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# Feasibility of sliding base isolation for rubble stone masonry buildings in the Himalayan Mountain range

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This paper studied the feasibility of a sliding base isolation layer to be used in rubble stone masonry buildings in rural areas in the Himalayan Mountain range to provide robust protection to important building like schools against strong earthquakes. In this paper, we carried out on-site investigations, quasi-static tests, and shaking table tests focusing on constructability as well as isolation performance. From the results of the feasibility study, the combination of styrofoam, concrete slab, and grease was found to be the most feasible to be used as the upper element, the lower element, and the lubricant, respectively, in the sliding isolation layer. The key features of the present sliding base isolation layer are: 1) the use of the materials that exist in rural mountain areas or those that can be easily transported from the neighboring towns and cities and 2) ease of construction and minimal change from the current construction practice. From the shaking table tests, we identified the conditions, e.g., grease amount, grease type, normal stress at the interface, and roughness of concrete slab surface, to achieve dynamic friction coefficients ranging from 0.08 to 0.16, suitable for sliding base isolation.

## KEYWORDS

rubble stone masonry, sliding base isolation, friction coefficient, constructability, transportability, Himalayan Mountain range, rural areas, shaking table tests

## 1 Introduction

Rubble stone masonry is one of the most prevalent building types in rural areas in the Himalayan Mountain range. It is known that rubble stone masonry walls, shown in [Figure 1A](#), are prone to strong earthquakes ([Ali et al., 2013](#); [Wang et al., 2018](#)). In fact, a number of rubble stone masonry buildings experienced collapse or severe damage in the 2015 Nepal Gorkha earthquake ([Goda et al., 2015](#); [Wang et al., 2018](#)). Even after the 2015 Nepal Gorkha earthquake, however, rubble stone masonry is often the only option available in the rural mountain areas ([Bothara and Brzev, 2011](#); [Schildkamp and Araki, 2019a](#); [Schildkamp and Araki, 2019b](#)). The main reason for using rubble stone masonry is



FIGURE 1  
Examples of (A) rubble stone masonry wall and (B) road access to rural mountain areas.

the limitations of construction materials available in rural areas in the Himalayan Mountain range. The road access to such rural mountain areas is often narrow and bumpy as shown in Figure 1B. This makes it difficult to transport conventional pre-formed masonry elements like bricks and blocks from the nearby towns and cities because they may break during the transportation and because the transportation cost and time are high and long, respectively.

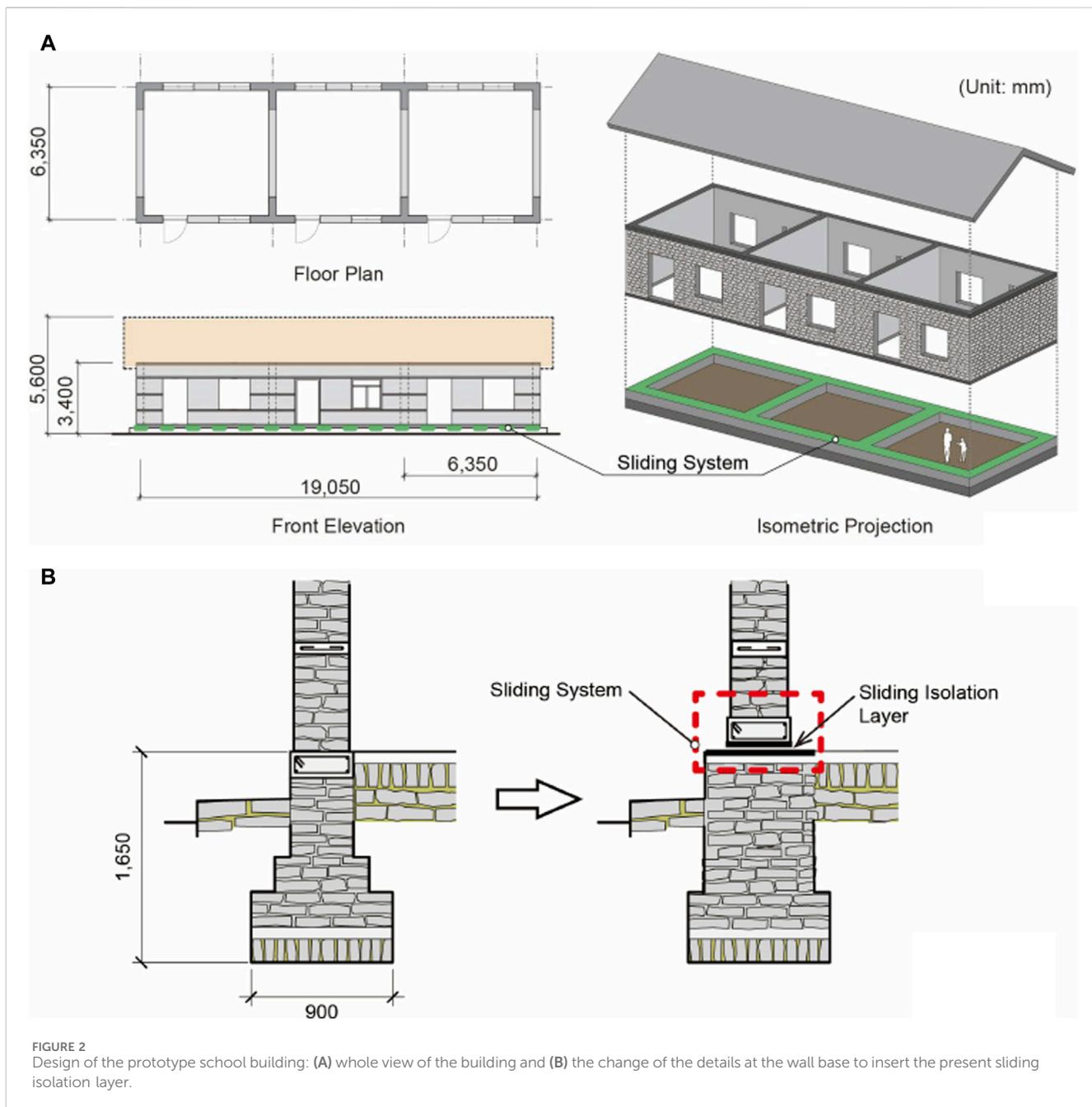
Considerable efforts have been made so far to enhance the seismic resistance of rubble stone masonry buildings. These efforts led to significant amount of literature on seismic design of rubble stone masonry buildings (Bothara and Brzev, 2011; Ali et al., 2013; Wang et al., 2018; Schildkamp and Araki, 2019a; Schildkamp and Araki, 2019b; Schildkamp et al., 2020; Schildkamp et al., 2021; Shrestha, et al., 2020; Parajuli, et al., 2020; Gautam et al., 2022; Khadka et al., 2023). While design and construction in accordance with such literature significantly reduce the risk of collapse or severe damage caused by strong earthquakes, uncertainty remains in their seismic resistance due to inherent variability in construction materials. Variability in skills of masons, who are often residents in rural mountain areas, is also a serious issue from the viewpoint of quality control.

