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Investigation on the Behavior of Bridge Piers Considering Rocking Isolation Constructed on Non-plastic Silts and Sands Using 1g Shaking Table Tests

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Abstract

Occurred damages on the bridge piers during earthquakes lead to significant financial losses worldwide every year and can cause social problems by disrupting traffic flow and transportation services. Rocking isolation of foundations is one of the damage reduction approaches to avoid structural damage on piers by transferring plastic hinges from piers to underlying soil media. The behavior of rocking foundations on non-plastic silts has not been investigated well until now in the literature. In this research, the characteristic seismic behavior of a bridge pier considering rocking isolation is evaluated using small-scale physical modeling tests. To this aim, eight shaking table tests (with sinusoidal excitations) are conducted where both sandy and silty materials are employed as the soil media. In addition to the effects of the underlying soil, the effects of the critical contact area ratio of the foundation and frequency of input motions are evaluated. Achieved results indicate that the considered bridge pier shows the same behavior trend for underlying silty soil and sandy one. However, because of the frequency-dependent behavior of non-plastic silty soil, the pier attracts lower accelerations and higher moments. Therefore, the achieved results show that the proposed design approaches of rocking foundations that are mostly extracted based on experimental studies on sands (or rarely on clay) can lead to non-conservative designs in silty soils.

Keywords

rocking isolation, bridge pier, shaking table test, non-plastic silt, sand, physical modeling

1 Introduction

With the developing need for transportation between cities, the construction of highways has been increasingly demanded. Bridges are one of the most important components of highways and can play a crucial role in the design projects of highways. Induced damages to bridges (by earthquakes or other loads) can disrupt traffic flow and cause unfavorable economic costs. The design of bridges (during the 1950s to 1970s) was mainly done using an elastic analysis where considered loads were significantly less than those of new design manuals. Such a design approach usually resulted in a footing reinforcement consisting of a single two-dimensional mat of reinforcement at the bottom of the footings without top or shear reinforcement for bridge piers to transfer structural loads to the ground. Experimental and numerical investigations indicated that actual seismic induced forces on bridge piers (that can make plastic hinges) could be three or four times larger than those loads implemented in the elastic analyses. Traditional retrofitting methods of bridge piers have several problems, including the requirement for large working space, ceasing traffic flow on highways, and so on. In recent decades, many researchers have investigated the rocking isolation of bridge piers as an alternative way to decrease the damage to piers and reduce retrofitting cost and time. A rocking foundation takes advantage of soil failure to protect the structure from seismic loading. Consequently, this foundation can act as a fuse, protecting and isolating the bridge structure from severe earthquake impact to a certain extent. Typically, this involves under-designing the foundation's geotechnical capacity (i.e., using foundations with smaller dimensions) and allowing the foundations to be lifted. Similarly, the construction of the rocking system involves the use of a smaller foundation and, in turn, transferring the plastic hinges to the soil [1].

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Investigations on the seismic behavior of bridges have attracted lots of attention until now. Priestly et al. [2] investigated the behavior of foundations considering uplifting and rocking them using some small-scale shaking table tests. Xiao et al. [3] applied some cyclic loading tests on scaled column-foundation systems to evaluate the efficiency of design criteria for rocking foundations. Psycharis and Jennings [4] investigated the dynamic behavior of a solid block under lateral movements. In their study, a simple Winkler model was used for modeling soil. beneath the block. Chopra and Yim [5] presented a simplified analytical approach by considering useful uplift effects of foundations to model a single degree of freedom structure. Adamidis et al. [6] proposed a numerical approach to model shallow circular or strip footings with rocking oscillation. Mergos and Kawashima [7], using a numerical study, evaluated the behavior of a bridge with five spans by considering the rocking isolation of the foundations. In this research, it has been shown that rocking isolation can reduce forces on piers significantly. Giouvanidis and Dong [8] compared the results of the conventional design approaches of bridge columns with design approaches that consider rocking isolation effects. Different researchers used shaking table tests to investigate the behavior of rocking foundations on sands [9–11] while, for better simulation of stress distribution of models, some other researchers employed centrifuge tests to investigate the behavior of rocking foundations [12–17]. Kim et al. [18] and Liu et al. [19] used centrifuge tests to investigate the behavior of low rises buildings with rock foundations. In addition to centrifuge and shaking table tests, some physical modeling tests using the snap-back loading approach have been undertaken to study the behavior of rocking foundations, and the achieved results were reported in the literature [20]. These tests revealed that the snap-back loading procedure could be a useful approach for investigating the nonlinear behavior of soil-rocking foundation systems. Numerical assessment of rocking foundations has also been considered to investigate different aspects of such foundations. For example, Harden and Hutchinson [21] used a simplified Winkler model to simulate the behavior of structure-foundation-soil interaction problems. Anastasopolous et al. [22] presented a performance-based design approach to evaluate the behavior of bridge piers with considering rocking isolation. Gelagoti et al. [23] employed a finite element (FE) approach to investigate the behavior of low-height buildings on rocking foundations. Using a numerical study, Namdar et al. [24] revealed that the shape of foundations has a significant effect on their behavior. In all of these studies, it has been shown that the behavior of structures on the rocking foundations can be improved, and damages on piers or columns can be reduced by using rocking foundations. Such a significant influence on the reduction of induced damages persuaded many researchers to conduct more investigations on the behavior of structures considering rocking isolation effects. In 2014, a revised version of the ASCE code that includes some topics related to rocking foundations was presented. Hakhamaneshi and Kutter [25] and Kutter et al. [26] applied a parametric study based on the ASCE 41 design code to evaluate the accuracy of this design approach. In this design code, the magnitude of the occurred uplift and permanent settlements are considered as the acceptance criteria for rocking foundations. However, studies using small-scale models (using shaking table tests or centrifuge modeling) are employed frequently; some other researchers used models with real scales to expand knowledge around the behavior of rocking foundations. Antonellis et al. [27, 28] used such model tests with real scales in large shaking table tests. This study has shown that the small foundations (considering rocking isolation) can significantly reduce destructive forces and permanent deformations in bridge piers. Therefore, small-scale tests, numerical evaluations, and real-scale tests have shown that rocking foundations' application can be considered an efficient approach to reducing damage to structures. Pap and Kollár [29] conducted a study to model of soil-structure interaction of objects resting on finite depth soil layer using a simplified model, and their finding showed that in modeling the soil-foundation interaction by finite element method, the effects of soil should be taken into account by their introduced model.

