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EXPERIMENTAL DETERMINATION OF KINETIC FRICTION FOR LOW-COST PVC-SAND-PVC SEISMIC ISOLATION SYSTEMS

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Abstract: This paper aims to experimentally determine the kinetic friction coefficient at the interface of a PVC-sand-PVC seismic isolation system using a uniaxial small-scale shaking table. The adoption of cost-effective and environmentally friendly seismic isolation methods in low-rise constructions has become increasingly essential, given the cost and implementation challenges of seismic isolation in low-income countries. The experiments were conducted to assess the variation in friction characteristics under nominal vertical stress levels of 5-10-15 kPa, representing the expected range at the foundation level for low-rise buildings. These tests were performed at sand surface densities of 1 kg/m^2 and 2 kg/m^2 under both dry and submerged conditions. Correlations were established between the kinetic friction coefficient, grain density, vertical pressure, and degree of saturation. The research demonstrates that the range of fluctuation in the kinetic friction coefficient is sufficiently limited, ensuring the effectiveness of the developed system, even in submerged conditions.

1 Introduction

The vulnerability of structures to seismic motion continues to result in significant casualties in earthquake-prone countries, particularly in low and middle-income economies. The Türkiye –Syria earthquake sequence (dual earthquakes of M_w=7.5 and M_w=7.8) resulted in enormous casualties of 50,000 lives in Türkiye and 8,000 lives in Syria on February 6, 2023. It is crucial to ensure the design and construction of earthquake-resistant structures to mitigate seismic risk.

The main principle of seismic isolation systems is to limit the transfer of seismic energy to the superstructure, thereby reducing its seismic demand and associated damage during an earthquake. The earliest use of this technique dates to systems developed by Touaillon (1870) and Bechtold (1906) in the late nineteenth and early twentieth centuries. These pioneering seismic isolation systems consisted of double concave ball bearings, in the form of a friction pendulum sliding isolator or of a rigid base plate system that was able to slide over solid spheres, respectively. Seismic isolation systems have started to be conceptualised as seismic energy dissipating mechanisms for buildings and infrastructures since the 1970s (Skinner et al,1974). In New Zealand, lead rubber bearings were developed and tested by Robinson and Tucker (1981) to protect one building and three bridges from earthquakes. Zayas et al. (1989) reported on the analytical and experimental performance of a friction pendulum device designed to enhance the seismic performance of structures. The behaviour and principles of double concave friction pendulum isolator were later studied by Fenz and Constantinou (2006) and others. This isolator has two different friction coefficients, which are slightly distinct for the double surfaces. Apart from being widely used in structures such as bridges and viaducts to enhance infrastructure resilience, the invention of seismic protection systems is increasingly being applied in structures like hospitals and schools to ensure continued functionality. Other facilities with a high seismic level of importance such as power plants, communication centres, fire brigades, and other critical post-disaster infrastructure can remain fully operational throughout their lifespan, thanks to cutting-edge seismic isolators, even in the aftermath of major earthquakes.

Utilising cost-effective base isolation techniques has become challenging for large portfolios of buildings with ordinary importance, due to the associated high costs and technology required. Pre-earthquake retrofit methods are now widely applied, but they typically require significant expertise and quality control procedures that may not be feasible at a large scale. Along these lines, recent research aims to devise low-cost base isolation solutions for enhancing at a reasonable cost, labour, and effort, the seismic performance of buildings in low and middle-income economies, including soil-rubber mixtures and PVC-sand-PVC configurations, and other promising techniques. Tsang et al. (2012) conducted numerical modelling using granulated scrap tires with a soil mixture around the foundation level as a low-cost GSI system. The results of the parametric study indicated that the rubber-soil mixtures-foundation-structure system experiences an average reduction of 40-70% in the horizontal acceleration of the footing and first-floor drift. Kuvat and Sadoglu (2020) carried out cyclic and monotonic triaxial tests on bitumen-sand mixtures for their cost effectiveness and high damping capacity for GSI applications. The shear modulus and damping ratio of the alternative GSI system were evaluated to be 2 and 1.5 times greater than those of rubber-sand blends, respectively. A scaled model of a prototype masonry structure was tested for seismic excitation using sand-rubber mixtures under strip foundations by Yin et al. (2022).

A low-cost seismic isolation practice was investigated for low-rise buildings by Li Lee (1987). It involved spreading rounded and sieved sand in a thin layer between two smooth marble plates beneath brick walls and with the coefficient of friction being measured around 0.2 from shaking table tests. The sand-rubber mixture layers were experimentally investigated with a timber interface also by Tsiavos et al. (2019). A winged direct shear apparatus was utilised to measure quasi-static friction, and angle of friction in the experimental setup, while a uniaxial shake table facility was used to conduct the kinetic frictional feature at the University of Bristol. Tsiavos et al. (2020) proposed an optimal sand surface density in the range of 0.04- 0.75 kg/m^2. Within the framework of the GCRF-funded SAFER Project, a comprehensive experimental campaign focusing on enhancing the seismic safety and resilience of schools in Nepal. In this framework a dual PVC sheet system was introduced encapsulating by a thin layer of sand. Non-perfectly rounded sand grains, acting like spherical ball bearings, help to reduce the resistance against between the two PVC surfaces. This system has the advantage of managing the response of the building by controlling the coefficient of kinetic friction, typically varying between 0.18 and 0.26 for the sliding interfaces for the tested condition.

Despite the advantages of the above system, uncertainties persist regarding the range of variation of the kinetic friction coefficient, which is one of the most critical parameters of the sliding layer interface. As a continuation of the previous study on the quasi-static friction coefficient Sezer et al. (2023), research experiments were conducted on the kinetic friction coefficient, scrutinising the results. Therefore, the objective of this study is to experimentally explore the variability of kinetic friction coefficients under increasing earthquake intensity and its impact on the performance of the PVC-sand-PVC seismic isolation system.