It is well known that base isolation is an effective approach to protect buildings from strong earthquakes (Naeim and Kelly, 1999). Base isolation reduces seismic forces by placing an isolation layer at the interface between the superstructure and its foundation. Base isolation is attractive because it provides robust seismic protection to buildings. Base isolation is attractive also because no or minimal change is required in construction materials and processes of the superstructure. In the last decades, low-cost base isolation has attracted attentions in the earthquake engineering community to protect non-engineered buildings in low to middle-income countries and areas (Qamaruddin et al., 1986; Kelly, 2002; Nanda et al., 2016;

Tsiavos et al., 2021a; Tsiavos et al., 2021b; Ali et al., 2022; Galano and Calabrese, 2023; Md at el., 2023). Although such low-cost base isolation is effective in many countries and areas, the materials used at the isolation layer are often locally unavailable in the rural areas in the Himalayan Mountain range, where rubble stone masonry is the most frequently constructed type of buildings. Transportation of such isolation layer materials from the nearby towns and cities is also difficult, if not impossible.

The purpose of this paper is to present a low-cost sliding base isolation for rubble stone masonry buildings in rural areas of the Himalayan Mountain range to protect important buildings like schools from strong earthquakes. To prevent severe damage of collapse, it is most important to follow the guidelines and recommendations (Bothara and Brzev, 2011; Ali et al., 2013; Wang et al., 2018; Schildkamp and Araki, 2019a; Schildkamp and Araki, 2019b; Schildkamp et al., 2020; Schildkamp et al., 2021; Khadka et al., 2023) to construct the superstructure of the rubble stone masonry building, wherein proper reinforcement and use of cement mortar are crucial. In addition to these prerequisites for the superstructure, this paper attempts to provide more robust seismic protection by inserting a sliding isolation layer at the interface between the superstructure and the foundation. The key features of the present low-cost sliding base isolation are: 1) the use of the materials that exist in rural mountain areas or those that can be easily transported from the neighboring towns and cities, and 2) ease of construction and minimal change from the current construction practice.

In this paper, first, we present a prototype building, to which the present sliding base isolation is applied. The design of the prototype building and the sliding isolation layer is based on the results of the on-site investigations in rural mountain areas in Nepal performed by the authors in December 2017. Second, quasi-static tests were performed to determine the reduction of the friction coefficient

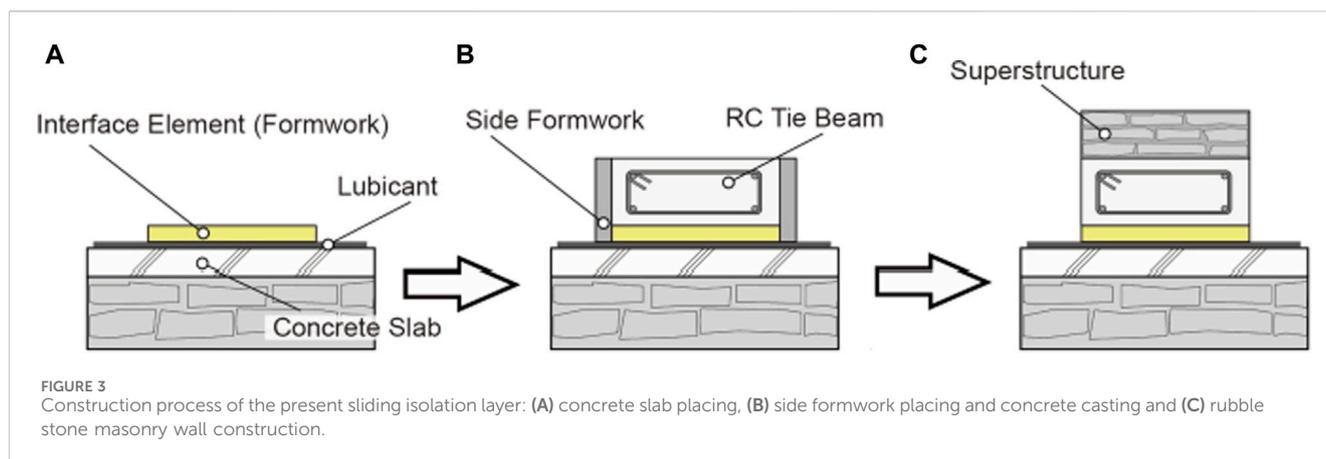


by using grease as a lubricant for several combinations of materials used in the sliding isolation layer. Third, shaking table tests were conducted to examine the performance of the present low-cost sliding isolation layer. Lastly, conclusions and recommendations for further study are provided.

## 2 Prototype building

Figure 2 illustrates a prototype school building to which the present low-cost sliding isolation is applied. We selected school as a prototype building because school buildings serve as a central facility to educate children, ensuring whose safety is of most importance, as well as a shelter for the community after strong earthquakes. The

prototype school building was designed based on our on-site investigation conducted in December 2017 as well as the experience of designing and constructing 19 schools performed by Thapa and Schildkamp during 2007–2012 in rural mountain areas in the middle west Nepal (Schildkamp and Araki, 2019a; Schildkamp and Araki, 2019b). The mountainous area where Thapa and Schildkamp built the school belongs to the Alpine-Himalayan belt, one of the most earthquake-prone regions in the world. Earthquakes in this area are caused by the movement of the Indian Plate toward the Eurasian Plate (Schildkamp et al., 2020). In the on-site investigation, we scrutinized the damage of school buildings designed and constructed by Thapa and Schildkamp caused by the 2015 Nepal Gorkha Earthquake. Interviews with the residents were also conducted to collect the information on the conventional



construction practice of school buildings in rural mountain areas and availability and transportability of construction materials. The results of the on-site investigation and the interviews with residents form the basis for developing the sliding isolation layer presented in this paper.

