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A low-cost seismic isolation and re-centering system for developing countries: large scale shaking table tests under uniaxial Ricker ground motions

B. R. Ge
University of Bristol, Bristol, UK, borui.ge@bristol.ac.uk

Y. C. Zhang, A. Diambra, R. De Risi, A. Sextos
University of Bristol, Bristol, UK, yichen.zhang@bristol.ac.uk, andrea.diambra@bristol.ac.uk, raffaele.derisi@bristol.ac.uk, a.sextos@bristol.ac.uk

ABSTRACT: Seismic isolation systems have been widely used to reduce seismic accelerations transmitted to superstructures by decoupling their motion from ground shaking. A new low-cost seismic isolation system, based on a PVC-sand-PVC layer at the foundation level of a building, was recently proposed at the University of Bristol and implemented at full scale in a one-storey building in Nepal. Under seismic action, the building is allowed to slide on the PVC-sand-PVC 'fuse' when ground acceleration exceeds the design threshold. This paper reports the further development of the system by introducing a new re-centering device. Shaking table tests on a 1m × 1m prototype foundation were conducted to investigate the frictional properties and re-centering performance of the combined PVC-sand-PVC layer and the self-centering system under uniaxial Ricker ground motions. The results demonstrate the effectiveness of the combined system in isolating the building acceleration response from the input ground acceleration, while limiting the resulting residual displacement.

1 INTRODUCTION

Base isolation has become a well-established strategy for mitigating earthquake-induced damage, as demonstrated in numerous studies (Buckle and Mayes, 1990; Skinner et al., 1993; Higashino and Okamoto, 2006). By introducing a flexible or sliding interface between the foundation and the superstructure, it effectively decouples structural motion from ground motion, thereby reducing seismic energy transmission. However, conventional systems such as laminated rubber bearings and friction pendulum isolators require high-quality materials and precise installation, limiting their adoption in regions with restricted technical and financial resources.

To overcome these challenges, several researchers have explored alternative low-cost or recycled isolation systems (Spizzuoco et al., 2014; Banović et al., 2018; Katsamakas et al., 2021). Among these, Tsiavos et al. (2020, 2021) proposed a particle-based PVC-‘sandwich’ (PVC-s) isolator, consisting of two PVC plates separated by a thin layer of rounded sand grains acting as a frictional fuse. Due to its simplicity and low-cost materials, the PVC-s system offers a promising solution for low-rise buildings in low-income regions lacking formal design frameworks or specialized expertise (Tsiavos et al., 2021).

Despite its effectiveness, the flat-surface PVC-s isolator allows unrestricted sliding, which can lead to residual displacements under strong or repeated earthquakes. To address this limitation, the current research proposes a cable-based self-centering device designed to work in conjunction with the PVC-s base isolator. This paper presents a series of shaking table tests conducted on a 1 m × 1 m prototype foundation equipped with the combined cable-based self-centering PVC-s isolation system. The tests were performed under uniaxial Ricker-type ground motions with varying peak accelerations. The results demonstrate the strong effectiveness of the integrated system in reducing response accelerations compared to the ground acceleration input and limiting residual displacements of the foundation.

2 CONCEPT OF THE CABLE-BASED SELF-CENTERING SYSTEM IN PVC-‘SANDWICH’ ISOLATION APPLICATIONS

The concept of the cable-based self-centering in a PVC-‘sandwich’ base-isolated masonry building is schematically illustrated in Figure 1. The PVC-s isolator comprises two PVC sheets separated by a thin layer of rounded sand grains. By appropriately tuning the interface friction, this layer effectively isolates the structural acceleration from ground motion once the lateral load induced by an earthquake exceeds the base sliding threshold. Otherwise, the PVC-s layer provides sufficient initial stiffness to resist lateral loads under serviceability conditions.

