

Correlation between intensity measures and seismic response of deformable rolling seismic isolators

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ABSTRACT

Seismic isolation is a highly effective method of seismic protection. However, its high cost has limited its application in lightweight structures. This study presents a low-cost, high-performance seismic isolator comprising a deformable elastomeric sphere rolling on concrete plates, one of which is concave to provide gravitational restoring force. Since the sphere deforms under compression, bilinear models cannot describe its response. A five-parameter analytical model is used to describe the seismic response of the isolators. The model is calibrated using lateral cyclic tests and validated against shake table tests. It captures all stages of the flag-shaped response, including positive and negative stiffness, the restoring force due to plate geometry, and the rolling friction coefficient. The model is then used to identify ground motion intensity measures (IMs) that best correlate with the isolator response in terms of maximum acceleration and maximum displacement. A wide range of design scenarios (considering different eigenperiods and rolling friction coefficients) is analyzed using 173 historical ground motions and 15 commonly used IMs. Results show that Peak Ground Acceleration (PGA) and Arias Intensity are the two best IMs, with the former correlating better with superstructure accelerations and the latter with isolator displacements.

Keywords: seismic isolation, lightweight structures, rolling bearings, elastomeric bearings

INTRODUCTION

Seismic isolation is a highly effective method of seismic protection that decouples the structure from ground motion, minimizing post-earthquake damage and residual drifts. Despite these advantages, its application in lightweight structures remains limited, primarily due to the high cost of isolators.

Rolling isolators were the first seismic isolation system officially documented (Touaillon, 1870), yet remain less widespread than flexible rubber and sliding bearings. Most rolling seismic isolators comprise steel spheres on steel surfaces (Lee et al, 2010; Harvey & Gavin, 2014; Harvey et al, 2014; Harvey & Kelly, 2016). The extensive use of steel increases cost and weight. Moreover, steel-on-steel rolling interfaces have low damping and are prone to surface damage during rolling. Rubber coatings can address this by increasing energy dissipation and reducing stress concentrations (Menga et al, 2017,2019; Zéhil & Gavin, 2013,2014). Tsai et al. (2010) tested steel spheres coated with an elastomeric material rolling on concave surfaces; as in friction bearings, the concave geometry adds gravitational restoring force, resembling pendulum mechanics. Recent studies have demonstrated the potential of rolling isolators for lightweight structures. Cui et al. (2012) isolated floors with solid elastomeric spheres rolling on concrete plates. Making plates with concrete instead of steel can reduce their cost. Cilsalar and Constantinou (2019) performed lateral cyclic tests of a similar system under small displacements, assuming bilinear response. Katsamakas et al. (2021,2022,2023,2024) and

Katsamakas and Vassiliou (2022,2023,2025) conducted shake table tests and large-displacement lateral cyclic tests of these isolators, demonstrating their high efficiency under ground motions and the importance of sphere deformability, which produces a flag-shaped response. Restrepo and Constantinou (2025) performed shake table tests proving system efficiency under triaxial seismic loading, and concluded that the system provides effective horizontal but not vertical isolation. Reyes et al. (2025,2026) proposed noninvasive methods to estimate the mass eccentricity of elastomeric spheres with steel cores and developed a finite element model for thermoplastic polyurethane.

Prior work on rolling isolators with elastomeric spheres has established their high efficiency and potential for lightweight structures. The present study builds on these findings and is the first to offer an extensive intensity measure analysis.

DESCRIPTION OF THE ISOLATOR AND MODELING OF RIGID ISOLATORS

The proposed seismic isolator comprises an elastomeric sphere that rolls between two concrete plates and is a low-cost, high-performance solution for isolating lightweight structures. To ensure constant gravitational restoring force, at least one of the two concrete plates must be concave. The design of a rolling isolator can start with the assumption that the rolling sphere and the concrete surfaces are rigid (Eq. (1)).

$$F = \frac{W}{4R_{eff}}u + \mu W \text{sign}(\dot{u}) \quad (1)$$

In Eq. (1) and Figure 1: F is the horizontal force applied to the isolator, W is the weight applied to the isolator, u is the lateral displacement of the isolator, $R_{eff} = R - r$, where R_{eff} is the effective radius of the isolator, R is the radius of curvature of the spherical concrete plate and r is the radius of the sphere. The first part is the gravitational restoring force of the system due to the plate's geometry and the second term is the friction part. The μ term is the rolling friction coefficient of the system: a macroscopic parameter that controls the initiation of rolling motion and energy dissipation. The isolation period of the system is: $T = 2\pi\sqrt{4R/g}$. The displacement capacity of the isolator is $\pm d_0 - D$ (Figure 1). The response predicted by Eq. (1) is bilinear, resembling the response of flexible elastomeric bearings and sliding bearings. The isolation period (T) and the rolling friction coefficient (μ) fully characterize the rigid-body response. The isolation period (T) is a design parameter (as in other isolators), while the rolling friction coefficient (μ) depends on the material, sphere size and W (Katsamakas et al, 2022).