Conventional construction practice obtained through the interviews with the residents can be summarized as follows. Highly inaccessible terrain limits the transportation of construction materials and equipment. Stone masonry buildings built by residents are non-engineered. Large variations in the type and quality of construction exist, with no established norm for training the residents adequately. Furthermore, the stone masonry buildings use rubble stones rather than pre-formed block stones. The mortar in joints is made of mud or non-standardized aggregate, resulting in uncertain seismic strength. Such construction conditions pose serious difficulties in quantitative evaluation of seismic resistance of buildings.

To protect important buildings like schools, it is crucial to follow the guidelines and recommendations for rubble stone masonry buildings in the literature (Bothara and Brzev, 2011; Ali et al., 2013; Wang et al., 2018; Schildkamp and Araki, 2019a; Schildkamp and Araki, 2019b; Schildkamp et al., 2020; Schildkamp et al., 2021; Khadka et al., 2023), where the use of cement mortar and proper reinforcement are strongly recommended. In addition to these prerequisites for the superstructure, this paper attempts to provide more robust seismic protection to rubble stone masonry buildings by inserting a sliding isolation layer at the interface between the superstructure and the foundation as shown in Figures 2A, B. More specifically, the sliding isolation layer is placed at the interface between the reinforced concrete tie beam placed below the bottom end of the masonry wall and the concrete slab placed on the foundation. Large residual displacement induced by a strong ground motion is often a serious issue when sliding isolation is applied. Nevertheless, it was observed in our on-site investigation that rubble stone masonry building in rural mountain areas usually have enough space around the building to move, which allows us to use the building even after large residual displacement takes place. The present low-cost sliding base isolation layer incorporates the following two main features. Firstly, it utilizes materials found in rural mountain areas or readily transportable from nearby towns and cities. Secondly, it prioritizes

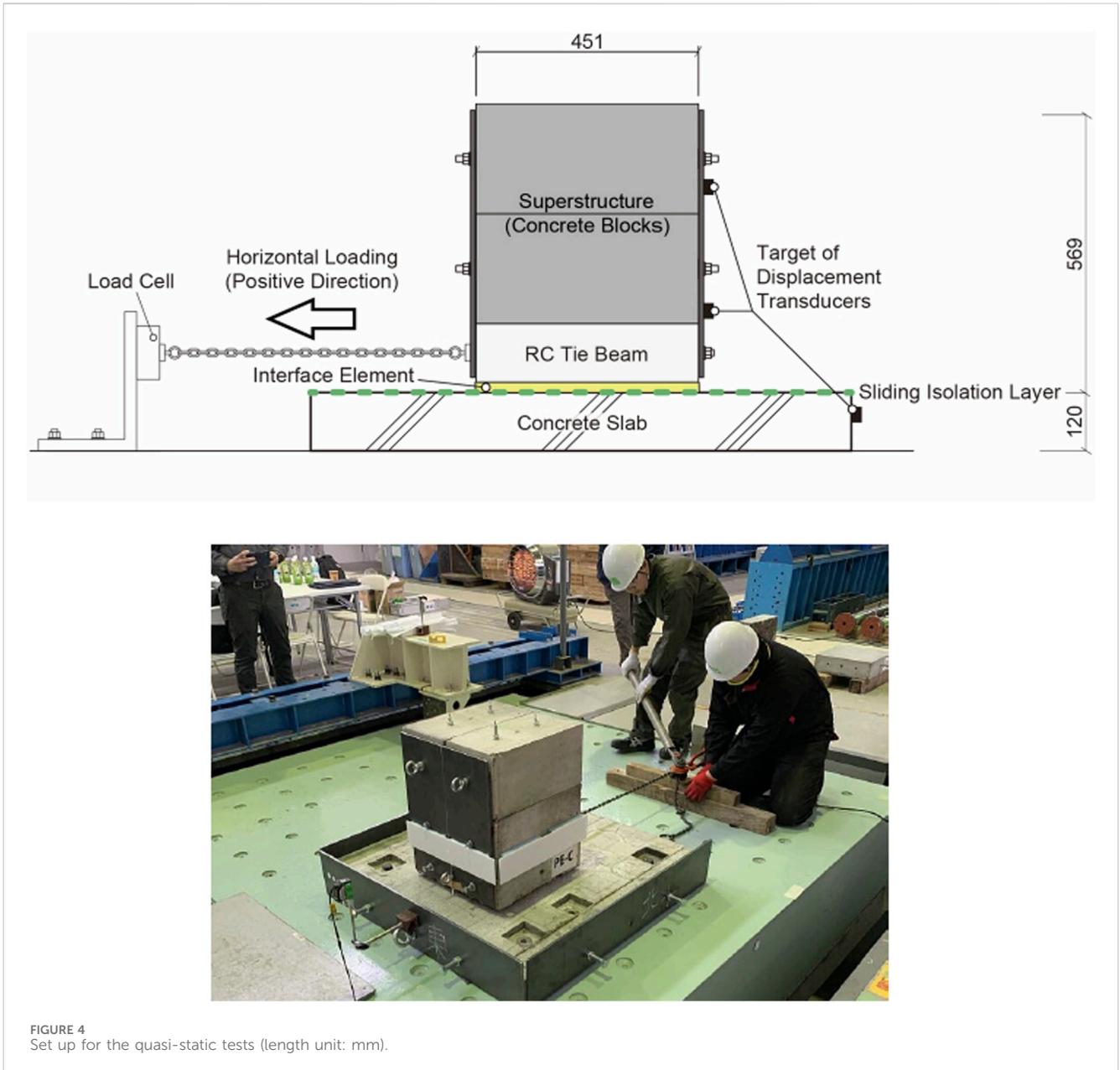
ease of construction and requires minimal deviation from the conventional building practices.

