - $S_{a\text{COL}} = 0.350g$
   - $T_{\text{eff}} = 3.13 \text{ sec}$
   - $S_{\text{MCE}}(T_{\text{eff}}) = 0.245g$

2. **Graph 2:**
   - $\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.2236 + 0.3334\epsilon(T_{\text{eff}})$

3. **Graph 3:**
   - $S_{a\text{COL}} = 0.360g$
   - $T_{\text{eff}} = 3.13 \text{ sec}$
   - $S_{\text{MCE}}(T_{\text{eff}}) = 0.245g$

4. **Graph 4:**
   - $\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1565 + 0.3485\epsilon(T_{\text{eff}})$

---

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$T_{\text{fixed}} = 0.30$ sec, $K_{e1}/K_{e2} = 1.75$, $Q_2/Q_1 = 0.6$, $R = 8$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

\[ S_{a\text{COL}} = 0.350g \]
$\beta_{RTH} = 0.398$
\[ S_{a\text{COL}} = 0.486g \]
$T_{\text{eff}} = 3.13$ sec
\[ S_{a\text{MCE}(T_{\text{eff}})} = 0.245g \]
Lower Bound

$\varepsilon_0 = 1.5$

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.2212 + 0.3330 \varepsilon(T_{\text{eff}}) \]

\[ S_{a(T_{\text{eff}})g} \]

\[ T_{\text{fixed}} = 0.30 $ sec, $K_{e1}/K_{e2} = 1.75$, $Q_2/Q_1 = 0.6$, $R = 8$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

\[ S_{a\text{COL}} = 0.370g \]
$\beta_{RTH} = 0.438$
\[ S_{a\text{COL}} = 0.532g \]
$T_{\text{eff}} = 3.13$ sec
\[ S_{a\text{MCE}(T_{\text{eff}})} = 0.245g \]
Upper Bound

$\varepsilon_0 = 1.5$

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1531 + 0.3486 \varepsilon(T_{\text{eff}}) \]

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.2212 + 0.3330 \varepsilon(T_{\text{eff}}) \]
\( T_{\text{fixed}} = 0.30 \, \text{sec}, \frac{K_{e_1}}{K_{e_2}} = 2.00, \frac{Q_i}{Q_i} = 0.6, R = 8, \) Isolated, Failure due to 30 mm Uplift

(with vertical ground motion)

\[ \text{Probability of Collapse} \]

\[ S_{a(\text{eff})} g \]

\[ S_{a\text{COL}} = 0.350g \]
\[ \beta_{\text{RTH}} = 0.398 \]
\[ S_{a\text{COL}} = 0.487g \]
\[ T_{\text{eff}} = 3.13 \, \text{sec} \]
\[ S_{\text{AMCE}}(T_{\text{eff}}) = 0.245g \]

Lower Bound

Empirical

w/o SSE

w/ SSE

\[ \epsilon_0 = 1.5 \]

\[ \text{ln}[S_{a\text{COL}}(T_{\text{eff}})] = -1.2190 + 0.3331 \epsilon(T_{\text{eff}}) \]

\( T_{\text{fixed}} = 0.30 \, \text{sec}, \frac{K_{e_1}}{K_{e_2}} = 2.00, \frac{Q_i}{Q_i} = 0.6, R = 8, \) Isolated, Failure due to 30 mm Uplift

(with vertical ground motion)

\[ \text{Probability of Collapse} \]

\[ S_{a(\text{eff})} g \]

\[ S_{a\text{COL}} = 0.370g \]
\[ \beta_{\text{RTH}} = 0.439 \]
\[ S_{a\text{COL}} = 0.534g \]
\[ T_{\text{eff}} = 3.13 \, \text{sec} \]
\[ S_{\text{AMCE}}(T_{\text{eff}}) = 0.245g \]

Upper Bound

Empirical

w/o SSE

w/ SSE

\[ \epsilon_0 = 1.5 \]

\[ \text{ln}[S_{a\text{COL}}(T_{\text{eff}})] = -1.1512 + 0.3495 \epsilon(T_{\text{eff}}) \]
$T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.50, \frac{Q_2}{Q_1} = 0.7, R = 8$, Isolated, Failure due to 30 mm Uplift

(with vertical ground motion)

$T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.50, \frac{Q_2}{Q_1} = 0.7, R = 8$, Isolated, Failure due to 30 mm Uplift

(with vertical ground motion)
$T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_2}{Q_1} = 0.7, R = 8$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)
$T_{\text{fixed}} = 0.30 \text{ sec}, K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.7, R = 8, \text{ Isolated, Failure due to 30 mm Uplift}$

(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{a\text{COL}}^{(T_{\text{eff}})} = 0.350g$

$\beta_{RTH} = 0.400$

$S_{a\text{COL}}^{(T_{\text{eff}})} = 0.486g$

$S_{a\text{MC}}^{(T_{\text{eff}})} = 0.245g$

Lower Bound

$\epsilon_0 = 1.5$

Empirical

- w/o SSE
- w/ SSE

$\ln[S_{a\text{COL}}^{(T_{\text{eff}})}] = -1.2236 + 0.3351\epsilon(T_{\text{eff}})$

$\ln[S_{a\text{COL}}^{(T_{\text{eff}})}] = -1.1518 + 0.3495\epsilon(T_{\text{eff}})$

(with vertical ground motion)

$\epsilon(T_{\text{eff}}) = 2$

$S_{a\text{COL}}^{(T_{\text{eff}})} = 0.370g$

$\beta_{RTH} = 0.439$

$S_{a\text{COL}}^{(T_{\text{eff}})} = 0.534g$

$S_{a\text{MC}}^{(T_{\text{eff}})} = 0.245g$

Upper Bound

$\epsilon_0 = 1.5$

Empirical

- w/o SSE
- w/ SSE

$\ln[S_{a\text{COL}}^{(T_{\text{eff}})}] = -1.2236 + 0.3351\epsilon(T_{\text{eff}})$

$\ln[S_{a\text{COL}}^{(T_{\text{eff}})}] = -1.1518 + 0.3495\epsilon(T_{\text{eff}})$

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$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.50, \frac{Q_2}{Q_1} = 0.5, R = 7$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

![Graph showing probability of collapse versus $S_a(T_{\text{eff}})g$ and $\epsilon(T_{\text{eff}})$]

$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.50, \frac{Q_2}{Q_1} = 0.5, R = 7$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

![Graph showing probability of collapse versus $S_a(T_{\text{eff}})g$ and $\epsilon(T_{\text{eff}})$]
\( T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, Q_2/Q_1 = 0.5, R = 7 \), Isolated, Failure due to 30 mm Uplift

(with vertical ground motion)
$T_{\text{fixed}}=0.25$ sec, $K_{e1}/K_{e2}=2.00$, $Q_2/Q_1=0.5$, $R=7$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

- $S_{a\text{COL}}=0.350g$
- $\beta_{RTN}=0.396$
- $S_{a\text{COL}}=0.480g$
- $T_{\text{eff}}=3.13$ sec
- $S_{\text{AMCE}}(T_{\text{eff}})=0.245g$
- Lower Bound
- Empirical
- w/o SSE
- w/ SSE

$e_0=1.5$

$\ln[S_{a\text{COL}}(T_{\text{eff}})]=-1.2289+0.3300e(T_{\text{eff}})$

$T_{\text{fixed}}=0.25$ sec, $K_{e1}/K_{e2}=2.00$, $Q_2/Q_1=0.5$, $R=7$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

- $S_{a\text{COL}}=0.360g$
- $\beta_{RTN}=0.434$
- $S_{a\text{COL}}=0.530g$
- $T_{\text{eff}}=3.13$ sec
- $S_{\text{AMCE}}(T_{\text{eff}})=0.245g$
- Upper Bound
- Empirical
- w/o SSE
- w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})]=-1.1587+0.3486e(T_{\text{eff}})$
\( T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, Q_2/Q_1 = 0.6, R = 7, \) Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

![Graph 1](image1)

![Graph 2](image2)

\( T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, Q_2/Q_1 = 0.6, R = 7, \) Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

![Graph 3](image3)

![Graph 4](image4)
$T_{\text{fixed}} = 0.25 \, \text{sec}, \quad \frac{K_{e1}}{K_{e2}} = 1.75, \quad Q_{2}/Q_{1} = 0.6, \quad R=7$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

$S_{a\text{COL}} = 0.350 \, \text{g}$
$\beta_{\text{RTN}} = 0.395$

$S_{a\text{COL}} = 0.478 \, \text{g}$
$T_{\text{eff}} = 3.13 \, \text{sec}$
$S_{\text{AMCE}}(T_{\text{eff}}) = 0.245 \, \text{g}$
Lower Bound

$\epsilon_{0} = 1.5$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.2305 + 0.3295\epsilon(T_{\text{eff}})$

$T_{\text{fixed}} = 0.25 \, \text{sec}, \quad \frac{K_{e1}}{K_{e2}} = 1.75, \quad Q_{2}/Q_{1} = 0.6, \quad R=7$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

$S_{a\text{COL}} = 0.360 \, \text{g}$
$\beta_{\text{RTN}} = 0.432$

$S_{a\text{COL}} = 0.524 \, \text{g}$
$T_{\text{eff}} = 3.13 \, \text{sec}$
$S_{\text{AMCE}}(T_{\text{eff}}) = 0.245 \, \text{g}$
Upper Bound

$\epsilon_{0} = 1.5$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1638 + 0.3455\epsilon(T_{\text{eff}})$
$T_{\text{fixed}} = 0.25 \text{ sec, } K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.6, R = 7$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{a\text{COL}} = 0.340g$

$S_{a\text{COL}} = 0.480g$

$S_{a\text{MCE}}(T_{\text{eff}}) = 0.245g$

$\epsilon_{\text{COL}} = 1.5$

$\beta_{\text{RTH}} = 0.395$

Empirical
- w/o SSE
- w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.2302 + 0.3302\epsilon(T_{\text{eff}})$

$\ln[S_{a\text{MCE}}(T_{\text{eff}})] = -1.1614 + 0.3473\epsilon(T_{\text{eff}})$
$T_{\text{fixed}} = 0.25 \text{ sec}, K_{e1}/K_{e2} = 1.50, Q_{2}/Q_{1} = 0.7, R = 7$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

$S_{a\text{COL}} = 0.350g, \beta_{RH} = 0.394$

$S_{a\text{COL}} = 0.478g, T_{\text{eff}} = 3.313 \text{ sec}$

$S_{\text{AMCE}(T_{\text{eff}})} = 0.245g$

Lower Bound

Empirical

w/o SSE

w/ SSE

$\bar{r}_{0} = 1.5$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.2331 + 0.3302\epsilon(T_{\text{eff}})$

$\epsilon(T_{\text{eff}})$

$T_{\text{fixed}} = 0.25 \text{ sec}, K_{e1}/K_{e2} = 1.50, Q_{2}/Q_{1} = 0.7, R = 7$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

$S_{a\text{COL}} = 0.350g, \beta_{RH} = 0.431$

$S_{a\text{COL}} = 0.518g, T_{\text{eff}} = 3.313 \text{ sec}$

$S_{\text{AMCE}(T_{\text{eff}})} = 0.245g$

Upper Bound

Empirical

w/o SSE

w/ SSE

$\bar{r}_{0} = 1.5$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1744 + 0.3448\epsilon(T_{\text{eff}})$

$\epsilon(T_{\text{eff}})$
$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, Q_2/Q_1 = 0.7, R=7$, Isolated, Failure due to 30 mm Uplift

(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{\text{ACOL}} = 0.350g$

$\beta_{\text{RTH}} = 0.395$

$S_{\text{ACOL}} = 0.478g$

$S_{\text{AMCE}}(T_{\text{eff}}) = 0.245g$

Lower Bound

Empirical

\[ \epsilon_0 = 1.5 \]

\[ \text{w/o SSE} \]

\[ \text{w/ SSE} \]

\[ \ln[S_{\text{ACOL}}(T_{\text{eff}})] = -1.2317 + 0.3299 \epsilon(T_{\text{eff}}) \]

Lower Bound

$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, Q_2/Q_1 = 0.7, R=7$, Isolated, Failure due to 30 mm Uplift

(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{\text{ACOL}} = 0.360g$

$\beta_{\text{RTH}} = 0.430$

$S_{\text{ACOL}} = 0.520g$

$S_{\text{AMCE}}(T_{\text{eff}}) = 0.245g$

Upper Bound

Empirical

\[ \epsilon_0 = 1.5 \]

\[ \text{w/o SSE} \]

\[ \text{w/ SSE} \]

\[ \ln[S_{\text{ACOL}}(T_{\text{eff}})] = -1.1701 + 0.3445 \epsilon(T_{\text{eff}}) \]

Upper Bound
$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, Q_2/Q_1 = 0.7, R=7$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{a\text{COL}} = 0.350g$

$\beta_{\text{HIN}} = 0.395$

$S_{a\text{COL}} = 0.478g$

Lower Bound

$\epsilon_0 = 1.5$

$S_{a\text{COL}} = 0.525g$

$S_{a\text{MCE}}(T_{\text{eff}}) = 0.245g$

Empirical

w/o SSE

w/ SSE

$\text{ln}[S_{a\text{COL}}(T_{\text{eff}})] = -1.2308 + 0.3305 \epsilon(T_{\text{eff}})$

$\text{ln}[S_{a\text{COL}}(T_{\text{eff}})] = -1.1648 + 0.3466 \epsilon(T_{\text{eff}})$

$\epsilon_0 = 1.5$

w/o SSE

w/ SSE

Upper Bound

Lower Bound

(w/ SSE)
$T_{\text{fixed}} = 0.20$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.5$, $R = 6$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)


\[ T_{\text{fixed}} = 0.20 \text{ sec}, \ K_{e1}/K_{e2} = 1.75, \ Q_2/Q_1 = 0.5, \ R=6, \ \text{Isolated, Failure due to 30 mm Uplift} \]

(with vertical ground motion)

\[ S_{a\text{COL}} = 0.340g, \ \beta_{HTH} = 0.392 \]

\[ S_{a\text{COL}} = 0.474g \]

\[ T_{\text{eff}} = 3.13 \text{ sec} \]

\[ S_{\text{AMCE}}(T_{\text{eff}}) = 0.245g \]

Lower Bound

\[ S_a(T_{\text{eff}})g \]

\[ \epsilon = 1.5 \]

Empirical

without SSE

with SSE

\[ \ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.2355 + 0.3255\epsilon(T_{\text{eff}}) \]

\[ \ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.1629 + 0.3415\epsilon(T_{\text{eff}}) \]

Upper Bound

\[ S_{a\text{COL}} = 0.360g, \ \beta_{HTH} = 0.432 \]

\[ S_{a\text{COL}} = 0.522g \]

\[ T_{\text{eff}} = 3.13 \text{ sec} \]

\[ S_{\text{AMCE}}(T_{\text{eff}}) = 0.245g \]

Empirical

without SSE

with SSE

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

310
$T_{\text{fixed}} = 0.20 \text{ sec}, \frac{k_{e1}}{k_{e2}} = 2.00, Q_2/Q_1 = 0.5, R = 6$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

概率 of Collapse

$S_a(T_{\text{eff}})g$

$\beta_{\text{RTN}} = 0.392$

$S_{a\text{COL}} = 0.340g$

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{a\text{MCE}}(T_{\text{eff}}) = 0.245g$

Lower Bound

Empirical
- w/o SSE
- w/ SSE

$\varepsilon_0 = 1.5$

$\text{Empirical}$

$\text{w/o SSE}$

$\text{w/ SSE}$

$\ln[S_a(T_{\text{eff}})] = 1.2356 + 0.3256(\varepsilon(T_{\text{eff}}))$

$\ln[S_a(T_{\text{eff}})] = 1.1806 + 0.3418(\varepsilon(T_{\text{eff}}))$

Probability of Collapse

$S_a(T_{\text{eff}})g$

Upper Bound

$\varepsilon_0 = 1.5$

$\text{Empirical}$

$\text{w/o SSE}$

$\text{w/ SSE}$
$T_{fixed} = 0.20\ sec$, $K_{e_1}/K_{e_2} = 1.50$, $Q_{2}/Q_1 = 0.6$, $R=6$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

$T_{eff} = 3.13\ sec$, $S_{a\text{COL}} = 0.245$g

$V_{RTH} = 0.360$g

$V_{COL} = 0.340$g

$\beta = 0.390$

$S_{a\text{COL}} = 0.473$g

$S_{a\text{COL}} = 0.518$g

$\epsilon_0 = 1.5$

Empirical

w/o SSE

w/ SSE

$\ln[S_{a\text{COL}}(T_{eff})] = -1.2369 + 0.3256\epsilon(T_{eff})$

$\ln[S_{a\text{COL}}(T_{eff})] = -1.1719 + 0.3423\epsilon(T_{eff})$

Lower Bound

Upper Bound

$S_{a\text{COL}}(T_{eff}) = 1.5$
$T_{\text{fixed}} = 0.20\ \text{sec}, \ K_{e1}/K_{e2} = 1.75, \ Q_2/Q_1 = 0.6, \ R = 6$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$T_{\text{eff}} = 3.13\ \text{sec}, \ S_{\text{a,COL}}(T_{\text{eff}}) = 0.245g$

Empirical

- $\epsilon_0 = 1.5$

- w/o SSE

- w/ SSE

$\ln[S_{\text{a,COL}}(T_{\text{eff}})] = -1.2371 + 0.3256\epsilon(T_{\text{eff}})$

Lower Bound

Upper Bound
$T_{\text{fixed}} = 0.20 \text{ sec, } K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.6, R = 6$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

![Graph 1](image1)

$T_{\text{fixed}} = 0.20 \text{ sec, } K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.6, R = 6$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

![Graph 2](image2)
\[ T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, \frac{Q_2}{Q_1} = 0.7, \text{ R}=6, \text{ Isolated, Failure due to 30 mm Uplift} \]
(with vertical ground motion)

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.2369 + 0.3257 \epsilon(T_{\text{eff}}) \]

\[ T_{\text{eff}} = 3.13 \text{ sec} \]

\[ S_{a\text{COL}} = 0.340g \]
\[ \beta_{RTN} = 0.390 \]

\[ S_{a\text{COL}} = 0.473g \]

\[ S_{a\text{MCE}}(T_{\text{eff}}) = 0.245g \]

\[ \epsilon_0 = 1.5 \]

\[ S_a(T_{\text{eff}})g \]

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] \]

\[ \epsilon(T_{\text{eff}}) \]

\[ \text{Empirical} \]
\[ \text{w/o SSE} \]
\[ \text{w/ SSE} \]

\[ \text{Empirical} \]
\[ \text{w/o SSE} \]
\[ \text{w/ SSE} \]

\[ \epsilon_0 = 1.5 \]
$T_{\text{fixed}} = 0.20$ sec, $\frac{K_{e1}}{K_{e2}} = 1.75$, $Q_2/Q_1 = 0.7$, $R = 6$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

$S_{aCOL} = 0.340g$
$eta_{RTN} = 0.390$

$S_{aCOL} = 0.473g$
$\epsilon_{\text{RTN}} = 1.5$

$T_{\text{eff}} = 3.13$ sec
$S_{\text{AMCE}}(T_{\text{eff}}) = 0.245g$

Lower Bound

- Empirical
- w/o SSE
- w/ SSE

$T_{\text{fixed}} = 0.20$ sec, $\frac{K_{e1}}{K_{e2}} = 1.75$, $Q_2/Q_1 = 0.7$, $R = 6$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

$S_{aCOL} = 0.370g$
$\beta_{RTN} = 0.428$

$S_{aCOL} = 0.513g$
$\epsilon_{\text{RTN}} = 1.5$

$T_{\text{eff}} = 3.13$ sec
$S_{\text{AMCE}}(T_{\text{eff}}) = 0.245g$

Upper Bound

$\ln(S_{aCOL}(T_{\text{eff}})) = -1.2372 + 0.3256\epsilon(T_{\text{eff}})$

Lower Bound

$\ln(S_{aCOL}(T_{\text{eff}})) = 1.1743 + 0.3373\epsilon(T_{\text{eff}})$

Upper Bound
$T_{\text{fixed}} = 0.20 \text{ sec, } K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.7, R = 6, \text{ Isolated, Failure due to 30 mm Uplift}$

(with vertical ground motion)
$T_{\text{fixed}} = 0.30\, \text{sec}, K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.5, R = 8$, Isolated, Failure due to Uplift not Considered

(with vertical ground motion)

![Graph 1](image1)