2 Experimental equipment, materials, and programme

2.1 Experimental setup

A uniaxial small-scale shaking table setup has been employed for the determination of kinetic friction of the sandwich PVC-Sand-PVC system, as illustrated in Figure 1. The sandwich PVC-Sand-PVC system was mounted on theshaking table, consisting of an acrylic platform actuated through an electromagnetic actuator controlled using a Matlab & Simulink (2012a) modelling environment. The bottom PVC sheet was securely fastened to the acrylic platform, while a rigid lead block was securely attached to top PVC sheet. The weight of the rigid block was chosen to match the desired vertical stress σ_v in the system, as depicted in Figure 1.

The direction of movement of the shaking table is denoted as Y-direction, while X represents the perpendicular horizontal direction. The system was equipped with a linear variable displacement transducer (LVDT) to monitor the movement of the shaking table along the Y-direction. Additionally, a laser dropper vibrometer (LDV) was used to measure the vibration velocity and displacement of the rigid block. Two accelerometers were placed on the rigid block and base acrylic platform in the plane of motion of the shaking table (Y-direction). Displacement characteristics were determined from the laser's response time, facilitated by a reflective tape attached to the rigid block. All transducers were connected to a data acquisition system linked to the dSPACE software, enabling precise control of the shaking table motion.

The sandwich PVC-sand-PVC system featured a bottom sheet with dimensions of 233 mm (Y-axis),125 mm (X-axis), and a square upper PVC sheet with dimensions 100 mm x 100mm. This configuration enables the top surface to move relative to the bottom PVC sheet.

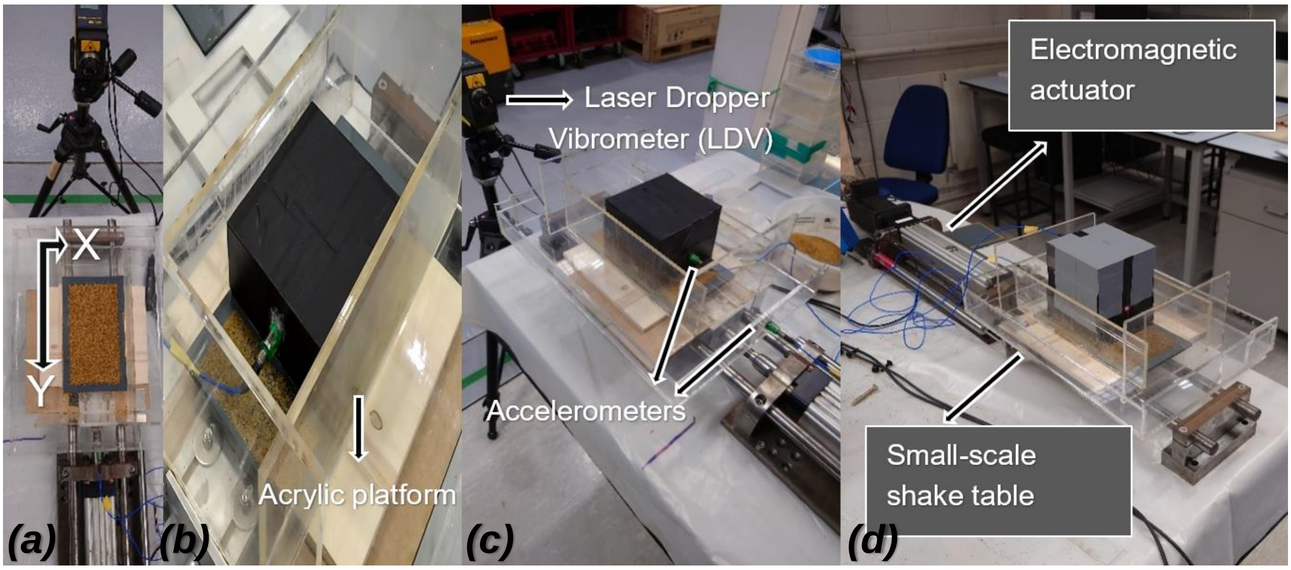
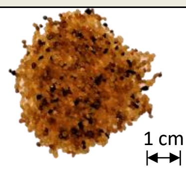


*Figure 1. **(a)** Plan view of the uniaxial shaking table and the rigid blocks corresponding to **(b)** 5 kPa**(c)** 10 kPa (**d)**15 kPa vertical stress level (σ_v).*

2.2 Materials

Unplasticised Polyvinyl Chloride (uPVC) and Leighton Buzzard (LB) sand were utilised for all the tests. LB sand, known for providing the most uniform results in quasi-static tests Sezer et al. (2023), was employed in this research. LB sand was selected for its uniformity, a subrounded particle shape, fractional characteristics. The median particle size (D_{50}) for LB sand is 0.889 mm. Other properties of the LB sand are summarised in Table 1.

Table 1. Properties of the tested Leighton Buzzard (LB) sand

Sand type	Source	D_{50} *(mm)*	Coefficient of uniformity *$Cu = D_{60}/D_{10}$*	Coefficient of Curvature *$C_c = (D_{30})^2/D_{60} \times D_{10}$*	Grain shape	Photographs
Leighton Buzzard (LB) sand	UK	0.889	1.445	0.960	Subrounded	

Notes: (1) DX refers to the sand particle size (diameter) at which x% of the material is finer

(2) Adapted from Sezer et. al.(2023) Experimental determination of friction at the interface of a sand-based, seismically isolated foundation

The thickness of the uPVCs used in the tests was 5 mm. Shore D hardness tests were conducted using a durometer, revealing that the uPVC had a hardness rating of 85 out of 100. A higher hardness value on a scale from 0 to 100 indicates a harder material.