Figure 3 shows the construction process of the sliding isolation layer. As shown in Figure 3A, concrete slab is placed on the foundation. An interface element with a lubricant is placed on the concrete slab. The interface element serves as the upper sliding surface as well as the bottom formwork for the reinforced concrete tie beam. After placing the side formworks as shown in Figure 3B, concrete is cast into the formwork. After removing the side formwork, rubble stone masonry wall is built on the reinforced concrete tie beam as shown in Figure 3C. It is worth nothing here that the cost increase of introducing this sliding system is roughly estimated as less than 5%–15% of the overall building cost. This estimation is based on the cost study by Schildkamp and Araki (Schildkamp and Araki, 2019b) and on our on-site investigations and interviews.

## 3 QUASI-STATIC tests

### 3.1 Materials and methods

Quasi-static tests were performed to determine the static friction coefficients of the sliding isolation layer for several combinations of materials used in the sliding isolation layer. Figure 4 shows the experimental setup. The test specimen consists of three portions: a) foundation (concrete slab fixed to the floor), b) sliding isolation layer, and c) superstructure (concrete blocks). During the tests, the lowest temperature was 7°C. Vertical load was applied to the sliding isolation layer by the weight of the superstructure. The weight of the superstructure was 3.05 kN and the vertical compressive stress at the sliding layer was 14.4 kN/m<sup>2</sup>. This value corresponds to about 1/3 of the vertical compressive stress (49.3 kN/m<sup>2</sup>) at the sliding layer of the prototype building discussed in Section 2. A block chain was used to apply the horizontal forced displacement to the superstructure manually. As shown in Figure 4, the block chain was fixed to the floor. The end of the steel chain was fixed to the lower portion of the superstructure. Monotonic forced displacement was applied by shortening the steel chain using the chain block. The tensile force applied to the superstructure was measured by the load cell placed at the end of the steel chain. The displacement of the



superstructure relative to the concrete slab was measured by laser displacement transducers fixed to the concrete slab.

Styrofoam, marble, pebble stone, and concrete were used in the interface element that provides the upper surface of the sliding isolation layer. These materials are locally available in rural areas in the Himalayan Mountain range or can be transported easily from nearby towns or cities. The nominal material properties for the styrofoam (JIS A 9521 extruded polystyrene foam insulation) are as follows: density is more than  $25 \text{ kg/m}^3$ , thermal conductivity is less than  $0.034 \text{ W/m K}$ , compressive strength is more than  $20 \text{ N/cm}^2$ , and water absorption rate is less than  $0.01 \text{ g/100 cm}^2$ . The marble used in this test was a serpentine green marble with smooth finish mined in the state of Rajasthan in the Northern India. The diameter of the pebble stones produced in the Philippines ranged from 40 to 60 mm. The design strength of the concrete block and the concrete slab was  $24 \text{ N/mm}^2$ . The grease amount was  $1 \text{ kg/m}^2$ . The nominal

material properties of the grease (NIGURUBU MP-DX grease, Japan), called G\_JA in this paper, are as follows: drip point is  $200^\circ\text{C}$ , viscosity at  $25^\circ\text{C}$  is 238, NLGI consistency number is 3, evaporation ( $99^\circ\text{C}$  22 h) is 0.20%, oil separate rate ( $100^\circ\text{C}$  24 h) is 0.20%, oxidative stability ( $99^\circ\text{C}$  100 h) is 25 kPa, water washout ( $79^\circ\text{C}$  1 h) is 1.6%, and thickener is lithium soap.

### 3.2 Results and discussions

Figures 5A, B illustrate the relationship between the horizontal force  $F$  and the displacement of the superstructure relative to the concrete slab without and with grease, respectively. The letters in the caption of Figure 5 represent the combination of the materials used at the sliding interface, where M, PE, S, C and G represent marble, pebble stone, styrofoam, concrete, and grease, respectively. As