MODELING OF DEFORMABLE ROLLING ISOLATORS

The rigid-body model is a reasonable design starting point. However, rolling isolators with elastomeric spheres deform (Figure 2). Under W , the spheres deform into an oval-like object with flat contact areas at the top and bottom support surfaces (Figure 2, B). Since W is sustained, the sphere further deforms due to creep effects. Even if W is removed, notable residual deformation remains. When a strong horizontal force (F) is applied, the system starts rolling.

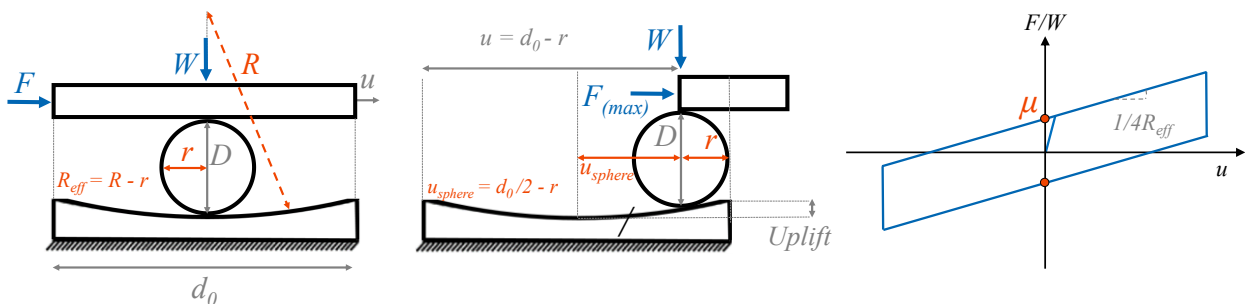


Figure 1. Rigid-body model of rolling seismic isolators. (Left), zero lateral displacement; (B), maximum lateral displacement; (C) bilinear force-displacement response.

Under small lateral displacements (u), the stiffness is positive and 2–3 times higher than the rigid-body prediction (Figure 2, C). For larger u , the sphere rolls past the pivot point (the sphere-plate contact point under pure compression). Beyond this point, the system stiffness becomes negative (Figure 2, D). These stages above describe the fluctuations of the restoring force due to sphere deformability. The overall response also includes the restoring force from the concave concrete surfaces and energy dissipation due to rolling friction. Figure 3 shows these 3 mechanisms.

This study uses a five-parameter numerical model to describe the lateral seismic behavior of elastomeric rolling isolators. The numerical model is described by the following equation (Eq. 4):

$$\frac{F}{m} = (\omega^2 \times u) + (Q \times \text{sign}(\dot{u})) + (Q_2 \times \tanh(10 \times u)) - (Q_3 \times u) + (a_1 \times \text{sign}(u) \times \text{betapdf}(|u/a_2|)) \quad (4)$$

where F is the restoring force of the isolator, m is the mass that the isolator carries, u is the horizontal displacement of the isolator, and ω is the cyclic frequency of rolling motion on the spherical plates according to the rigid body model. The cyclic frequency is related to the rigid-body eigenperiod of the isolator as $\omega = 2\pi/T$. The force at zero displacement (normalized to m), Q , equals $\mu \times g$, where μ is the rolling friction coefficient and g is the gravitational acceleration. The term Q_2 is the model parameter that controls the additional breakaway force stemming from the flattening of the sphere (Figure 2, B). The term Q_3 controls the negative stiffness branch that stems from the shape change of the sphere (Figure 2, D). The units of all the parameters used in the model are: u (m), Q (m/s²), Q_2 (m/s²), Q_3 (1/s²), a_1 (m/s²), a_2 (m). Parameters a_1 and a_2 modify the amplitude and lateral displacement the peak of the positive stiffness branch that is physically related to the overcoming of the pivot point (Figure 2, C).