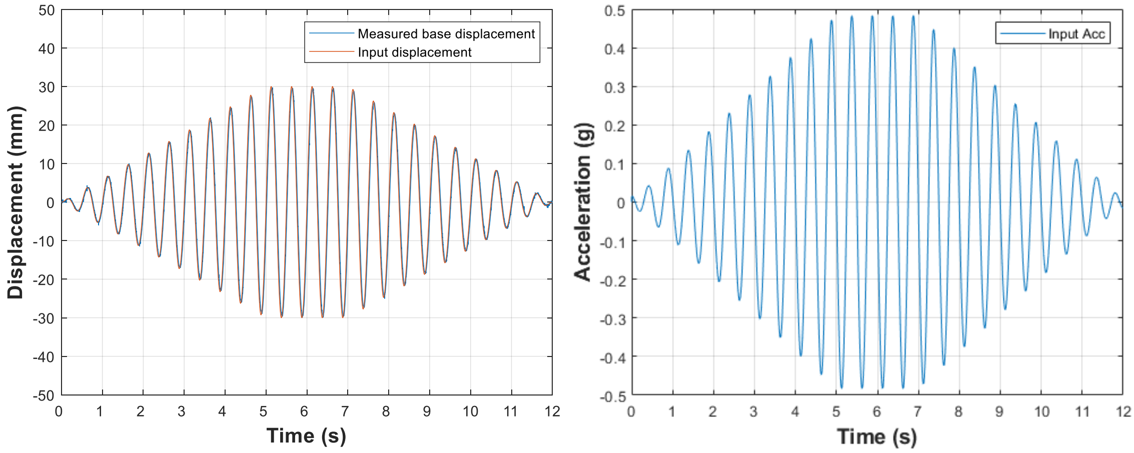
2.3 Testing programme

The experimental testing programme comprised a total of 4 tests, initially focusing on assessing the repeatability of the experimental results (RT tests). Subsequently, an additional 11 tests were conducted to investigate the effects of vertical stress and the amount of sand on the kinetic friction of the PVC-sand-PVC sandwich system. The quantity of sand used was determined by the surface density (ρ_S), as defined in Eq. (1):

$$\rho_S = \frac{M_S}{A} \quad (1)$$

where M_S represents the mass of the LB sand, and A is the upper PVC surface area. Two sand surface densities (1 kg/m^2 and 2 kg/m^2) were employed. Three rigid blocks, with masses of 5.1 kg, 10.2 kg, and 15.3 kg, were placed on the top of the upper PVC to impose the desired vertical stress level (σ_v) of 5 kPa, 10 kPa and 15 kPa, which corresponds to the range expected at the foundation level for one or two storey buildings.

In the test abbreviation, the number following 'T' represents the sand surface density (ρ_S), the subsequent number indicates the applied vertical stress (σ_v), and the last letter indicates whether the environmental condition is dry (D) or submerged (S).



(a) ***(b)***

Figure 2. Loading sequence in the experiment ***(a)*** *measured base and input displacements of the ground motion* ***(b)*** *acceleration input of the ground motion.*

A series of fifteen dynamic tests were conducted using the ramped sine wave depicted in Figure 2.The loading sequence of the experiment involved applying a ramped sinusoidal input displacement of the ground motion, as illustrated in Figure 2a and defined in Eq.2. The ramped sinusoidal seismic wave had a maximum amplitude (Amp) of 30 mm, corresponding to 0.483 g in the plane of motion of the shaking table along the Y axis, as shown in Figure 2b. The dominant frequency (f) of the ground motion remained steady throughout the experiment at a value of 2 Hz. The ascending ramp sine wave persisted for 5 seconds, remained constant between 5 and 7 seconds, and then descended between 7 and 12 seconds. The input ground displacement (IGD) was determined using by Eq. (2):

$$IGD = Amp \times sin(2\pi \times f)) \quad (2)$$

3 Initial test results: system checking and repeatability tests

3.1 Validation of acceleration measurements

The accurate determination of the acceleration of the upper PVC sheet-block system is of utmost importance for identifying the kinetic friction of the sandwich PVC-sand-PVC system. Acceleration can be directly measured from the accelerometer reading or inferred by double derivation of the displacement measured by the laser dropper vibrometer (LDV).

Figure 3 presents a comparison of the accelerations measured for test T_1_10_D determined using the two abovementioned methods. The accelerometer measured the direct motion of the rigid block (RB), while the

LDV was used to check and gain confidence in the acceleration time history response of the RB in Figure 3. It is observed that the matching between the two methods is acceptable.

Table 2. Phase 2: List of tests and main results

Test No	Test Name	Sand surface density ρ_s (kg/m²)	Vertical stress level of the RB σ_v (kPa)	Kinetic friction coeffi-cient μ_k (-)	Average RB displace-ment d_{avg} (mm)	Standard deviation of the kinetic friction SD (-)	Coeff. of variation of the kinetic friction CV (-)	Max. RB dis-place-ment d_{max} (mm)	Max. RB accel-eration a_{max} (g)
1R	1RT_1_5_D	1	5	0.2552	17.94	0.0196	0.0767	20.12	0.282
2R	2RT_1_5_D	1	5	0.2518	17.71	0.0201	0.0801	20.61	0.281
3R	3RT_1_5_D	1	5	0.2485	17.77	0.0337	0.1367	21.32	0.293
4R	4RT_1_5_D	1	5	0.2497	17.21	0.0198	0.0795	20.53	0.282
5	T_1_10_D	1	10	0.1872	13.18	0.0101	0.0540	14.67	0.209
6	T_1_15_D	1	15	0.1864	13.12	0.0115	0.0612	15.20	0.221
7	T_1_5_S	1	5	0.1908	14.00	0.0171	0.0894	15.49	0.208
8	T_1_10_S	1	10	0.2030	14.28	0.0152	0.0750	16.01	0.229
9	T_1_15_S	1	15	0.2252	15.62	0.0164	0.0727	17.50	0.253
10	T_2_5_D	2	5	0.1788	10.16	0.0308	0.1722	16.11	0.217
11	T_2_10_D	2	10	0.1763	12.20	0.0127	0.0720	13.97	0.207
12	T_2_15_D	2	15	0.1800	12.64	0.0106	0.0591	15.34	0.201
13	T_2_5_S	2	5	0.2070	14.88	0.0231	0.1116	16.89	0.230
14	T_2_10_S	2	10	0.2374	13.18	0.0356	0.1500	21.32	0.293
15	T_2_15_S	2	15	0.2383	16.55	0.0134	0.0563	18.87	0.260