Previous research has looked deeply into how rocking foundations behave and how effective they are at minimizing caused damages. These applied studies have been mostly limited to the foundations constructed on sand and clays. Investigations on the behavior of foundations with rocking isolation on silty soils were scarce in previously done studies. This vacancy of knowledge leads to a major requirement to apply some studies about the behavior of rocking foundations on silty soils and to present a comparison between this behavior and the behavior of rocking foundations on sands (where it has been mostly conducted till now). In this paper, the behavior of a bridge pier constructed on non-plastic silts and fine-grained sands was studied using small-scale physical modeling tests with a shaking table apparatus. For simplicity, both soils were considered dry, while further investigations can be applied to study the effects of saturation. The paper is organized as follows: Details of the test program are explained in the next section. Achieved results are presented in Section 3, and the conclusions are provided in the last section of the paper.

2 Testing device, material, and procedure

Based on the previously proposed design approaches for rocking foundations, one of the most significant parameters that can affect the behavior of a rocking foundation is the ratio of A/A_c. A/A_c is the critical contact area ratio of the considered rocking foundation. In this relationship, A is the total base area of the footing, and Ac is the minimum area of footing that is required to be in contact with the ground to support the applied vertical loads. The critical contact area ratio is equivalent to the static vertical factor of safety (FSv = A/A_c). A/A_c incorporates the effects of soil properties (unit weight and shear strength), foundation geometry (width, length, and depth of embedment), and the applied vertical load on the foundation.

The values of FS_v (Safety factor with respect to concentric vertical loading) could be calculated based on the characteristics of the foundation and structure and by utilizing the bearing capacity equations. By assuming the ultimate bearing capacity independent of the shape and size of the loaded area, the value of the A/A_c could be considered equal to FS_v. However, according to the bearing capacity shape factor, the depth factor, and the term of $(1/2)\gamma BN_\gamma$ in Terzaghi's bearing capacity equation, the A/A_c ratio would be different from the FS_v. It is because of the changes in the contact geometry during the rocking movement of the foundation [12].

In this paper, the applied experimental tests were carried out for two different models with a single degree of freedom (SDOF) superstructure. The used superstructure-foundation system was constructed on dry sands and silts. The geometry of the superstructure was determined based on the full-scale pier of a bridge with a 1.82-m-diameter. To evaluate the effects of A/A_c, two different values of A/A_c (4 and 10) were employed in this research. The changes in values of A/A_c were provided using different weights applied to the top of the structure (to reach different static factors of safety). For this purpose, the applied weights that they used to obtain the considered ratios of A/A_c, were selected to be equal to 30 kg and 20 kg. The fundamental periods of the structure (in modeled scale) were equal to 0.055 s (for the tests with 20 kg concentrated mass) and 0.062 s (for the tests with 30 kg concentrated mass). Based on the applied hammer test and the free decay response of the soil-structure system, the fundamental periods of the used systems were calculated as 0.1 s and 0.12 s for the concentrated mass of 20 kg and 30 kg, respectively. Accordingly, a series of seismic shaking table tests were conducted. For all geometrical parameters such as the height of the pier, depth, and length of the foundation, 1 g scaling laws were considered with geometric scale factor λ equal to 25. The thickness of the column and other used steel plates were considered to satisfy rigidity conditions for the superstructure. Using this assumption, the thickness of the used steel plates was selected equal to 5 mm to avoid any deformation against applied seismic and static loads. In this research, the embedment depth ratios (D/B) were considered equal to zero, and the superstructure was built directly on the surface of the soil media. 3D sketches for superstructure-foundation systems are depicted in Fig. 1. A rigid box with dimensions of 65 × 100 × 60 cm (respectively, width, length, and depth) was used as a soil

