



## **Design and construction of the first building worldwide with a low-cost PVC-sand seismic isolation system**

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### **Abstract**

This paper presents the experimental validation, design and construction of the world's first building supported on a novel, low-cost, low-tech PVC-sand (PVC-s) seismic isolation system, implemented in a two-story reinforced concrete (RC) school building in Kathmandu, Nepal. Developed collaboratively by the University of Bristol and the National Society for Earthquake Technology – Nepal (NSET), the PVC-s system encapsulates locally sourced sand between two polyvinyl chloride (PVC) sheets, forming a friction-based interface beneath the raft foundation. This interface acts as a mechanical “fuse”, permitting controlled sliding during seismic events once frictional resistance is exceeded, thereby mitigating seismic energy transmission to the superstructure. Extensive experiments have validated the static and kinetic friction coefficient of Nepalese sand samples, tested in a shear box and on the shaking table of the University of Bristol. The system is designed to activate at spectral accelerations between 0.20g and 0.25g, aligning with regional seismic design parameters. A 15–20% increase in construction costs is considered a reasonable trade-off given the significantly enhanced seismic performance and the local context.

Keywords: seismic isolation, low-cost, PVC-s system, resilient structures, Nepal

# 1 Introduction

Seismic isolation is a highly efficient design method that aims to decouple structures from ground motions as a means to significantly reduce seismic forces through period elongation and displacement concentration within the isolation devices (Stewart et al., 1999). However, conventional seismic isolation systems, such as rubber bearings (Mokha et al., 1990) and friction pendulum systems (Becker & Mahin, 2013; Han et al., 2021), often require high initial investment as well as extensive technical expertise for the design, implementation, construction and maintenance throughout the structure's life cycle. This cost and complexity render conventional isolation techniques practically unfeasible in low-income regions and developing countries. In these areas, resources are limited and inevitably structural vulnerability to strong earthquakes is disproportionately high. In this light, it is crucial to develop cost-effective, locally resourced and easy to implement design alternatives that can reduce the probability of collapse (Tsiavos & Sextos, 2023). The above, specifically for lightweight, low-rise structures is often achieved using fibre-reinforced elastomeric isolators (Tan et al., 2014; Zhou et al., 2023), rolling rubber spheres (Katsamakas & Vassiliou, 2023) or deformable rolling bearings (Cilsalar & Constantinou, 2019; Restrepo & Constantinou, 2025). Alternatively, the isolation devices are replaced by an interface between the structure and the foundation. This concept of Geotechnical Seismic Isolation (GSI) may require an ad-hoc designed soil-foundation-structure scheme with low-modulus materials placed directly beneath the foundation (Gazetas, 2015), a naturally liquefiable soil (Karatzia et al., 2019), foundation rocking (Anastasopoulos et al., 2012), improved soil layer (Pecker, 2003; Tsang, 2008) or the placement of geosynthetics (Banović et al., 2023), sand, gravel, geofoams, EPS (Expanded Polystyrene) beads-sand mixtures, Natural Stone Pebbles, Wrapped Stones (Rasheed & Málaga-Chuquitaype, n.d.), Sand Cushion (GSI-SC), Rubber-Soil Mixtures (RSM) and Gravel-Rubber Mixtures (GRM). By concentrating failure at the soil-foundation interface, the seismic demand to the superstructure can be drastically reduced. An experimentally verified method for low-cost friction-based seismic base-isolation system utilising a layer of sand particles within two sheets of PVC has been proposed (Tsiavos, Alexander, & Sextos, 2019; Tsiavos, Haladij, et al., 2020; Tsiavos, Sextos, et al., 2020; Tsiavos, Sextos, Stavridis, Dietz, Dihoru, Di Michele, et al., 2021) following extensive research on sand-rubber mixtures (Tsiavos, Alexander, Diambra, et al., 2019) and PVC sheets with various types of rollers (Tsiavos, Sextos, Stavridis, Dietz, Dihoru, & Alexander, 2021) among other configurations. The PVC-s system was specifically engineered to allow for a sliding-rolling mechanism of sand particles encapsulated between the two PVC sheets.