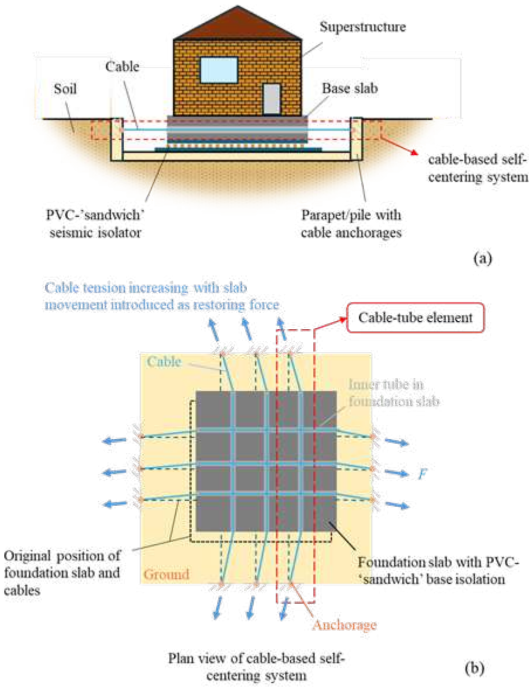


Figure 1. Concept of the cable-based self-centering system: (a) schematics of an exemplary application in a masonry building; (b) plan view of the system.

On this basis, the cable-based self-centering system features a grid of elastic cables embedded within the base slab between the superstructure and the sliding isolator, as shown in Figure 1(b). Each cable is threaded through protective tubes cast into the slab and anchored at both ends to the ground. During seismic excitation, relative movement between the ground and the foundation elongates the cables, generating tensile forces that act as restoring forces motivate the structure sliding back to the original position.

Achieving an effective balance between the "fuse" function of the sliding isolation system and the self-centering performance requires a proper understanding of the interaction mechanism between the two systems. Therefore, this study presents the experimental program on the combined system under uniaxial Ricker-type ground motions, with their engagement and the overall effectiveness at varying ground peak acceleration to be assessed.

3 CONFIGURATION OF SHAKE TABLE TESTS

Two foundation configurations were tested in this study: specimen P1, featuring only the PVC-'sandwich' (PVC-s) isolator, and specimen C1, which incorporated additional self-centering cables in the y-direction (Cable-s). As shown in Figure 2 for the specimen C1, the setup comprised a 1 m × 1 m, 1.15 mass block mounted on a PVC-s isolation layer and equipped with self-centering cables anchored to rigid steel frames at both ends.

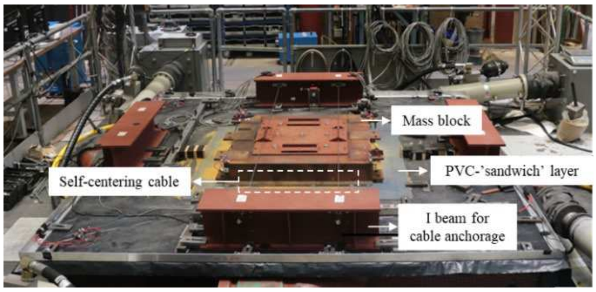


Figure 2. Test setup of the cable-s system specimen on the shaking table.

The Leighton Buzzard sand used in this study is a rounded to subrounded quartz sand, with its original properties as sale summarized in Table 1. The PVC-s isolator consisted of two PVC sheets and a thin layer of Leighton Buzzard sand acting as a frictional interface. The sand is deposited with a target surface density of 1 kg/m2 over the 1 m × 1 m area at the central of bottom PVC surface that fixed on the shaking table (i.e. the original position of mass block before tests).

Table 1. Original properties of Leighton Buzzard sand used in this study.

Void ratio *e*		**Density *ρ* (Mg/m^3)**		**D_{50} (mm)**	**C_u**	**C_c**
e_{max}	e_{min}	ρ_{max}	ρ_{min}			
0.84	0.53	1.73	1.44	0.88	1.44	1.00

The steel block with 1 ton mass is used to represent the base slab equipped with housing for cable-confined tubes along the principal sliding direction. Each tube was fabricated by paired steel angles with curved edges to minimize cable wear and enable smooth motion. Stainless-steel wire ropes (Ø4 mm, 2.8 m length, 13.4 kN breaking load) were used as self-centering cables, with their ends fixed on the I beams through adjustable anchorages. The effective unconstraint ratio of the system was determined as 0.90, defined by the ratio of unconfined (i.e. not confined within tubes in the foundation block) to total cable length. Prior tensile tests performed on short cable samples indicated an elastic stiffness of approximately 1099 kN up to 60% of the breaking load.