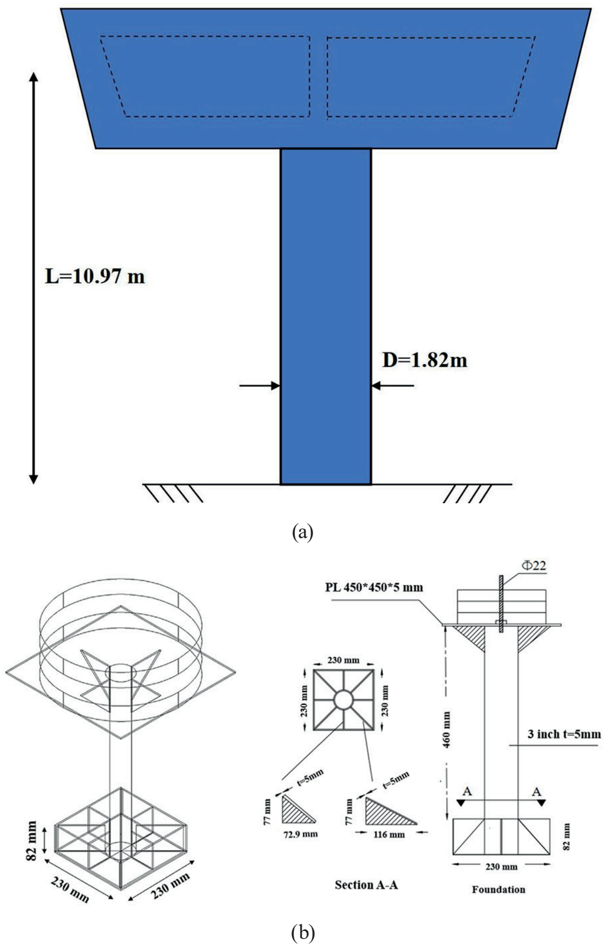


Fig. 1 Schematic view of the employed (a) prototype and (b) model of the bridge pier

container. The selection of the dimensions of the sandbox in our research was based on the dimension of the used shaking table apparatus and available sandboxes. Based on the achieved results (which are presented in Section 3) it can be seen that for the modeled system these dimensions were sufficient. Table 1 indicates the applied scaling law (based on the relationships proposed by Iai [30]) to calculate different parameters of the model. As mentioned before, two different types of soils were used in the applied tests. Firoozkuh No. 161 fine sand, which is the product of the crushing parent rocks from the Firoozkuh region of Iran, was selected as the sand material [31]. Fig. 2 shows the grain size distribution of the selected sand. SEM (scanning electron microscopy) photo of this material is shown in Fig. 3(a). The used non-plastic silts were prepared from the riversides of the Shabester River from Iran. The grain size distribution of the silt material is shown in Fig. 2, and the SEM photo of this soil is shown in Fig. 3(c). Table 2 indicates the main properties of the used soils for the tests. The tested samples (for shaking table tests) were prepared using a wet tamping procedure with 75% and 5% relative moisture densities. All samples were prepared in twelve 50 mm-thickness layers (supplying a depth of 600 mm).

Finally, the mass plates were symmetrically joined to the column to attain the intended mass centroid. In order to record the acceleration and displacement data for the experimental system, measurement instrumentations consisting of accelerometers and linear variable differential transformers (LVDTs) were used at different locations of the testing setup. Locations of the Accelerometers and horizontal LVDTs are shown in Fig. 4 and distinguished with ACC, and LVDT labels in this figure, respectively.

Table 1 scale coefficients of different quantities in this study

Quantity	Target Scale Factor (prototype/model) $P/m = \lambda$	Scale Factor Value Used Based on $\lambda = 25$
Length	λ	25
Poison Ratio	1	1
Strain	$\lambda^{0.5}$	5
Mass Density	1	1
Stress	λ	25
Time	$\lambda^{0.75}$	11.18
Frequency	$1/\lambda^{0.75}$	0.089
Shear Modulus	$\lambda^{0.5}$	5
Soil displacement	$\lambda^{1.5}$	125
Soil and structure velocity	$\lambda^{0.75}$	11.18
Shear wave velocity	$\lambda^{0.25}$	2.23
Soil Damping	1	1
Porosity	1	1
Soil and structure amplitude	1	1

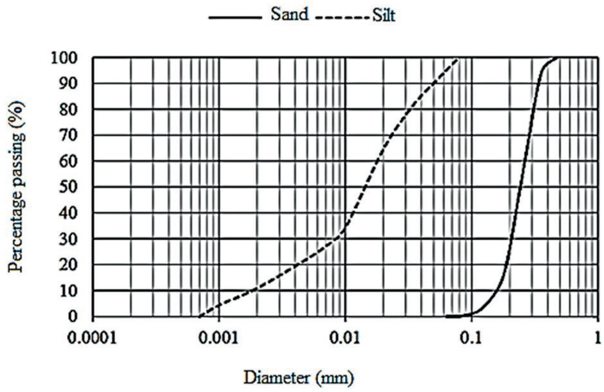
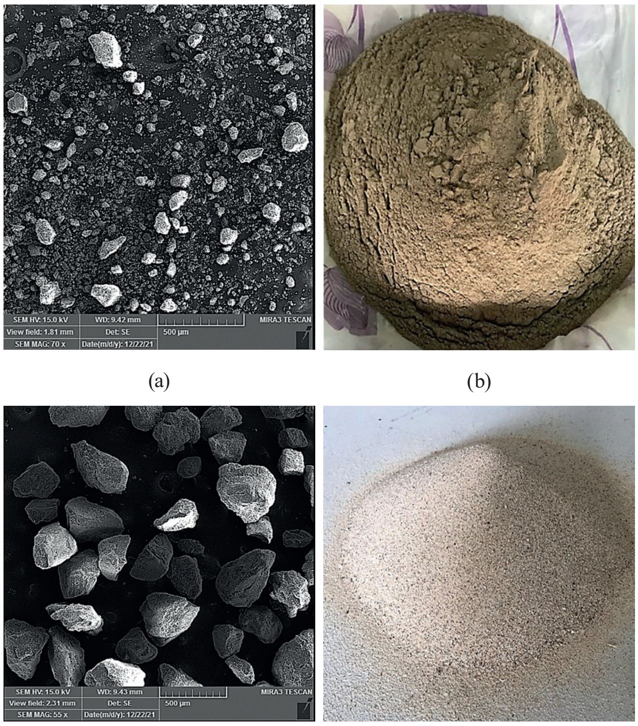