![Graph 2](image2)

$T_{\text{fixed}} = 0.30\, \text{sec}, K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.5, R = 8$, Isolated, Failure due to Uplift not Considered

(with vertical ground motion)

![Graph 3](image3)

![Graph 4](image4)
$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.75, \frac{Q_2}{Q_1} = 0.5, R=8$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

$S_{a\text{COL}} = 0.360g$
$\beta_{RTH} = 0.266$

$a_{\text{COL}} = 0.462g$
$T_{\text{eff}} = 3.13 \text{ sec}$
$S_{\text{AMCE}}(T_{\text{eff}}) = 0.245g$

Lower Bound

Empirical
- w/o SSE
- w/ SSE

$\epsilon_0 = 1.5$

$\ln[\ln S_{a\text{COL}}(T_{\text{eff}})] = -1.0833 + 0.2074\epsilon(T_{\text{eff}})$

$\epsilon(T_{\text{eff}})$

$S_{a\text{COL}}(T_{\text{eff}})$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0485 + 0.2486\epsilon(T_{\text{eff}})$

$\epsilon(T_{\text{eff}})$

$S_{a\text{COL}}(T_{\text{eff}})$

$\ln[S_{a\text{COL}}(T_{\text{eff}})]$
$T_{\text{fixed}}=0.30 \text{ sec, } K_{e1}/K_{e2}=2.00, Q_{e}/Q_{e}=0.5, R=8$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

$S_{a\text{COL}}=0.360g$
$\beta_{RTW}=0.266$
$S_{a\text{COL}}=0.462g$
$T_{\text{eff}}=3.13 \text{ sec}$
$S_{\text{AMCE}}(T_{\text{eff}})=0.245g$

Lower Bound

$\epsilon_{0}=1.5$

Empirical
- w/o SSE
- w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})^{g}] = -1.0814 + 0.2056 \epsilon(T_{\text{eff}})$

Lower Bound

$T_{\text{fixed}}=0.30 \text{ sec, } K_{e1}/K_{e2}=2.00, Q_{e}/Q_{e}=0.5, R=8$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

$S_{a\text{COL}}=0.380g$
$\beta_{RTW}=0.332$
$S_{a\text{COL}}=0.511g$
$T_{\text{eff}}=3.13 \text{ sec}$
$S_{\text{AMCE}}(T_{\text{eff}})=0.245g$

Upper Bound

$\epsilon_{0}=1.5$

Empirical
- w/o SSE
- w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})^{g}] = -1.0447 + 0.2484 \epsilon(T_{\text{eff}})$

Upper Bound
$T_{\text{fixed}} = 0.30$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.6$, $R = 8$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

$T_{\text{fixed}} = 0.30$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.6$, $R = 8$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)
\[ T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_2}{Q_1} = 0.6, R = 8, \text{ Isolated, Failure due to Uplift not Considered} \]

(with vertical ground motion)

\[ S_a(T_{\text{eff}})g\]

Empirical
- w/o SSE
- w/ SSE

\[ \varepsilon_0 = 1.5 \]

\[ \ln[S_{aCOL}(T_{\text{eff}})] = -1.0883 + 0.2083\varepsilon(T_{\text{eff}}) \]

Lower Bound

\[ \ln[S_{aCOL}(T_{\text{eff}})] = -1.0511 + 0.2503\varepsilon(T_{\text{eff}}) \]

Upper Bound
$T_{\text{fixed}} = 0.30 \text{ sec}, K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.6, R = 8$, Isolated, Failure due to Uplift not Considered

(with vertical ground motion)
$T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, Q_x/Q_1 = 0.7, R = 8$, Isolated, Failure due to Uplift not Considered

(with vertical ground motion)

$S_{\text{aCOL}} = 0.360g, \beta_{RTH} = 0.274$

Lower Bound

Empirical

- w/o SSE
- w/ SSE

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{\text{MCE}}(T_{\text{eff}}) = 0.245g$

$\epsilon_0 = 1.5$

$\ln[\frac{S_{\text{aCOL}}(T_{\text{eff}})}{\epsilon(T_{\text{eff}})}] = -1.1002 + 0.2146 \epsilon(T_{\text{eff}})$

$\ln[\frac{S_{\text{aCOL}}(T_{\text{eff}})}{\epsilon(T_{\text{eff}})}] = -1.0646 + 0.2583 \epsilon(T_{\text{eff}})$
$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.75, Q_{x}/Q_{y} = 0.7, R = 8$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

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$T_{\text{eff}} = 3.13 \text{ sec, } S_{a\text{COL}} = 0.245g$

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$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0929 + 0.2096\epsilon(T_{\text{eff}})$

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$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0556 + 0.2540\epsilon(T_{\text{eff}})$
\[ T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, \frac{Q_2}{Q_1} = 0.7, R = 8, \] Isolated, Failure due to Uplift not Considered

(with vertical ground motion)
$T_{\text{fixed}} = 0.25 \text{ sec, } K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.5, R = 7$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

![Graph 1](image1)

$T_{\text{eff}} = 3.13 \text{ sec, } S_{\text{aCOL}}(T_{\text{eff}}) = 0.245g$

$\varepsilon_0 = 1.5$

- **Empirical**
- **w/o SSE**
- **w/ SSE**

$\ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.1031 + 0.2086 \epsilon(T_{\text{eff}})$

- Lower Bound

$T_{\text{fixed}} = 0.25 \text{ sec, } K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.5, R = 7$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

![Graph 2](image2)

$T_{\text{eff}} = 3.13 \text{ sec, } S_{\text{aCOL}}(T_{\text{eff}}) = 0.245g$

$\varepsilon_0 = 1.5$

- **Empirical**
- **w/o SSE**
- **w/ SSE**

$\ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.0860 + 0.2512 \epsilon(T_{\text{eff}})$

- Upper Bound
\( T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_2}{Q_1} = 0.5, R = 7, \) Isolated, Failure due to Uplift not Considered (with vertical ground motion)

![Graph 1](image1)

\( T_{\text{eff}} = 3.13 \text{ sec}, S_{a\text{MCE}}(T_{\text{eff}}) = 0.245g \)

\( S_{a\text{COL}} = 0.350g \)

\( \beta_{\text{RTH}} = 0.270 \)

\( \epsilon_0 = 1.5 \)

![Graph 2](image2)

\( \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1010 + 0.2077\epsilon(T_{\text{eff}}) \)

![Graph 3](image3)

\( T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_2}{Q_1} = 0.5, R = 7, \) Isolated, Failure due to Uplift not Considered (with vertical ground motion)

![Graph 4](image4)

\( T_{\text{eff}} = 3.13 \text{ sec}, S_{a\text{MCE}}(T_{\text{eff}}) = 0.245g \)

\( S_{a\text{COL}} = 0.370g \)

\( \beta_{\text{RTH}} = 0.337 \)

\( \epsilon_0 = 1.5 \)

\( \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0642 + 0.2515\epsilon(T_{\text{eff}}) \)

![Graph 5](image5)
$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, \frac{Q_2}{Q_1} = 0.5, R = 7$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$, $S_{\text{MCE}}(T_{\text{eff}}) = 0.245g$

Lower Bound

Empirical
- w/o SSE
- w/ SSE

$S_a(T_{\text{eff}})g$

Probability of Collapse

$\varepsilon_0 = 1.5$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0993 + 0.2071\varepsilon(T_{\text{eff}})$

Lower Bound

Upper Bound

$S_{a\text{COL}} = 0.350g$

$\beta_{\text{RET}} = 0.269$

$S_{a\text{COL}} = 0.454g$

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{\text{MCE}}(T_{\text{eff}}) = 0.245g$

Empirical
- w/o SSE
- w/ SSE

$S_a(T_{\text{eff}})g$

Probability of Collapse

$\varepsilon_0 = 1.5$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0801 + 0.2525\varepsilon(T_{\text{eff}})$

Upper Bound
$T_{\text{fixed}} = 0.25$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.6$, R = 7, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)
$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_2}{Q_1} = 0.6, R = 7, \text{ Isolated, Failure due to Uplift not Considered}$

(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{aCol} = 0.350g$

$\beta_{RTH} = 0.270$

$S_{aCol} = 0.453g$

$S_{aMCE} = 0.245g$

Lower Bound

$\epsilon_0 = 1.5$

Empirical

w/o SSE

w/ SSE

$\ln[S_{aCol}(T_{\text{eff}})] = -1.1031 + 0.2074\epsilon(T_{\text{eff}})$

Lower Bound

$S_{a}(T_{\text{eff}})g$

$\epsilon(T_{\text{eff}})$

$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_2}{Q_1} = 0.6, R = 7, \text{ Isolated, Failure due to Uplift not Considered}$

(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{aCol} = 0.370g$

$\beta_{RTH} = 0.342$

$S_{aCol} = 0.502g$

$S_{aMCE} = 0.245g$

Upper Bound

$\epsilon_0 = 1.5$

Empirical

w/o SSE

w/ SSE

$\ln[S_{aCol}(T_{\text{eff}})] = -1.0725 + 0.2556\epsilon(T_{\text{eff}})$

Upper Bound

$S_{a}(T_{\text{eff}})g$

$\epsilon(T_{\text{eff}})$
$T_{\text{fixed}} = 0.25 \text{ sec, } K_{e_1}/K_{e_2} = 2.00$, $Q_2/Q_1 = 0.6$, $R = 7$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

\begin{align*}
S_{a\text{COL}} &= 0.350g \\
\beta_{RTH} &= 0.269 \\
S_{a\text{COL}} &= 0.453g \\
T_{\text{eff}} &= 3.13 \text{ sec} \\
S_{\text{MCE}}(T_{\text{eff}}) &= 0.245g \\
\end{align*}

Empirical
- w/o SSE
- w/ SSE

$\epsilon_{0} = 1.5$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1016 + 0.2071 \epsilon(T_{\text{eff}})$

Lower Bound

$T_{\text{fixed}} = 0.25 \text{ sec, } K_{e_1}/K_{e_2} = 2.00$, $Q_2/Q_1 = 0.6$, $R = 7$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

\begin{align*}
S_{a\text{COL}} &= 0.370g \\
\beta_{RTH} &= 0.340 \\
S_{a\text{COL}} &= 0.504g \\
T_{\text{eff}} &= 3.13 \text{ sec} \\
S_{\text{MCE}}(T_{\text{eff}}) &= 0.245g \\
\end{align*}

Empirical
- w/o SSE
- w/ SSE

$\epsilon_{0} = 1.5$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0688 + 0.2547 \epsilon(T_{\text{eff}})$

Upper Bound

\[332\]
\( T_{\text{fixed}} = 0.25 \text{ sec}, K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.7, R = 7 \), Isolated, Failure due to Uplift not Considered (with vertical ground motion)

\[
\text{Lower Bound} \\
\text{Empirical}
\]

\[
\text{w/o SSE} \\
\text{w/ SSE}
\]

\[
\text{Empirical}
\]

\[
\text{w/o SSE} \\
\text{w/ SSE}
\]

\[
\text{Empirical}
\]

\[
\text{w/o SSE} \\
\text{w/ SSE}
\]

\[
\text{Empirical}
\]

\[
\text{w/o SSE} \\
\text{w/ SSE}
\]

\[
\text{Empirical}
\]

\[
\text{w/o SSE} \\
\text{w/ SSE}
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\[
\text{Empirical}
\]

\[
\text{w/o SSE} \\
\text{w/ SSE}
\]

\[
\text{Empirical}
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\[
\text{w/o SSE} \\
\text{w/ SSE}
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\text{Empirical}
\]

\[
\text{w/o SSE} \\
\text{w/ SSE}
\]

\[
\text{Empirical}
\]

\[
\text{w/o SSE} \\
\text{w/ SSE}
\]
$T_{\text{fixed}} = 0.25$ sec, $K_{e1}/K_{e2} = 1.75$, $Q_2/Q_1 = 0.7$, $R = 7$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)
$T_{\text{fixed}} = 0.25 \text{ sec, } K_{e1}/K_{e2} = 2.00, \quad Q_2/Q_1 = 0.7, \quad R = 7$, Isolated, Failure due to Uplift not Considered

(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec, } S_{\text{aCOL}}(T_{\text{eff}}) = 0.245g$

$\epsilon_0 = 1.5$

Empirical

$\text{w/o SSE}$

$\text{w/ SSE}$

$\ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.1046 + 0.2088 \epsilon(T_{\text{eff}})$

Lower Bound

$\ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.0754 + 0.2597 \epsilon(T_{\text{eff}})$

Upper Bound
$$T_{\text{fixed}} = 0.20 \text{ sec, } K_{e1}/K_{e2} = 1.50, \frac{Q_2}{Q_1} = 0.5, R=6, \text{ Isolated, Failure due to Uplift not Considered}$$
(with vertical ground motion)
$T_{\text{fixed}} = 0.20 \text{ sec}, K_{e1}/K_{e2} = 1.75, Q_2/Q_1 = 0.5, R = 6$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

\begin{align*}
S_{a_{\text{COL}}} &= 0.350g \\
\beta_{RTH} &= 0.269 \\
S_{a_{\text{COL}}} &= 0.450g \\
T_{\text{eff}} &= 3.13 \text{ sec} \\
S_{\text{AMCE}}(T_{\text{eff}}) &= 0.245g \\
\text{Lower Bound}
\end{align*}

$\epsilon = 1.5$

Empirical
\begin{itemize}
\item w/o SSE
\item w/ SSE
\end{itemize}

\begin{align*}
\ln[S_{a_{\text{COL}}}(T_{\text{eff}})] &= -1.1114 + 0.2086 \epsilon(T_{\text{eff}}) \\
\text{Lower Bound}
\end{align*}

$T_{\text{fixed}} = 0.20 \text{ sec}, K_{e1}/K_{e2} = 1.75, Q_2/Q_1 = 0.5, R = 6$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

\begin{align*}
S_{a_{\text{COL}}} &= 0.370g \\
\beta_{RTH} &= 0.339 \\
S_{a_{\text{COL}}} &= 0.500g \\
T_{\text{eff}} &= 3.13 \text{ sec} \\
S_{\text{AMCE}}(T_{\text{eff}}) &= 0.245g \\
\text{Upper Bound}
\end{align*}

$\epsilon = 1.5$

Empirical
\begin{itemize}
\item w/o SSE
\item w/ SSE
\end{itemize}

\begin{align*}
\ln[S_{a_{\text{COL}}}(T_{\text{eff}})] &= -1.0688 + 0.2503 \epsilon(T_{\text{eff}}) \\
\text{Upper Bound}
\end{align*}
$T_{\text{fixed}} = 0.20 \text{ sec}, K_{\text{eff}}/K_{\text{eq}} = 2.00, Q_2/Q_1 = 0.5, R = 6$, Isolated, Failure due to Uplift not Considered

(with vertical ground motion)

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$T_{\text{fixed}}=0.20\text{ sec}, K_{e1}/K_{e2}=1.50, Q_{z}/Q_{x}=0.6, R=6$, Isolated, Failure due to Uplift not Considered

(with vertical ground motion)

$T_{\text{eff}}=3.13\text{ sec}$, $S_{\text{aCOL}}=0.350g$, $S_{\text{aCOL}}=0.450g$, $S_{\text{AMCE}}(T_{\text{eff}})=0.245g$

Lower Bound

Empirical

w/o SSE

w/ SSE

$\epsilon=1.5$

$\ln[S_{\text{aCOL}}(T_{\text{eff}})]=-1.1161+0.2118\epsilon(T_{\text{eff}})$

Lower Bound

$T_{\text{fixed}}=0.20\text{ sec}, K_{e1}/K_{e2}=1.50, Q_{z}/Q_{x}=0.6, R=6$, Isolated, Failure due to Uplift not Considered

(with vertical ground motion)

$T_{\text{eff}}=3.13\text{ sec}$, $S_{\text{aCOL}}=0.370g$, $S_{\text{aCOL}}=0.494g$, $S_{\text{AMCE}}(T_{\text{eff}})=0.245g$

Upper Bound

Empirical

w/o SSE

w/ SSE

$\epsilon=1.5$

$\ln[S_{\text{aCOL}}(T_{\text{eff}})]=-1.0961+0.2611\epsilon(T_{\text{eff}})$

Upper Bound
$T_{\text{fixed}} = 0.20 \text{ sec, } K_{e1}/K_{e2} = 1.75, Q_2/Q_1 = 0.6, R=6$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

Lower Bound

$S_{aCOL} = 0.350g$

$S_{\text{ACOL}} = 0.450g$

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{\text{AMCE}}(T_{\text{eff}}) = 0.245g$

Empirical

w/o SSE

w/ SSE

$T_{\text{fixed}} = 0.20 \text{ sec, } K_{e1}/K_{e2} = 1.75, Q_2/Q_1 = 0.6, R=6$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

Lower Bound

$S_{aCOL} = 0.370g$

$S_{\text{ACOL}} = 0.498g$

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{\text{AMCE}}(T_{\text{eff}}) = 0.245g$

Empirical

w/o SSE

w/ SSE

$T_{\text{fixed}} = 0.20 \text{ sec, } K_{e1}/K_{e2} = 1.75, Q_2/Q_1 = 0.6, R=6$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

$\ln[S_{aCOL}(T_{\text{eff}})] = -1.1153 + 0.2115 \epsilon(T_{\text{eff}})$

Lower Bound

$\ln[S_{aCOL}(T_{\text{eff}})] = -1.0803 + 0.2558 \epsilon(T_{\text{eff}})$

Upper Bound
\( T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, \frac{Q_2}{Q_1} = 0.6, R = 6 \), Isolated, Failure due to Uplift not Considered (with vertical ground motion)

\[ \ln[S_{a,\text{COL}}(T_{\text{eff}})] = -1.1144 + 0.2106 \epsilon(T_{\text{eff}}) \]

\( T_{\text{eff}} = 3.13 \text{ sec} \)

\[ S_{a,\text{COL}} = 0.245g \]

\( S_{\text{AMCE}}(T_{\text{eff}}) = 0.245g \)

Lower Bound

\( \epsilon_0 = 1.5 \)

\( \beta_{RTM} = 0.269 \)

\( S_{a,\text{COL}} = 0.340g \)

Empirical

- w/o SSE
- w/ SSE

\( S_{a}(T_{\text{eff}})g \)

Probability of Collapse

\[ 0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1 \]

\( 0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \)

Upper Bound

\( \ln[S_{a,\text{COL}}(T_{\text{eff}})] = -1.0734 + 0.2534 \epsilon(T_{\text{eff}}) \)

\( \epsilon(T_{\text{eff}}) \)

Probability of Collapse

\[ 0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1 \]

\( 0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \)

Lower Bound
$T_{\text{fixed}}=0.20$ sec, $K_{e1}/K_{e2}=1.50$, $Q_2/Q_1=0.7$, $R=6$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

With vertical ground motion:

- $S_{a\text{COL}}=0.350g$
- $R_{\text{THK}}=0.272$
- $S_{a\text{COL}}=0.450g$
- $T_{\text{eff}}=3.13$ sec
- $S_{\text{AMCE}}(T_{\text{eff}})=0.245g$
- Lower Bound

Empirical
- w/o SSE
- w/ SSE

$S_a(T_{\text{eff}})$

- $\varepsilon=1.5$

$\ln[S_a\text{COL}(T_{\text{eff}})]=-1.1173+0.2126\varepsilon(T_{\text{eff}})$

Lower Bound

With vertical ground motion:

- $S_{a\text{COL}}=0.370g$
- $R_{\text{THK}}=0.356$
- $S_{a\text{COL}}=0.488g$
- $T_{\text{eff}}=3.13$ sec
- $S_{\text{AMCE}}(T_{\text{eff}})=0.245g$
- Upper Bound

Empirical
- w/o SSE
- w/ SSE

$S_a(T_{\text{eff}})$

- $\varepsilon=1.5$

$\ln[S_a\text{COL}(T_{\text{eff}})]=-1.1080+0.2600\varepsilon(T_{\text{eff}})$

Upper Bound
$T_{\text{fixed}} = 0.20$ sec, $K_{e1}/K_{e2} = 1.75$, $Q_2/Q_1 = 0.7$, $R=6$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

![Graph showing probability of collapse vs. $S_a(T_{\text{eff}})$ and $\epsilon(T_{\text{eff}})$]

$T_{\text{eff}} = 3.13$ sec, $S_{a\text{COL}} = 0.350g$, $\beta_{RTH} = 0.270$

Lower Bound

Empirical

- w/o SSE
- w/ SSE

$S_{a\text{COL}} = 0.450g$

$S_{a\text{MCE}}(T_{\text{eff}}) = 0.245g$

Empirical

- w/o SSE
- w/ SSE

$S_{a\text{COL}} = 0.370g$

$\beta_{RTH} = 0.354$

$S_{a\text{COL}} = 0.489g$

$T_{\text{eff}} = 3.13$ sec

$S_{a\text{MCE}}(T_{\text{eff}}) = 0.245g$

Upper Bound

$\epsilon_0 = 1.5$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1155 + 0.2113 \epsilon(T_{\text{eff}})$

Lower Bound

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1016 + 0.2578 \epsilon(T_{\text{eff}})$

Upper Bound

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$T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, \frac{Q_z}{Q_1} = 0.7, R = 6$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

![Graph showing the relationship between $S_a(T_{\text{eff}})$ and $\epsilon(T_{\text{eff}})$ with empirical and without SSE predictions.]