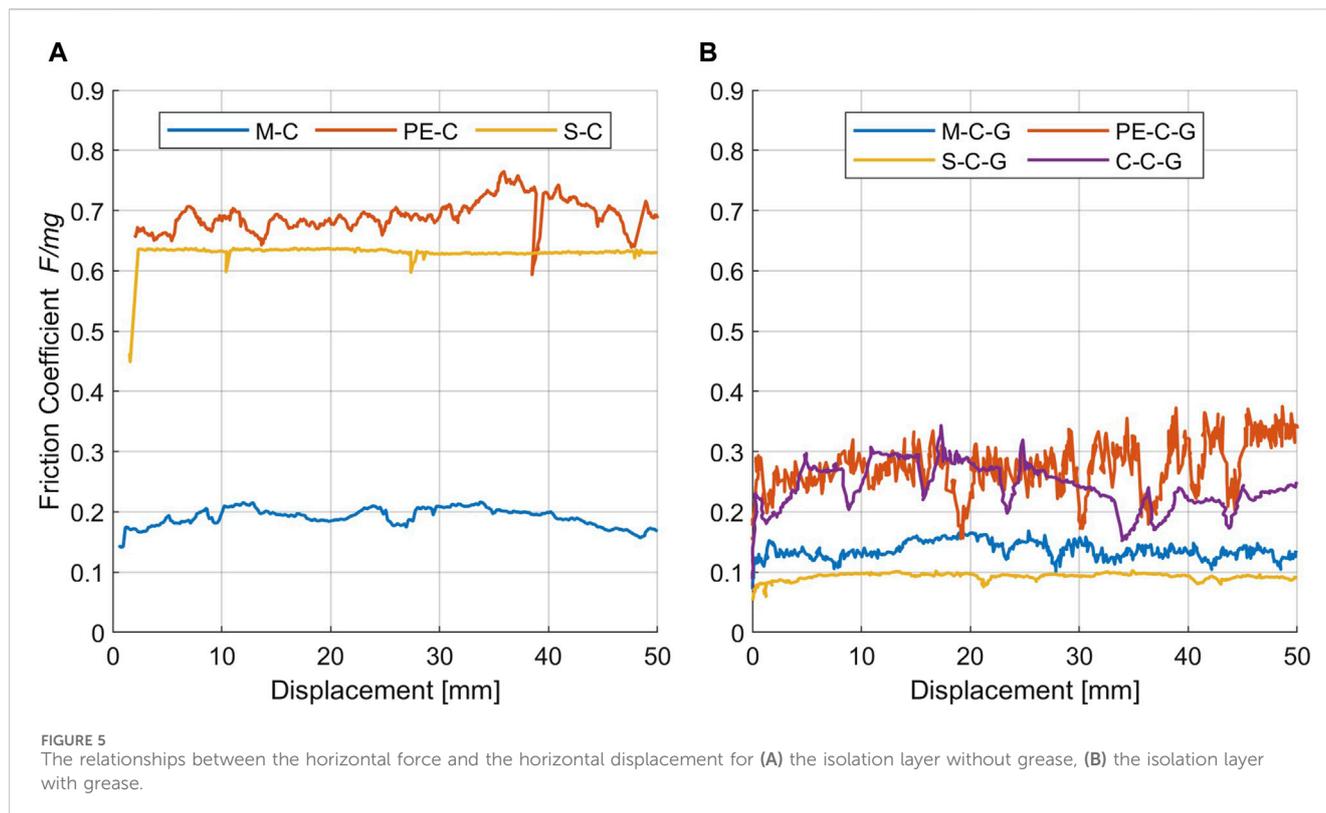


TABLE 1 The values of the static friction coefficient  $\mu_s$  obtained from the quasi-static tests.

Interface element		Styrofoam	Marble	Pebble stone	Concrete
Lubricant	None	0.64	0.22	0.77	>0.60*
	Grease	0.10	0.17	0.38	0.34

mentioned in Section 3.1, the value of the weight  $mg$ , where  $m$  is the mass and  $g$  is the gravity acceleration, of the superstructure was 3.05 kN. Table 1 summarizes the values of the static friction coefficient  $\mu_s$  obtained from the quasi-static friction tests. Here, the static friction coefficient  $\mu_s$  is defined by  $\mu_s = F_{\max}/mg$ , where  $F_{\max}$  is the maximum value of  $F$  during the tests in for each combination of the materials used in the sliding isolation layer. If grease was not used, the static friction coefficient suitable for sliding isolation can be obtained only when marble was used as the interface material. Note here that 0.6 is often used as the design value for the static friction coefficient between concrete and concrete. In contrast, styrofoam and marble can be used as the interface material if grease was applied.

## 4 Shaking table tests

### 4.1 Materials and methods

From the quasi-static tests conducted in Section 3, we identified that the static friction coefficient was low enough to be used in sliding isolation layers in the following 2 cases: 1) styrofoam and

concrete with grease and 2) marble and concrete with grease. As discussed in Section 2, light materials like styrofoam are highly desirable from the viewpoint of transportability from the nearby towns and cities to the rural mountain areas. In Section 4, therefore, a series of shaking table tests were conducted for the sliding layers consisting of the materials used in the former case, i.e., styrofoam and concrete with grease. In the shaking table tests, first, we determined a baseline condition and examined its isolation performance. Then, we studied the influences of the variations in the materials and loading conditions on the isolation performance.

Figure 6 shows the setup of the shaking table tests. Steel plates were used to change the weight of the superstructure. The superstructure was supported by two interface elements located at both ends of the superstructure. The concrete slab was fixed to the shaking table. Steel guide plates with Teflon sheets were placed at both sides of the superstructure to restrict the direction of motion in one direction. Input base motion was applied to this direction of motion using the shaking table. Accelerometers were placed on the superstructure and the concrete slab. The absolute displacements of the superstructure and the concrete slab were measured using the laser displacement transducers placed on the ground. The relative displacement between the superstructure and the concrete slab was