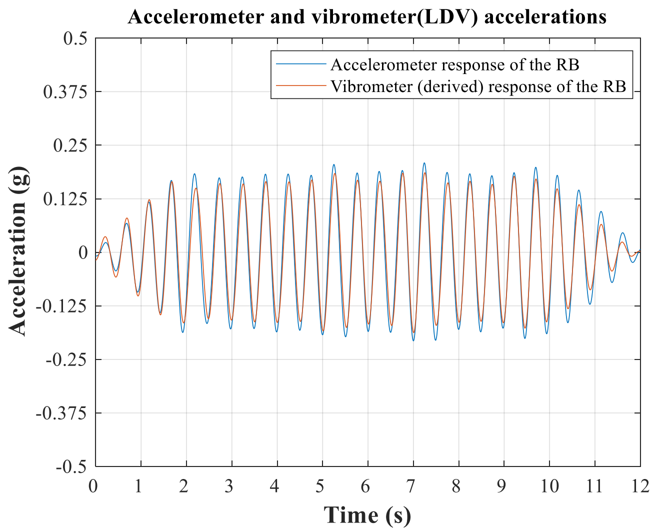


Figure 3. Comparison of accelerometer and laser dropper vibrometer (LDV) acceleration time history response of the rigid block (RB) for uPVC-LB sandwich test at a surface density of 1 kg/m² and vertical stress level of 10 kPa- Dry.

3.2 Repeatability of experimental results

Testing four samples under the same conditions was performed to evaluate and verify the repeatability of the experimental procedure (RT_1_5_D). The results are presented in Figure 4, illustrating the acceleration response of the rigid block. The acceleration response history can be divided into two phases based on the experimental findings. Phase 1 is characterized by a duration of approximately the first and last 2-3 seconds, during which the displacements and accelerations of both the ground and the rigid block coincide. When the acceleration response of the rigid block are not surpassed by the ground motion (GM) acceleration, the sliding mechanism is not activated, and the system is deemed as moving with the ground. Phase 2 demonstrates the mobilisation of the seismic isolation, as the acceleration of the rigid block is significantly lower and relatively constant compared to the ground motion input. Therefore, the absolute mean value of the local maxima and minima during Phase 2 (the period when the upper PVC sheet-block system slides with respect to the lower PVC) were used to determine the kinetic friction coefficients (μ_k) from the acceleration response history.

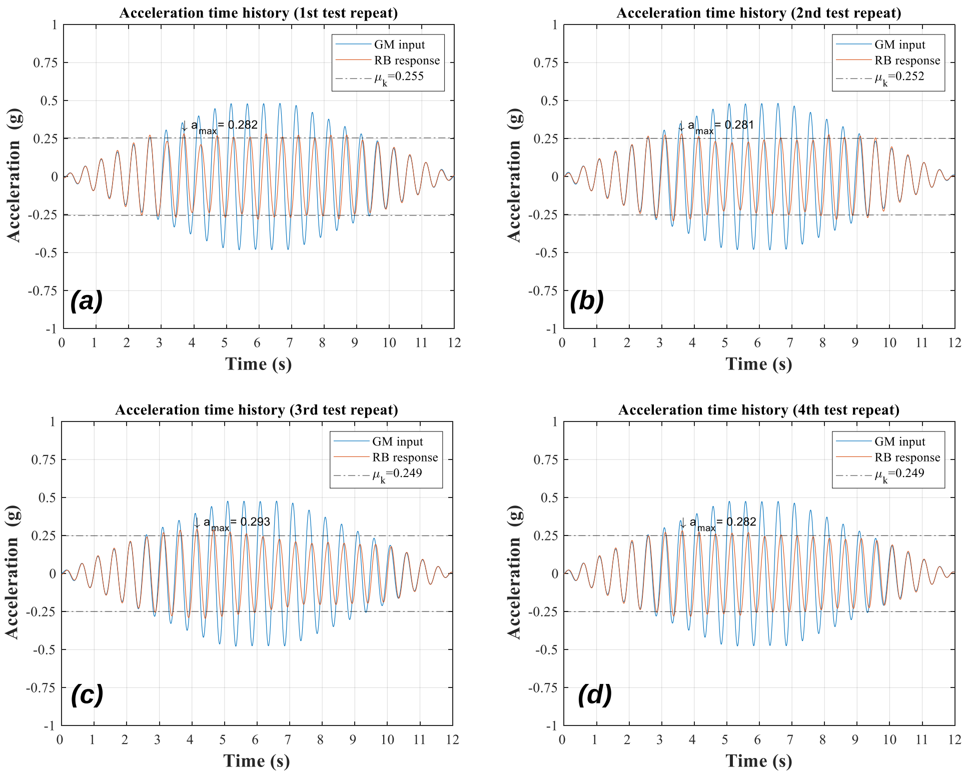


Figure 4. Ground Motion (GM) input, acceleration responses and the kinetic friction coefficient of the Rigid Block (RB) for the repeated uPVC-LB sandwich test at a surface density of 1 kg/m^2 and vertical stress level of 5 kPa- Dry ***(a)*** *1RT_1_5_D* ***(b)*** *2RT_1_5_D* ***(c)*** *3RT_1_5_D* ***(d)*** *4RT_1_5_D.*

The acceleration response history threshold is associated with the demand for the force of kinetic friction (F_k) to maintain the relative acceleration response of the rigid block among PVC-sand-PVC systems. The dashed lines in the acceleration history shown in Figure 4 represent the acceleration threshold levels, which are linked to the force of kinetic friction (F_k) required to keep the Rigid Block (RB) acceleration response constant among PVC-sand-PVC systems. The kinetic friction force is defined in Eq.3 for the sliding system:

$$F_k = \mu_k \times N \tag{3}$$

where F_k is the kinetic friction force, μ_k is the kinetic friction coefficient, and N is the normal force.