$T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, \frac{Q_z}{Q_1} = 0.7, R = 6$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

![Graph showing the relationship between $S_a(T_{\text{eff}})$ and $\epsilon(T_{\text{eff}})$ with empirical and without SSE predictions.]

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E.3. Results for eastern site with latitude $40.9^\circ$, longitude $29.2^\circ$ $\bar{\varepsilon}_0(T_1) = 2.0$


t_1=0.30 \text{ sec, } K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.5, R=8, \text{ Non-isolated}

(without vertical ground motion)

\begin{align*}
\ln[S_{aCOL}(T_1)] &= 0.4904 + 0.2312/(T_1) \\
\ln[S_{aCOL}(T_1)] &= 0.4907 + 0.2336/(T_1)
\end{align*}
$T_1 = 0.30 \text{ sec, } K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.5, R = 8, \text{ Non-isolated}$

(without vertical ground motion)

$T_1 = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.6, R = 8, \text{ Non-isolated}$

(without vertical ground motion)
$T_1 = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_2}{Q_1} = 0.6, R = 8$, Non-isolated
(without vertical ground motion)

$T_1 = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, \frac{Q_2}{Q_1} = 0.6, R = 8$, Non-isolated
(without vertical ground motion)
$T_1 = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.7, R=8, \text{ Non-isolated}$

(without vertical ground motion)

$T_1 = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.75, Q_2/Q_1 = 0.7, R=8, \text{ Non-isolated}$

(without vertical ground motion)
\[ T_1 = 0.30 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 2.00, Q_2/Q_1 = 0.7, R = 8, \text{ Non-isolated} \]

(without vertical ground motion)

\[ T_1 = 0.25 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.50, Q_2/Q_1 = 0.5, R = 7, \text{ Non-isolated} \]

(without vertical ground motion)
$T_1 = 0.25\text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.75, \frac{Q_2}{Q_1} = 0.5, R = 7$, Non-isolated

(without vertical ground motion)

\begin{align*}
S_{sCOL} &= 1.740g, \\
\beta_{RTR} &= 0.458, \\
S_{aMCE}(T_1) &= 1.860g
\end{align*}

\begin{align*}
\ln[S_{sCOL}(T_1)] &= 0.3528 + 0.2960(T_1) \\
\epsilon(T_1) &= 2.0
\end{align*}

$T_1 = 0.25\text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 2.00, \frac{Q_2}{Q_1} = 0.5, R = 7$, Non-isolated

(without vertical ground motion)

\begin{align*}
S_{sCOL} &= 1.690g, \\
\beta_{RTR} &= 0.444, \\
S_{aCOL}(T_1) &= 2.481g
\end{align*}

\begin{align*}
\ln[S_{aCOL}(T_1)] &= 0.3425 + 0.2832(T_1) \\
\epsilon(T_1) &= 2.0
\end{align*}
$T_1 = 0.25 \text{ sec, } \frac{K_{e1}}{K_{e2}} = 1.50, \frac{Q_2}{Q_1} = 0.6, R = 7, \text{ Non-isolated}$

(without vertical ground motion)

\begin{align*}
S_{SCOL} = 1.700g & \quad \beta_{TR} = 0.453 \\
S_{SCOL} = 2.362g & \quad (T_1 = 0.25 \text{ sec}) \\
S_{EMCE(T_1)} = 1.860g
\end{align*}

Empirical
- w/o SSE
- w/ SSE

\begin{align*}
\ln[S_{SCOL}(T_1)] &= 0.3068 + 0.2764\epsilon(T_1) \\
\ln[S_{SCOL}(T_1)] &= 0.3313 + 0.2782\epsilon(T_1)
\end{align*}

$T_1 = 0.25 \text{ sec, } \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_2}{Q_1} = 0.6, R = 7, \text{ Non-isolated}$

(without vertical ground motion)

\begin{align*}
S_{SCOL} = 1.760g & \quad \beta_{TR} = 0.458 \\
S_{SCOL} = 2.429g & \quad (T_1 = 0.25 \text{ sec}) \\
S_{EMCE(T_1)} = 1.860g
\end{align*}

Empirical
- w/o SSE
- w/ SSE
\[ T_1 = 0.25 \text{ sec}, K_{e_1}/K_{e_2} = 2.00, Q_2/Q_1 = 0.6, R = 7, \text{ Non-isolated} \]

(without vertical ground motion)

\[ S_{\text{a, COL}} = 1.800g, \quad \beta_{\text{RTR}} = 0.461 \]

\[ S_{\text{a, MCE}}(T_1) = 1.860g \]

\[ r_0 = 2.0 \]

\[ T_1 = 0.25 \text{ sec}, K_{e_1}/K_{e_2} = 1.50, Q_2/Q_1 = 0.7, R = 7, \text{ Non-isolated} \]

(without vertical ground motion)

\[ S_{\text{a, COL}} = 1.670g, \quad \beta_{\text{RTR}} = 0.431 \]

\[ S_{\text{a, MCE}}(T_1) = 1.860g \]

\[ r_0 = 2.0 \]
$T_1 = 0.25$ sec, $K_{e1}/K_{e2} = 1.75$, $Q_2/Q_1 = 0.7$, $R=7$, Non-isolated
(without vertical ground motion)

$T_1 = 0.25$ sec, $K_{e1}/K_{e2} = 2.00$, $Q_2/Q_1 = 0.7$, $R=7$, Non-isolated
(without vertical ground motion)
\[ T_1 = 0.20 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.50, \frac{Q_2}{Q_1} = 0.5, R = 6, \text{ Non-isolated} \]

(without vertical ground motion)

\[ S_{acol} = 1.660g, \quad \beta_{RTR} = 0.408 \]
\[ S_{acol} = 2.326g \]
\[ T_1 = 0.20 \text{ sec}, \quad S_{WMC} = 1.860g \]

Empirical

- w/o SSE
- w/ SSE

\[ \ln[S_{acol}(T_1)] = 0.3271 + 0.2590(T_1) \]

\[ \ln[S_{acol}(T_1)] = 0.3312 + 0.2410(T_1) \]

\[ T_1 = 0.20 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.75, \frac{Q_2}{Q_1} = 0.5, R = 6, \text{ Non-isolated} \]

(without vertical ground motion)

\[ S_{acol} = 1.610g, \quad \beta_{RTR} = 0.399 \]
\[ S_{acol} = 2.254g \]
\[ T_1 = 0.20 \text{ sec}, \quad S_{WMC} = 1.860g \]

Empirical

- w/o SSE
- w/ SSE

\[ \ln[S_{acol}(T_1)] = 0.3271 + 0.2590(T_1) \]

\[ \ln[S_{acol}(T_1)] = 0.3312 + 0.2410(T_1) \]
$T_1 = 0.20$ sec, $\frac{K_{e1}}{K_{e2}} = 2.00$, $Q_2/Q_1 = 0.5$, $R = 6$, Non-isolated
(without vertical ground motion)

$T_1 = 0.20$ sec, $\frac{K_{e1}}{K_{e2}} = 1.50$, $Q_2/Q_1 = 0.6$, $R = 6$, Non-isolated
(without vertical ground motion)
$T_1 = 0.20$ sec, $K_{e1}/K_{e2} = 1.75$, $Q_2/Q_1 = 0.6$, $R=6$, Non-isolated
(without vertical ground motion)
$T_1 = 0.20 \text{ sec, } K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.7, R = 6, \text{ Non-isolated}$

(without vertical ground motion)
\[ T_1 = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, Q_2/Q_1 = 0.7, R = 6, \text{ Non-isolated} \]

(without vertical ground motion)

\[ T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, Q_2/Q_1 = 0.5, R = 8, \text{ Isolated, Failure due to 30 mm Uplift} \]

(with vertical ground motion)
\( T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{1}}{K_{2}} = 1.50, \frac{Q_{1}}{Q_{2}} = 0.5, R = 8, \) Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

![Graph showing probability of collapse vs. Sa(Teff)g with regression line and empirical data points.]

\( T_{\text{eff}} = 3.13 \text{ sec}, \quad S_{\text{aCOL}}(T_{\text{eff}}) = 0.669g, \quad S_{\text{AMCE}}(T_{\text{eff}}) = 0.297g 

\)

\( \varepsilon_{0} = 2.0 \)

---

\( T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{1}}{K_{2}} = 1.75, \frac{Q_{1}}{Q_{2}} = 0.5, R = 8, \) Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

![Graph showing probability of collapse vs. Sa(Teff)g with regression line and empirical data points.]

\( T_{\text{eff}} = 3.13 \text{ sec}, \quad S_{\text{aCOL}}(T_{\text{eff}}) = 0.608g, \quad S_{\text{AMCE}}(T_{\text{eff}}) = 0.297g 

\)

\( \varepsilon_{0} = 2.0 \)
$T_{\text{fixed}}=0.30 \text{ sec, } K_{e1}/K_{e2}^{2}=1.75, \ Q_2/Q_1=0.5, \ R=8, \ \text{Isolated, Failure due to 30 mm Uplift}$

(with vertical ground motion)

---

$T_{\text{fixed}}=0.30 \text{ sec, } K_{e1}/K_{e2}^{2}=2.00, \ Q_2/Q_1=0.5, \ R=8, \ \text{Isolated, Failure due to 30 mm Uplift}$

(with vertical ground motion)
$T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, Q_2/Q_1 = 0.5, R = 8$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

- $S_{a\text{COL}} = 0.370g$
- $\beta_{\text{RTN}} = 0.439$
- $T_{\text{eff}} = 3.13 \text{ sec}$
- $S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$
- Upper Bound

- $\epsilon_0 = 2.0$

- Empirical
- w/o SSE
- w/ SSE

$T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, Q_2/Q_1 = 0.6, R = 8$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

- $S_{a\text{COL}} = 0.350g$
- $\beta_{\text{RTN}} = 0.399$
- $T_{\text{eff}} = 3.13 \text{ sec}$
- $S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$
- Lower Bound

- $\epsilon_0 = 2.0$

- Empirical
- w/o SSE
- w/ SSE
$T_{\text{fixed}}=0.30 \text{ sec, } K_{e1}/K_{e2}=1.50, Q_2/Q_1=0.6, R=8$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

$T_{\text{eff}}=3.13 \text{ sec}$
$S_{\text{aCOL}}(T_{\text{eff}})=0.360g$
$S_{\text{aMCE}}(T_{\text{eff}})=0.297g$

$\varepsilon_0=2.0$

$\beta_{RTRI}=0.398$
$S_{\text{aCOL}}=0.606g$

$T_{\text{eff}}=3.13 \text{ sec}$
$S_{\text{aMCE}}(T_{\text{eff}})=0.297g$

$\varepsilon=2.0$

$\in[S_{\text{aCOL}}(T_{\text{eff}})] = -1.0997 + 0.3485(\varepsilon(\text{eff}))$

$\in[S_{\text{aCOL}}(T_{\text{eff}})] = -1.1669 + 0.3330(\varepsilon(\text{eff}))$

Lower Bound

Empirical
w/o SSE
w/ SSE
$T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_2}{Q_1} = 0.6, R = 8$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{a_{\text{COL}}} = 0.370g$  
$S_{a_{\min}} = 0.671g$  
$\beta_{\text{RTN}} = 0.438$

$\epsilon = 2.0$

$S_{a(T_{\text{eff}})}g$

Empirical  
w/ SSE  
w/ SSE

$\ln[S_{a_{\text{COL}}}(T_{\text{eff}})] = -1.0963 + 0.3486\epsilon(T_{\text{eff}})$

Upper Bound

$T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, \frac{Q_2}{Q_1} = 0.6, R = 8$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{a_{\text{COL}}} = 0.350g$  
$S_{a_{\min}} = 0.608g$  
$\beta_{\text{RTN}} = 0.398$

$\epsilon = 2.0$

$S_{a(T_{\text{eff}})}g$

Empirical  
w/ SSE  
w/ SSE

$\ln[S_{a_{\text{COL}}}(T_{\text{eff}})] = -1.1646 + 0.3331\epsilon(T_{\text{eff}})$

Lower Bound
$T_{fixed} = 0.30\,\text{sec},\ K_{e1}/K_{e2} = 2.00,\ Q_2/Q_1 = 0.6,\ R = 8,$ Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

$T_{eff} = 3.13\,\text{sec}$

$S_{acol} = 0.370g$

$\beta_{RTR} = 0.439$

$S_{acol} = 0.674g$

$S_{amce}(T_{eff}) = 0.297g$

Upper Bound

$\epsilon = 2.0$

Empirical

$w/o\ SSE$

$w/\ SSE$

$\ln[S_{acol}(T_{eff})] = 0.1094 + 0.3495\epsilon(T_{eff})$

$\ln[S_{acol}(T_{eff})] = 0.1094 + 0.3495\epsilon(T_{eff})$

Lower Bound

$\ln[S_{acol}(T_{eff})] = 0.1094 + 0.3495\epsilon(T_{eff})$
\[ T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, \frac{Q_2}{Q_1} = 0.7, R = 8, \text{ Isolated, Failure due to 30 mm Uplift} \]

(with vertical ground motion)

\[ T_{\text{eff}} = 3.13 \text{ sec} \]

\[ S_{\text{a(COL)}} = 0.360g \]

\[ S_{\text{a(COL)}} = 0.668g \]

\[ S_{\text{a(MCE)}} = 0.297g \]

\[ \varepsilon = 2.0 \]

\[ \varepsilon_{\text{RTK}} = 0.436 \]

\[ \varepsilon_{\text{RTK}} = 0.398 \]

\[ S_{\text{a(COL)}} = 0.606g \]

\[ S_{\text{a(MCE)}} = 0.297g \]

\[ \varepsilon = 2.0 \]

\[ \varepsilon_{\text{RTK}} = 0.398 \]

\[ \ln[S_{\text{a(COL)}}(T_{\text{eff}})] = -1.1025 + 0.3497 \varepsilon(T_{\text{eff}}) \]

\[ \ln[S_{\text{a(COL)}}(T_{\text{eff}})] = -1.1686 + 0.3336 \varepsilon(T_{\text{eff}}) \]
$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.75, \frac{Q_2}{Q_1} = 0.7, R=8$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$
$S_{a\text{COL}}(T_{\text{eff}}) = 0.370g$
$\beta_{RTN} = 0.438$

$S_{a\text{COL}}(T_{\text{eff}}) = 0.671g$

$S_{\text{MCE}}(T_{\text{eff}}) = 0.297g$
Upper Bound

$\varepsilon_0 = 2.0$

[Graph showing Probability of Collapse vs $S_a(T_{\text{eff}})$]

$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 2.00, \frac{Q_2}{Q_1} = 0.7, R=8$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$
$S_{a\text{COL}}(T_{\text{eff}}) = 0.350g$
$\beta_{RTN} = 0.400$

$S_{a\text{COL}}(T_{\text{eff}}) = 0.607g$

$S_{\text{MCE}}(T_{\text{eff}}) = 0.297g$
Lower Bound

$\varepsilon_0 = 2.0$

[Graph showing Probability of Collapse vs $S_a(T_{\text{eff}})$]
$T_{\text{fixed}} = 0.30$ sec, $K_{e1}/K_{e2} = 2.00$, $Q_1/Q_1 = 0.7$, $R=8$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

$T_{\text{fixed}} = 0.25$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_1/Q_1 = 0.5$, $R=7$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)
$T_{\text{fixed}} = 0.25$ sec, $K_{e_1}/K_{e_2} = 1.50$, $Q_j/Q_i = 0.5$, $R = 7$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)
$T_{fixed} = 0.25$ sec, $K_{eff}/K_{eff} = 1.75$, $Q/Q_1 = 0.5$, $R=7$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

$T_{eff} = 3.13$ sec

$S_{a\text{COL}} = 0.360g$

$\beta_{RTF} = 0.396$

$S_{a\text{COL}} = 0.597g$

$S_{a\text{MCE}} = 0.297g$

$\epsilon_0 = 2.0$

$\ln[S_{a\text{COL}}(T_{eff})] = -1.1044 + 0.3467\epsilon(T_{eff})$

$\ln[S_{a\text{COL}}(T_{eff})] = -1.1751 + 0.3300\epsilon(T_{eff})$

$\epsilon_0 = 2.0$

$S_{a}(T_{eff})g$

$\ln[S_{a\text{COL}}(T_{eff})]$
\( T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{\text{e1}}}{K_{\text{e2}}} = 2.00, Q_{\text{2}} / Q_{\text{1}} = 0.50, R = 7, \) Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

\[
\begin{align*}
S_{\text{aCOL}} &= 0.360g \\
\beta_{\text{RTN}} &= 0.434 \\
T_{\text{eff}} &= 3.13 \text{ sec} \\
S_{\text{aMEC}}(T_{\text{eff}}) &= 0.297g \\
\end{align*}
\]

\[
\begin{align*}
\ln[S_{\text{aCOL}}(T_{\text{eff}})] &= -1.1018 + 0.3484(\epsilon(T_{\text{eff}})) \\
\end{align*}
\]

\( T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{\text{e1}}}{K_{\text{e2}}} = 1.50, Q_{\text{2}} / Q_{\text{1}} = 0.60, R = 7, \) Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

\[
\begin{align*}
S_{\text{aCOL}} &= 0.350g \\
\beta_{\text{RTN}} &= 0.395 \\
T_{\text{eff}} &= 3.13 \text{ sec} \\
S_{\text{aMEC}}(T_{\text{eff}}) &= 0.297g \\
\end{align*}
\]

\[
\begin{align*}
\ln[S_{\text{aCOL}}(T_{\text{eff}})] &= -1.1780 + 0.3296(\epsilon(T_{\text{eff}})) \\
\end{align*}
\]
$T_{\text{fixed}} = 0.25 \text{ sec}, K_{e_1}/K_{e_2} = 1.50, Q_2/Q_1 = 0.6, R = 7$, Isolated, Failure due to 30 mm Uplift

(with vertical ground motion)

\[ S_{a_{\text{COL}}} = 0.360g \quad \beta_{\text{RTR}} = 0.431 \]

\[ S_{a_{\text{MC}}} = 0.655g \]

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{a_{\text{MC}}}(T_{\text{eff}}) = 0.297g$

Upper Bound

$\epsilon = 2.0$

Empirical

- w/o SSE
- w/ SSE

\[ \log(S_{a_{\text{COL}}}(T_{\text{eff}})) = -1.1115 + 0.3442 \epsilon(T_{\text{eff}}) \]

Lower Bound

$T_{\text{fixed}} = 0.25 \text{ sec}, K_{e_1}/K_{e_2} = 1.75, Q_2/Q_1 = 0.6, R = 7$, Isolated, Failure due to 30 mm Uplift

(with vertical ground motion)

\[ S_{a_{\text{COL}}} = 0.350g \]

$S_{a_{\text{MC}}}(T_{\text{eff}}) = 0.595g$

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{a_{\text{MC}}}(T_{\text{eff}}) = 0.297g$

Lower Bound

$\epsilon = 2.0$

Empirical

- w/o SSE
- w/ SSE

\[ \log(S_{a_{\text{COL}}}(T_{\text{eff}})) = -1.1768 + 0.3285 \epsilon(T_{\text{eff}}) \]

Lower Bound
$T_{\text{fixed}} = 0.25 \text{ sec}, K_{e1}/K_{e2} = 1.75$, $Q_2/Q_1 = 0.6$, $R = 7$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

\begin{enumerate}
\item $S_{a\text{COL}} = 0.360g$
\item $\delta_{RTR} = 0.432$
\item $S_{a\text{COL}} = 0.659g$
\item $T_{\text{eff}} = 3.13 \text{ sec}$
\item $S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$
\item Upper Bound
\end{enumerate}

\begin{enumerate}
\item $\epsilon_{0} = 2.0$
\item Empirical
\item w/o SSE
\item w/ SSE
\end{enumerate}