Before testing, the mass block and anchorage I-beams were precisely positioned to ensure the cables remained straight between the two anchorage points, with their midsections properly seated within the confining tubes. The cables were then lightly pre-tensioned to achieve accurate alignment, verified by using a square angle and spirit level.

3.1 Ground motions

The shaking table was driven by Ricker wavelet ground motions with peak ground accelerations (PGAs) ranging from 0.4g to 1.2g, as shown in Figure 3. The Ricker wavelet was selected for its smooth, single-pulse waveform and well-defined frequency content, providing controlled and repeatable excitation. This setup allowed systematic evaluation of the nonlinear sliding and self-centering behaviour of the combined system under moderate to strong seismic intensities.

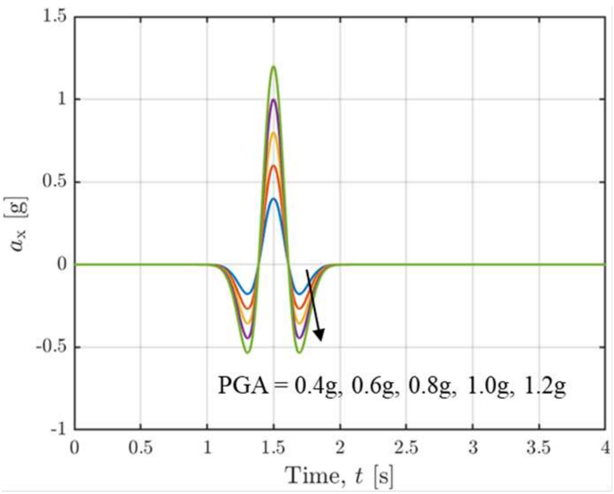


Figure 3. Acceleration time histories of the Ricker wavelets used in the shaking table tests.

3.2 Instrumentation

Instrumentation for the shake table tests included accelerometers placed at the corners of both the shake table and the foundation slab to capture input and response accelerations, as well as displacement transducers for tracking slab motion in the uniaxial directions. Cable forces were monitored continuously through load cells at the anchorages. All data were synchronously recorded at 512 Hz, enabling detailed evaluation of acceleration response and foundation displacement under dynamic loads.

By comparing the experimental results of the two configurations, the next section presents and discusses the isolation efficiency and self-centering performance of the proposed base isolation system under varying ground acceleration levels.

4 TEST RESULTS

4.1 Hysteretic curves under Ricker ground motions

Figure 4 reports the hysteretic responses of the two specimens, P1 and C1 in a Ricker ground motion with PGA = 1.0g, obtained from the accelerometer records of the mass block. The hysteretic response of the PVC-‘sandwich’ (PVC-s) isolation system exhibited an approximately rectangular shape, typical of friction-based isolators. The equivalent friction coefficient roughly stabilized at 0.20, consistent with previous findings on static direct shear tests for similar sand-based interfaces in Sezer et al. (2023).

When integrated with self-centering cables, the hysteretic behaviour of the combined system transformed into a flag-shaped curve, combining the base sliding friction and elastic restoring force generated by the cables. The response remained nearly flat within initial sliding displacement, while the restoring force of the cables presented a clear non-linear increase with the sliding displacement beyond 50 mm. The sliding range approximately remained comparable to that of the PVC-s system, and the gradient of the hysteretic loops was nearly constant across all acceleration levels, demonstrating stable stiffness and consistent self-centering performance.

Comparison of the two systems shows that the Cable-s hysteretic response can be interpreted as the superposition of PVC-s friction and cable elasticity. It should be noted that, under Ricker wavelet excitation, the residual displacement is smaller than the x-axis intersection of the hysteretic curve (i.e., force equilibrium point), indicating that the system tended to ‘freeze’ where the restoring force fell down under the level of base friction. This behaviour reflects the dynamic nature of self-centering mechanism, which is governed by energy dissipation and velocity-dependent friction rather than static force balance. Similar trends reported in previous studies (e.g., Medeot, 2004; Cardone et al., 2012) confirm that residual displacements are generally smaller than static predictions, underscoring the need for dynamic tests to properly evaluate re-centering performance.