Assuming a completely horizontal contact surface and considering only the force of gravity (F_g) acting in the vertical direction, which is equal to the normal force (N) on the rigid block, Eq. 4 is obtained.

$$F_g = N = m \times g \tag{4}$$

where *m* represents the mass of the rigid block and g is the acceleration due to gravity.

By re-arranging Eq.3 and Eq.4, it is found that:

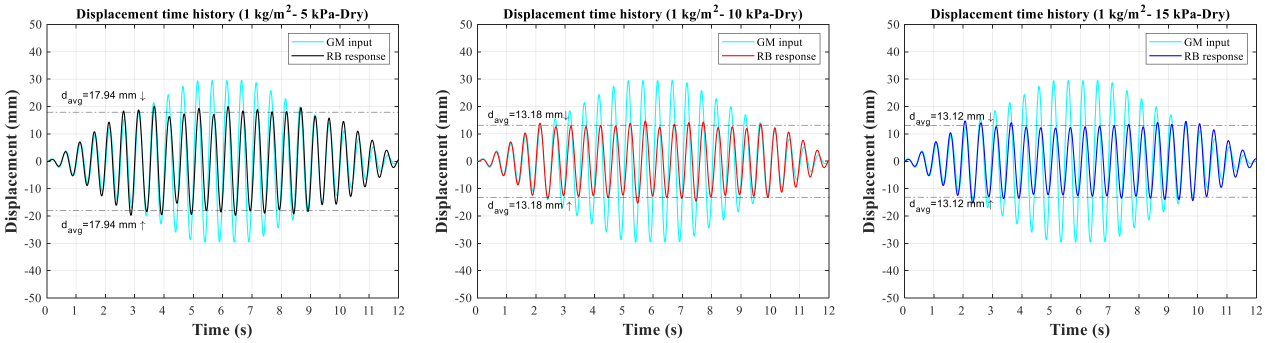
$$F_k = \mu_k \times m \times g = m \times a \rightarrow \quad \mu_k = \frac{a}{g} \tag{5}$$

where *a* represents the experimentally obtained acceleration of the rigid block (RB). Due to the mass cancellations, Eq. 5 defines the kinetic friction coefficient (μ_k) as the ratio of the rigid block acceleration (a) threshold, represented by the mean of absolute maxima and minima in Phase 2, to the acceleration of gravity.

4 Experimental results

4.1 Results for tests under dry conditions

The experimentally obtained average and maximum displacement response of the rigid blocks are shown in Figure 5 and Figure 7,respectively. These figures represent typical experimental results for the uPVC-LB sandwich test with a sand surface density (ρ_s) of 1 kg/m^2 and three vertical stress levels (σ_v) of 5-10-15 kPa under dry conditions.



(a) T_1_5_D **(b)** T_1_10 _D **(c)** T_1_15_D

Figure 5. Average displacement response(d_{avg}) of the rigid blocks (RB) for the ramped sine wave ground motion (GM) input under dry conditions: ***(a)*** *ρ_s=1kg/m^2-σ_v=5 kPa* ***(b)*** *ρ_s=1kg/m^2-σ_v=10 kPa* ***(c)*** *ρ_s=1kg/m^2-σ_v=15 kPa.*

The average displacements (d_{avg}) of the rigid blocks (RB) for peaks and troughs considered between 2-10 seconds (Phase 2) are 17.94 mm, 13.18 mm and 13.12 mm in Figure 5 (a,b,c, respectively). Meanwhile, the peak average displacements occur under 15 kPa stress for tested conditions, except for 1kg/m^2-5 kPa-dry in Figure 5a. Incorporating the lowest dry sand surface density and vertical pressure is believed to result in higher relative displacement and acceleration response than the higher density and pressure. Overall, average displacements(d_{avg}) ranged from 10 to 18 mm during Phase 2 for all tests.

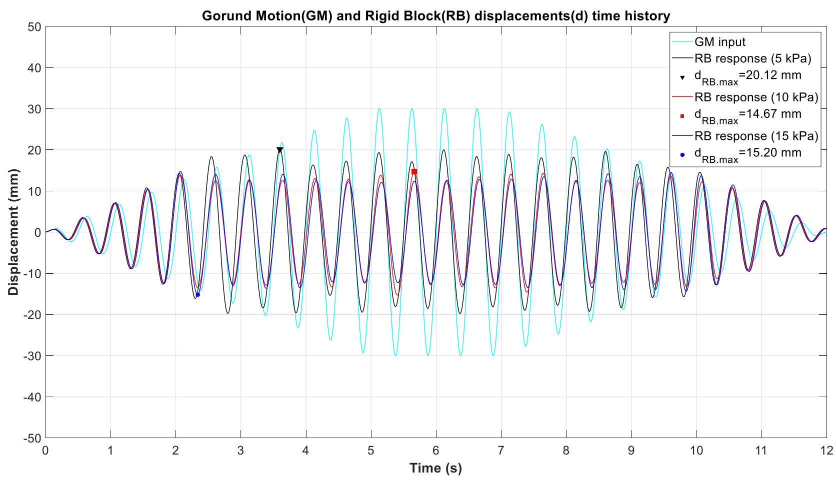
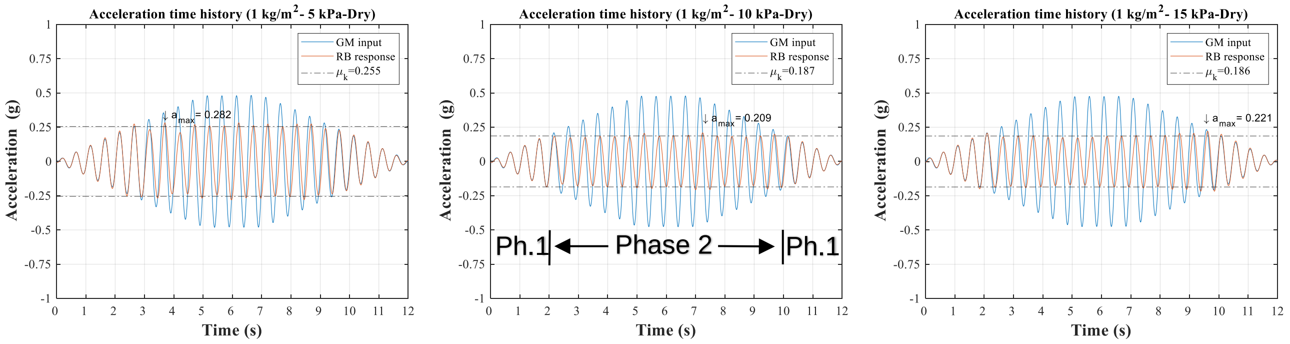


Figure 6. Maximum displacement (d_{max}) responses of the rigid blocks (RB) for the ramped sine wave ground motion (GM) input at ρ_s= 1 kg/m^2 under dry conditions.