$T_{\text{fixed}} = 0.25 \text{ sec}, K_{e1}/K_{e2} = 2.00$, $Q_2/Q_1 = 0.6$, $R = 7$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

\begin{enumerate}
\item $S_{a\text{COL}} = 0.340g$
\item $\beta_{RTR} = 0.395$
\item $S_{a\text{COL}} = 0.597g$
\item $T_{\text{eff}} = 3.13 \text{ sec}$
\item $S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$
\item Lower Bound
\end{enumerate}

\begin{enumerate}
\item $\epsilon_{0} = 2.0$
\item Empirical
\item w/o SSE
\item w/ SSE
\end{enumerate}
$T_{\text{fixed}} = 0.25 \text{ sec}, K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.6, R = 7$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

\begin{align*}
S_{\text{COL}} &= 0.360g \\
\beta_{RTR} &= 0.433 \\
S_{\text{COL}} &= 0.664g \\
T_{\text{eff}} &= 3.13 \text{ sec} \\
S_{\text{MCE}}(T_{\text{eff}}) &= 0.297g
\end{align*}

Upper Bound

$\epsilon_0 = 2.0$

Empirical

- w/o SSE
- w/ SSE

\begin{align*}
\ln[S_{\text{COL}}(T_{eff})] &= -1.1047 + 0.3473\epsilon(T_{eff}) \\
&\text{Upper Bound}
\end{align*}

$T_{\text{fixed}} = 0.25 \text{ sec}, K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.7, R = 7$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

\begin{align*}
S_{\text{COL}} &= 0.350g \\
\beta_{RTR} &= 0.394 \\
S_{\text{COL}} &= 0.595g \\
T_{\text{eff}} &= 3.13 \text{ sec} \\
S_{\text{MCE}}(T_{\text{eff}}) &= 0.297g
\end{align*}

Lower Bound

$\epsilon_0 = 2.0$

Empirical

- w/o SSE
- w/ SSE

\begin{align*}
\ln[S_{\text{COL}}(T_{eff})] &= -1.1793 + 0.3302\epsilon(T_{eff}) \\
&\text{Lower Bound}
\end{align*}
$T_{\text{fixed}} = 0.25 \text{ sec, } K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.7, \text{ Isolated, Failure due to 30 mm Uplift}$

(with vertical ground motion)
$T_{\text{fixed}} = 0.25 \text{ sec, } K_{e1}/K_{e2} = 1.75, \frac{Q_2}{Q_1} = 0.7, R = 7$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec, } S_{a\text{COL}}(T_{\text{eff}}) = 0.654g$

$\epsilon_{\text{RTN}} = 0.430$

Empirical
- w/o SSE
- w/ SSE

$\epsilon_{\text{eff}} = 2.0$

$S_{a}(T_{\text{eff}})g$

Probability of Collapse

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1139 + 0.3445\epsilon(T_{\text{eff}})$

Upper Bound

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1709 + 0.3305\epsilon(T_{\text{eff}})$

Lower Bound

$T_{\text{fixed}} = 0.25 \text{ sec, } K_{e1}/K_{e2} = 2.00, \frac{Q_2}{Q_1} = 0.7, R = 7$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$S_{a\text{COL}}(T_{\text{eff}})g$

Probability of Collapse

$\epsilon(T_{\text{eff}})$

$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, \frac{Q_2}{Q_1} = 0.7, R = 7$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, \frac{Q_2}{Q_1} = 0.5, R = 6$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)
$T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, \frac{Q_{2}}{Q_{1}} = 0.5, R = 6$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$S_{a\text{COL}} = 0.360g$
$\sigma_{RTR} = 0.431$

$S_{a\text{COL}} = 0.653g$
$T_{\text{eff}} = 3.13 \text{ sec}$
$S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$
Upper Bound

$\epsilon_{0} = 2.0$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1094 + 0.3413(\epsilon_{T_{\text{eff}}})$

$T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_{2}}{Q_{1}} = 0.5, R = 6$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$S_{a\text{COL}} = 0.340g$
$\beta_{RTR} = 0.392$

$S_{a\text{COL}} = 0.588g$
$T_{\text{eff}} = 3.13 \text{ sec}$
$S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$
Lower Bound

$\epsilon_{0} = 2.0$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1824 + 0.3255(\epsilon_{T_{\text{eff}}})$
$T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_2}{Q_1} = 0.5, R = 6$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

![Graph 1](image1)

$T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, \frac{Q_2}{Q_1} = 0.5, R = 6$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

![Graph 2](image2)
\[ T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, Q_2/Q_1 = 0.5, R = 6, \text{ Isolated, Failure due to 30 mm Uplift} \]

(with vertical ground motion)

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1049 + 0.3418 \epsilon(T_{\text{eff}}) \]

Upper Bound

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1838 + 0.3256 \epsilon(T_{\text{eff}}) \]

Lower Bound

\[ T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, Q_2/Q_1 = 0.6, R = 6, \text{ Isolated, Failure due to 30 mm Uplift} \]

(with vertical ground motion)
$T_{\text{fixed}} = 0.20$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.6$, $R = 6$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

![Graph 1]

$T_{\text{fixed}} = 0.20$ sec, $K_{e1}/K_{e2} = 1.75$, $Q_2/Q_1 = 0.6$, $R = 6$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

![Graph 2]
$T_{\text{fixed}} = 0.20 \text{ sec, } K_{e1}/K_{e2} = 1.75$, $Q_2/Q_1 = 0.6$, $R=6$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{a\text{COL}} = 0.370g$

$\sigma_{RTT} = 0.431$

$S_{a\text{COL}} = 0.655g$

$S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$

Upper Bound

$\epsilon_{0} = 2.0$

In $[S_{a\text{COL}}(T_{\text{eff}})] = -1.1110 + 0.3437 \epsilon(T_{\text{eff}})$

$T_{\text{fixed}} = 0.20 \text{ sec, } K_{e1}/K_{e2} = 2.00$, $Q_2/Q_1 = 0.6$, $R=6$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{a\text{COL}} = 0.340g$

$\beta_{RTT} = 0.391$

$S_{a\text{COL}} = 0.587g$

$S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$

Lower Bound

$\epsilon_{0} = 2.0$

In $[S_{a\text{COL}}(T_{\text{eff}})] = -1.1838 + 0.3255 \epsilon(T_{\text{eff}})$
\( T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 2.00, Q_2/Q_1 = 0.6, R = 6, \text{ Isolated, Failure due to 30 mm Uplift} \)
(with vertical ground motion)

\begin{align*}
\text{Probability of Collapse} \\
S_a(T_{\text{eff}})g \\
\epsilon_0 = 2.0
\end{align*}

\begin{align*}
\text{Empirical} & \text{ w/o SSE} & \text{w/ SSE} \\
S_{\text{aCOL}} = 0.370g & \beta_{RTH} = 0.432 \\
S_{\text{aMC}} = 0.656g & T_{\text{eff}} = 3.13 \text{ sec} \\
S_{\text{aMC}}(T_{\text{eff}}) = 0.297g & \text{Upper Bound}
\end{align*}

\begin{align*}
\ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.1082 + 0.3436(\epsilon(T_{\text{eff}})) \\
\epsilon(T_{\text{eff}})
\end{align*}

\begin{align*}
S_{a}(T_{\text{eff}})g \\
\epsilon_0 = 2.0
\end{align*}

\begin{align*}
\text{Empirical} & \text{ w/o SSE} & \text{w/ SSE} \\
S_{\text{aCOL}} = 0.340g & \beta_{RTH} = 0.390 \\
S_{\text{aMC}} = 0.587g & T_{\text{eff}} = 3.13 \text{ sec} \\
S_{\text{aMC}}(T_{\text{eff}}) = 0.297g & \text{Lower Bound}
\end{align*}

\begin{align*}
\ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.1838 + 0.3257(\epsilon(T_{\text{eff}})) \\
\epsilon(T_{\text{eff}})
\end{align*}
\( T_{\text{fixed}} = 0.20 \text{ sec}, K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.7, R = 6, \) Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

\[ S_{accoli} = 0.360g \]
\[ S_{acoli} = 0.636g \]
\[ \epsilon_{RTN} = 0.426 \]
\[ T_{\text{eff}} = 3.13 \text{ sec} \]
\[ S_{aMCE}(T_{\text{eff}}) = 0.297g \]
Upper Bound

\[ \text{Empirical} \]
\[ \text{w/o SSE} \]
\[ \text{w/ SSE} \]

\( \epsilon = 2.0 \)

\( T_{\text{fixed}} = 0.20 \text{ sec}, K_{e1}/K_{e2} = 1.75, Q_2/Q_1 = 0.7, R = 6, \) Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

\[ S_{acoli} = 0.340g \]
\[ S_{acoli} = 0.587g \]
\[ \beta_{RTN} = 0.390 \]
\[ T_{\text{eff}} = 3.13 \text{ sec} \]
\[ S_{aMCE}(T_{\text{eff}}) = 0.297g \]
Lower Bound

\[ \text{Empirical} \]
\[ \text{w/o SSE} \]
\[ \text{w/ SSE} \]

\( \epsilon = 2.0 \)
$T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 2.00, Q_2/Q_1 = 0.7, R=6$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

$T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.50, Q_2/Q_1 = 0.5, R=8$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)
$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.5, R=8$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

- $S_{\text{aCOL}} = 0.380g$
- $\beta_{\text{RTN}} = 0.234$
- $T_{\text{eff}} = 3.13 \text{ sec}$
- $S_{\text{aMCE}}(T_{\text{eff}}) = 0.297g$

Empirical
- w/o SSE
- w/ SSE

$\sigma_0 = 2.0$

$\ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.0132 + 0.2497\epsilon(T_{\text{eff}})$

Upper Bound

$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.75, Q_2/Q_1 = 0.5, R=8$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

- $S_{\text{aCOL}} = 0.360g$
- $\beta_{\text{RTN}} = 0.266$
- $S_{\text{aCOL}} = 0.530g$
- $T_{\text{eff}} = 3.13 \text{ sec}$
- $S_{\text{aMCE}}(T_{\text{eff}}) = 0.297g$

Empirical
- w/o SSE
- w/ SSE

$\sigma_0 = 2.0$

$\ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.0494 + 0.2074\epsilon(T_{\text{eff}})$

Lower Bound
$T_{\text{fixed}} = 0.30 \text{ sec}, K_{e1}/K_{e2} = 1.75, Q_2/Q_1 = 0.5$, R=8, Isolated, Failure due to Uplift not Considered

(with vertical ground motion)

\[ S_{a\text{COL}} = 0.360g, \quad \beta_{RTR} = 0.266 \]
\[ S_{a\text{COL}} = 0.529g, \quad T_{\text{eff}} = 3.13 \text{ sec}, \quad S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g \]

Empirical
- w/o SSE
- w/ SSE

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0079 + 0.2486\epsilon(T_{\text{eff}}) \]

Upper Bound

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0479 + 0.2056\epsilon(T_{\text{eff}}) \]

Lower Bound

\[ \epsilon_{0} = 2.0 \]
$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 2.00, Q_z/Q_1 = 0.5, R = 8$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

$S_a(T_{\text{eff}})g$

$S_{a,\text{COL}} = 0.380g$

$S_{a,\text{COL}} = 0.602g$

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{a,\text{MCE}}(T_{\text{eff}}) = 0.297g$

Upper Bound

$\epsilon = 2.0$

Empirical

w/o SSE

w/ SSE

$\ln[S_{a,\text{COL}}(T_{\text{eff}})] = -1.0042 + 0.2484\epsilon(T_{\text{eff}})$

$\ln[S_{a,\text{MCE}}(T_{\text{eff}})]$

Upper Bound

$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.50, Q_z/Q_1 = 0.6, R = 8$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

$S_a(T_{\text{eff}})g$

$S_{a,\text{COL}} = 0.360g$

$S_{a,\text{COL}} = 0.528g$

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{a,\text{MCE}}(T_{\text{eff}}) = 0.297g$

Lower Bound

$\epsilon = 2.0$

Empirical

w/o SSE

w/ SSE

$\ln[S_{a,\text{COL}}(T_{\text{eff}})] = -1.0583 + 0.2098\epsilon(T_{\text{eff}})$

$\ln[S_{a,\text{MCE}}(T_{\text{eff}})]$

Lower Bound

388
$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e_1}/K_{e_2} = 1.50, Q_2/Q_1 = 0.6, R = 8$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

- $S_{a_{\text{COL}}} = 0.380g$
- $\beta_{R_{TR}} = 0.335$
- $S_{a_{\text{COL}}} = 0.600g$
- $T_{\text{eff}} = 3.13 \text{ sec}$
- $S_{a_{\text{MCE}}}(T_{\text{eff}}) = 0.297g$

Upper Bound

$\varepsilon = 2.0$

Empirical

- w/o SSE
- w/ SSE

$\ln[S_{a_{\text{COL}}}(T_{\text{eff}})] = -1.0161 + 0.252\varepsilon(T_{\text{eff}})$

- $\varepsilon(T_{\text{eff}})$

Lower Bound

$\ln[S_{a_{\text{COL}}}(T_{\text{eff}})] = -1.0544 + 0.2083\varepsilon(T_{\text{eff}})$

Lower Bound
\( T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_2}{Q_1} = 0.6, R=8, \) Isolated, Failure due to Uplift not Considered

(with vertical ground motion)

\( \text{Empirical} \quad \text{w/o SSE} \quad \text{w/ SSE} \)

\( \varepsilon_0 = 2.0 \)

\( T_{\text{eff}} = 3.13 \text{ sec} \)

\( S_{a_{\text{COL}}} = 0.360g \)

\( \beta_{\text{RTR}} = 0.266 \)

\( S_{a_{\text{COL}}} = 0.529g \)

\( S_{a_{\text{MCE}}} = 0.297g \)

\( \text{Lower Bound} \)

\( \text{Empirical} \quad \text{w/o SSE} \quad \text{w/ SSE} \)

\( \varepsilon_0 = 2.0 \)

\( \ln[S_{a_{\text{COL}}}(T_{\text{eff}})] = -1.0013 + 0.2503\varepsilon(T_{\text{eff}}) \)

\( \ln[S_{a_{\text{COL}}}(T_{\text{eff}})] = -1.0506 + 0.2070\varepsilon(T_{\text{eff}}) \)

\( \ln[S_{a_{\text{MCE}}}(T_{\text{eff}})] = -1.0506 + 0.2070\varepsilon(T_{\text{eff}}) \)
$T_{\text{fixed}} = 0.30$ sec, $K_{e1}/K_{e2} = 2.00$, $Q_2/Q_1 = 0.6$, $R = 8$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

$T_{\text{eff}} = 3.13$ sec

$S_{\text{aCOL}} = 0.380g$
$\beta_{BRK} = 0.333$

$S_{\text{aCOL}} = 0.603g$
$T_{\text{eff}} = 3.13$ sec
$S_{\text{aMCE}}(T_{\text{eff}}) = 0.297g$
Upper Bound

Empirical
- w/o SSE
- w/ SSE

$\ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.0058 + 0.2500\epsilon(T_{\text{eff}})$

$T_{\text{fixed}} = 0.30$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.7$, $R = 8$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

$S_{\text{aCOL}} = 0.360g$
$\beta_{BRK} = 0.274$

$S_{\text{aCOL}} = 0.529g$
$T_{\text{eff}} = 3.13$ sec
$S_{\text{aMCE}}(T_{\text{eff}}) = 0.297g$
Lower Bound

Empirical
- w/o SSE
- w/ SSE

$\ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.0652 + 0.2146\epsilon(T_{\text{eff}})$
$T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.75, \frac{Q_2}{Q_1} = 0.7, R = 8$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

$S_a(T_{\text{eff}}) g$

$S_{a\text{COL}} = 0.380 g$

$\beta_{RTR} = 0.341$

$S_{a\text{COL}} = 0.603 g$

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{a\text{MCE}}(T_{\text{eff}}) = 0.297 g$

Upper Bound

Empirical

w/o SSE

w/ SSE

$\epsilon_0 = 2.0$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0225 + 0.2583 (T_{\text{eff}})$

Lower Bound

Empirical

w/o SSE

w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0588 + 0.2096 (T_{\text{eff}})$

Upper Bound
$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.75, Q_{z}/Q_{y} = 0.7, R=8$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

![Graph 1](image1)

$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 2.00, Q_{z}/Q_{y} = 0.7, R=8$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

![Graph 2](image2)
394 sec, $K_{e1}/K_{e2} = 2.00$, $Q_2/Q_1 = 0.7$, $R = 8$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

![Graph 1](image1.png)

$T_{\text{fixed}} = 0.30$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.5$, $R = 7$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

![Graph 2](image2.png)
$T_{\text{fixed}} = 0.25 \text{ sec}, K_{e1}/K_{e2} = 1.50, Q_x/Q_y = 0.5, R=7$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)
$T_{\text{fixed}} = 0.25 \text{ sec, } K_{e1}/K_{e2} = 1.75, \ Q_2/Q_1 = 0.5, \ R=7, \ Isolated, \ Failure \ due \ to \ Uplift \ not \ Considered$

(with vertical ground motion)

$S_{a(T_{\text{eff}})}g$

Probability of Collapse

Empirical
- w/o SSE
- w/ SSE

$S_{a\text{COL}} = 0.370g$
$\varepsilon_{\text{RTF}} = 0.337$
$S_{a\text{COL}} = 0.584g$
$T_{\text{eff}} = 3.13 \text{ sec}$
$S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$

Upper Bound

$\varepsilon_0 = 2.0$

In $[S_{a\text{COL}}(T_{\text{eff}})] = -1.0232 + 0.2515 \varepsilon(T_{\text{eff}})$

Lower Bound

$S_{a\text{COL}}(T_{\text{eff}})$ $\varepsilon(T_{\text{eff}})$

(with vertical ground motion)

$T_{\text{fixed}} = 0.25 \text{ sec, } K_{e1}/K_{e2} = 2.00, \ Q_2/Q_1 = 0.5, \ R=7, \ Isolated, \ Failure \ due \ to \ Uplift \ not \ Considered$

$S_{a\text{COL}} = 0.350g$
$\varepsilon_{\text{RTF}} = 0.269$
$S_{a\text{COL}} = 0.521g$
$T_{\text{eff}} = 3.13 \text{ sec}$
$S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$

Lower Bound

$\varepsilon_0 = 2.0$

In $[S_{a\text{COL}}(T_{\text{eff}})] = -1.0855 + 0.2071 \varepsilon(T_{\text{eff}})$

Lower Bound
$T_{\text{fixed}} = 0.25$ sec, $K_{e1}/K_{e2} = 2.00$, $Q_2/Q_1 = 0.5$, $R=7$, Isolated, Failure due to Uplift not Considered

(with vertical ground motion)

Probability of Collapse

$S_{a}(T_{\text{eff}})g$

Empirical

w/o SSE

w/ SSE

$S_{a\text{COL}} = 0.370g$

$\gamma_{\text{RTN}} = 0.335$

$S_{a\text{COL}} = 0.598g$

$T_{\text{eff}} = 3.13$ sec

$S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$

Upper Bound

$\epsilon_0 = 2.0$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0190 + 0.2525\epsilon(T_{\text{eff}})$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = 1.0726 + 0.2109\epsilon(T_{\text{eff}})$

(with vertical ground motion)

Probability of Collapse

$S_{a}(T_{\text{eff}})g$

Empirical

w/o SSE

w/ SSE

$S_{a\text{COL}} = 0.350g$

$\beta_{\text{RTN}} = 0.273$

$S_{a\text{COL}} = 0.522g$

$T_{\text{eff}} = 3.13$ sec

$S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$

Lower Bound

$\epsilon_0 = 2.0$
\( T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, \frac{Q_x}{Q_y} = 0.6, R = 7, \) Isolated, Failure due to Uplift not Considered (with vertical ground motion)

\begin{align*}
\text{Empirical} & \quad \text{w/o SSE} \quad \text{w/ SSE} \\
S_a(T_{\text{eff}})g & \\
\varepsilon = 2.0 & \\
\beta_{\text{RTT}} = 0.270 & \\
S_{a\text{COL}} = 0.350g & \\
S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g & \\
\text{Upper Bound} & \\
\text{Lower Bound} & \\
\end{align*}