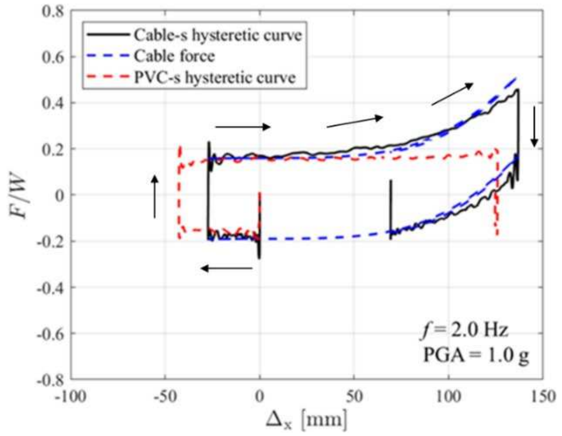
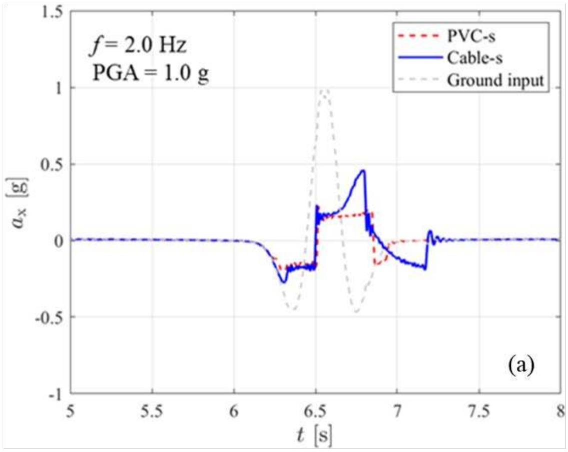


Figure 4. Comparison of hysteretic curves of the Cable-s and PVC-s systems.

4.2 Self-centering capability analysis



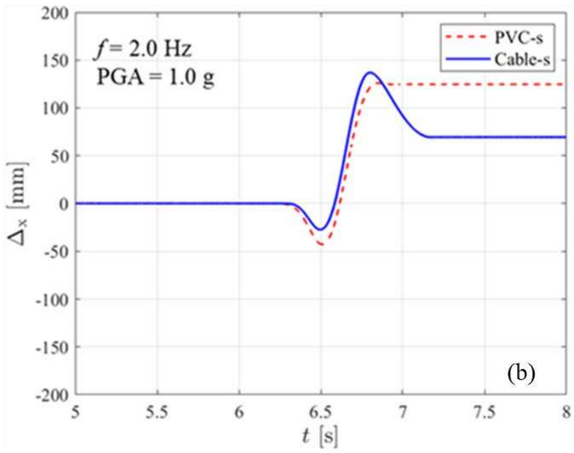


Figure 5. Acceleration (a) and displacement (b) comparison of the PVC-s and Cable-s system under Ricker ground motion.

To directly demonstrate the seismic isolation effect, Figure 5 compares the acceleration time history of the ground input, and responses of the PVC-s and Cable-s systems in a high excitation case with GPA = 1.0g. The PVC-s system reduced the foundation acceleration to about 0.2g, dominated by the interface friction of PVC-sand-PVC layer. In the Cable-s configuration, acceleration spikes appeared due to cable activation, which increased with the larger displacements induced by Ricker wavelets. However, the system still maintained effective base isolation by limiting overall acceleration response to roughly half of the ground motion. Although cable engagement slightly increased acceleration because of added stiffness, a complete assessment under real seismic records with broader frequency content would better reflect the system's performance.

The displacement records in Figure 6 show that the two systems reached similar peak displacements under the applied excitation; however, they differed markedly in their post-excitation behaviour. The PVC-s system remained offset after shaking because it lacks a restoring mechanism. By contrast, the Cable-s system exhibited partial re-centering capability.