This paper presents the implementation of the PVC-s method in the case of a low-rise school in Kathmandu, Nepal, following a detailed engineering study that aimed at meeting both national standards and the desired performance objectives. To the best of the authors' knowledge, this represents the first design of its kind. A brief overview of the key steps taken along with the challenges encountered from the conceptual phase through to implementation is provided below.

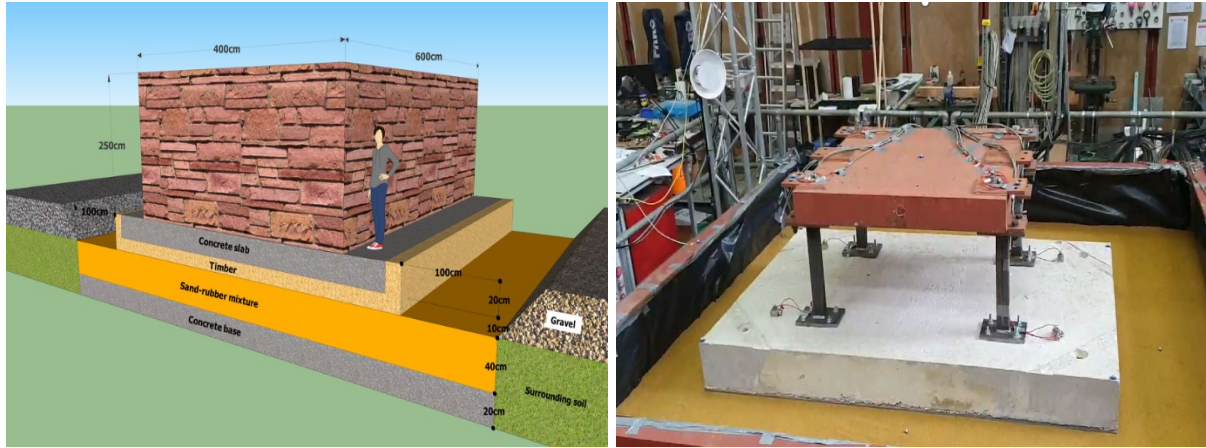


Figure 1.1 PVC-s conceptual overview (left) and equivalent SDOF system tested at the University of Bristol (right).



Figure 1.2 Alternative sand samples tested (left) and PVC-s moderate scale testing campaign on the shaking table of the University of Bristol (right).

## 2 The ‘hybrid’ sliding/ductile Seismic Isolation Concept

As mentioned, PVC-s is a novel, low-cost, easy-to implement, friction-based seismic isolation system which encapsulates locally resourced grains between two sheets of polyvinyl chloride (PVC) covering the area underneath the raft foundation. This “hybrid” system requires that the superstructure is designed according to local seismic code (i.e., with adequate strength and ductility), with the interface acting as a “fuse” that promotes sliding once the friction force is exceeded. The limitations of the PVC-s system relate to the lack of self-recentering capability, damage to utilities in the absence of flexible joints, and potential variation of the friction coefficient due to ageing or water intrusion. The latter have been experimentally explored (Sezer et al., 2024) and the resulting coefficient of variation (COV) of friction remained within the tolerable limits of 0.15 to 0.2. The broader perspective, however, is that the proposed PVC-s isolation system offers an additional layer of safety by effectively controlling the seismic energy transmitted to the

superstructure, which is an essential advantage in regions where capacity design principles and quality control cannot be reliably ensured.

### 3 Architectural Features and Structural System

The building presented herein is a four classroom, two-storey RC school building with 44 m<sup>2</sup> area, located at the north-east part of the Kathmandu Valley. The architectural layout of the building corresponds to one of the official structural typologies approved in Nepal commonly constructed after the devastating  $M_w$  7.8 Gorkha earthquake in 2015 (Goda et al., 2015), updated to comply with the latest seismic design code in Nepal (Government of Nepal, 2020). The implementation of the PVC-s low-cost seismic isolation scheme is approved on the basis of its beneficial role and its full compliance with the design and detailing provisions applicable to conventional buildings. The building is a reinforced concrete structure resting on a raft foundation that is seismically isolated using the low-cost PVC-sand-PVC (PVC-s) system. The PVC sheets have a thickness of 3 mm and the encapsulated sand interface is single grain with density of 2kg/m<sup>2</sup>. The friction coefficient is experimentally assessed with a mean value of 0.21 and a coefficient of variation (COV) equal to 0.25, for vertical stress ranging between 10-32 kPa for the seismic load combination (G+0.3Q±E). Given that the PVC-s acts as an additional level of safety, the above uncertainty is deemed tolerable.