Fig. 2 Grain size distribution of the used sands and silts



(a) (b)

(c) (d)

Fig. 3 (a) SEM photo of the used non-plastic silt, (b) the used non-plastic silts, (c) SEM photo of the Firoozkuh No. 161 fine sand, (d) Firoozkuh No. 161 fine sand

Table 2 Main properties of the used sand and silt material

Name	G_s	e_{min}	e_{max}	D_r (%)	V_s (m/s)	φ peak (°)	C (kPa)
Firoozkuh No. 161 sand	2.65	0.54	0.94	75%	185	39.2	0
Shabestar non-plastic silt	2.67	0.67	1.11	75%	148	33.6	0

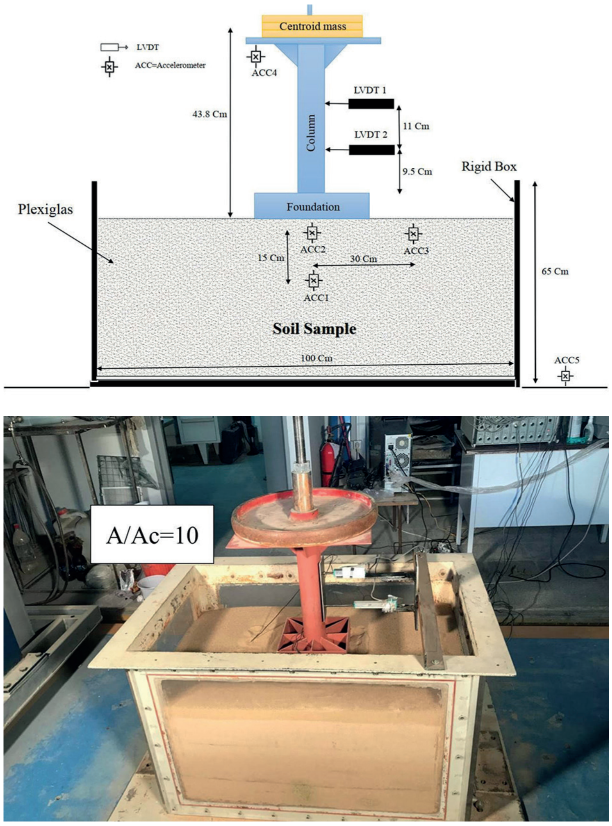


Fig. 4 Locations of the used instruments for measurement of displacements and accelerations

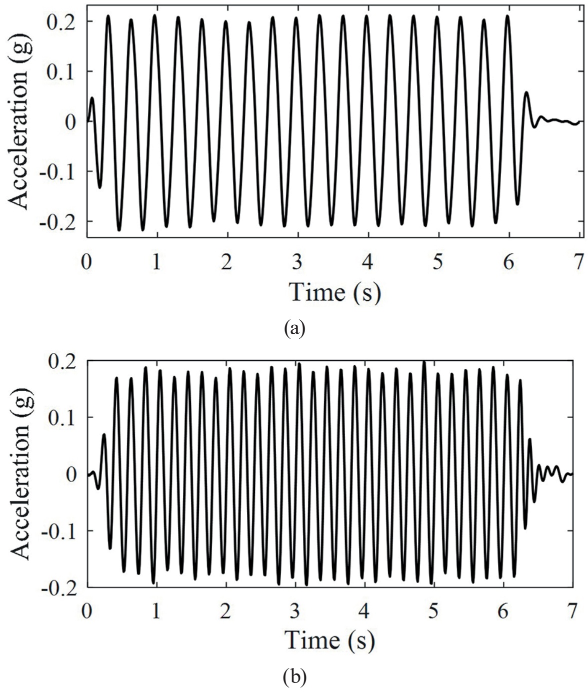


Fig. 5 Acceleration time histories of input motions with frequencies of (a) 3 Hz, (b) 5 Hz

With this regard, ACC5, which was installed on the shaking table deck, reflected the input excitation motion. ACC1 was installed at the bottom and center of the foundation with a vertical distance of 150 mm, and ACC2 was located above ACC1 with a vertical distance of 100 mm from ACC1 and 50 mm from the bottom of the foundation. ACC3 was located at the level of ACC2 and at a distance of 150 mm near the soil surface. ACC4 was placed on the superstructure center of mass. Moreover, LVDT1 and LVDT2 were located in front of the column to record the horizontal displacement of the superstructure at that position. The distance between the two LVDTs was about 110 mm. To measure induced settlements of the model, the particle image velocimetry (PIV) method was used.

Two input motions with different frequencies were used to investigate the effects of the input seismic excitation on the results. The used input motions are depicted in Fig. 5, and as can be seen in this figure, motions with frequencies of 3 Hz and 5 Hz were applied to models. Based on the national seismic code of Iran (which corresponds with most of the other seismic codes), the maximum shear forces would be generated due to the periods of 0.15 s to 0.45 s (f = 6.66 Hz and 2.22 Hz). Therefore, the employed input frequencies (3 and 5 Hz) are in the most critical ranges of the input motion's frequencies of the seismic design codes, and they can be used to assess the most crucial seismic behavior of the considered bridge piers.