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0378 + 0.2580 \varepsilon(T_{\text{eff}}) \]

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0693 + 0.2074 \varepsilon(T_{\text{eff}}) \]
$T_{\text{fixed}} = 0.25 \text{ sec, } K_{e1}/K_{e2} = 1.75, Q_2/Q_1 = 0.6, R = 7$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

Probability of Collapse

$S_a(T_{\text{eff}})g$

- $S_{a\text{COL}} = 0.370g$
- $\gamma_{RTN} = 0.342$
- $S_{a\text{COL}} = 0.595g$
- $T_{\text{eff}} = 3.13 \text{ sec}$
- $S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$
- Upper Bound

$\epsilon_0 = 2.0$

Empirical
- w/o SSE
- w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0308 + 0.2556\epsilon(T_{\text{eff}})$

- Upper Bound

$T_{\text{fixed}} = 0.25 \text{ sec, } K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.6, R = 7$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

Probability of Collapse

$S_a(T_{\text{eff}})g$

- $S_{a\text{COL}} = 0.350g$
- $\beta_{RTN} = 0.269$
- $S_{a\text{COL}} = 0.520g$
- $T_{\text{eff}} = 3.13 \text{ sec}$
- $S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$
- Lower Bound

$\epsilon_0 = 2.0$

Empirical
- w/o SSE
- w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0679 + 0.2071\epsilon(T_{\text{eff}})$

- Lower Bound

399
$T_{\text{fixed}} = 0.25 \text{ sec}, K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.6, R = 7$, Isolated, Failure due to Uplift not Considered

(with vertical ground motion)
$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, \frac{Q_2}{Q_1} = 0.7, R = 7$, Isolated, Failure due to Uplift not Considered

(with vertical ground motion)

$S_{a\text{COL}} = 0.350g$
$\beta_{\text{RTR}} = 0.348$
$S_{a\text{COL}} = 0.593g$
$T_{\text{eff}} = 3.13 \text{ sec}$
$S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$
Upper Bound
$\epsilon_0 = 2.0$

Empirical
- w/o SSE
- w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0492 + 0.2633(\epsilon(T_{\text{eff}}))$

$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_2}{Q_1} = 0.7, R = 7$, Isolated, Failure due to Uplift not Considered

(with vertical ground motion)

$S_{a\text{COL}} = 0.350g$
$\beta_{\text{RTR}} = 0.273$
$S_{a\text{COL}} = 0.522g$
$T_{\text{eff}} = 3.13 \text{ sec}$
$S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$
Lower Bound
$\epsilon_0 = 2.0$

Empirical
- w/o SSE
- w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0731 + 0.2113(\epsilon(T_{\text{eff}}))$
$T_{\text{fixed}} = 0.25 \text{ sec, } K_{e1}/K_{e2} = 1.75, \frac{Q_2}{Q_1} = 0.7, R = 7$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

\begin{align*}
S_a(T_{\text{eff}}) &\text{g} \\
\beta_{\text{RTR}} &\approx 0.272 \\
S_{a\text{COL}} &\approx 0.521 \text{g} \\
T_{\text{eff}} &\approx 3.13 \text{ sec} \\
S_{a\text{MCE}}(T_{\text{eff}}) &\approx 0.297 \text{g} \\
\epsilon_0 &\approx 2.0
\end{align*}

\begin{align*}
\ln[S_{a\text{COL}}(T_{\text{eff}})] &\approx -1.0410 + 0.2596 \epsilon(T_{\text{eff}}) \\
\text{Upper Bound}
\end{align*}
$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, \frac{Q_z}{Q_1} = 0.7, R = 7$, Isolated, Failure due to Uplift not Considered

(with vertical ground motion)

$T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, \frac{Q_z}{Q_1} = 0.5, R = 6$, Isolated, Failure due to Uplift not Considered

(with vertical ground motion)
$T_{\text{fixed}} = 0.20$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.5$, $R=6$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

$T_{\text{eff}} = 3.13$ sec
$S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$
Upper Bound

$S_{a\text{COL}} = 0.370g$
$\beta_{RTN} = 0.341$

$S_{a\text{COL}} = 0.590g$

$\epsilon_0 = 2.0$

$S_a(T_{\text{eff}}) g$

Empirical
w/o SSE
w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0337 + 0.2527 \epsilon(T_{\text{eff}})$

$S_{a\text{COL}}(T_{\text{eff}})$

Empirical
w/o SSE
w/ SSE

$\epsilon(T_{\text{eff}})$

Lower Bound

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0774 + 0.2086 \epsilon(T_{\text{eff}})$

$S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$
Lower Bound
$T_{\text{fixed}} = 0.20$ sec, $K_{e1}/K_{e2} = 1.75$, $Q_2/Q_1 = 0.5$, $R = 6$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

Probability of Collapse

$S_{a\text{COL}} = 0.370g$  
$S_{a\text{COL}} = 0.590g$  
$S_{a\text{MCE}(T_{\text{eff}})} = 0.297g$

Upper Bound

$\epsilon_0 = 2.0$

Empirical

-w/o SSE

-w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0280 + 0.2503\epsilon(T_{\text{eff}})$

$S_{a\text{COL}}(T_{\text{eff}})g$

$\epsilon(T_{\text{eff}})$

$T_{\text{eff}} = 3.13$ sec

$S_{a\text{MCE}(T_{\text{eff}})} = 0.297g$

Lower Bound

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0756 + 0.2069\epsilon(T_{\text{eff}})$

$S_{a}(T_{\text{eff}})g$

$\epsilon(T_{\text{eff}})$
$T_{\text{fixed}} = 0.20$ sec, $K_{e1}/K_{e2} = 2.00$, $Q_{2}/Q_{1} = 0.5$, $R=6$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

$S_{acol} = 0.370g$  
$\gamma_{RTR} = 0.337$  
$T_{\text{eff}} = 3.13$ sec  
$S_{aMCE}(T_{\text{eff}}) = 0.297g$  
Upper Bound

$\varepsilon_{0} = 2.0$  
Empirical  
-w/o SSE  
-w/ SSE

$\ln[S_{acol}(T_{\text{eff}})] = -1.0239 + 0.2493\times(T_{\text{eff}})$  
Upper Bound

$T_{\text{fixed}} = 0.20$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_{2}/Q_{1} = 0.6$, $R=6$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

$S_{acol} = 0.350g$  
$\beta_{RTR} = 0.271$  
$S_{acol} = 0.518g$  
$T_{\text{eff}} = 3.13$ sec  
$S_{aMCE}(T_{\text{eff}}) = 0.297g$  
Lower Bound

$\varepsilon_{0} = 2.0$  
Empirical  
-w/o SSE  
-w/ SSE

$\ln[S_{acol}(T_{\text{eff}})] = -1.0815 + 0.2118\times(T_{\text{eff}})$  
Lower Bound
$T_{\text{fixed}} = 0.20 \text{ sec}, K_{e1}/K_{e2} = 1.75, Q_\frac{2}{1} = 0.6, R = 6$. Isolated, Failure due to Uplift not Considered
(with vertical ground motion)
$T_{\text{fixed}}=0.20 \text{ sec, } K_{e1}/K_{e2}=1.75, Q_2/Q_1=0.6, R=6$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

- $S_{a \text{COL}}=0.370g$
- $\gamma_{\text{RTN}}=0.344$
- $T_{\text{eff}}=3.13 \text{ sec}$
- $S_{a \text{MCE}}(T_{\text{eff}})=0.297g$
- Upper Bound

- $\varepsilon_0=2.0$

- $\text{Empirical}$
- w/o SSE
- w/ SSE

$\ln[S_{a \text{COL}}(T_{\text{eff}})]=1.0386+0.2558\varepsilon(T_{\text{eff}})$

$T_{\text{fixed}}=0.20 \text{ sec, } K_{e1}/K_{e2}=2.00, Q_2/Q_1=0.6, R=6$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

- $S_{a \text{COL}}=0.340g$
- $\beta_{\text{RTN}}=0.269$
- $S_{a \text{COL}}=0.517g$
- $T_{\text{eff}}=3.13 \text{ sec}$
- $S_{a \text{MCE}}(T_{\text{eff}})=0.297g$
- Lower Bound

- $\varepsilon_0=2.0$

- $\text{Empirical}$
- w/o SSE
- w/ SSE

$\ln[S_{a \text{COL}}(T_{\text{eff}})]=1.0801+0.2106\varepsilon(T_{\text{eff}})$
$T_{\text{fixed}} = 0.20 \text{ sec}, K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.6, R=6$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{a\text{COL}}(T_{\text{eff}}) = 0.370g$

$S_{a\text{COL}}(T_{\text{eff}}) = 0.591g$

$S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$

$\beta_{\text{RTR}} = 0.342$

$\beta_{\text{RTH}} = 0.272$

$\varepsilon = 2.0$

$S_a(T_{\text{eff}})g$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0321 + 0.2534\varepsilon(T_{\text{eff}})$

$\ln[S_{a\text{MCE}}(T_{\text{eff}})] = -1.0826 + 0.2126\varepsilon(T_{\text{eff}})$
$T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, \frac{Q_2}{Q_1} = 0.7, R = 6$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)
$T_{\text{fixed}} = 0.20 \text{ sec, } K_{e1}/K_{e2} = 1.75, \frac{Q_2}{Q_1} = 0.7, R=6$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

$S_{a\text{COL}} = 0.370g$
$S_{a\text{COL}} = 0.580g$
$T_{\text{eff}} = 3.13 \text{ sec}$
$S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$
Upper Bound
$\varepsilon_0 = 2.0$

Empirical
- w/o SSE
- w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0595 + 0.2578 \varepsilon(T_{\text{eff}})$

$T_{\text{fixed}} = 0.20 \text{ sec, } K_{e1}/K_{e2} = 2.00, \frac{Q_2}{Q_1} = 0.7, R=6$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

$S_{a\text{COL}} = 0.340g$
$S_{a\text{COL}} = 0.518g$
$T_{\text{eff}} = 3.13 \text{ sec}$
$S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$
Lower Bound
$\varepsilon_0 = 2.0$

Empirical
- w/o SSE
- w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0803 + 0.2111 \varepsilon(T_{\text{eff}})$
E.4. Results for eastern site with latitude 40.9°, longitude 29.2° \( \bar{\varepsilon}_0(T_1) = 1.5 \)

\[ T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 2.00, \frac{Q_e}{Q_s} = 0.7, R = 6, \] Isolated, Failure due to Uplift not Considered (with vertical ground motion)
$T_i = 0.30 \text{ sec, } K_{e_1}/K_{e_2} = 1.75, Q_2/Q_1 = 0.5, R = 8, \text{ Non-isolated}$

(without vertical ground motion)
$T_1 = 0.30 \, \text{sec, } K_{e1}/K_{e2} = 1.50, \, Q_2/Q_1 = 0.6, \, R = 8, \, \text{Non-isolated (without vertical ground motion)}$

\begin{align*}
S_{a \, \text{COL}} &= 1.700g \\
\beta_{\text{RTR}} &= 0.416 \\
S_{a \, \text{COL}} &= 2.129g \\
\end{align*}

$T_1 = 0.30 \, \text{sec, } K_{e1}/K_{e2} = 1.75, \, Q_2/Q_1 = 0.6, \, R = 8, \, \text{Non-isolated (without vertical ground motion)}$

\begin{align*}
S_{a \, \text{COL}} &= 1.740g \\
\beta_{\text{RTR}} &= 0.415 \\
S_{a \, \text{COL}} &= 2.221g \\
\end{align*}
$T_1 = 0.30 \text{ sec, } K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.6, R = 8$, Non-isolated
(without vertical ground motion)

$T_1 = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.7, R = 8$, Non-isolated
(without vertical ground motion)
$T_1 = 0.30\text{ sec, } K_{e1}/K_{e2} = 1.75, \frac{Q_2}{Q_1} = 0.7, R = 8, \text{ Non-isolated (without vertical ground motion)}$

![Graph 1](image1)

$T_1 = 0.30\text{ sec, } K_{e1}/K_{e2} = 2.00, \frac{Q_2}{Q_1} = 0.7, R = 8, \text{ Non-isolated (without vertical ground motion)}$

![Graph 2](image2)
$T_1 = 0.25$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.5$, $R = 7$, Non-isolated
(without vertical ground motion)
\[ T_1 = 0.25 \text{ sec}, K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.5, R = 7, \text{ Non-isolated} \]

(without vertical ground motion)

\[ T_1 = 0.25 \text{ sec}, K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.6, R = 7, \text{ Non-isolated} \]

(without vertical ground motion)
$T_1 = 0.25 \text{ sec, } K_{e1}/K_{e2} = 1.75, Q_2/Q_1 = 0.6, R = 7, \text{ Non-isolated}$

(without vertical ground motion)

$T_1 = 0.25 \text{ sec, } K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.6, R = 7, \text{ Non-isolated}$

(without vertical ground motion)
$T_1 = 0.25$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.7$, $R = 7$, Non-isolated (without vertical ground motion)

$T_1 = 0.25$ sec, $K_{e1}/K_{e2} = 1.75$, $Q_2/Q_1 = 0.7$, $R = 7$, Non-isolated (without vertical ground motion)
$T_1 = 0.25 \text{ sec, } K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.7, R = 7$, Non-isolated
(without vertical ground motion)

$T_1 = 0.20 \text{ sec, } K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.5, R = 6$, Non-isolated
(without vertical ground motion)
$T_1 = 0.20$ sec, $K_{e1}/K_{e2} = 1.75$, $Q_2/Q_1 = 0.5$, $R = 6$, Non-isolated (without vertical ground motion)

$S_{aCOL} = 1.610g$, $\beta_{TTR} = 0.399$

$S_{aMCE}(T_1) = 1.860g$

$\epsilon_0 = 1.5$

$S_a(T_1)/g$

$\ln[S_{aCOL}(T_1)] = 0.3312 + 0.2410(T_1)$

$T_1 = 0.20$ sec, $K_{e1}/K_{e2} = 2.00$, $Q_2/Q_1 = 0.5$, $R = 6$, Non-isolated (without vertical ground motion)

$S_{aCOL} = 1.520g$, $\beta_{TTR} = 0.386$

$S_{aMCE}(T_1) = 1.860g$

$\epsilon_0 = 1.5$

$S_a(T_1)/g$

$\ln[S_{aCOL}(T_1)] = 0.3388 + 0.2170(T_1)$
\[ T_1 = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, Q_2/Q_1 = 0.6, R = 6, \text{ Non-isolated} \]

(without vertical ground motion)

\[ S_{a(COL)} = 1.490g, \quad \beta_{RTR} = 0.415 \]

\[ S_{a(MCE)}(T_1) = 1.860g \]

\[ \epsilon_0 = 1.5 \]

\[ \ln[S_{a(COL)}(T_1)] = 0.2753 + 0.2440(T_1) \]

\[ T_1 = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, Q_2/Q_1 = 0.6, R = 6, \text{ Non-isolated} \]

(without vertical ground motion)

\[ S_{a(COL)} = 1.520g, \quad \beta_{RTR} = 0.411 \]

\[ S_{a(MCE)}(T_1) = 1.860g \]

\[ \epsilon_0 = 1.5 \]

\[ \ln[S_{a(COL)}(T_1)] = 0.2922 + 0.2544(T_1) \]
$T_1 = 0.20 \text{ sec, } K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.6, R=6, \text{ Non-isolated}$

(without vertical ground motion)

$T_1 = 0.20 \text{ sec, } K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.7, R=6, \text{ Non-isolated}$

(without vertical ground motion)

\[ \ln[S_{\text{COL}}(T_1)] = 0.3156 + 0.2553(T_1) \]

\[ \ln[S_{\text{COL}}(T_1)] = 0.2473 + 0.2361(T_1) \]
$T_1 = 0.20 \text{ sec}, K_{e_1}/K_{e_2} = 1.75, Q'/Q_1 = 0.7, R = 6$, Non-isolated
(without vertical ground motion)

$T_1 = 0.20 \text{ sec}, K_{e_1}/K_{e_2} = 2.00, Q'/Q_1 = 0.7, R = 6$, Non-isolated
(without vertical ground motion)
$T_{\text{fixed}} = 0.30 \text{ sec}, K_{a1}/K_{a2} = 1.50, \frac{Q_2}{Q_1} = 0.5, R = 8$, Isolated
(without vertical ground motion)

![Diagram 1](image)

$T_{\text{fixed}} = 0.30 \text{ sec}, K_{a1}/K_{a2} = 1.75, \frac{Q_2}{Q_1} = 0.5, R = 8$, Isolated
(without vertical ground motion)

![Diagram 2](image)
$T_{\text{fixed}} = 0.30 \text{ sec}, \ K_{e_1}/K_{e_2} = 2.00, \ Q_2/Q_1 = 0.5, \ R = 8$, Isolated
(without vertical ground motion)

\[ S_{a\text{COL}} = 0.380g \]
\[ \sigma_{e_1} = 0.222 \]
\[ S_{a\text{COL}} = 0.491g \]
\[ T_{e_1} = 3.13 \text{ sec} \]
\[ S_{a\text{MCE}}(T_{e_1}) = 0.297g \]

Lower Bound

$\varepsilon_0 = 2.0$

Empirical

w/o SSE

w/ SSE

$S_a(T_{eff}) g$

$\ln[S_{a\text{COL}}(T_{eff})]$

$\ln[S_{a\text{MCE}}(T_{eff})]$

$\ln[S_{a\text{COI}}(T_{eff})]$

$\ln[S_{a\text{VIO}}(T_{eff})]$

$\ln[S_{a\text{COL}}(T_{eff})]$

Lower Bound

$\varepsilon(T_{eff})$

$\varepsilon(T_{eff})$

$\varepsilon(T_{eff})$

$\varepsilon(T_{eff})$
$T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_2}{Q_1} = 0.6, R = 8$, Isolated

(without vertical ground motion)

$S_{a(COL)} = 0.380g$

$\beta_{RTR} = 0.224$

$S_{a(COL)} = 0.492g$

$T_{\text{eff}} = 3.13 \text{ sec}$

$L_{\text{MCE}}(T_{\text{eff}}) = 0.297g$

Lower Bound

$\phi_0 = 2.0$

Empirical

w/o SSE

w/ SSE

$\ln[S_{a(COL)}(T_{\text{eff}})] = -1.0056 + 0.1479\epsilon(T_{\text{eff}})$

Lower Bound

$T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, \frac{Q_2}{Q_1} = 0.6, R = 8$, Isolated

(without vertical ground motion)

$S_{a(COL)} = 0.380g$

$\beta_{RTR} = 0.223$

$S_{a(COL)} = 0.490g$

$T_{\text{eff}} = 3.13 \text{ sec}$

$L_{\text{MCE}}(T_{\text{eff}}) = 0.297g$

Lower Bound

$\phi_0 = 2.0$

Empirical

w/o SSE

w/ SSE

$\ln[S_{a(COL)}(T_{\text{eff}})] = -1.0039 + 0.1454\epsilon(T_{\text{eff}})$

Lower Bound
$T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.50, \frac{Q_2}{Q_1} = 0.7, R = 8$, Isolated (without vertical ground motion)

Lower Bound

- Empirical
- w/o SSE
- w/ SSE

$S_{a\text{COL}} = 0.380g$
$\beta_{RTR} = 0.224$
$S_{a\text{COL}} = 0.491g$

$T_{e\text{eff}} = 3.13 \text{ sec}$
$S_{a\text{MCE}}(T_{e\text{eff}}) = 0.297g$

$e_0 = 2.0$

$\ln[S_{a\text{COL}}(T_{e\text{eff}})] = 1.0058 + 0.1469 \epsilon(T_{e\text{eff}})$

Lower Bound
$T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 2.00, \frac{Q_2}{Q_1} = 0.7, R = 8$, Isolated
(without vertical ground motion)

$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.50, \frac{Q_2}{Q_1} = 0.5, R = 7$, Isolated
(without vertical ground motion)
\( T_{\text{fixed}} = 0.25 \text{ sec, } K_{e_1}/K_{e_2} = 1.75, \frac{Q_2}{Q_1} = 0.5, R = 7, \text{ Isolated} \)

(without vertical ground motion)

\( S_{a_{\text{COL}}} = 0.380 \text{g} \)
\( \beta_{\text{RTR}} = 0.221 \)

\( S_{a_{\text{COL}}} = 0.484 \text{g} \)
\( T_{\epsilon} = 3.13 \text{ sec} \)
\( S_{a_{\text{AMCA}}}(T_{\epsilon}) = 2.097 \text{g} \)