Figure 6 indicates that the peak maximum displacement (d_{max}) of the rigid blocks (RB) occurs at 5 kPa vertical stress level, as also shown in Table *2* for dry conditions. The maximum displacements (d_{max}) of the RBs are 20.12 mm,14.67 mm, and 15.20 mm for the vertical stress levels of 5-10-15 kPa, respectively. The observed maximum relative displacements fall within the range of 14-21 mm, relative to the maximum ground displacement of 30 mm.



(a) T_1_5 _D **(b)** T_1_10 _D **(c)** T_1_15 _D

Figure 7. Maximum acceleration(a_{max}) responses of the rigid blocks (RB) for the ramped sine wave ground motion (GM) input under dry conditions: ***(a)*** *ρ_s=1kg/m^2 - σ_v=5kPa* ***(b)*** *ρ_s=1kg/m^2 - σ_v=10kPa* ***(c)*** *ρ_s=1kg/m^2- σ_v=15 kPa.*

The experimentally obtained maximum acceleration(a_{max}) responses of the rigid blocks (RB) are presented in Figure 7 and Figure 8,respectively. The overall maximum acceleration responses are observed at the lowest stress level of -5 kPa for all dry conditions. Specifically, the maximum RB acceleration (a_{max}) values corresponding to 5 kPa,10 kPa and 15 kPa stress levels are 0.282g, 0.209g and 0.221g, respectively, under dry condition.

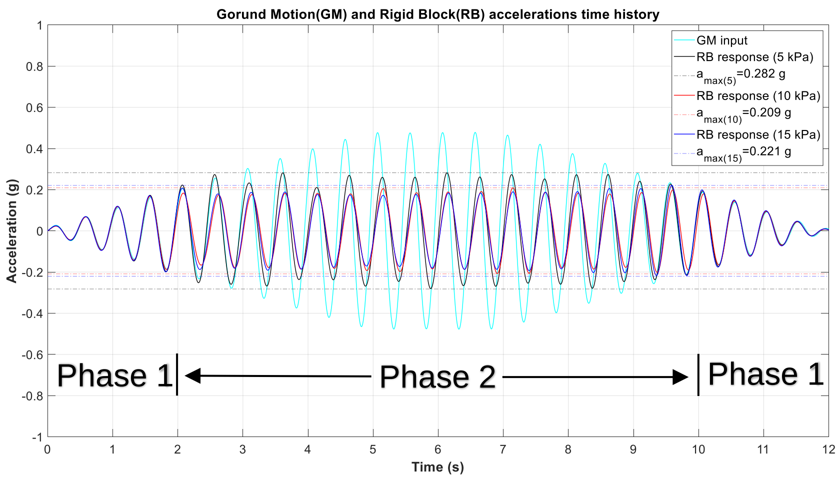


Figure 8. Maximum acceleration(a_{max}) responses of the rigid blocks (RB) for the ramped sine wave ground motion (GM) input at ρ_s= 1 kg/m^{2}sand surface density under dry conditions.

It is crucial to emphasise that these individual values may not precisely reflect the kinetic friction coefficient of the entire system. However, the maximum acceleration (a_{max}) response of the rigid blocks is significant for analysing how the superstructure will respond to a seismic motion and for designing earthquake-resistant structures. Overall, the maximum accelerations were measured in the range of 0.201g - 0.293g during all tests.

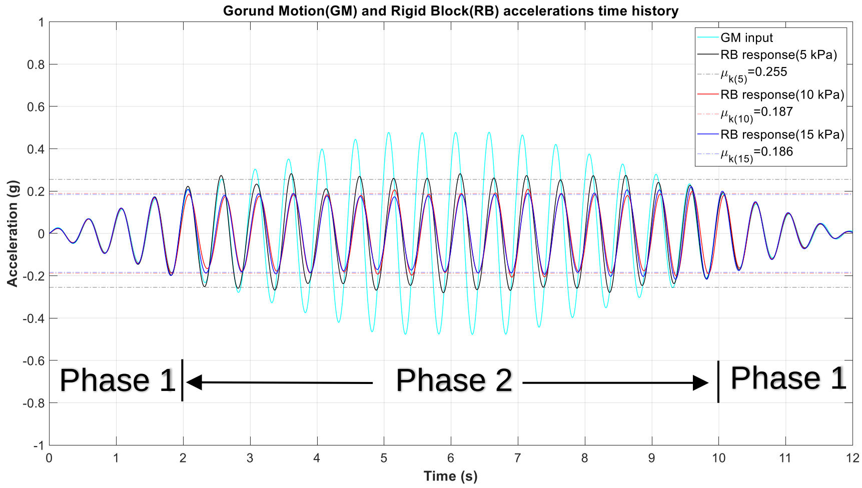


Figure 9. Kinetic friction coefficients (μ_k) *of the PVC–sand–PVC sandwich system with the rigid blocks (RB) for the ramped sine wave ground motion (GM) input for* ρ_s*= 1 kg/m*^{2} *sand surface density under dry condition*

The kinetic friction coefficients(μ_k) of the PVC–sand–PVC sandwich systems for 1 kg/m^2 sand surface density with the rigid blocks (RB) are illustrated in Figure 9**Error! Reference source not found.**. The seismic isolation effect is primarily governed by local peaks and troughs in Phase 2, and these fluctuations remain relatively stable throughout the defined Phase 2. In the 2-10 seconds range, the average rigid block accelerations of the absolute maxima and minima are 0.255g, 0.187g, and 0.186g, respectively. The average value of absolute maxima and minima serves as a representation of the kinetic friction coefficient (μ_k) of the rigid block, as shown in Figure 9. It is noteworthy that the friction coefficients for 10-15 kPa are remarkably close to each other. Overall, the kinetic friction coefficients of the system are measured between 0.176 and 0.255.