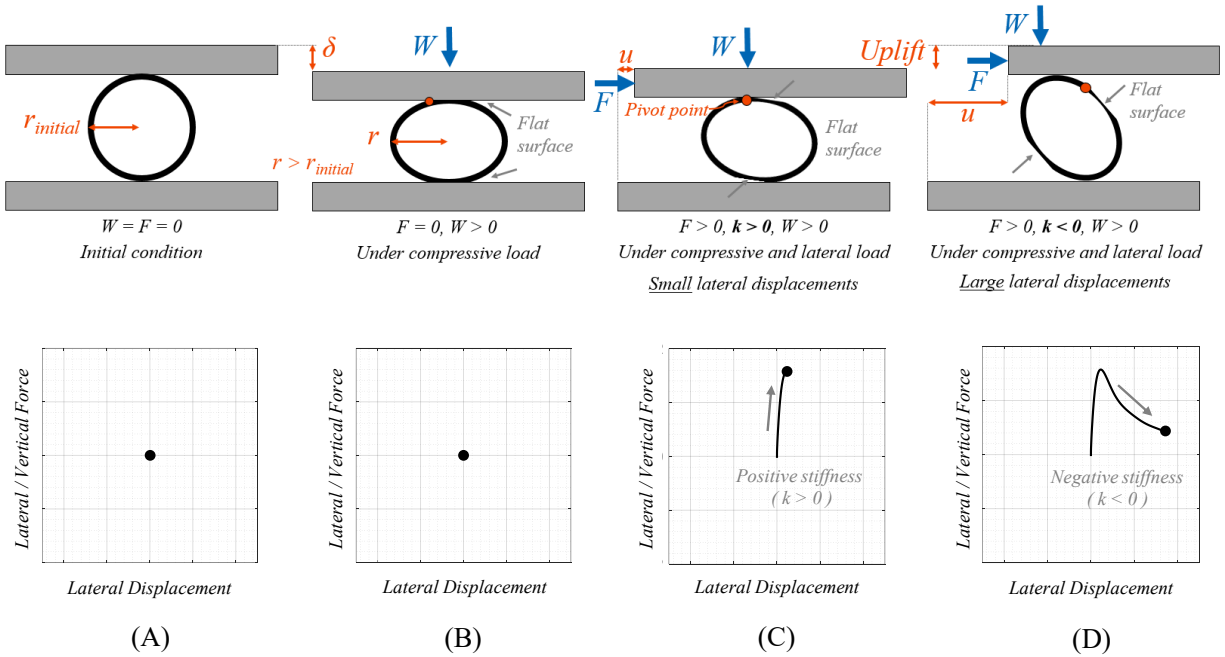


Figure 2. Response stages of a deformable rolling seismic isolator.

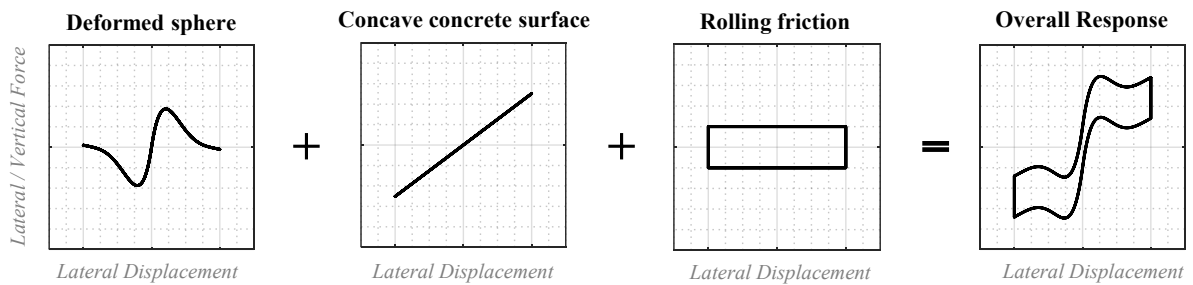


Figure 3. Visualization of the response components of the isolator.