Lower Bound

- Empirical
- w/o SSE
- w/ SSE

\( \epsilon_0 = 2.0 \)

\( \ln[S_{a_{\text{COL}}}(T_{\epsilon})] = -1.0120 + 0.1433 \epsilon(T_{\epsilon}) \)

Lower Bound

\( T_{\text{fixed}} = 0.25 \text{ sec, } K_{e_1}/K_{e_2} = 2.00, \frac{Q_2}{Q_1} = 0.5, R = 7, \text{ Isolated} \)

(without vertical ground motion)

\( S_{a_{\text{COL}}} = 0.380 \text{g} \)
\( \beta_{\text{RTR}} = 0.221 \)

\( S_{a_{\text{COL}}} = 0.484 \text{g} \)
\( T_{\epsilon} = 3.13 \text{ sec} \)
\( S_{a_{\text{AMCA}}}(T_{\epsilon}) = 2.097 \text{g} \)

Lower Bound

- Empirical
- w/o SSE
- w/ SSE

\( \epsilon_0 = 2.0 \)

\( \ln[S_{a_{\text{COL}}}(T_{\epsilon})] = -1.0121 + 0.1430 \epsilon(T_{\epsilon}) \)

Lower Bound
$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.50, \frac{Q_2}{Q_1} = 0.6, R = 7$, Isolated
(without vertical ground motion)

$S_{a\text{COL}} = 0.380g$
$\beta_RTR = 0.222$
$S_{a\text{COL}} = 0.483g$
$T_{\text{eff}} = 3.13 \text{ sec}$
$S_{a\text{MC}}(T_{\text{eff}}) = 0.297g$

Lower Bound

$\epsilon_0 = 2.0$

Empirical

- w/o SSE
- w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0139 + 0.1435\epsilon(T_{\text{eff}})$

Lower Bound

$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.75, \frac{Q_2}{Q_1} = 0.6, R = 7$, Isolated
(without vertical ground motion)

$S_{a\text{COL}} = 0.380g$
$\beta_RTR = 0.222$
$S_{a\text{COL}} = 0.484g$
$T_{\text{eff}} = 3.13 \text{ sec}$
$S_{a\text{MC}}(T_{\text{eff}}) = 0.297g$

Lower Bound

$\epsilon_0 = 2.0$

Empirical

- w/o SSE
- w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0132 + 0.1434\epsilon(T_{\text{eff}})$

Lower Bound
\[ T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{a_1}}{K_{a_2}} = 2.00, \frac{Q_2}{Q_1} = 0.6, \text{ R=7, Isolated} \]

(without vertical ground motion)

\[ T_{\text{eff}} = 3.13 \text{ sec} \]

\[ S_{a_{\text{COL}}} = 0.380 g \]

\[ \beta_{\text{RTR}} = 0.221 \]

\[ S_{a_{\text{COL}}} = 0.483 g \]

\[ \bar{e}_0 = 2.0 \]

\[ S_{a_{\text{MC}}}(T_{\text{eff}}) = 0.297 g \]

\[ \ln[S_{a_{\text{COL}}}(T_{\text{eff}})] = -1.0125 + 0.1428 \epsilon(T_{\text{eff}}) \]

Lower Bound

\[ \text{Empirical} \]

\[ \text{w/o SSE} \]

\[ \text{w/ SSE} \]

\[ S_a(T_{\text{eff}}) g \]

\[ \epsilon(T_{\text{eff}}) \]

\[ S_a(T_{\text{eff}}) g \]

\[ \ln[S_{a_{\text{COL}}}(T_{\text{eff}})] = -1.0139 + 0.1435 \epsilon(T_{\text{eff}}) \]

Lower Bound

\[ \text{Empirical} \]

\[ \text{w/o SSE} \]

\[ \text{w/ SSE} \]
$T_{\text{fixed}} = 0.25 \text{ sec, } K_{e_1}/K_{e_2} = 1.75, \ Q_2/Q_1 = 0.7, \ R = 7, \ \text{Isolated}$

(without vertical ground motion)

\[ S_{a\text{COL}} = 0.380g \]
\[ \beta_{RTR} = 0.221 \]
\[ S_{a\text{COL}} = 0.484g \]
\[ T_{\text{eff}} = 3.13 \text{ sec} \]
\[ S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g \]

Lower Bound

Empirical

- w/o SSE
- w/ SSE

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0133 + 0.1433 \epsilon(T_{\text{eff}}) \]

Lower Bound

\[ \epsilon(T_{\text{eff}}) \]

\[ S_{a}(T_{\text{eff}})g \]

\[ T_{\text{fixed}} = 0.25 \text{ sec, } K_{e_1}/K_{e_2} = 2.00, \ Q_2/Q_1 = 0.7, \ R = 7, \ \text{Isolated} \]

(without vertical ground motion)

\[ S_{a\text{COL}} = 0.380g \]
\[ \beta_{RTR} = 0.221 \]
\[ S_{a\text{COL}} = 0.484g \]
\[ T_{\text{eff}} = 3.13 \text{ sec} \]
\[ S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g \]

Lower Bound

Empirical

- w/o SSE
- w/ SSE

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.01427 + 0.1427 \epsilon(T_{\text{eff}}) \]

Lower Bound

\[ \epsilon(T_{\text{eff}}) \]
\[ T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, \frac{Q_2}{Q_1} = 0.5, R = 6, \text{ Isolated} \]

(without vertical ground motion)

\[ S_{a\text{COL}} = 0.370g, \quad \beta_{\text{RTR}} = 0.220 \]

\[ S_{a\text{COL}} = 0.476g \]

\[ T_{\text{eff}} = 3.13 \text{ sec} \]

\[ S_{\text{aMCE}(T_{\text{eff}})} = 0.297g \]

Lower Bound

\( \epsilon = 2.0 \)

Empirical

- w/o SSE
- w/ SSE

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0231 + 0.1402(\epsilon(T_{\text{eff}})) \]

Lower Bound
$T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, \frac{Q_2}{Q_1} = 0.5, R = 6$, Isolated

(without vertical ground motion)

\begin{align*}
\text{Empirical} & \quad \text{w/o SSE} \\
\text{w/ SSE} & \quad \text{Lower Bound}
\end{align*}

\begin{align*}
T_{\text{eff}} = 3.13 \text{ sec} \\
S_{\text{aCOL}}(T_{\text{eff}}) = 0.370g \\
\beta_{\text{RTR}} = 0.220 \\
S_{\text{aCOL}} = 0.476g \\
S_{\text{amCOL}}(T_{\text{eff}}) = 0.297g \\
\varepsilon_{0} = 2.0
\end{align*}

\begin{align*}
\ln[S_{\text{aCOL}}(T_{\text{eff}})] & = -1.0233 + 0.1408(\epsilon(T_{\text{eff}})) \\
\text{Lower Bound}
\end{align*}

\begin{align*}
\text{Empirical} & \quad \text{w/o SSE} \\
\text{w/ SSE} & \quad \text{Lower Bound}
\end{align*}

\begin{align*}
T_{\text{eff}} = 3.13 \text{ sec} \\
S_{\text{aCOL}}(T_{\text{eff}}) = 0.370g \\
\beta_{\text{RTR}} = 0.219 \\
S_{\text{aCOL}} = 0.477g \\
S_{\text{amCOL}}(T_{\text{eff}}) = 0.297g \\
\varepsilon_{0} = 2.0
\end{align*}

\begin{align*}
\ln[S_{\text{aCOL}}(T_{\text{eff}})] & = -1.0229 + 0.1408(\epsilon(T_{\text{eff}})) \\
\text{Lower Bound}
\end{align*}
$T_{\text{fixed}} = 0.20$ sec, $K_{e_1}/K_{e_2} = 1.75$, $Q_2/Q_1 = 0.6$, $R=6$, Isolated
(without vertical ground motion)

Lower Bound

Empirical
w/o SSE
w/ SSE

$e_0 = 2.0$

$S_{a\text{COL}} = 0.370g$
$\beta_{\text{RTR}} = 0.220$

$S_{a\text{COL}} = 0.477g$

$T_{\text{eff}} = 3.13$ sec

$S_{a\text{MC}}(T_{\text{eff}}) = 0.297g$

Lower Bound

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0236 + 0.1415\epsilon(T_{\text{eff}})$

$\epsilon(T_{\text{eff}})$

Lower Bound

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0234 + 0.1407\epsilon(T_{\text{eff}})$

Lower Bound
$T_{\text{fixed}} = 0.20 \text{ sec}, K_{e_1}/K_{e_2} = 1.50, Q_2/Q_1 = 0.7, R = 6, \text{ Isolated}$

(without vertical ground motion)
$T_{\text{fixed}} = 0.20 \text{ sec, } K_{e_1}/K_{e_2} = 2.00, \frac{Q_2}{Q_1} = 0.7, R = 6, \text{ Isolated}$

(without vertical ground motion)

$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e_1}/K_{e_2} = 1.50, \frac{Q_2}{Q_1} = 0.5, R = 8, \text{ Isolated}$

(without vertical ground motion)
\[ T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_2}{Q_1} = 0.5, \text{ R=8, Isolated} \]

(without vertical ground motion)
\[ T_{\text{fixed}} = 0.30 \text{ sec}, K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.6, R = 8, \text{ Isolated} \]

(without vertical ground motion)
\(T_{\text{fixed}} = 0.30 \text{ sec}, K_{e_1}/K_{e_2} = 2.00, Q_2/Q_1 = 0.6, R = 8, \text{ Isolated}

(without vertical ground motion)

\[\text{Probability of Collapse vs. } S_a(T_{\text{eff}})g\]

\[\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0039 + 0.1454\epsilon(T_{\text{eff}})\]

\(T_{\text{eff}} = 3.13 \text{ sec}, S_{a\text{COL}}(T_{\text{eff}}) = 0.297g\)

Lower Bound

\(\epsilon = 1.5\)

Empirical

- w/o SSE
- w/ SSE

\(S_a(T_{\text{eff}})g\)

\(\epsilon(T_{\text{eff}})\)
$T_{\text{fixed}} = 0.30$ sec, $K_{e_1}/K_{e_2} = 1.75$, $Q_2/Q_1 = 0.7$, $R=8$, Isolated
(without vertical ground motion)
$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.50, \frac{Q_2}{Q_1} = 0.5, R = 7$, Isolated
(without vertical ground motion)

![Graph 1](image1)

![Graph 2](image2)

$T_{\text{eff}} = 3.13 \text{ sec}, S_{a\text{COL}}(T_{\text{eff}}) = 0.297g$

Lower Bound

- Empirical
- w/o SSE
- w/ SSE

$\quad e_0 = 1.5$

$S_a(T_{\text{eff}})g$

$\quad \ln(S_{a\text{COL}}(T_{\text{eff}})) = -1.0135 + 0.1436e(T_{\text{eff}})$

$\quad \ln(S_{a\text{COL}}(T_{\text{eff}})) = -1.0120 + 0.1433e(T_{\text{eff}})$

Lower Bound
\[ T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 2.00, \frac{Q_2}{Q_1} = 0.5, R = 7, \text{ Isolated} \]

(without vertical ground motion)
\( T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.75, \frac{Q_2}{Q_1} = 0.6, \text{ R} = 7, \text{ Isolated} \)

(without vertical ground motion)
\( T_{\text{fixed}} = 0.25 \text{ sec}, K_{e_1}/K_{e_2} = 1.50, Q_2/Q_1 = 0.7, R = 7, \text{ Isolated} \)

(without vertical ground motion)
$T_{\text{fixed}}=0.25$ sec, $K_{e_1}/K_{e_2}=2.00$, $Q_2/Q_1=0.7$, $R=7$, Isolated

(without vertical ground motion)

$T_{\text{fixed}}=0.20$ sec, $K_{e_1}/K_{e_2}=1.50$, $Q_2/Q_1=0.5$, $R=6$, Isolated

(without vertical ground motion)
$T_{\text{fixed}} = 0.20 \text{ sec, } K_{e_1}/K_{e_2} = 1.75, \ Q_2/Q_1 = 0.5, \ R = 6, \ \text{Isolated}$

(without vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec, } S_{a_{\text{COL}}}(T_{\text{eff}}) = 0.297g$

$\beta_{\text{RTR}} = 0.220$

$S_{a_{\text{COL}}} = 0.370g$

$\varepsilon_0 = 1.5$

Empirical

- w/o SSE
- w/ SSE

Lower Bound

$\ln[S_{a_{\text{COL}}}(T_{\text{eff}})] = -1.0244 + 0.1411 \varepsilon(T_{\text{eff}})$

$\varepsilon(T_{\text{eff}}) = -1.0233 + 0.1408 \ln[S_{a_{\text{COL}}}(T_{\text{eff}})]$

Lower Bound

$S_{a}(T_{\text{eff}})g$

Probabilty of Collapse

$0.2.4.6.8.10.12.14.16.18.2$

$\ln[S_{a_{\text{COL}}}(T_{\text{eff}})]$

$\varepsilon(T_{\text{eff}})$

$0.2.4.6.8.10.12.14.16.18.2$
$T_{fixed} = 0.20 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.50, \frac{Q_2}{Q_1} = 0.6, R = 6, \text{ Isolated}$

(without vertical ground motion)

- $S_{aCOL} = 0.370g$
- $\beta_{RTR} = 0.219$
- $S_{aCOL} = 0.444g$
- $T_{eff} = 3.13 \text{ sec}$
- $S_{aMCE}(T_{eff}) = 0.297g$
- Lower Bound

- Empirical
- w/o SSE
- w/ SSE

$\ln[S_{aCOL}(T_{eff})] = -1.0229 + 0.1409\epsilon(T_{eff})$

Lower Bound

$T_{fixed} = 0.20 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.75, \frac{Q_2}{Q_1} = 0.6, R = 6, \text{ Isolated}$

(without vertical ground motion)

- $S_{aCOL} = 0.370g$
- $\beta_{RTR} = 0.229$
- $S_{aCOL} = 0.444g$
- $T_{eff} = 3.13 \text{ sec}$
- $S_{aMCE}(T_{eff}) = 0.297g$
- Lower Bound

- Empirical
- w/o SSE
- w/ SSE

$\ln[S_{aCOL}(T_{eff})] = -1.0236 + 0.1415\epsilon(T_{eff})$

Lower Bound
$T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 2.00, \frac{Q_2}{Q_1} = 0.6, R = 6, \text{ Isolated}$

(without vertical ground motion)
\[ T_{\text{fixed}} = 0.20 \text{ sec}, \quad K_{e1}/K_{e2} = 1.75, \quad Q_2/Q_1 = 0.7, \quad R = 6, \text{ Isolated} \]

(without vertical ground motion)

\[ S_{a\text{COL}} = 0.370g, \quad \beta_{RTR} = 0.220 \]

\[ S_{a\text{COL}} = 0.444g \]

\[ T_{\text{eff}} = 3.13 \text{ sec} \]

\[ S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g \]

Lower Bound

\[ \varepsilon_{0} = 1.5 \]

Empirical

- w/o SSE
- w/ SSE

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = 1.0236 + 0.1415\varepsilon(T_{\text{eff}}) \]

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = 1.0234 + 0.1407\varepsilon(T_{\text{eff}}) \]

Lower Bound
\[ T_{\text{fixed}} = 0.30 \, \text{sec}, \quad K_{e_1}/K_{e_2} = 1.50, \quad Q_2/Q_1 = 0.5, \quad R = 8, \quad \text{Isolated, Failure due to 30 mm Uplift} \]

(with vertical ground motion)
\( T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{a1}}{K_{a2}} = 1.75, Q_2/Q_1 = 0.5, R = 8, \) Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

\[ \text{Empirical} \quad \text{w/o SSE} \quad \text{w/ SSE} \]

\( S_{a\text{COL}} = 0.350g \quad \beta_{RTH} = 0.399 \)

\( S_{a\text{COL}} = 0.515g \)

\( T_{\text{eff}} = 3.13 \text{ sec} \)

\( S_{\text{EMCE}}(T_{\text{eff}}) = 0.297g \)

Lower Bound

\( \varepsilon = 1.5 \)

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1635 + 0.3330\varepsilon(T_{\text{eff}}) \]

\[ \text{Lower Bound} \]

\( T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{a1}}{K_{a2}} = 1.75, Q_2/Q_1 = 0.5, R = 8, \) Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

\[ \text{Empirical} \quad \text{w/o SSE} \quad \text{w/ SSE} \]

\( S_{a\text{COL}} = 0.370g \quad \beta_{RTH} = 0.438 \)

\( S_{a\text{COL}} = 0.564g \)

\( T_{\text{eff}} = 3.13 \text{ sec} \)

\( S_{\text{EMCE}}(T_{\text{eff}}) = 0.297g \)

Upper Bound

\( \varepsilon = 1.5 \)

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0953 + 0.3487\varepsilon(T_{\text{eff}}) \]

\[ \text{Upper Bound} \]
\( T_{\text{fixed}} = 0.30 \text{ sec}, K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.5, R = 8, \) Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

\[ \text{Empirical} \quad \text{w/o SSE} \quad \text{w/ SSE} \]

\( S_{a_{\text{COL}}} = 0.350g \quad \beta_{\text{RTH}} = 0.399 \)
\( S_{a_{\text{COL}}} = 0.515g \quad T_{\text{eff}} = 3.13 \text{ sec} \)
\( S_{\text{AMCE}}(T_{\text{eff}}) = 0.297g \)

Lower Bound

\( \varepsilon_0 = 1.5 \)

\[ \ln[S_{a_{\text{COL}}}(T_{\text{eff}})] = -1.1635 + 0.3334\varepsilon(T_{\text{eff}}) \]

\( \text{Empirical} \quad \text{w/o SSE} \quad \text{w/ SSE} \)

\( S_{a_{\text{COL}}} = 0.370g \quad \beta_{\text{RTH}} = 0.439 \)
\( S_{a_{\text{COL}}} = 0.566g \quad T_{\text{eff}} = 3.13 \text{ sec} \)
\( S_{\text{AMCE}}(T_{\text{eff}}) = 0.297g \)

Upper Bound

\[ \ln[S_{a_{\text{COL}}}(T_{\text{eff}})] = -1.0924 + 0.3494\varepsilon(T_{\text{eff}}) \]
$T_{\text{fixed}} = 0.30 \text{ sec}, K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.6, R=8$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

$S_{a,\text{COL}} = 0.350g$
$\beta_{\text{RTH}} = 0.399$

$S_{a,\text{COL}} = 0.512g$

$T_{\text{eff}} = 3.13 \text{ sec}$
$S_{\text{AMCE}}(T_{\text{eff}}) = 0.297g$

Lower Bound

$\varepsilon_0 = 1.5$

Empirical
w/o SSE
w/ SSE

$S_a(T_{\text{eff}})g$

$\ln[S_{a,\text{COL}}(T_{\text{eff}})] = -1.1692 + 0.3334\varepsilon(T_{\text{eff}})$

Lower Bound

$\varepsilon(T_{\text{eff}})$

$S_{\text{AMCE}}(T_{\text{eff}}) = 0.297g$

Upper Bound

$\varepsilon_0 = 1.5$

Empirical
w/o SSE
w/ SSE
$T_{\text{fixed}}=0.30$ sec, $K_{e1}/K_{e2}=1.75$, $Q_{c}/Q_{t}=0.6$, $R=8$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)
$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.6, R = 8$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec, } S_{\text{aCOL}} = 0.350 \text{ g, } S_{\text{aMCE}}(T_{\text{eff}}) = 0.439 \text{ g}$

$S_{\text{a}}(T_{\text{eff}})g$

0.1 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

Probability of Collapse

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

$\gamma_{RH} = 0.398$

Empirical
- w/o SSE
- w/ SSE

$T_{\text{eff}} = 3.13 \text{ sec, } S_{\text{aCOL}} = 0.514 \text{ g, } S_{\text{aMCE}}(T_{\text{eff}}) = 0.297 \text{ g}$

Lower Bound

Empirical
- w/o SSE
- w/ SSE

$T_{\text{eff}} = 3.13 \text{ sec, } S_{\text{aCOL}} = 0.370 \text{ g, } S_{\text{aMCE}}(T_{\text{eff}}) = 0.566 \text{ g}$

$\gamma_{RH} = 0.439$

Upper Bound

Empirical
- w/o SSE
- w/ SSE

$T_{\text{eff}} = 3.13 \text{ sec, } S_{\text{aCOL}} = 0.370 \text{ g, } S_{\text{aMCE}}(T_{\text{eff}}) = 0.566 \text{ g}$