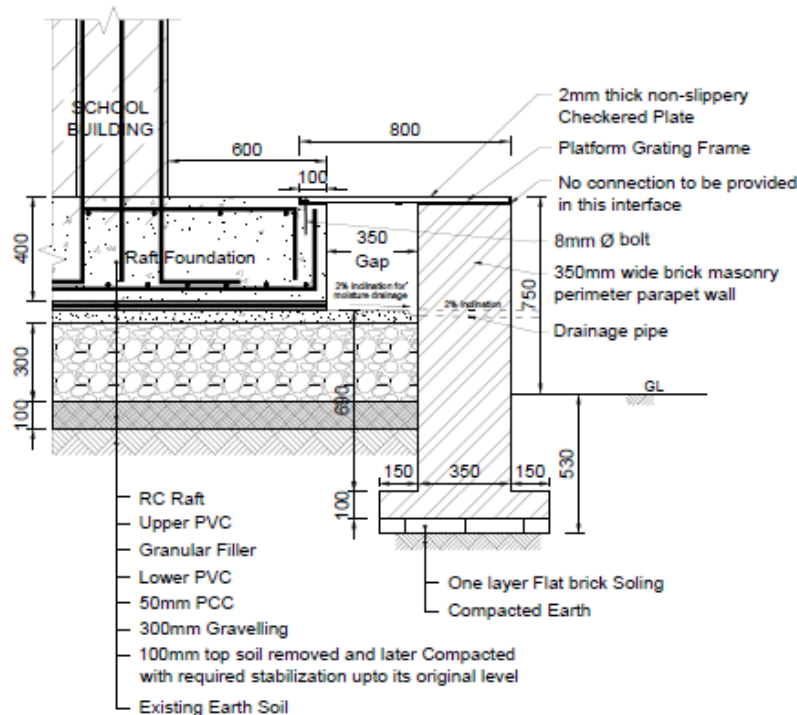


Figure 3.1 Layout of the PVC-s system.

The system is designed to be triggered when the inertial force exceeds the frictional resistance at the PVC-s surface. The activation threshold is set at 0.21g corresponding to the mean friction force,

which is approximately 50% lower than the design peak ground acceleration at the site (seismic zoning factor  $Z=0.35g$ , importance class II with  $I=1.25$  according to the local seismic code NBC). In this “hybrid” design concept, the threshold aims to mitigate damage associated with the design-level earthquake considering the behaviour (i.e., force reduction) factor adopted, equal to  $q=4.0 \times 1.5=6.0$  as per NBC, which implies significant energy dissipation through stable inelastic response cycles within the predefined plastic hinges. The foundation and the PVC-s are built above ground to facilitate free sliding and prevent pounding on the surrounding soil. A sacrificial brick parapet is constructed with a 35 cm gap, a value derived numerically to correspond to a 1% probability of exceedance in 50 years (Sextos et al., 2022). This sacrificial element is conceptually similar to bridge abutment backwalls in the United States, which are designed to fail in shear in order to protect the underlying stem wall (Taskari & Sextos, 2015).

## 4 Construction process

### 4.1 Preparatory works and parapet construction

Following the initial compaction works, a layer of flat brick soling is laid on the soil surface. The brick masonry parapet wall presented in Figure 3.1, with a 350 mm gap around the building perimeter, is then constructed. This parapet wall, which is expected to fail in shear in case of excessive displacements and pounding, is built with bricks and cement mortar and defines the footprint of the building. The base for the building is further prepared by leveling and compacting the earth surface using a mechanical compaction roller. A 150 mm layer of gravel is then placed over the compacted base and the surface is re-compacted. Next, a smooth and level, 50 mm thick layer of plain cement concrete (PCC) is laid over the compacted surface.



Figure 4.1 Construction of the sacrificial parapet (left) and surface leveling (right).