Parameters Q_2 , Q_3 , a_1 , and a_2 are calibrated to fit the experimental results of the lateral cyclic tests of Katsamakas & Vassiliou (2023). Based on this calibration, the following values are used: $Q_2 = 0.15$, $Q_3 = 3.5$, $a_1 = 0.15$, and $a_2 = 0.20$ (Figure 4, left). The experimental tests of Katsamakas & Vassiliou (2023) were conducted at 1:2 scale. Therefore, the results need to be converted to full-scale values. Based on the scaling laws of Katsamakas & Vassiliou (2022) the following values are used in full scale: $Q_2 = 0.30$, $Q_3 = 1.75$, $a_1 = 0.15$, and $a_2 = 0.40$ (Figure 4, right). All values hereafter are in full scale. It is noted that these values are not meant to describe a specific isolation configuration but to be accurate and representative of a class of deformable elastomeric isolators. The parameters of investigation include the rolling friction coefficient (μ), the rigid-body isolator eigenperiod (T). The considered values of μ were: $\mu = 0.05$, $\mu = 0.10$, $\mu = 0.15$, and $\mu = 0.20$. These values cover a wide range of design scenarios (sphere size, sphere material, and W). A wide range of eigenperiods are considered, including $T = 2$ sec, $T = 3$ sec, and $T = 4$ sec, values commonly used in seismic isolation applications.

A total of 156 real, unscaled ground motions were used to quantify the seismic performance of the isolators and were applied to each design scenario. The ground motions are drawn from the PEER ground motion database (Acheta et al, 2014) and include all motions from FEMA P695 (2009) across all categories (far field, near-field pulse-like, near-field non-pulse-like). Figure 5 plots the elastic spectra of the ground motions, together with the design spectrum of Eurocode 8 (EN 1998-1:2004) assuming soil type A, importance factor 1, $a_{gR} = 0.24$ g and $\zeta = 5\%$. Two response quantities are used to quantify the efficiency of the isolators: a) the Peak Superstructure Acceleration (PSA) and b) the maximum displacement (u_{max}) of the isolator. Previous studies were unable to identify a correlation between isolator response quantities and earthquake intensity measure. The following Intensity Measures (IM) are used in the present study and correlated to the isolator's response: Peak Ground Acceleration (PGA); Peak Ground Velocity (PGV); Peak Ground Displacement (PGD); Arias Intensity; Spectral Acceleration at $T = 0.5, 1, 2, 2.5, 3, 3.5, 4$ sec; and Spectral Velocity at $T = 0.5, 1, 2, 2.5, 3, 3.5, 4$ sec.

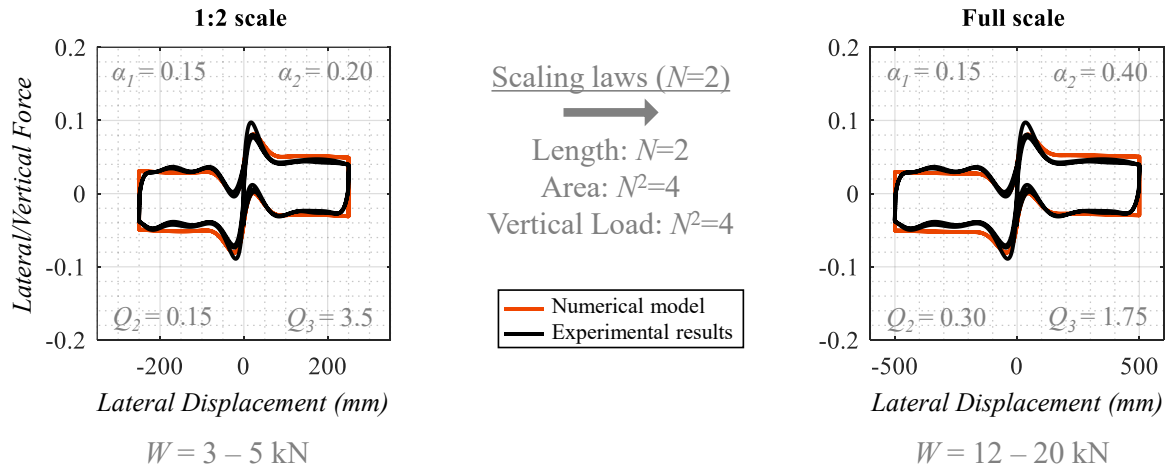


Figure 4. Calibration of the numerical model and conversion from half- to full-scale.

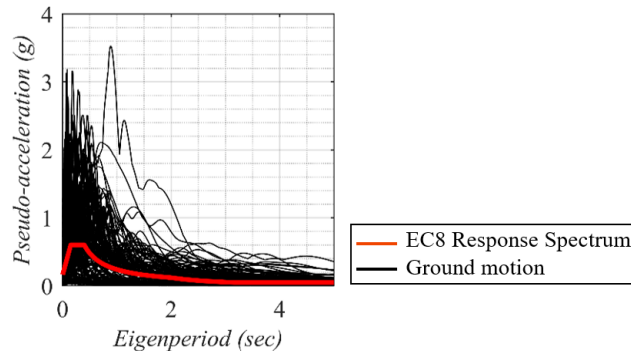


Figure 5. Response spectra of the ground motions used.