In this research, eight shaking table tests were undertaken considering the effects of different soils (sands and silts), different frequencies of input motions (3 Hz, 5 Hz), and different ratios of A/A_c (provided by different weights of superstructure). Details of the test program are presented in Table 3. It has been shown by the previously applied investigations in the literature (Gajan and Kutter [12]), that there is a threshold value for A/A_c, where by approaching the A/A_c values to this threshold, desirable isolation/energy dissipation can occur. The majority of research used a value between 10 and 15 as their cutoff. Accordingly, in this

Table 3 Details of the test program

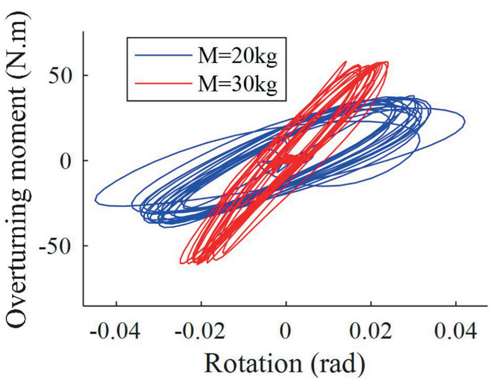
A/A_c	Concentrated mass (kg)	Frequency of input motion (Hz)	Type of soil	Name
10	20	3	Sand	Test 1
4	30	3	Sand	Test 2
10	20	5	Sand	Test 3
4	30	5	Sand	Test 4
10	20	3	Silt	Test 5
4	30	3	Silt	Test 6
10	20	5	Silt	Test 7
4	30	5	Silt	Test 8

research, two different A/A_c values were selected: one near the threshold ($A/A_c = 10$), and the other below it (to investigate the effects of the critical contact area ratios).

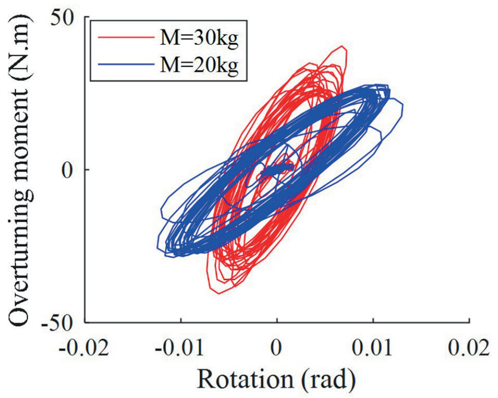
3 Results and discussions

3.1 Rocking behavior of the model

This section presents the achieved results from the applied shaking table tests. First, the behavior of the rocking foundation on Firoozkuh No. 161 sand is evaluated. Considering enough distance between the frequencies of input motions and the fundamental frequencies of the structural models, it can be confirmed that resonant effects can not affect the overall responses of the modeled system. However, a more precise extraction of the fundamental frequencies and dampings of the system considering the nonlinear behavior of the system is presented in Section 3.2. As shown in Fig. 6, by increasing concentrated mass (corresponding to decreasing A/A_c), the maximum occurred rotation was decreased. In addition, Fig. 7 shows that occurred rotations were decreased by increasing the frequency of input motion. By considering Fig. 7(a)

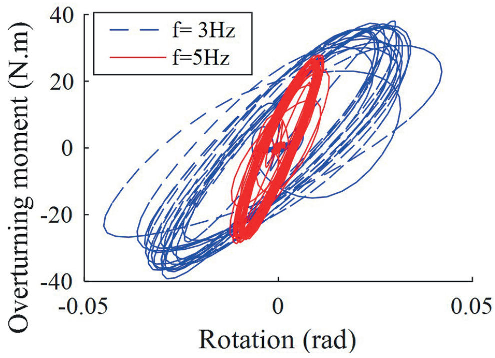


(a)

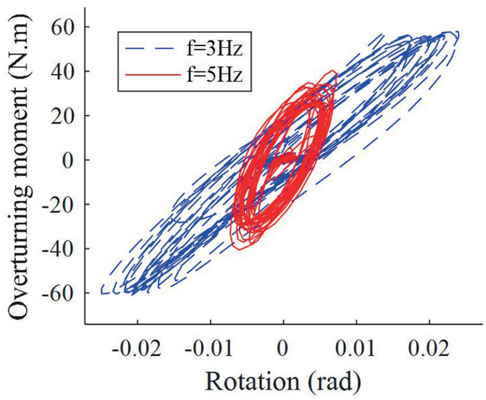


(b)

Fig. 6 Effect of the concentrated mass on the overturning moment and occurred rotations of the rocking foundation constructed on sand (a) frequency of input motion equal to 3 Hz, (b) frequency of input motion equal to 5 Hz



(a)

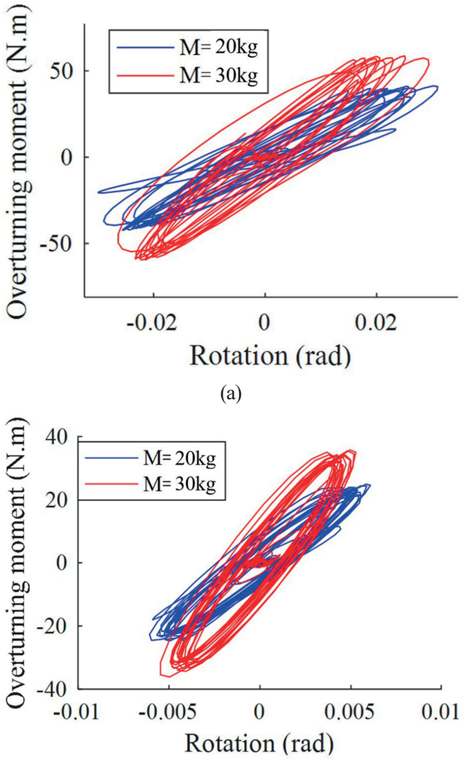


(b)