$\gamma_{RH} = 0.439$

Empirical
- w/o SSE
- w/ SSE
$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.50, \frac{Q_2}{Q_1} = 0.7, \text{ R} = 8, \text{ Isolated, Failure due to 30 mm Uplift}$

(with vertical ground motion)
\( T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, \frac{Q_2}{Q_1} = 0.7, R=8, \text{ Isolated, Failure due to 30 mm Uplift} \)

(with vertical ground motion)

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1686 + 0.3336\epsilon(T_{\text{eff}}) \]

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0980 + 0.3495\epsilon(T_{\text{eff}}) \]
$T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, Q_2/Q_1 = 0.7, R = 8$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{a\text{COL}} = 0.350g$

$\beta_{RTH} = 0.400$

$S_{a\text{COL}} = 0.514g$

$S_{\text{AMCE}}(T_{\text{eff}}) = 0.297g$

$\epsilon_0 = 1.5$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = \ln[1.1690 + 0.3351\epsilon(T_{\text{eff}})]$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = \ln[-1.0947 + 0.3495\epsilon(T_{\text{eff}})]$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = \ln[1.1690 + 0.3351\epsilon(T_{\text{eff}})]$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = \ln[-1.0947 + 0.3495\epsilon(T_{\text{eff}})]$

Empirical

w/o SSE

w/ SSE

Empirical

w/o SSE

w/ SSE

Empirical

w/o SSE

w/ SSE

Empirical

w/o SSE

w/ SSE
$T_{\text{fixed}} = 0.25\ \text{sec}, \ K_{e_1}/K_{e_2} = 1.50, \ Q_2/Q_1 = 0.5, \ R = 7$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

---

$T_{\text{eff}} = 3.13\ \text{sec}, \ S_{a\text{COL}} = 0.297g, \ S_{a\text{COL}} = 0.350g, \ \beta_{RTH} = 0.395$

---

$T_{\text{fixed}} = 0.25\ \text{sec}, \ K_{e_1}/K_{e_2} = 1.50, \ Q_2/Q_1 = 0.5, \ R = 7$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

---

$S_{a\text{COL}} = 0.360g, \ S_{a\text{COL}} = 0.555g, \ \beta_{RTH} = 0.431$

---

$S_{a\text{COL}} = 0.297g$

---

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1767 + 0.3292(\epsilon(T_{\text{eff}}))$

---

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1070 + 0.3454(\epsilon(T_{\text{eff}}))$

---

$\epsilon_0 = 1.5$

---

Empirical, w/o SSE, w/ SSE
$T_{fixed} = 0.25 \text{ sec}, K_{e1}/K_{e2} = 1.75, Q_2/Q_1 = 0.5, R = 7$, Isolated, Failure due to 30 mm Uplift

(with vertical ground motion)
$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 2.00, Q_2/Q_1 = 0.5, R = 7$, Isolated, Failure due to 30 mm Uplift

(with vertical ground motion)
$T_{\text{fixed}}=0.25 \text{ sec, } K_{e1}/K_{e2}=1.50, \frac{Q_2}{Q_1}=0.6, R=7$, Isolated, Failure due to 30 mm Uplift

(with vertical ground motion)

Lower Bound

$T_{\text{eff}}=3.13 \text{ sec}$

$S_{a,\text{COL}}=0.350g$

$S_{a,\text{COL}}=0.505g$

Empirical

w/o SSE

w/ SSE

$\beta_{\text{RTN}}=0.395$

$\rho_0=1.5$

$S_{a,\text{COL}}=0.360g$

$S_{a,\text{COL}}=0.551g$

$\beta_{\text{RTN}}=0.431$

Upper Bound

$\rho_0=1.5$

Lower Bound

$T_{\text{eff}}=3.13 \text{ sec}$

$S_{a,\text{MCE}}(T_{\text{eff}})=0.297g$

$S_{a,\text{MCE}}(T_{\text{eff}})=0.297g$

$\ln[S_{a,\text{COL}}(T_{\text{eff}})] = -1.1780 + 0.3296 \varepsilon(T_{\text{eff}})$

$\ln[S_{a,\text{COL}}(T_{\text{eff}})] = -1.1115 + 0.3442 \varepsilon(T_{\text{eff}})$

Empirical

w/o SSE

w/ SSE
$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, Q_2/Q_1 = 0.6, R=7$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

In-SaCOL $T_{\text{eff}}$, $\ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.1768 + 0.3295 \epsilon(T_{\text{eff}})$

In-SaCOL $T_{\text{eff}}$, $\ln[S_{\text{aCOL}}(T_{\text{eff}})] = -1.1074 + 0.3455 \epsilon(T_{\text{eff}})$
$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, \frac{Q_2}{Q_1} = 0.6, R = 7$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)
$T_{\text{fixed}} = 0.25$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.7$, $R = 7$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$S_{aCOl} = 0.350g$
$eta_{RTH} = 0.394$
$S_{aCOl} = 0.505g$
$T_{eff} = 3.13$ sec
$S_{AMCE}(T_{eff}) = 0.297g$

Lower Bound

$\epsilon = 1.5$

Empirical
w/o SSE
w/ SSE

$\ln[S_{aCOl}(T_{eff})] = -1.1793 + 0.3302 \epsilon(T_{eff})$

Lower Bound

$T_{\text{fixed}} = 0.25$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.7$, $R = 7$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$S_{aCOl} = 0.350g$
$eta_{RTH} = 0.431$
$S_{aCOl} = 0.548g$
$T_{eff} = 3.13$ sec
$S_{AMCE}(T_{eff}) = 0.297g$

Upper Bound

$\epsilon = 1.5$

Empirical
w/o SSE
w/ SSE

$\ln[S_{aCOl}(T_{eff})] = -1.1182 + 0.3448 \epsilon(T_{eff})$

Upper Bound
$T_{\text{fixed}} = 0.25 \text{ sec, } K_{e1}/K_{e2} = 1.75, Q_2/Q_1 = 0.7,$ R = 7, Isolated, Failure due to 30 mm Uplift

(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{a\text{COL}} = 0.350g$

$\beta_{\text{RTH}} = 0.395$

$S_{a\text{COL}} = 0.505g$

$S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$

Lower Bound

$\epsilon_0 = 1.5$

Empirical

- w/o SSE
- w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1779 + 0.3299\epsilon(T_{\text{eff}})$

Lower Bound

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1139 + 0.3445\epsilon(T_{\text{eff}})$

Upper Bound

$S_{a\text{COL}}(T_{\text{eff}})$

$\epsilon(T_{\text{eff}})$
$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{\epsilon_1}}{K_{\epsilon_2}} = 2.00, \frac{Q_2}{Q_1} = 0.7, R = 7, \text{ Isolated, Failure due to 30 mm Uplift}

(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{a\text{COL}} = 0.506g$

$S_{a\text{COL}} = 0.350g$

$\beta_{RTN} = 0.395$

Lower Bound

$S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$

$\epsilon_0 = 1.5$

Empirical

$\circ$ w/o SSE

$-$ w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1769 + 0.3305\epsilon(T_{\text{eff}})$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1083 + 0.3466\epsilon(T_{\text{eff}})$

$\circ$ Empirical

$\circ$ w/o SSE

$-$ w/ SSE

Upper Bound

Lower Bound
$T_{\text{fixed}} = 0.20$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.5$, $R = 6$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

\begin{align*}
S_{a_{\text{COL}}} &= 0.340g \\
\beta_{\text{RTN}} &= 0.391 \\
S_{a_{\text{COL}}} &= 0.499g \\
T_{\text{eff}} &= 3.13$ sec \\
S_{\text{AMCE}}(T_{\text{eff}}) &= 0.297g
\end{align*}

\begin{align*}
\ln[S_{a_{\text{COL}}}(T_{\text{eff}})] &= -1.829 + 0.3256\varepsilon(T_{\text{eff}}) \\
\ln[S_{a_{\text{COL}}}(T_{\text{eff}})] &= -1.1094 + 0.3413\varepsilon(T_{\text{eff}})
\end{align*}

$T_{\text{fixed}} = 0.20$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.5$, $R = 6$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

\begin{align*}
S_{a_{\text{COL}}} &= 0.360g \\
\beta_{\text{RTN}} &= 0.431 \\
S_{a_{\text{COL}}} &= 0.550g \\
T_{\text{eff}} &= 3.13$ sec \\
S_{\text{AMCE}}(T_{\text{eff}}) &= 0.297g
\end{align*}

\begin{align*}
\ln[S_{a_{\text{COL}}}(T_{\text{eff}})] &= -1.1094 + 0.3413\varepsilon(T_{\text{eff}})
\end{align*}
$T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.75, \frac{Q_2}{Q_1} = 0.5, R = 6$, Isolated, Failure due to 30 mm Uplift

(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}, \quad S_{\text{aCOL}}(T_{\text{eff}}) = 0.340g$

$\beta_{\text{RTH}} = 0.392$

$T_{\text{eff}} = 3.13 \text{ sec}, \quad S_{\text{aCOL}}(T_{\text{eff}}) = 0.500g$

$S_{\text{AMCE}}(T_{\text{eff}}) = 0.297g$

Lower Bound

$\epsilon_0 = 1.5$

Empirical

w/o SSE

w/ SSE

$\ln[S_{aCOL}(T_{\text{eff}})] = -1.1824 + 0.3255\epsilon(T_{\text{eff}})$

Lower Bound

$T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.75, \frac{Q_2}{Q_1} = 0.5, R = 6$, Isolated, Failure due to 30 mm Uplift

(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}, \quad S_{\text{aCOL}}(T_{\text{eff}}) = 0.360g$

$\beta_{\text{RTH}} = 0.432$

$S_{\text{aCOL}}(T_{\text{eff}}) = 0.552g$

$S_{\text{AMCE}}(T_{\text{eff}}) = 0.297g$

Upper Bound

$\epsilon_0 = 1.5$

Empirical

w/o SSE

w/ SSE

$\ln[S_{aCOL}(T_{\text{eff}})] = -1.1072 + 0.3415\epsilon(T_{\text{eff}})$

Upper Bound
$T_{\text{fixed}} = 0.20$ sec, $K_{e1}/K_{e2} = 2.00$, $Q_2/Q_1 = 0.5$, $R = 6$, Isolated, Failure due to 30 mm Uplift

(with vertical ground motion)
$T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 1.50, \frac{Q_2}{Q_1} = 0.6, R = 6$, Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{0.340g}^{\text{COL}}$

$S_{0.499g}^{\text{COL}}$

$S_{0.297g}^{\text{AME}}$

Lower Bound

Empirical
- w/o SSE
- w/ SSE

$\varepsilon_0 = 1.5$

$\beta_{RTH} = 0.390$

$\ln[S_{0.340g}^{\text{COL}}(T_{\text{eff}})] = -1.838 + 0.3256 \varepsilon(T_{\text{eff}})$

$\ln[S_{0.499g}^{\text{COL}}(T_{\text{eff}})] = -1.257 + 0.3256 \varepsilon(T_{\text{eff}})$

$\ln[S_{0.297g}^{\text{AME}}(T_{\text{eff}})] = -1.257 + 0.3256 \varepsilon(T_{\text{eff}})$

$\ln[S_{0.360g}^{\text{COL}}(T_{\text{eff}})] = -1.1161 + 0.3423 \varepsilon(T_{\text{eff}})$

$\ln[S_{0.547g}^{\text{COL}}(T_{\text{eff}})] = -1.257 + 0.3423 \varepsilon(T_{\text{eff}})$

Upper Bound

Empirical
- w/o SSE
- w/ SSE

$\varepsilon_0 = 1.5$

$\beta_{RTH} = 0.429$
$T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, Q_2/Q_1 = 0.6, R = 6$, Isolated, Failure due to 30 mm Uplift (with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{a\text{COL}} = 0.340\text{g}$

$S_{a\text{COL}} = 0.499\text{g}$

$S_{\text{AMCE}(T_{\text{eff}})} = 0.297\text{g}$

Lower Bound

$\varepsilon_0 = 1.5$

Empirical

w/o SSE

w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1840 + 0.3256\varepsilon(T_{\text{eff}})$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1110 + 0.3437\varepsilon(T_{\text{eff}})$

Upper Bound

Lower Bound
$T_{fixed} = 0.20 \text{ sec, } \frac{K_{e1}}{K_{e2}} = 2.00, \frac{Q_2}{Q_1} = 0.6, R = 6, \text{ Isolated, Failure due to 30 mm Uplift (with vertical ground motion)}$

\begin{align*}
\text{Probability of Collapse} \quad \text{vs} \quad S_a(T_{eff})g,
\end{align*}

\begin{align*}
\text{Empirical} \quad \text{vs} \quad \text{w/o SSE} \quad \text{vs} \quad \text{w/ SSE}
\end{align*}

\begin{align*}
\frac{\ln[S_{a\text{COL}}(T_{eff})]}{\epsilon(T_{eff})} = -1.1838 + 0.3255 \epsilon(T_{eff})
\end{align*}

\begin{align*}
\text{Lower Bound}
\end{align*}

---

$T_{fixed} = 0.20 \text{ sec, } \frac{K_{e1}}{K_{e2}} = 2.00, \frac{Q_2}{Q_1} = 0.6, R = 6, \text{ Isolated, Failure due to 30 mm Uplift (with vertical ground motion)}$

\begin{align*}
\text{Probability of Collapse} \quad \text{vs} \quad S_a(T_{eff})g,
\end{align*}

\begin{align*}
\text{Empirical} \quad \text{vs} \quad \text{w/o SSE} \quad \text{vs} \quad \text{w/ SSE}
\end{align*}

\begin{align*}
\frac{\ln[S_{a\text{COL}}(T_{eff})]}{\epsilon(T_{eff})} = -1.1082 + 0.3436 \epsilon(T_{eff})
\end{align*}

\begin{align*}
\text{Upper Bound}
\end{align*}
$T_{\text{fixed}} = 0.20 \text{ sec, } K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.7, R=6, \text{ Isolated, Failure due to 30 mm Uplift}$

(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec, } S_{a\text{COL}} = 0.340g, \beta_{RTH} = 0.390$

$S_{a\text{COL}} = 0.499g, S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$

Lower Bound

Empirical
w/o SSE
w/ SSE

$\epsilon_0 = 1.5$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1838 + 0.3257\epsilon(T_{\text{eff}})$

Lower Bound

$T_{\text{fixed}} = 0.20 \text{ sec, } K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.7, R=6, \text{ Isolated, Failure due to 30 mm Uplift}$

(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec, } S_{a\text{COL}} = 0.360g, \beta_{RTH} = 0.426$

$S_{a\text{COL}} = 0.539g, S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$

Upper Bound

Empirical
w/o SSE
w/ SSE

$\epsilon_0 = 1.5$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.1235 + 0.3368\epsilon(T_{\text{eff}})$

Upper Bound
$T_{\text{fixed}} = 0.20 \text{ sec}, K_{e_1}/K_{e_2} = 1.75, Q_2/Q_1 = 0.7, R = 6$, Isolated, Failure due to 30 mm Uplift

(with vertical ground motion)
\( T_{\text{fixed}} = 0.20 \text{ sec}, \ K_{e1}/K_{e2} = 2.00, \ Q_2/Q_1 = 0.7, \ R = 6, \) Isolated, Failure due to 30 mm Uplift
(with vertical ground motion)
$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.50, Q_{2}/Q_{1} = 0.5, R=8$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

$S_{a\text{COL}} = 0.360g$

$\beta_{\text{RHN}} = 0.269$

$S_{a\text{COL}} = 0.478g$

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{\text{AMCE}} = 0.297g$

$\varepsilon_{0} = 1.5$

$\text{Empirical}$

$\text{w/o SSE}$

$\text{w/ SSE}$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0536 + 0.2101\varepsilon(T_{\text{eff}})$

$\text{Lower Bound}$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0132 + 0.2497\varepsilon(T_{\text{eff}})$

$\text{Upper Bound}$

$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.50, Q_{2}/Q_{1} = 0.5, R=8$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

$S_{a\text{COL}} = 0.380g$

$\beta_{\text{RHN}} = 0.334$

$S_{a\text{COL}} = 0.528g$

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{\text{AMCE}} = 0.297g$

$\varepsilon_{0} = 1.5$

$\text{Empirical}$

$\text{w/o SSE}$

$\text{w/ SSE}$
$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.75, Q_2/Q_1 = 0.5, R=8, \text{ Isolated, Failure due to Uplift not Considered}$

(with vertical ground motion)

$S_a(T_{\text{eff}})g$

Probability of Collapse

$S_{a\text{COL}} = 0.360g$

$S_{a\text{COL}} = 0.478g$

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{\text{AMCE}}(T_{\text{eff}}) = 0.297g$

Lower Bound

$\varepsilon_0 = 1.5$

Empirical

w/o SSE

w/ SSE

$\ln(S_{a\text{COL}}(T_{\text{eff}})) = -1.0494 + 0.2074\varepsilon(T_{\text{eff}})$

Lower Bound

$S_a(T_{\text{eff}})g$

Probability of Collapse

$S_{a\text{COL}} = 0.380g$

$S_{a\text{COL}} = 0.530g$

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{\text{AMCE}}(T_{\text{eff}}) = 0.297g$

Upper Bound

$\varepsilon_0 = 1.5$

Empirical

w/o SSE

w/ SSE

$\ln(S_{a\text{COL}}(T_{\text{eff}})) = -1.0079 + 0.2486\varepsilon(T_{\text{eff}})$

Upper Bound
\[ T_{\text{fixed}} = 0.30 \text{ sec, } K_{e_1}/K_{e_2} = 2.00, Q_x/Q_y = 0.5, R = 8, \text{ Isolated, Failure due to Uplift not Considered} \]

(with vertical ground motion)
$T_{\text{fixed}} = 0.30 \text{ sec, } K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.6$, R=8, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

$S_a(T_{\text{eff}})g$

Probability of Collapse

$S_{aCOL} = 0.360g$

$S_{aCOL} = 0.475g$

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{aMCE}(T_{\text{eff}}) = 0.297g$

Lower Bound

$\epsilon_0 = 1.5$

$S_a(T_{\text{eff}})g$

Probability of Collapse

$S_{aCOL} = 0.380g$

$S_{aCOL} = 0.529g$

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{aMCE}(T_{\text{eff}}) = 0.297g$

Upper Bound

$\epsilon_0 = 1.5$

$\ln[S_{aCOL}(T_{\text{eff}})] = -1.0583 + 0.2098 \epsilon(T_{\text{eff}})$

Lower Bound

$\ln[S_{aCOL}(T_{\text{eff}})] = -1.0161 + 0.2526 \epsilon(T_{\text{eff}})$

Upper Bound
$T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, Q_2/Q_1 = 0.6, R = 8$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

- $S_{\text{aCOL}} = 0.360g$
- $\beta_{RTH} = 0.268$
- $S_{\text{aCOL}} = 0.476g$
- $T_{\text{eff}} = 3.13 \text{ sec}$
- $S_{\text{MCE}}(T_{\text{eff}}) = 0.297g$

Empirical
- w/o SSE
- w/ SSE

$T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 1.75, Q_2/Q_1 = 0.6, R = 8$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

- $S_{\text{aCOL}} = 0.380g$
- $\beta_{RTH} = 0.334$
- $S_{\text{aCOL}} = 0.530g$
- $T_{\text{eff}} = 3.13 \text{ sec}$
- $S_{\text{MCE}}(T_{\text{eff}}) = 0.297g$

Empirical
- w/o SSE
- w/ SSE
$T_{\text{fixed}} = 0.30 \text{ sec}$, $K_{e1}/K_{e2} = 2.00$, $Q_2/Q_1 = 0.6$, $R=8$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)
$T_{\text{fixed}} = 0.30 \text{ sec}, K_{e1}/K_{e2} = 1.50, Q_2/Q_1 = 0.7, R = 8$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)
\( T_{\text{fixed}} = 0.30 \text{ sec}, K_{e1}/K_{e2} = 1.75, Q_2/Q_1 = 0.7, R=8, \text{ Isolated, Failure due to Uplift not Considered} \)

(with vertical ground motion)

\[ \ln[S_{a,\text{COL}}(T_{\text{eff}})] = -1.0588 + 0.2096 \epsilon(T_{\text{eff}}) \]

\[ \ln[S_{a,\text{COL}}(T_{\text{eff}})] = -1.0141 + 0.2540 \epsilon(T_{\text{eff}}) \]
\[ T_{\text{fixed}} = 0.30 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, Q_2/Q_1 = 0.7, R = 8, \text{ Isolated, Failure due to Uplift not Considered} \]