Figure 6 further examines the influence of PGA on the peak and residual displacement responses of the two systems. The peak displacement ($\Delta_{x,p}$) of the PVC-s and Cable-s system was broadly similar regardless of the GPAs, indicating that cable engagement had little restraint on the maximum sliding momentum. Peak displacement increased proportionally with PGA for both systems, reflecting the input-dependent nature of the Ricker ground motions.

In contrast, the residual displacement ($\Delta_{x,r}$) showed clear differences between the two systems. The PVC-s system exhibited a steady increase in $\Delta_{x,r}$ with rising PGA due to the absence of restoring mechanism. The Cable-s system, however, showed a distinct turning point at the PGA level where the cable force exceeded the base friction (see Figure 6(b)). Beyond this activation threshold, the cables generated sufficient recovery force to substantially reduce residual displacement. The amount of return motion increased with the peak displacement, reflecting the displacement-dependent nature of cable elongation and the corresponding rise in restoring force. Although full re-centering was not
cable-based self-centering devices to enhance seismic resilience in resource-constrained settings. The findings also provide valuable data for calibrating analytical models and informing the design of future self-centering base-isolation systems.

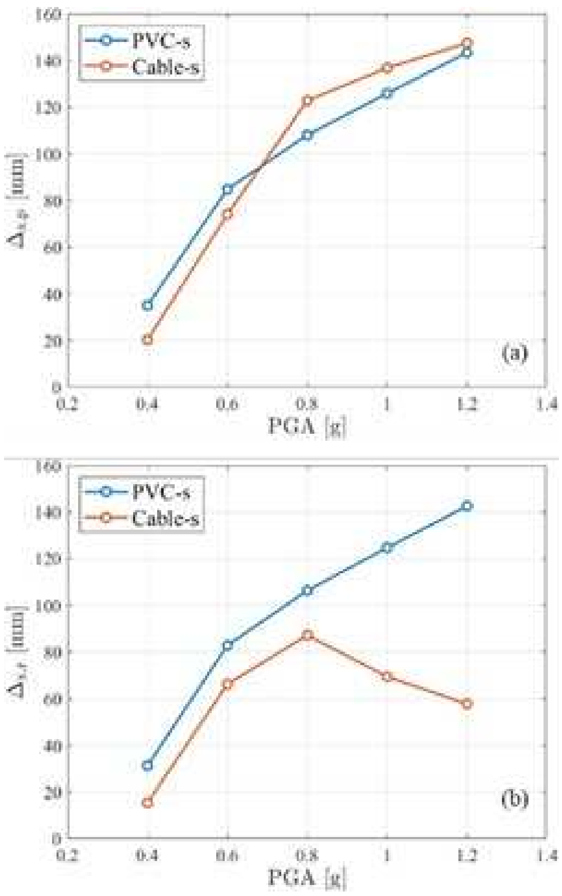


Figure 6. Acceleration (a) and displacement (b) comparison of the PVC-s and Cable-s system under Ricker ground motion.

5 CONCLUSION

This study experimentally evaluated the dynamic behaviour of a low-cost PVC-'sandwich' (PVC-s) sliding isolator and its enhanced configuration incorporating a cable-based self-centering mechanism. Shaking table tests using Ricker-type ground motions demonstrated that the PVC-s system effectively limited transmitted acceleration to approximately 0.2g but accumulated significant residual displacement due to the absence of restoring forces. The addition of self-centering cables notably improved the post-excitation performance, by introducing a displacement-dependent recovery mechanism that reduced residual offsets once he resultant cable force in the sliding direction exceeded the base friction. Although full re-centering was not achieved, the Cable-s system consistently outperformed the standalone PVC-s configuration in controlling residual displacement while maintaining comparable isolation efficiency.

Overall, the results highlight the potential of combining low-cost sliding isolation with simple cable-based self-centering devices to enhance seismic resilience in resource-constrained settings. The findings also provide valuable data for calibrating analytical models and informing the design of future self-centering base-isolation systems.

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