RESULTS

Figure 6 shows an indicative numerical analysis that confirms the effectiveness of the proposed isolator under the 1999 Chi-chi ground motion as recorded at CHY101 station. The isolator has $\mu=0.05$ and $T = 4$ sec and similar conclusions hold for other values of μ and T . In Figure 6, the isolator caps the accelerations transmitted to the superstructure below 0.1g for the given ground motion with a PGA of 0.32g, while maintaining reasonable peak displacements (below 160 mm) and zero residual displacements.

Figure 7 shows the results of the Intensity Measure (IM) analysis. The vertical and the horizontal axes show the response parameters (PSA and u_{max}) and the IMs, respectively. Out of the IMs considered in the present study, three had the highest correlation values and are shown here in detail: PGA, PGV and Arias Intensity. The results of Figure 7 are for $T = 3$ sec and $\mu = 0.10$. Results are in log-scale, which is a common visualization approach used in IM studies (Giouvanidis & Dimitrakopoulos, 2018). The correlation coefficient, R , is noted inside each subplot. Figure 8 shows the R -values between the response parameters and the IMs for all considered designs (T and μ). Results from Figures 7 and 8 show that:

- The selected IMs (PGA, PGV, and Arias Intensity) correlate very well with the response parameters (PSA, and u_{max}), with $R \geq 0.88$ in all cases.
- The IMs highly correlate with PSA with $R \geq 0.88$. The correlation slightly depends on T and μ . Higher T leads to lower R , whereas no clear trend is observed between μ and R .
- PGA is overall the best IM for predicting PSA with $R \geq 0.93$.
- The correlation between the IMs and u_{max} is even higher ($R \geq 0.92$). This correlation is completely unaffected by T for PGV and the Arias intensity, as all lines coalesce.
- The Arias Intensity is overall the best IM for predicting u_{max} ($R \geq 0.94$).

Results demonstrate that the three prioritized IMs are highly correlated with the response quantities, with PGA and Arias Intensity showing slightly higher R -values overall. The IMs correlate even better with u_{max} . PGA is the best IM for predicting PSA, while Arias Intensity is the best IM for predicting u_{max} .

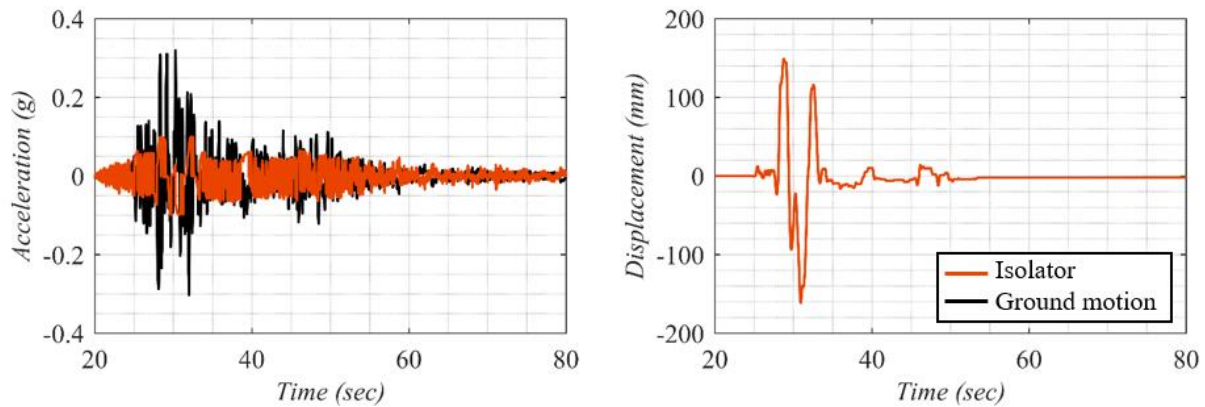


Figure 6. Seismic response of the isolator under the 1999 Chi-chi ground motion (CHY101 station) for $\mu=0.05$ and $T = 4$ sec.