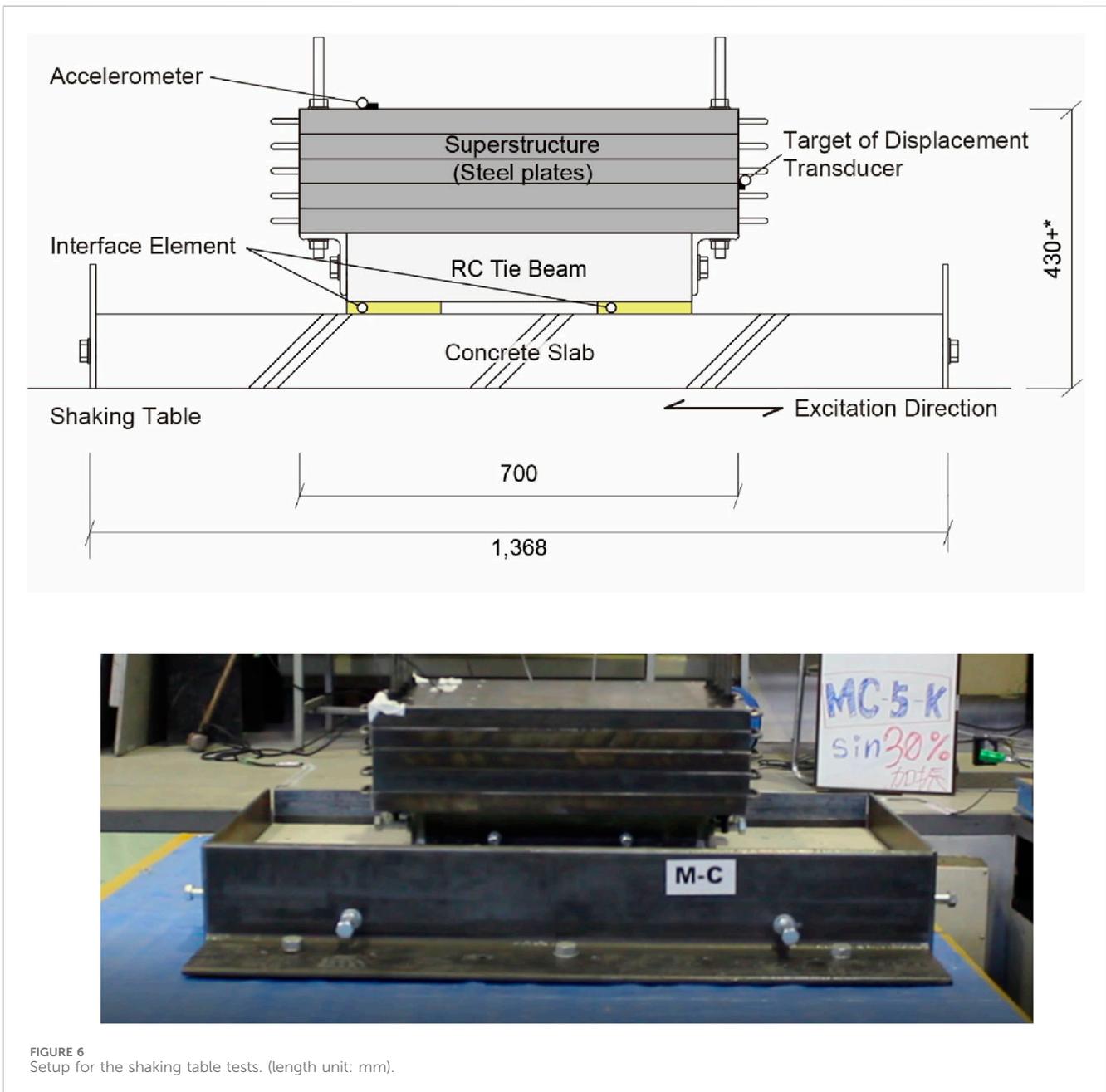


FIGURE 6  
Setup for the shaking table tests. (length unit: mm).

obtained by subtracting these absolute displacements. The lowest temperature during the shaking table tests was 9 °C.

The baseline conditions for the shaking-table tests were determined from the results of the preliminary shaking table tests, the discussions made in Section 2 to design the prototype building, and the results of the quasi-static tests performed in Section 3. As discussed at the first of this section, the combination of the materials used for the interface element and the lubricant were styrofoam and grease, respectively. The baseline value of the grease amount was determined in the preliminary shaking table tests so that sufficient grease remained on the concrete slab surface after applying a couple of harmonic excitations. The results of the preliminary shaking table tests suggested the grease amount of 600 g/m<sup>2</sup>. For reference, the grease amount

applied in the quasi-static tests was 1 kg/m<sup>2</sup>, which were determined by trial and error. The compressive stress at the sliding isolation layers was set to 53.4 kN/m<sup>2</sup> by placing five steel plates to the superstructure. This value is slightly higher than 49.3 kN/m<sup>2</sup>, which corresponds the compressive stress at the sliding isolation layer of the prototype rubble stone building as discussed in Section 2. The same grease, whose details were given in Section 3, was used as the baseline material for the lubricant. A formwork with a smooth surface was used to cast the concrete slab to obtain very smooth surface at the upper side of the concrete slab. Harmonic excitations of 1.5 Hz were applied as the input base. The frequency of the harmonic excitations was determined from the results of the preliminary tests so that sliding of the specimen was stable up to 1 g excitation. In



**FIGURE 7**  
Preparation of a rough upper surface for the concrete slab by troweled finish.

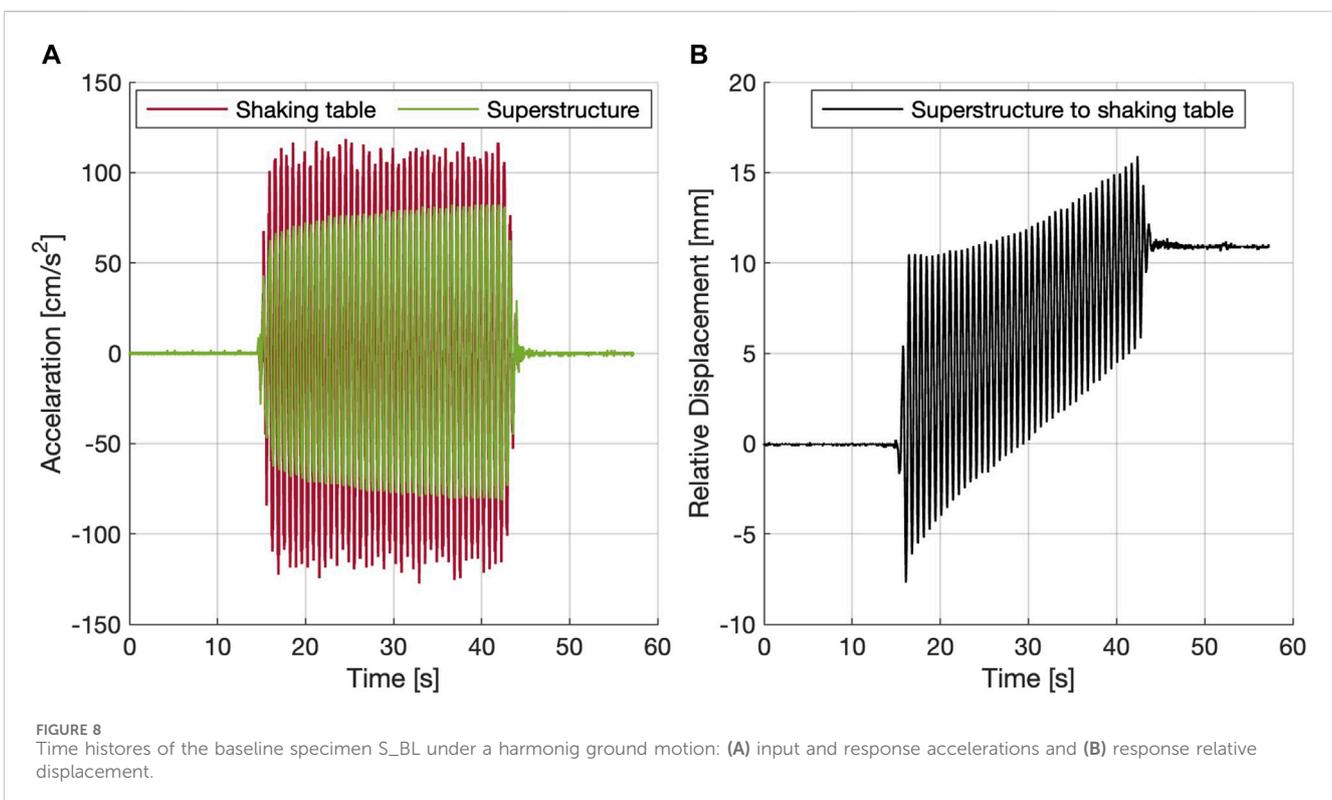
each case, the acceleration amplitude was increased with an increment of  $0.5 \text{ m/s}^2$  until the superstructure began to slide.