(with vertical ground motion)

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0566 + 0.2088 \epsilon(T_{\text{eff}}) \]

\[ T_{\text{eff}} = 3.13 \text{ sec} \]

\[ S_{a\text{COL}} = 0.360g \]

\[ \beta_{RTN} = 0.270 \]

\[ S_{a\text{COL}} = 0.475g \]

\[ S_{a\text{MC}}(T_{\text{eff}}) = 0.297g \]

Lower Bound

\[ \bar{c}_{0} = 1.5 \]

Empirical

- w/o SSE
- w/ SSE

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0076 + 0.2511 \epsilon(T_{\text{eff}}) \]

\[ T_{\text{eff}} = 3.13 \text{ sec} \]

\[ S_{a\text{COL}} = 0.380g \]

\[ \beta_{RTN} = 0.335 \]

\[ S_{a\text{COL}} = 0.532g \]

\[ S_{a\text{MC}}(T_{\text{eff}}) = 0.297g \]

Upper Bound

\[ \bar{c}_{0} = 1.5 \]
$T_{\text{fixed}} = 0.25 \text{ sec, } K_{e1}/K_{e2} = 1.50, \frac{Q}{Q_1} = 0.5, R = 7$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

![Graph 1](image1)

$S_a(T_{\text{eff}})g$

$\beta_{\text{RTH}} = 0.271$

$S_{a\text{COL}} = 0.350g$

$T_{eff} = 3.13 \text{ sec}$

$S_{a\text{MC}}(T_{eff}) = 0.297g$

Lower Bound

Empirical

- w/o SSE
- w/ SSE

$\bar{\epsilon}_0 = 1.5$

$\ln[S_{a\text{COL}}(T_{eff})] = -1.0690 + 0.2086 \epsilon(T_{eff})$

Upper Bound

$\ln[S_{a\text{MC}}(T_{eff})] = -1.0270 + 0.2512 \epsilon(T_{eff})$

![Graph 2](image2)
$T_{\text{fixed}} = 0.25$ sec, $K_{e1}/K_{e2} = 1.75$, $Q_z/Q_1 = 0.5$, $R = 7$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

$S_{a\text{COL}} = 0.350g$
$\beta_{RTH} = 0.270$
$S_{a\text{COL}} = 0.470g$
$T_{eff} = 3.13$ sec
$S_{\text{AMCE}(T_{eff})} = 0.297g$

$\text{Empirical}$
$\text{w/o SSE}$
$\text{w/ SSE}$

$\varepsilon_0 = 1.5$

$\ln[S_{a\text{COL}}(T_{eff})] = -1.0671 + 0.2077 \epsilon(T_{eff})$

$T_{\text{fixed}} = 0.25$ sec, $K_{e1}/K_{e2} = 1.75$, $Q_z/Q_1 = 0.5$, $R = 7$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

$S_{a\text{COL}} = 0.370g$
$\beta_{RTH} = 0.337$
$S_{a\text{COL}} = 0.524g$
$T_{eff} = 3.13$ sec
$S_{\text{AMCE}(T_{eff})} = 0.297g$

$\text{Empirical}$
$\text{w/o SSE}$
$\text{w/ SSE}$

$\varepsilon_0 = 1.5$

$\ln[S_{a\text{COL}}(T_{eff})] = -1.0232 + 0.2515 \epsilon(T_{eff})$
\[ T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 2.00, \frac{Q_2}{Q_1} = 0.5, R = 7, \text{ Isolated, Failure due to Uplift not Considered} \]

(with vertical ground motion)

![Diagram 1](image1)

\[ \ln[S_{a,\text{COL}}(T_{\text{eff}})] = -1.0655 + 0.2071\varepsilon(T_{\text{eff}}) \]

![Diagram 2](image2)

\[ T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e_1}}{K_{e_2}} = 2.00, \frac{Q_2}{Q_1} = 0.5, R = 7, \text{ Isolated, Failure due to Uplift not Considered} \]

(with vertical ground motion)

![Diagram 3](image3)

\[ \ln[S_{a,\text{COL}}(T_{\text{eff}})] = -1.0190 + 0.2525\varepsilon(T_{\text{eff}}) \]

![Diagram 4](image4)
$T_{\text{fixed}} = 0.25 \text{ sec}, K_{e1}/K_{e2} = 1.50, Q_{2}/Q_{1} = 0.6, R = 7$, Isolated, Failure due to Uplift not Considered

(with vertical ground motion)

\begin{align*}
S_{a\text{COL}} &= 0.350g \\
\beta_{RTH} &= 0.273 \\
S_{a\text{COL}} &= 0.469g \\
T_{\text{eff}} &= 3.13 \text{ sec} \\
S_{\text{AMCE}}(T_{\text{eff}}) &= 0.297g \\
\text{Lower Bound}
\end{align*}

\begin{align*}
\epsilon &= 1.5 \\
\text{Empirical} \\
w/o SSE \\
w/ SSE
\end{align*}

\begin{align*}
\ln[S_{a\text{COL}}(T_{\text{eff}})] &= -1.0726 + 0.2109\epsilon(T_{\text{eff}}) \\
\text{Lower Bound}
\end{align*}

\begin{align*}
S_{a}(T_{\text{eff}})g \\
\epsilon(T_{\text{eff}})
\end{align*}

$T_{\text{fixed}} = 0.25 \text{ sec}, K_{e1}/K_{e2} = 1.50, Q_{2}/Q_{1} = 0.6, R = 7$, Isolated, Failure due to Uplift not Considered

(with vertical ground motion)

\begin{align*}
S_{a\text{COL}} &= 0.370g \\
\beta_{RTH} &= 0.344 \\
S_{a\text{COL}} &= 0.522g \\
T_{\text{eff}} &= 3.13 \text{ sec} \\
S_{\text{AMCE}}(T_{\text{eff}}) &= 0.297g \\
\text{Upper Bound}
\end{align*}

\begin{align*}
\epsilon &= 1.5 \\
\text{Empirical} \\
w/o SSE \\
w/ SSE
\end{align*}

\begin{align*}
\ln[S_{a\text{COL}}(T_{\text{eff}})] &= -1.0376 + 0.2580\epsilon(T_{\text{eff}}) \\
\text{Upper Bound}
\end{align*}

492
$T_{\text{fixed}} = 0.25$ sec, $K_{e1}/K_{e2} = 1.75$, $Q_2/Q_1 = 0.6$, $R=7$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

$T_{\text{eff}} = 3.13$ sec, $S_{a\text{COL}} = 0.350g$
$\gamma_{\text{RTT}} = 0.270$
$S_{a\text{COL}} = 0.469g$

$S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$

$S_a(T_{\text{eff}})g$

$\epsilon_0 = 1.5$

Empirical

w/o SSE

w/ SSE

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0693 + 0.2074\epsilon(T_{\text{eff}})$

$\ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0308 + 0.2556\epsilon(T_{\text{eff}})$

$S_{a\text{COL}}(T_{\text{eff}})$

$\epsilon(T_{\text{eff}})$

$\ln[S_{a\text{COL}}(T_{\text{eff}})]$

$\epsilon(T_{\text{eff}})$
$T_{\text{fixed}} = 0.25 \, \text{sec}$, $K_{e1}/K_{e2} = 2.00$, $Q_2/Q_1 = 0.6$, $R = 7$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

$S_{aCOL} = 0.350 \, \text{g}$
$\beta_{RTH} = 0.269$

$S_{aCOL} = 0.469 \, \text{g}$

$T_{\text{eff}} = 3.13 \, \text{sec}$
$S_{\text{MCE}}(T_{\text{eff}}) = 0.297 \, \text{g}$

Lower Bound

$\varepsilon_0 = 1.5$

Empirical
- w/o SSE
- w/ SSE

$\ln[S_{aCOL}(T_{\text{eff}})] = -1.0679 + 0.2071 \varepsilon(T_{\text{eff}})$

Lower Bound

$T_{\text{fixed}} = 0.25 \, \text{sec}$, $K_{e1}/K_{e2} = 2.00$, $Q_2/Q_1 = 0.6$, $R = 7$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

$S_{aCOL} = 0.370 \, \text{g}$
$\beta_{RTH} = 0.340$

$S_{aCOL} = 0.526 \, \text{g}$

$T_{\text{eff}} = 3.13 \, \text{sec}$
$S_{\text{MCE}}(T_{\text{eff}}) = 0.297 \, \text{g}$

Upper Bound

$\varepsilon_0 = 1.5$

Empirical
- w/o SSE
- w/ SSE

$\ln[S_{aCOL}(T_{\text{eff}})] = -1.0253 + 0.2547 \varepsilon(T_{\text{eff}})$

Upper Bound
$T_{\text{fixed}}=0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}}=1.50, \frac{Q_2}{Q_1}=0.7, R=7$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)
$T_{\text{fixed}} = 0.25$ sec, $K_{e1}/K_{e2} = 1.75$, $Q_z/Q_1 = 0.7$, $R = 7$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

- $S_a(T_{\text{eff}})g$
- $\epsilon(T_{\text{eff}})$

$T_{\text{eff}} = 3.13$ sec,
$S_{a\text{COL}}(T_{\text{eff}}) = 0.297$g,
Lower Bound
$\epsilon_0 = 1.5$

Empirical
w/o SSE
w/ SSE

$\ln[S_a(T_{\text{eff}})] = -1.0731 + 0.2113 \epsilon(T_{\text{eff}})$

Lower Bound

$T_{\text{eff}} = 3.13$ sec,
$S_{a\text{COL}}(T_{\text{eff}}) = 0.297$g,
Upper Bound
$\epsilon_0 = 1.5$

Empirical
w/o SSE
w/ SSE

$\ln[S_a(T_{\text{eff}})] = -1.0410 + 0.2596 \epsilon(T_{\text{eff}})$

Upper Bound
$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, \frac{Q_{2}}{Q_{1}} = 0.7, R = 7$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

$S_{a(COL)} = 0.350g$
$\beta_{HTN} = 0.272$
$S_{a(COL)} = 0.469g$
$T_{eff} = 3.13 \text{ sec}$
$S_{a(MCE)}(T_{eff}) = 0.297g$

$\epsilon(0) = 1.5$

$\ln[S_{a(COL)}(T_{eff})] = -1.0705 + 0.2088 \epsilon(T_{eff})$

Lower Bound

Empirical
- w/o SSE
- w/ SSE

$T_{\text{fixed}} = 0.25 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, \frac{Q_{2}}{Q_{1}} = 0.7, R = 7$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

$S_{a(COL)} = 0.370g$
$\beta_{HTN} = 0.343$
$S_{a(COL)} = 0.525g$
$T_{eff} = 3.13 \text{ sec}$
$S_{a(MCE)}(T_{eff}) = 0.297g$

$\epsilon(0) = 1.5$

$\ln[S_{a(COL)}(T_{eff})] = -1.0331 + 0.2597 \epsilon(T_{eff})$

Upper Bound

Empirical
- w/o SSE
- w/ SSE
\[ T_{\text{fixed}} = 0.20 \text{ sec, } K_{e1}/K_{e2} = 1.50, \frac{Q_{2}}{Q_1} = 0.5, R = 6, \text{ Isolated, Failure due to Uplift not Considered} \]

(with vertical ground motion)

\[ \ln[S_{a,\text{COL}}(T_{\text{eff}})] = -1.0793 + 0.2104e(T_{\text{eff}}) \]

\[ T_{\text{eff}} = 3.13 \text{ sec, } S_{\text{AMCE}}(T_{\text{eff}}) = 0.297g \]

\[ \epsilon_0 = 1.5 \]

Empirical

w/o SSE

w/ SSE

\[ S_a(T_{\text{eff}})g \]

\[ \epsilon(T_{\text{eff}}) \]

\[ \ln[S_{a,\text{COL}}(T_{\text{eff}})] = -1.0337 + 0.2527e(T_{\text{eff}}) \]

Upper Bound

\[ S_a(T_{\text{eff}})g \]

\[ \epsilon(T_{\text{eff}}) \]
$T_{\text{fixed}} = 0.20 \text{ sec}, K_{e1}/K_{e2} = 1.75, Q_2/Q_1 = 0.5, R = 6$, Isolated, Failure due to Uplift not Considered

(with vertical ground motion)

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{a|\text{COL}} = 0.350g$

$S_{a|\text{COL}} = 0.466g$

Lower Bound

$\varepsilon_0 = 1.5$

Empirical

w/o SSE

w/ SSE

$\ln[S_{a|\text{COL}}(T_{\text{eff}})] = -1.0774 + 0.2086\varepsilon(T_{\text{eff}})$

$\ln[S_{a|\text{COL}}(T_{\text{eff}})] = -1.0280 + 0.2503\varepsilon(T_{\text{eff}})$

Upper Bound

Lower Bound

499
$T_{\text{fixed}} = 0.20 \text{ sec, } K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.5, R=6$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)
$T_{\text{fixed}} = 0.20$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.6$, $R = 6$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

$S_{\text{aCOL}} = 0.350$ g
$\beta_{RTH} = 0.271$

$S_{\text{aCOL}} = 0.466$ g
$T_{\text{eff}} = 3.13$ sec
$S_{\text{AMEC}}(T_{\text{eff}}) = 0.297$ g

Empirical
- w/o SSE
- w/ SSE

$\varepsilon_0 = 1.5$

$\ln|S_{\text{aCOL}}(T_{\text{eff}})| = -1.0815 + 0.2118 \varepsilon(T_{\text{eff}})$

$T_{\text{fixed}} = 0.20$ sec, $K_{e1}/K_{e2} = 1.50$, $Q_2/Q_1 = 0.6$, $R = 6$, Isolated, Failure due to Uplift not Considered (with vertical ground motion)

$S_{\text{aCOL}} = 0.370$ g
$\beta_{RTH} = 0.352$

$S_{\text{aCOL}} = 0.516$ g
$T_{\text{eff}} = 3.13$ sec
$S_{\text{AMEC}}(T_{\text{eff}}) = 0.297$ g

Empirical
- w/o SSE
- w/ SSE

$\varepsilon_0 = 1.5$

$\ln|S_{\text{aCOL}}(T_{\text{eff}})| = -1.0535 + 0.2611 \varepsilon(T_{\text{eff}})$
$T_{\text{fixed}} = 0.20 \text{ sec}, K_{e1}/K_{e2} = 1.75, Q_2/Q_1 = 0.6$, R = 6, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

\begin{align*}
\text{Probability of Collapse} & \\
S_a(T_{\text{eff}})g & \\
\text{Empirical} & \\
w/o SSE & \\
w/ SSE & \\
\epsilon_0 = 1.5
\end{align*}

\begin{align*}
\ln[S_a\text{COL}(T_{\text{eff}})] & = -1.0808 + 0.2115 \epsilon(T_{\text{eff}}) & \\
\text{Lower Bound}
\end{align*}

\begin{align*}
S_{a\text{COL}} = 0.350g & \\
\beta_{\text{RTH}} = 0.279
\end{align*}

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{\text{MCE}}(T_{\text{eff}}) = 0.297g$

$\text{Lower Bound}$

$T_{\text{fixed}} = 0.20 \text{ sec}, K_{e1}/K_{e2} = 1.75, Q_2/Q_1 = 0.6$, R = 6, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

\begin{align*}
\text{Probability of Collapse} & \\
S_a(T_{\text{eff}})g & \\
\text{Empirical} & \\
w/o SSE & \\
w/ SSE & \\
\epsilon_0 = 1.5
\end{align*}

\begin{align*}
\ln[S_a\text{COL}(T_{\text{eff}})] & = -1.0386 + 0.2558 \epsilon(T_{\text{eff}}) & \\
\text{Upper Bound}
\end{align*}

\begin{align*}
S_{a\text{COL}} = 0.370g & \\
\beta_{\text{RTH}} = 0.344
\end{align*}

$T_{\text{eff}} = 3.13 \text{ sec}$

$S_{\text{MCE}}(T_{\text{eff}}) = 0.297g$

$\text{Upper Bound}$

502
\( T_{\text{fixed}} = 0.20 \text{ sec}, \frac{K_{e1}}{K_{e2}} = 2.00, \frac{Q_2}{Q_1} = 0.6, R = 6, \) Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

\[ S_{a}(T_{\text{eff}})g \]
\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0801 + 0.2106 \epsilon(T_{\text{eff}}) \]

\[ S_{a\text{COL}} = 0.340g \]
\[ \theta_{RTH} = 0.269 \]
\[ S_{a\text{COL}} = 0.466g \]
\[ T_{\text{eff}} = 3.13 \text{ sec} \]
\[ S_{a\text{COL}}(T_{\text{eff}}) = 0.297g \]

Lower Bound

Empirical
- w/o SSE
- w/ SSE

\( \epsilon = 1.5 \)

\( S_{a}(T_{\text{eff}})g \)
\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0801 + 0.2106 \epsilon(T_{\text{eff}}) \]

\[ S_{a\text{COL}} = 0.370g \]
\[ \theta_{RTH} = 0.342 \]
\[ S_{a\text{COL}} = 0.521g \]
\[ T_{\text{eff}} = 3.13 \text{ sec} \]
\[ S_{a\text{COL}}(T_{\text{eff}}) = 0.297g \]

Upper Bound

Empirical
- w/o SSE
- w/ SSE

\( \epsilon = 1.5 \)
$T_{\text{fixed}} = 0.20 \text{ sec}, K_{e1}/K_{e2} = 1.50, Q_{z}/Q_{1} = 0.7, R = 6$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

![Diagram showing probability of collapse vs. $S_a(T_{\text{eff}})$ with empirical and model predictions.

$T_{\text{eff}} = 3.13 \text{ sec}$, $S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$

Lower Bound

- Empirical
- w/o SSE
- w/ SSE

$\epsilon_0 = 1.5$

$\log[10][S_{a\text{COL}}(T_{\text{eff}})] = -1.0826 + 0.2126\epsilon(T_{\text{eff}})$

Lower Bound

![Diagram showing logarithm of probability of collapse vs. $\epsilon(T_{\text{eff}})$ with empirical and model predictions.

$T_{\text{fixed}} = 0.20 \text{ sec}, K_{e1}/K_{e2} = 1.50, Q_{z}/Q_{1} = 0.7, R = 6$, Isolated, Failure due to Uplift not Considered
(with vertical ground motion)

![Diagram showing probability of collapse vs. $S_a(T_{\text{eff}})$ with empirical and model predictions.

$T_{\text{eff}} = 3.13 \text{ sec}$, $S_{a\text{MCE}}(T_{\text{eff}}) = 0.297g$

Upper Bound

- Empirical
- w/o SSE
- w/ SSE

$\epsilon_0 = 1.5$

$\log[10][S_{a\text{COL}}(T_{\text{eff}})] = -1.0856 + 0.2600\epsilon(T_{\text{eff}})$

Upper Bound
(with vertical ground motion)

\[ T_{\text{fixed}} = 0.20 \text{ sec}, K_{e1}/K_{e2} = 1.75, Q_2/Q_1 = 0.7, R = 6, \text{ Isolated}, \text{ Failure due to Uplift not Considered} \]

\[ \beta_{\text{RTH}} = 0.270 \]

\[ S_{a\text{COL}} = 0.350g \]

\[ S_{a\text{COL}} = 0.466g \]

\[ T_{\text{eff}} = 3.13 \text{ sec} \]

\[ S_{\text{AMCE}}(T_{\text{eff}}) = 0.297g \]

Lower Bound

Empirical

w/o SSE

w/ SSE

\[ \varepsilon_{0} = 1.5 \]

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0810 + 0.2113(\varepsilon(T_{\text{eff}})) \]

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0810 + 0.2113(\varepsilon(T_{\text{eff}})) \]

\[ \varepsilon_{0} = 1.5 \]

\[ S_{a}(T_{\text{eff}})g \]

\[ S_{a}(T_{\text{eff}})g \]

Upper Bound

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0810 + 0.2113(\varepsilon(T_{\text{eff}})) \]

\[ \ln[S_{a\text{COL}}(T_{\text{eff}})] = -1.0810 + 0.2113(\varepsilon(T_{\text{eff}})) \]
$T_{\text{fixed}} = 0.20 \text{ sec, } K_{e1}/K_{e2} = 2.00, Q_2/Q_1 = 0.7, R = 6$, Isolated, Failure due to Uplift not Considered

(with vertical ground motion)
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