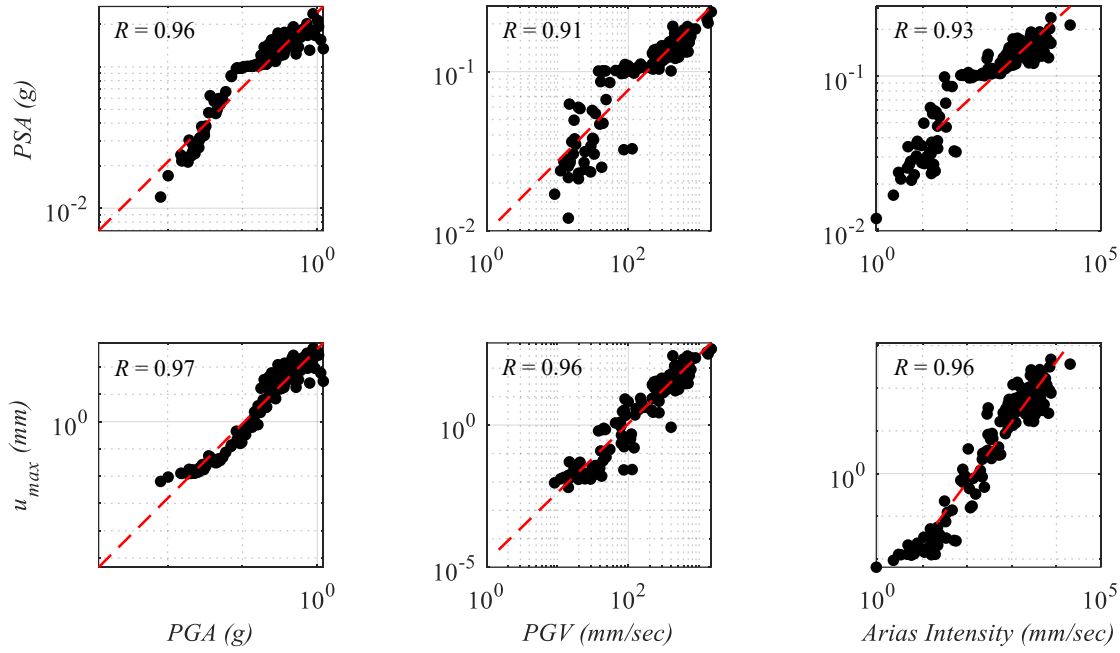


Figure 7. Correlation between the response parameters and the intensity measures.

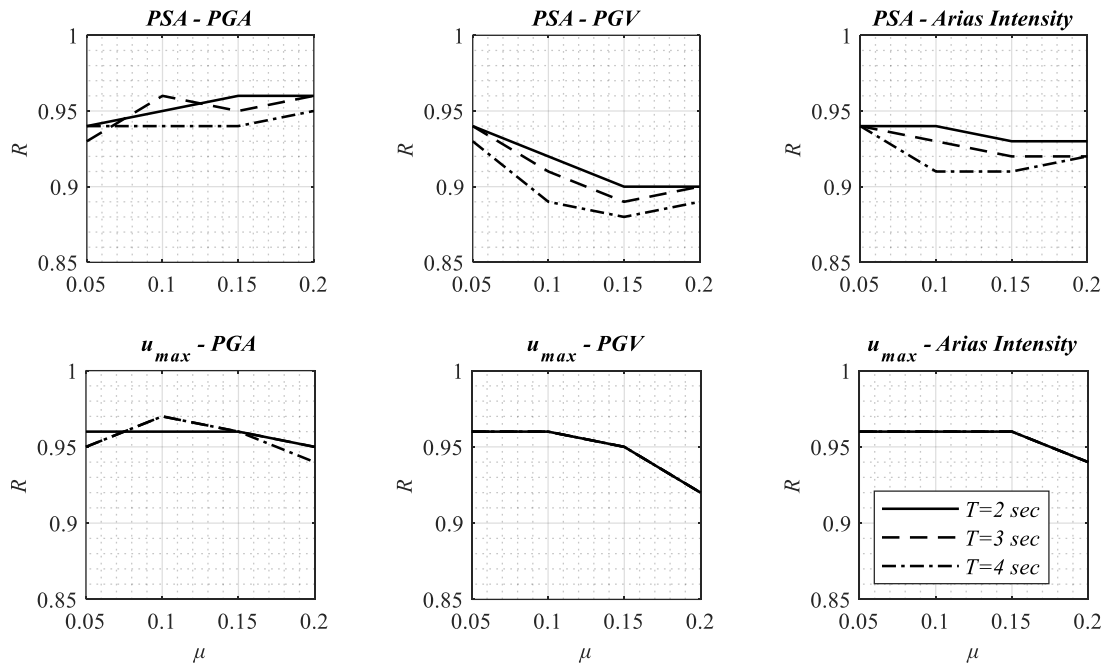


Figure 8. Summary of the R values between the response parameters and the IMs.