### 4.2 PVC-s interface

On top of the PCC, the first layer of 3 mm thick PVC sheet is installed. A layer of granular sand is evenly spread over the first 3 mm PVC sheet, serving as a granular filler at an application rate of 0.75 to 1 kg/m<sup>2</sup> acting as the intermediate layer in a “sandwich” configuration between two

PVC sheets. The spreading is carried out at an optimal time of day to minimize surface moisture and avoid interference from wind, as the process is delicate. The preparation of the PVC-s follows specific guidelines issued as part of SAFER-BUILD project for easy and reliable sieving and sand spreading. A second PVC sheet with 3mm thickness is then laid on top of the sand layer. The adjacent PVC sheets are sealed using waterproof tape to ensure continuity. This PVC-s sandwich layer serves as the low-cost seismic isolator interface for the mat foundation constructed above. Care is taken to ensure the sand layer remains uniform, undisturbed, and no thicker than a single grain throughout.



Figure 4.2 Spreading of the sand across the PVC surface (left) and PVC-s isolation (right).

### 4.3 Mat foundation

The bottom reinforcement grid for the mat foundation (16 mm diameter bars spaced at 175 mm center-to-center,  $\text{Ø}16/175$ ) is placed directly above the upper PVC sheet layer, with an adequate concrete cover of 50 mm. Column reinforcement is then erected in position as per the design to the Nepalese Seismic Code NBC-2020. Once the column reinforcement is completed, the top reinforcement mesh (16 mm diameter bars spaced at 250 mm center-to-center,  $\text{Ø}16/250$ ) is applied. The reinforcement grids are securely tied using binding wire. Having accomplished the reinforcement works and detailing, formwork is installed in place to prepare for the concreting of the mat foundation. The resulting 400 mm thick mat foundation rests atop the PVC-s sandwich layer and enables controlled sliding when earthquake forces exceed the threshold adopted as part of the “hybrid” design described in Section 2.

### 4.1 Superstructure

After the completion of the mat foundation, formwork is installed around the column reinforcement, and the vertical columns with dimensions 350 mm  $\times$  350 mm are cast. Air pockets and the formation of honeycombs at the column bases are prevented through vibration. Once the formwork is removed, brick masonry walls are constructed according to the architectural layout. Reinforced concrete lintel bands, each 75 mm thick and 230 mm wide matching the wall thickness, are provided above and below the openings.



Figure 4.3 Overview of the mat foundation construction.



Figure 4.4 Finalization of the superstructure construction (top) and delivery of the operational school (bottom).

Plastering, floor finishes, painting, and the installation of electrical and plumbing fittings was carried out next followed by doors and windows fitting. As part of the quality control scheme, concrete cubes of dimensions  $150 \text{ mm} \times 150 \text{ mm} \times 150 \text{ mm}$  were cast using standard molds. The

concrete was then poured in three layers, each compacted 25 times using tamping rods. After 24 hours, the specimens were demolded and cured in a water tank maintained at  $27 \pm 2^\circ\text{C}$  until the designated testing dates. Compressive strength tests were then conducted at 7 and 28 days.

## 5 Performance and Cost

The construction of the building was completed in August 2023. The overall construction cost of the building was £57,500, of which £11,500 corresponds to the additional PVC-s isolation system. When compared to a conventional building designed at the same site and with the same expected architectural requirements, this indicates a 20% cost increase. However, because the PVC-s isolation is expected to greatly reduce seismic forces, improve seismic performance, and minimize earthquake-induced damage and maintenance over the building's life cycle, the advantages of the isolation system are thought to outweigh the additional expense.

## 6 Conclusions

This work demonstrates the successful design and construction of the world's first building employing the low-cost, low-tech, PVC-sand (PVC-s) seismic isolation system. Implemented in a low-rise school in Kathmandu, the system proved to be a viable, economical, and easy-to-construct alternative to conventional isolation technologies, which are not feasible to be applied in this context. Despite a modest 15-20% increase in the construction cost, PVC-s significantly reduces seismic demand, as it limits the seismic energy transmitted to the superstructure by acting as a mechanical “fuse”. The use of local materials (sand and PVC sheets), common construction techniques, and alignment with detailed design guidelines and the Nepalese Seismic Code demonstrate the system's applicability. It is deemed that the PVC-s system enhances resilience for underprivileged communities where quality control and seismic code enforcement are often limited. Its successful implementation serves as a scalable model for improving earthquake safety in similarly vulnerable regions.

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