After conducting the shaking table test using the baseline condition, a series of the shaking table tests were conducted to investigate the influence of the following five factors on the isolation performance: a) the grease amount, b) the grease type, b) the vertical compressive stress, d) the surface conditions of the concrete slab, and e) the types of input base motions. To examine the influence of the grease amount, 5 cases of grease amounts ( $100 \text{ g/m}^2$ ,  $200 \text{ g/m}^2$ ,  $300 \text{ g/m}^2$ ,  $400 \text{ g/m}^2$ ,  $500 \text{ g/m}^2$ ) were applied. To study the influence of the vertical

compressive stress at the sliding isolation layer, the number of the steel plate was reduced from five to 3, which corresponds the compressive stresses  $34.7 \text{ kN/m}^2$ , resulted in 35% reduction from the baseline value. To investigate the effect of the grease type, two additional types of grease, produced in India and widely available in Nepal, were used. The physical properties of the Indian greases, called G\_IND1 and G\_IND2 in this paper, were as follows: drip point was  $240 \text{ }^\circ\text{C}$  and  $180 \text{ }^\circ\text{C}$ , viscosity at  $25 \text{ }^\circ\text{C}$  was 280 and 220–250, NLGI consistency number was 2.5 and 3, and thickener was lithium complex soap and lithium system, respectively. To study the influence of the variations in the roughness of the upper surface of the concrete slab caused by masons' skills, a relatively rough surface was prepared using a wooden trowel as shown in Figure 7. To examine the influence of input motion, the 1940 EL Centro N–S record was employed as an earthquake ground motion. The ground motion record is most widely available and was selected to use in this paper to obtain the results that can be easily compared with the results of existing and future studies.

## 4.2 Results and discussions

Figure 8 shows the result of the shaking table test for the baseline specimen S\_BL. From Figure 8A, reduction of acceleration can be clearly observed. Define the dynamic friction coefficient  $\mu_D$  by  $\mu_D = a_R/g$ , where  $a_R$  is the maximum absolute response acceleration of the superstructure and  $g$  is the gravitational acceleration. Then, the dynamic friction coefficient  $\mu_D$  can be obtained as 0.08 from



**FIGURE 8**  
Time histories of the baseline specimen S\_BL under a harmonic ground motion: (A) input and response accelerations and (B) response relative displacement.

TABLE 2 Dynamic friction coefficient  $\mu_D$  obtained from the shaking table tests.

Specimen	Grease		Vertical stress (kN/m <sup>2</sup> )	Concrete slab surface	Input motion	Dynamic friction coefficient
	amount (g/m <sup>2</sup> )	type				
S_BL	600	G_JA	49.3	very smooth	harmonic	0.08
S_GA	500	*	*	*	*	0.10
	400					0.08
	300					0.10
	200					0.24
	100					0.75
S_GT	*	G_IND1	*	*	*	0.10
		G_IND2				0.24
S_VS	*	*	34.7	*	*	0.11
S_CSS	*	*	*	smooth	*	0.12
S_IM	*	*	*	*	earthquake	0.16
S_IM-CSS	*	*	*	smooth	earthquake	0.16

\* Same value as the baseline specimen S\_BL.