CONCLUSIONS

This paper performs an Intensity Measure (IM) analysis of a low-cost, high-performance seismic isolator for lightweight structures. The isolator comprises an elastomeric sphere that rolls between two concrete plates, one of which is concave to provide gravitational restoring force. The deformability of the sphere leads to a flag-shaped hysteretic response. The study uses a five-parameter numerical model that is validated against shake table tests. Different isolator eigenperiods (T), and rolling friction coefficients (μ) are used. The seismic response of the isolators is correlated with earthquake intensity measures (IMs).

Out of the considered IMs, the Peak ground acceleration (PGA), the Peak Ground Velocity (PGV) and the Arias Intensity are the three best intensity measures. PGA is the best IM for predicting the accelerations of the isolator, while Arias Intensity and PGV correlate better with the isolator displacements. The findings address a critical gap in the understanding of deformable rolling isolators and facilitate their practical implementation in lightweight structures.

REFERENCES

- Ancheta T.D., et al. (2014). NGA-West2 database. *Earthquake Spectra*, 30(3), pp. 989-1005.
- Cilsalar H., Constantinou M.C. (2019). Behavior of a spherical deformable rolling seismic isolator for lightweight residential construction. *Bulletin of Earthquake Engineering*, 17, pp. 4321–4345. <https://doi.org/10.1007/s10518-019-00626-z>
- Cilsalar H., Constantinou M.C. (2019). Development and Validation of a Seismic Isolation System for Lightweight Residential Construction. Technical Report MCEER, Report No. 19-0001.
- Cui S., Bruneau M., Constantinou M.C. (2012). Integrated Design Methodology for Isolated Floor Systems in Single-Degree-of-Freedom Structural Fuse Systems. Technical Report MCEER, Report No. 12-0004.
- European Committee for Standardization (CEN). (2004). Eurocode 8: Design of Structures for Earthquake Resistance, Part 1: General Rules, Seismic Actions and Rules for Buildings. EN 1998-1:2004. European Union.
- FEMA P695. (2009). Quantification of Building Seismic Performance Factors. Federal Emergency Management Agency.
- Giouvanidis A.I., Dimitrakopoulos E.G. (2018). Rocking amplification and strong-motion duration. *Earthquake Engineering & Structural Dynamics*, 47(10), pp. 2094-2116.
- Harvey P.S., Gavin H.P. (2014). Double rolling isolation systems: A mathematical model and experimental validation. *International Journal of Nonlinear Mechanics*, 61, pp. 80-92.
- Harvey P.S., Kelly K.C. (2016). A review of rolling-type seismic isolation: Historical development and future directions. *Engineering Structures*, 125, pp. 521-531. <https://doi.org/10.1016/j.engstruct.2016.07.031>
- Harvey P.S., Zéhil G.P., Gavin H.P. (2014). Experimental validation of a simplified model for rolling isolation systems. *Earthquake Engineering and Structural Dynamics*, 43, pp. 1067–1088. DOI: 10.1002/eqe.2387
- Katsamakas A.A., Del Giudice L., Vassiliou M.F. (2024). Experimental study of grout-filled, reused tennis balls as seismic isolation bearings for lightweight structures. 18th World Conference on Earthquake Engineering (WCEE 2024).
- Katsamakas A.A., Belser G., Vassiliou M.F., Blondet M. (2022). Experimental investigation of a spherical rubber isolator for use in low income countries. *Engineering Structures*, 250, 113522. <https://doi.org/10.1016/j.engstruct.2021.113522>
- Katsamakas A.A., Belser G., Vassiliou M.F., Blondet M., Stojadinovic B. (2021). Experimental investigation of spherical rubber seismic isolation bearings. COMPDYN 8th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering.
- Katsamakas A.A., Belser G., Vassiliou M.F., Stojadinovic B., Blondet M. (2022). Shake-table testing of low-cost seismic isolation bearings based on rolling rubber spheres. 3rd International Conference on Natural Hazards & Infrastructure (ICONHIC 2022).
- Katsamakas, A. A., Chollet, M., Eyyi, S., & Vassiliou, M. F. (2021). Feasibility study on re-using tennis balls as seismic isolation bearings. *Frontiers in Built Environment*, 7, 768303. <https://doi.org/10.3389/fbuil.2021.768303>
- Katsamakas A.A., Chollet M., Eyyi S., Vassiliou M.F. (2022). Low-cost and sustainable seismic isolation with re-used tennis balls: Lateral cyclic tests. *Third European Conference on Earthquake Engineering and Seismology – 3ECEES*, pp. 2542-2549.