Fig. 7 Effect of the frequency on the overturning moment and occurred rotations of the rocking foundation constructed on sand (a) M = 20, (b) M = 30

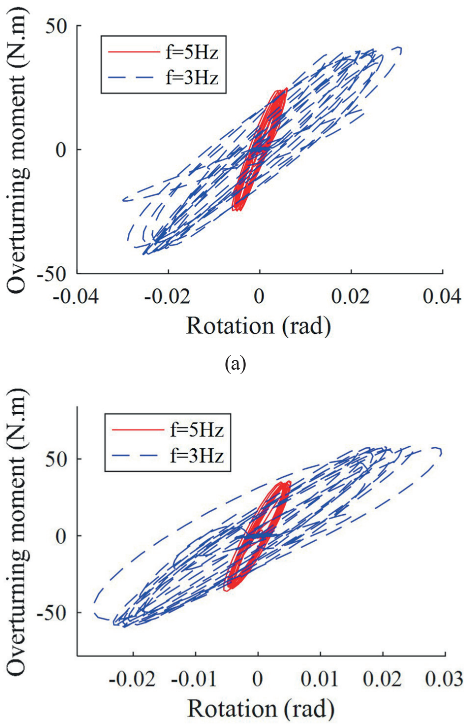
and Fig. 7(b), it can be found that frequency has a significant effect on the induced overturning moments. As mentioned above, there was a sufficient distance between the fundamental frequency of the system and the frequencies of the input motions. Therefore, the achieved results and the induced effects can be interpreted as the influences of the frequencies of the applied excitations.

To evaluate the behavior of the pier with a rocking foundation, additional tests were carried out using the non-plastic silt of Shabestar. Same as the sandy soil, achieved results for overturning moments regarding occurred rotations will be investigated, first. Fig. 8 shows that the same trend in silty soil can be found compared to the overturning moment-rotation curves of the tests with sandy soil. Based on the achieved results, an increment in the magnitudes of the concentrated masses led to a decrease in overturning moments and occurred rotations. However, Fig. 8 shows that the concentrated mass's effect was decreased compared to tests carried out using sandy soil. In addition, Fig. 9 shows that (in the tests with silty soil) the effects of the frequency of input motion were increased compared to the same tests with sandy soils.



(a)
(b)

Fig. 8 Effect of the concentrated mass on the overturning moment and occurred rotations of the rocking foundation constructed on non-plastic silt (a) frequency of input motion equal to 3 Hz, (b) frequency of input motion equal to 5 Hz



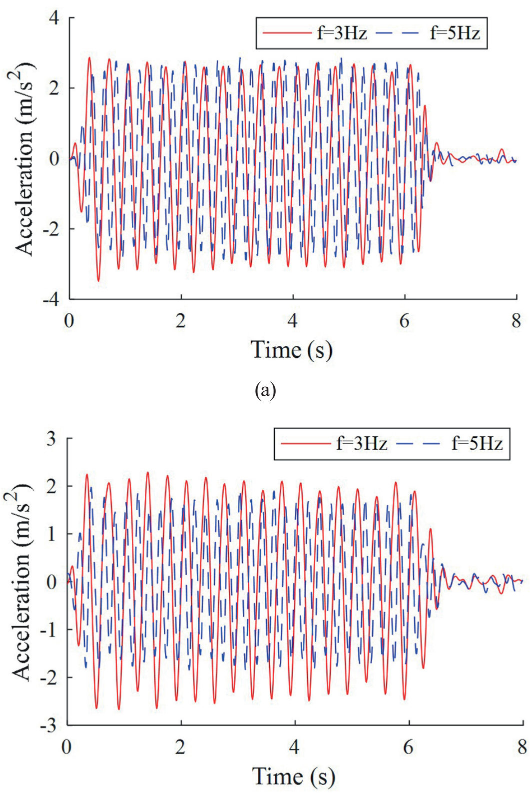
(a)
(b)

Fig. 9 Effect of the frequency on the overturning moment and occurred rotations of the rocking foundation constructed on silt
(a) M = 20, (b) M = 30

Recorded acceleration time histories for the mass center of the piers with A/A_c = 4 and A/A_c = 10, which were constructed on the sand, are presented in Fig. 10. It can be seen that larger peak accelerations were occurred in the pier for a larger frequency of input motions in sandy soils with A/A_c = 4, while for a foundation with A/A_c = 10, differences between the peak accelerations were negligible for different frequencies of input motions.

For piers constructed on non-plastic silt, it can be seen in Fig. 11 that larger peak accelerations were induced in the pier for the lower frequency of input motion (for both A/A_c = 4 and A/A_c = 10).

A comparison between the recorded acceleration time histories for the mass center of the superstructure is presented in Fig 12. This figure shows that the achieved acceleration time histories under the excitations with the frequency of 3 Hz are mostly similar for the models with sandy and silty soils. However, for input motions with higher frequency (frequency of 5 Hz), the bridge pier on sand experienced larger induced accelerations. Fig. 12 shows that the observed differences in peak accelerations for models with sandy and silty soils would be larger by increasing the ratios of A/A_c.