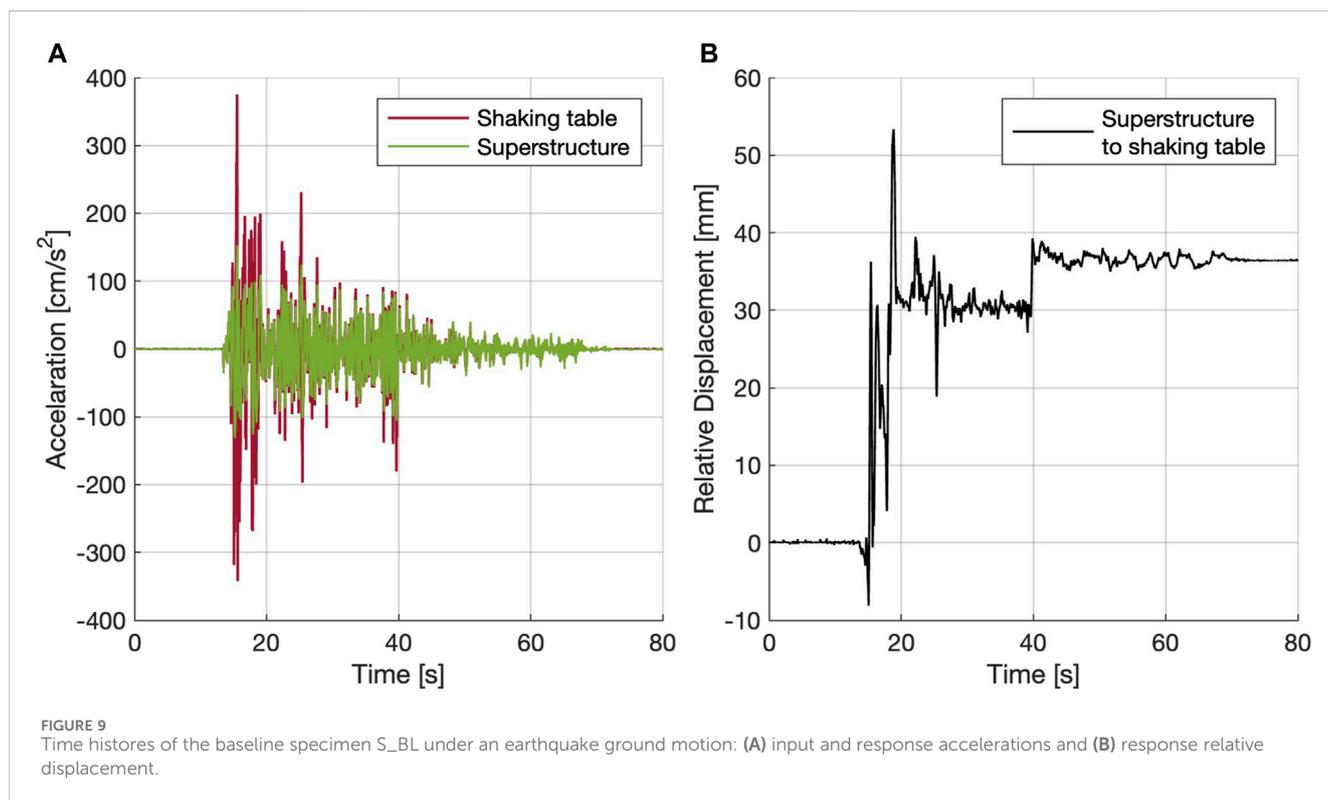


FIGURE 9 Time histories of the baseline specimen S\_BL under an earthquake ground motion: (A) input and response accelerations and (B) response relative displacement.

Figure 8A. The relative displacement of the superstructure to the shaking table accumulated in one direction as shown in Figure 8B. It is well known that such accumulation of relative displacement can be observed in dynamic friction responses under harmonic base excitations.

Table 2 summarizes the dynamic friction coefficient  $\mu_D$  obtained from the shaking table tests. The observations and discussions made for each specimen are as follows.

- All specimens: Basically, the acceleration and displacement responses of the specimens were similar to those of Specimen S\_BL, the baseline specimen, if sliding took place under harmonic excitations.
- S\_GA: Grease amount was changed. It can be identified that 300 g/m<sup>2</sup> is the minimum grease amount to obtain enough isolation performance. Increasing the grease amount above this value did not enhance the isolation performance.

- S\_GT: Grease type was changed. Relatively larger acceleration was observed for one Indian grease S\_GT2 while enough isolation performance comparable to the baseline specimen S\_BL was obtained for the other Indian grease S\_GT1. It is difficult to explain the difference from the nominal physical properties like viscosity. This result suggests the importance of obtaining dynamic friction coefficients from physical tests before applying grease to practical applications.
- S\_VS: Vertical stress at the sliding interface layer was changed. It can be seen that 35% reduction of the vertical stress did not change the isolation performance. This result demonstrated the robustness of the present sliding isolation layer against the variation of the weight of the superstructure.
- S\_CSS: It can be observed that relatively rougher concrete slab surface did not change the isolation performance significantly. This suggests that the construction practice available in rural mountain areas can be applied to smoothen the upper side of the concrete slab without compromising isolation performance.
- S\_IM: The specimen was subjected to an earthquake ground motion. It was observed that the dynamic coefficient was about 2 times higher than those obtained from the shaking table tests using harmonic excitations. **Figures 9A,B** show the time histories of the responses. One possible explanation for the larger dynamic coefficient is viscosity of grease. It appears that frequency components of the input motion higher than the frequency of the harmonic excitations resulted in higher frequency response, which led to the increase of the dynamic friction coefficient. It is known that the displacement response has a random nature when sliding isolation layer is inserted (Hu et al., 2020). These results suggest that shaking table tests using a variety of ground motion records and synthetic ground motions, including those with larger peak ground accelerations, are necessary for properly assessing the isolation performance of the sliding isolation layer using grease.
- S\_IM\_CSS: The specimen with the rougher concrete slab, the same concrete slab surface as S\_CSS, was subjected to the same earthquake ground motion as S\_IM. The following two observations, which were similar to S\_IM and S\_CSS, can be made: 1) The relatively rough concrete slab surface did not change the isolation performance significantly. 2) The dynamic coefficient was higher than those obtained from the shaking table tests using harmonic excitations. These results support the discussions made for both S\_CSS and S\_IM.

## 5 Conclusion

This paper studied the feasibility of sliding isolation layers to be used in rubble stone masonry buildings in rural mountain areas in the Himalayan Mountain range to provide robust protection to important building like schools against strong earthquake ground motions. In the feasibility study, on-site

investigations including interview survey to residents, quasi-static tests, and shaking table tests were carried out. From the feasibility study, the combination of styrofoam, concrete slab, and grease as the upper element, the lower element, and lubricant, respectively, was found to be the most feasible to be used in the sliding isolation layer. The key features of the present low-cost sliding base isolation are: 1) the use of materials that exist in rural mountain areas or those that can be easily transported from the neighboring towns and cities and 2) ease of construction and minimal change from the conventional construction practice. From the quasi-static and dynamic friction tests, we identified the conditions, e.g., grease amount, grease type, vertical stress, roughness of concrete slab surface, and input motions, to obtain dynamic friction coefficient ranging from 0.08 to 0.16 to be used in sliding isolation layer. It should be noted that the focus of this paper was placed only on the constructability and the isolation performance at the initial stage during the whole life cycle of the building. Among many factors, durability of grease is an important issue that needs to be addressed. Placing grease exclusively at closed spaces like the sliding interface is anticipated to mitigate degradation risks caused by factors such as exposure to ultraviolet rays from sunlight and contamination by dirt or debris. Investigation by the authors is underway on the long-term performance to address this issue.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Author contributions

YS: Writing—original draft, Writing—review and editing, Investigation. MT: Data curation, Project administration, Writing—review and editing. RE: Data curation, Writing—review and editing, Methodology. JT: Methodology, Writing—review and editing, Conceptualization, Investigation, Project administration. YA: Investigation, Writing—review and editing, Funding acquisition, Writing—original draft. SP: Investigation, Writing—review and editing, Conceptualization, Methodology. SL: Conceptualization, Investigation, Methodology, Writing—review and editing. KI: Conceptualization, Investigation, Methodology, Writing—review and editing. JG: Methodology, Writing—review and editing, Data curation. KS: Methodology, Writing—review and editing, Investigation. IF: Methodology, Writing—review and editing, Data curation. TM: Methodology, Writing—review and editing, Conceptualization, Funding acquisition, Project administration, Supervision.

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