The coefficients of variation (CV), also known as relative standard deviation (RSD) are determined using Eq.6.

$$CV = \frac{\sigma}{|\mu|} \tag{6}$$

where σ is the standard deviation, and |μ| is the kinetic friction coefficient, representing the average value of the absolute acceleration of the rigid block at peaks and troughs during Phase 2.

The coefficients of variations (CVs) for dry conditions with 1 kg/m^2 sand surface density are 7.67% (5kPa), 5.40% (10kPa), and 6.12% (15kPa) at Phase 2. Notably, the CV is highest at 17.22% (5 kPa) for 2 kg/m^2-dry condition, while the CVs for 10-15 kPa are lower than 8%. Experimentally data indicate that the variability generally decreases with increasing the vertical stress levels; however, it tends to occur at a slightly higher level under submerged conditions for the same sand surface density (ρ_s) and vertical stress level (σ_v). The coefficient of variations(CV) for the kinetic friction coefficient, overall, is lower than 17% and the standard deviation of the coefficient is lower than 0.0356 for all the tested condition. This difference is believed to be attributed to the random dispersion of sand particles on the PVC surface.

4.2 Effect of submerged condition

An equal amount of water was gently injected into the pre-spread sand mass through a syringe, over lower PVC, to create a submerged environment for the PVC-sand-PVC system. The term "fully saturated Submerged (S) environment" refers to a condition where a geomaterial or content has absorbed the maximum amount of water it can hold while being completely submerged. Figure 10 illustrates a comparison of the kinetic friction coefficients obtained from the tests conducted in dry condtions (horizontal axis) and submerged condtions (vertical axis). The figure indicates that, in general, the kinetic friction coefficients for submerged samples are higher than those for dry samples. The repeatability tests in Figure 4 show that the kinetic friction coefficients for the 1 kg/m^2 - 5 kPa dry conditions result in μ_{kd} = 0.255, which is the only higher coefficient compared to the submerged test (μ_{ks}). It is noteworthy that the outlier occurs under dry condition with the lowest vertical stress level of 5 kPa(σ_v) and sand surface density of 1 kg/m^2(ρ_s).

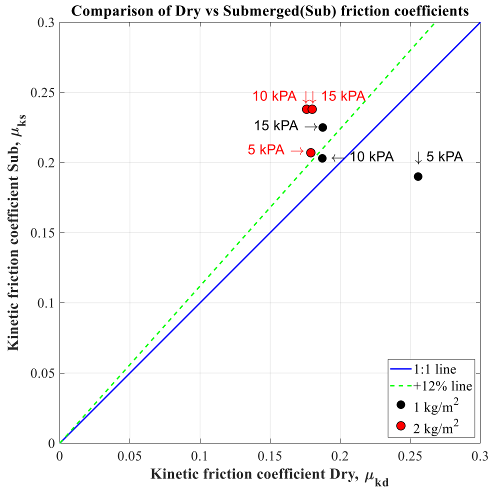
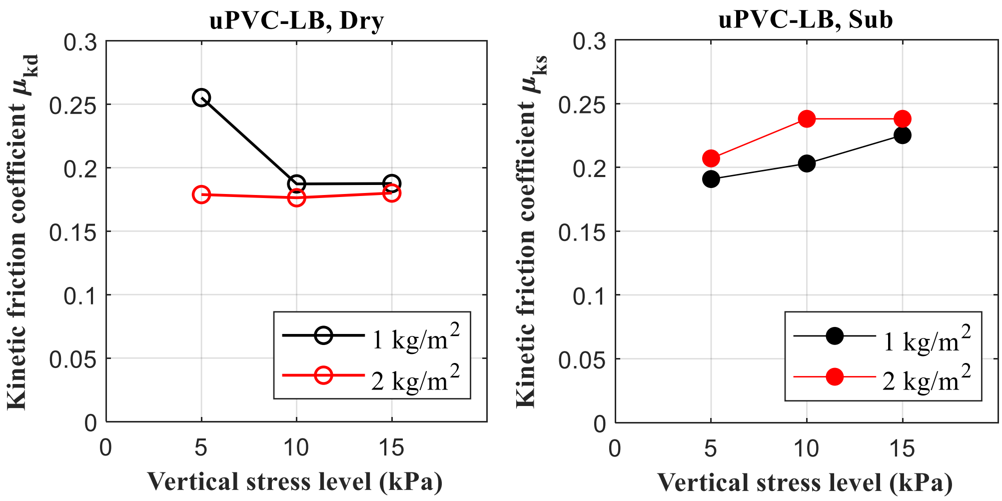


Figure 10. Comparison of the kinetic friction coefficients for the uPVC-LB sandwich system under dry and submerged conditions

This observation aligns with the previous quasi-static friction study (Sezer et al., 2023), indicating that the submerged system acts as an anti-lubricant. The earlier study focused on the quasi-static friction coefficient of the PVC sandwich system, while the current research explores the variation in the kinetic friction coefficient. The results indicate that the quasi-static friction coefficient is approximately 10% higher in submerged tests for the same amount of sand and vertical stress. Similarly, the kinetic friction coefficient is approximately 12% higher under the same testing condition. This consistent trend across both studies suggests that the coefficients of both quasi-static and kinetic friction of the system increase when the interface sand material is saturated with a water-based lubricant.

4.3 Effect of stress level

Figure 11 illustrates the trends in the variation of the kinetic friction coefficient with three stress levels for two sand surface densities under both dry and submerged conditions.