(a)
(b)

Fig. 10 Acceleration time histories of the mass center of a pier constructed on sand (a) A/A_c = 10, (b) A/A_c = 4

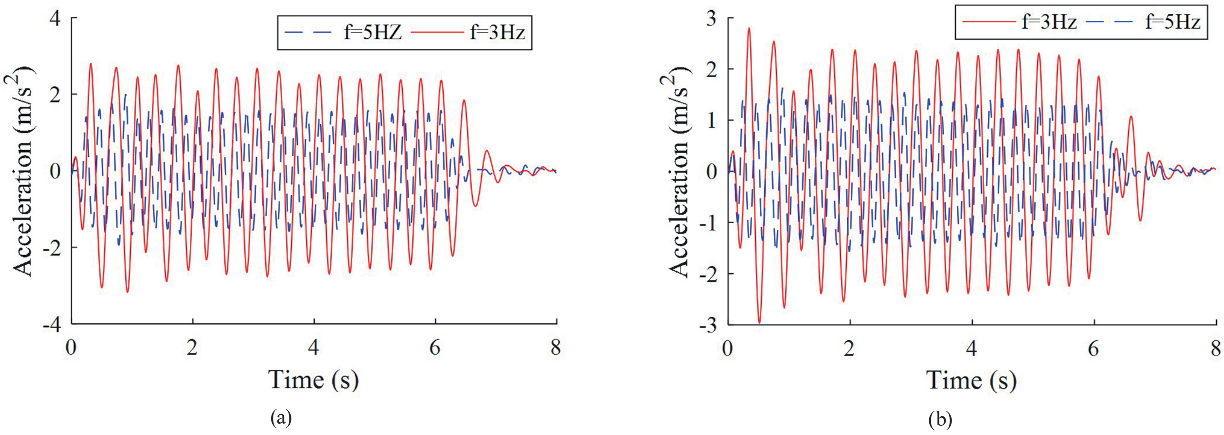


Fig. 11 Acceleration time histories of the mass center of a pier constructed on non-plastic silt (a) $A/A_c = 10$, (b) $A/A_c = 4$

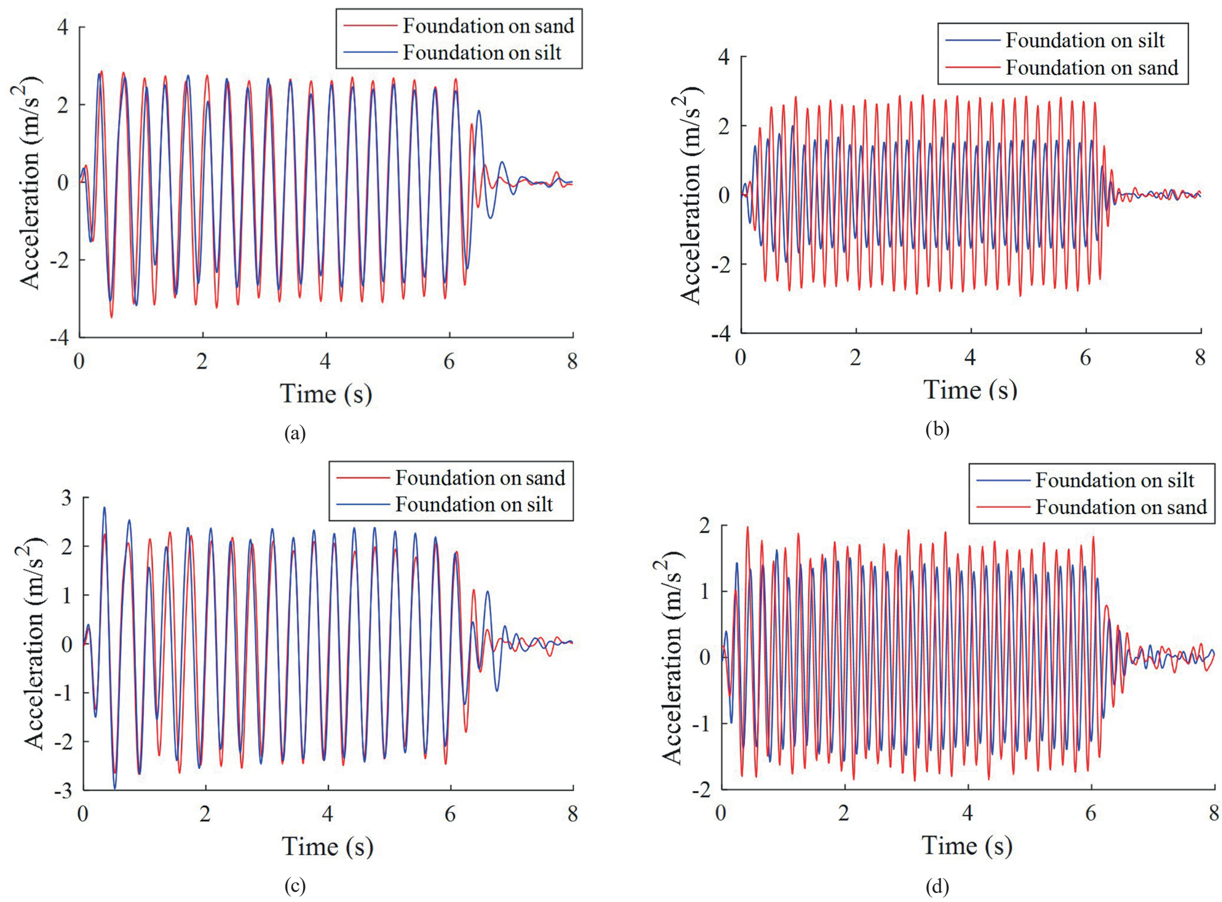
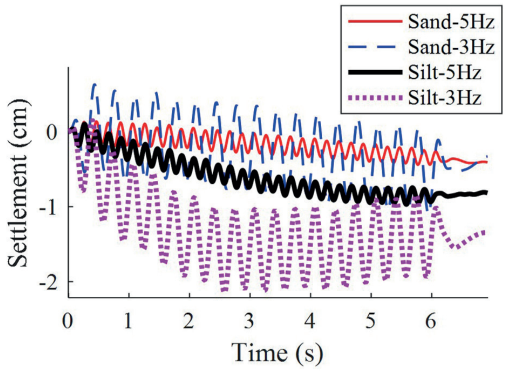
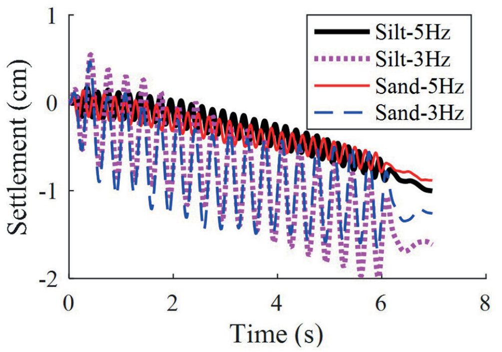