- Katsamakas A.A., Chollet M., Eyyi S., Vassiliou M.F. (2022). Re-using tennis balls as low-cost seismic isolation devices: Experimental Investigation. 3rd International Conference on Natural Hazards & Infrastructure (ICONHIC 2022), p. 411. Innovation Center on Natural Hazards and Infrastructure.
- Katsamakas A.A., Del Giudice L., Reyes S.I., Candebat-Sanchez D., Vassiliou M.F. (2023). Experimental and numerical assessment of grout-filled tennis balls as seismic isolation bearings. *Engineering Structures*, 294, 116716.
- Katsamakas A.A., Vassiliou M.F. (2022). Lateral cyclic response of deformable rolling seismic isolators for low-income countries. Third European Conference on Earthquake Engineering and Seismology (3ECEE), Bucharest, Romania, September 4-9.
- Katsamakas A.A., Vassiliou M.F. (2023). Experimental Parametric Study and Phenomenological Modeling of a Deformable Rolling Seismic Isolator. *Journal of Earthquake Engineering*. DOI: 10.1080/13632469.2023.2189978
- Katsamakas A.A., Vassiliou M.F. (2023). Shake-table testing of resilient, low-cost seismic isolators based on rolling rubber spheres. 2023 New Zealand Society for Earthquake Engineering (NZSEE) Conference, Auckland, New Zealand, April 19-21.
- Katsamakas, A.A., Vassiliou, M. F. (2025). Experimental testing of rolling seismic isolators using rubber spheres or grout-filled tennis balls. In 19th World Conference on Seismic Isolation (19WCSI).
- Lee G., Ou Y.C., Niu T., Song J., Liang Z. (2010). Characterization of a Roller Seismic Isolation Bearing with Supplemental Energy Dissipation for Highway Bridges. *Journal of Structural Engineering*, 136(5), pp. 502-510.
- Menga N., Bottiglione F., Carbone G. (2019). The nonlinear dynamic behavior of a Rubber-Layer Roller Bearing (RLRB) for vibration isolation. *Journal of Sound and Vibration*, 463, 114952.
- Menga N., Foti D., Carbone G. (2017). Viscoelastic frictional properties of rubber-layer roller bearings (RLRB) seismic isolators. *Meccanica*, 52(11), pp. 2807-2817.
- Restrepo, S. L., & Constantinou, M. C. (2025). Shake table testing of a seismic isolation system for lightweight structures. *Earthquake Engineering & Structural Dynamics*, 54(2), 562-582.
- Reyes S.I., Kocur G.K., Markert B., Vassiliou M.F. (2025). Noninvasive Methods to Estimate the Mass Eccentricity of Steel-Cored Elastomeric Spheres for Seismic Isolation. *Journal of Engineering Mechanics*.
- Reyes S.I., Konstantinidis D., Vassiliou M.F. (2026). Finite Element Modeling of a Thermoplastic Polyurethane Ball for Rolling Seismic Isolation. *Earthquake Engineering & Structural Dynamics*. <https://doi.org/10.1002/eqe.70114>
- Reyes S.I., Lopez E.L., Vassiliou M.F. (2025). Validation of a three-dimensional finite element constitutive modeling approach for a thermoplastic polyurethane calibrated with uniaxial tests. *Engineering Structures*, 322, 119044.
- Touaillon J. (1870). Improvement in Buildings. US Patent 99,973.
- Tsai C.S., Lin Y.C., Chen W.S., Su H.C. (2010). Tri-Directional Shaking Table Tests of Vibration Sensitive Equipment With Static Dynamics Interchangeable-Ball Pendulum System. *Earthquake Engineering and Engineering Vibration*, 9(1), pp. 103–112. <https://doi.org/10.1007/s11803-010-9009-4>
- Zéhil G.P., Gavin H.P. (2013). Simplified approaches to viscoelastic rolling resistance. *International Journal of Solids and Structures*, 50(6), pp. 853-862.
- Zéhil G.P., Gavin H.P. (2014). Rolling resistance of a rigid sphere with viscoelastic coatings. *International Journal of Solids and Structures*, 51(3-4), pp. 822-838.