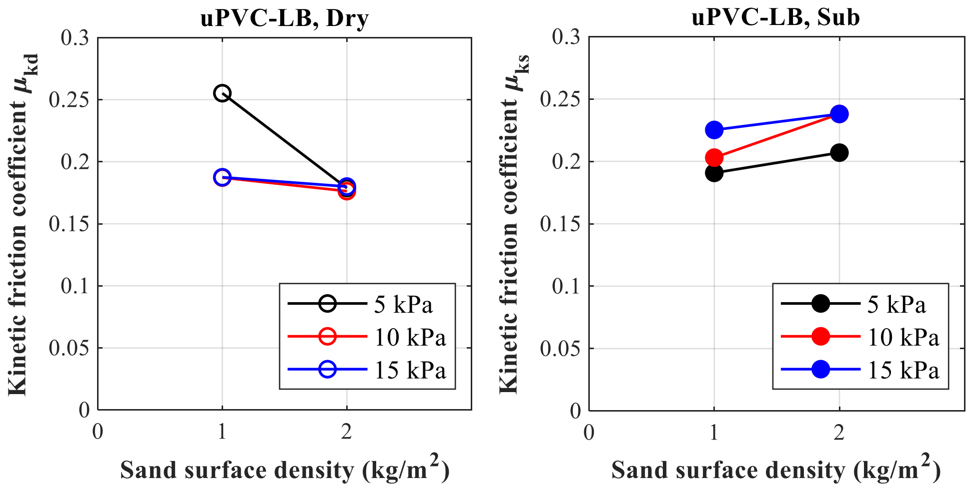
(a) *PVC-sand-PVC, Dry* **(b)** *PVC-sand-PVC, Submerged(Sub)*

Figure 11. Variations of the kinetic friction coefficient versus vertical stress level for Dry ***(a)*** *and Submerged* ***(b)*** *the PVC–sand–PVC sandwich test conditions*

The coefficient of friction (μ_{kd}) remains relatively stable under dry conditions, except for the stress level of 5 kPa-1 kg/m^2 in Figure 11a. However, the submerged kinetic friction coefficient (μ_{ks}) either increases or at least remains constant with the increase in stress level, as shown in Figure 11b. The kinetic coefficient of friction increases directly proportional around 18% when the vertical stress rises from 5 to 15 kPa for submerged tests.

4.4 Effect of surface density

Figure 12 illustrates the variation of the kinetic friction coefficient trends with two sand surface densities for three stress levels under both dry and submerged conditions.



***(a)** PVC-sand-PVC, Dry* ***(b)** PVC-sand-PVC, Submerged*

*Figure 12. Variations of the kinetic friction coefficient versus sand surface density for Dry **(a)** and Submerged **(b)** the PVC–sand–PVC sandwich test conditions*

In Figure 12a, there is a clear trend of decreasing the kinetic friction coefficient (μ_{kd}) despite falling at different rates. It decreases as the sand surface density increases under dry conditions. This phenomenon reverses back for the submerged states. The coefficient of the kinetic friction(μ_{ks}) is directly proportional to sand surface density change in Figure 12b under submerged conditions. For a higher vertical stress levels(10-15 kPa), the kinetic friction coefficients emerge at higher values for both densities than 5 kPa under wet conditions. The kinetic friction coefficients(μ_k) are almost at the same value for the higher stress levels of 10-15 kPa under both wet and dry conditions at 2 kg/m^2 sand surface density.

Finally, the variation of the kinetic friction coefficient, which is the main objective of the research, shows a considerable difference under dry conditions at 1 kg/m^2 sand surface density with a 5 kPa vertical stress level of the RB. This difference in the coefficient between vertical stress levels is almost zero for the 2 kg/m^2 situation as can be seen in Figure 12a. As uncovered in the quasi-static experiment of Sezer et al. (2023), it may be useful to consider surface densities exceeding 1 kg/m^2, especially at low vertical stress level and dry condition to minimise the variations in the friction properties of the existing system.

5 Conclusions

The experimental research, conducted using a uniaxial small-scale shaking table, aimed to discover the variability of the kinetic friction coefficient for the PVC-sand-PVC configuration. The following conclusions are drawn.

- The peak maximum displacement occurs at the lowest stress level of 5 kPa in all dry conditions. In contrast, for the saturated test configuration, the peak maximum displacement takes place either at 10 kPa or 15 kPa. Overall, maximum displacements (d_{max}) of the rigid block varied from 14 to 21 mm, while average displacements (d_{avg}) were measured in the range of 10 to 18 mm for all tests.
- The change in vertical stress levels does not significantly affect the kinetic friction coefficient (μ_{kd}) in dry conditions, except for σ_v=5 kPa. However, for submerged samples, the kinetic friction coefficient (μ_{ks}) either increases or remains constant with an increase in vertical stress level.
- It is observed that the coefficient of friction drops as the sand surface density increases from 1 kg/m^2 to 2kg/m^2 under dry conditions. However, the increment in sand surface density causes a rise in the kinetic friction coefficient for the submerged tests. Thus, the surface density change exhibits a completely reverse effect under dry versus submerged conditions regarding the kinetic friction coefficient.

- The kinetic friction coefficient for submerged samples is higher (by approximately 12%) compared to that of the dry test specimens under the same test configuration. This finding aligns with our previous quasi-static friction determination study by Sezer et al. (2023), indicating that the submerged system acts as an anti-lubricant. It is thought that the crucial factor contributing to the kinetic friction difference between dry and submerged conditions is neither the stress level nor the change in sand surface density, but rather the anti-lubricant and suction phenomenon caused by submerged conditions.

In conclusion, applying vertical stresses to sand surface densities (ρ_s) of 1 and 2 kg/m^2 did not significantly affect to the kinetic friction coefficient under dry conditions,and it is observed at approximately 0.18. However, in submerged conditions, the kinetic friction coefficient increases as a result of both an increased sand surface density and vertical foundation stress. Overall, it remains stable enough, which builds confidence to ensure the efficiency of the developed PVC-sand-PVC system.

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