Fig. 12 Comparison between induced acceleration time histories for pier model constructed on sand and silt (a) $F = 3$ Hz and $A/A_c = 10$, (b) $F = 5$ Hz and $A/A_c = 10$, (c) $F = 3$ Hz and $A/A_c = 4$, (d) $F = 5$ Hz and $A/A_c = 4$ (F = Frequency of input motion)

Recorded Settlements for the applied different tests are depicted in Fig. 13. As the occurrence of excessive settlements can cause extensive damage to structures [32], the maximum settlements should be controlled and limited in the design of piers. As Fig. 13 shows for tests with $A/A_c = 10$, differences between settlements of the foundations on sandy and silty soils are considerable. Fig. 13(a) shows that the foundation on non-plastic silt experienced larger settlements. In addition, it can be inferred from Fig. 13(a) that the frequency of the input motions does not have a significant effect on the occurred settlements in sandy soil. However, a larger frequency in silty soil led to a lower value of settlements. As shown in Fig. 13(b) (for foundations with $A/A_c = 4$), differences between settlements of the foundations on silty and sandy soils are decreased, especially for higher frequency.



(a)



(b)

Fig. 13 Occurred settlements of the model for (a) $A/A_c = 10$, (b) $A/A_c = 4$

3.2 The free decay responses of the models

Using hammer impact tests, the fundamental period of the system can be calculated for the linear phase of excitations. Considering the non-linear behavior is the best approach for investigating the rocking behavior of the foundation-column systems [11]. In this respect, it was critical to reconnoiter some factors such as basic period and damping ratio proportional to the system's acceleration response amplitude in time instant. The free decay motion to derive the instantaneous frequency suggested by Kashani et al. [33] was used in this research among other techniques of computation. As shown in Fig. 14, an output acceleration time history can be divided into two major sections using this technique.

The achieved instantaneous frequencies and damping ratios for two applied tests are presented in Fig. 15. As can be seen in this figure, for both models, the instantaneous period, T_n, decreased with increasing time. The trends of the results are in agreement with the results of Arabpanahan et al. [11]. As can be seen in Fig. 15, the damping ratio tends to decline over time for both systems. This is because the system becomes stiffer as the contact area between the soil and the foundation is restored, resulting in less acceleration and rotation and less uplift of the foundation. In this regard, f_n increases and reciprocally T_n decreases.

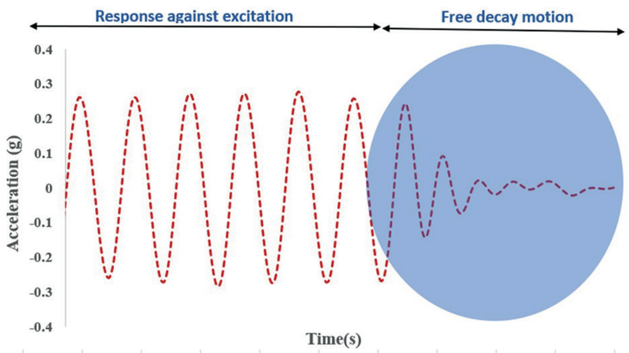


Fig. 14 A sample separation of the acceleration response of the tests during and after the applied excitation

4 Conclusions

The behavior of the rocking foundations built on non-plastic silts is rarely investigated in the literature. In this paper, using eight shaking table small-scale tests, a comparison between the behavior of a rocking foundation constructed on fine sands and non-plastic silts is presented. A single-degree-of-freedom superstructure with two different ratios of A/A_c is employed as a small-scale bridge pier. Different ratios of A/A_c are provided by different values of static vertical safety factors and different concentrated masses. Two types of input motions with frequencies of 3 Hz and 5 Hz are used to evaluate the effects of the frequency on the behavior of rocking foundations. In this research, sinusoidal excitations were used to access the seismic behavior of the considered system. Based on the achieved results, it is shown that for rocking foundations created on non-plastic silt, the concentrated mass's effect is decreased compared to tests carried out using sandy soil. In addition, it is indicated that in the tests with silty soil, the effects of the frequency of input motion are increased in comparison with the same tests with sandy soils. However, silty soil reduces induced accelerations on piers more than sandy soil. Based on the achieved results, it can be concluded that rocking foundations on non-plastic silts and sands show almost the same trend of behavior. However, as the silty soils have more sensitivity to the frequency of input motions, the design approaches for rocking foundations on silts should be modified. Using analytical approaches that were proposed based on experimental investigations on sands or clays can lead to non-conservative designs in silty soils.

Statement and declaration

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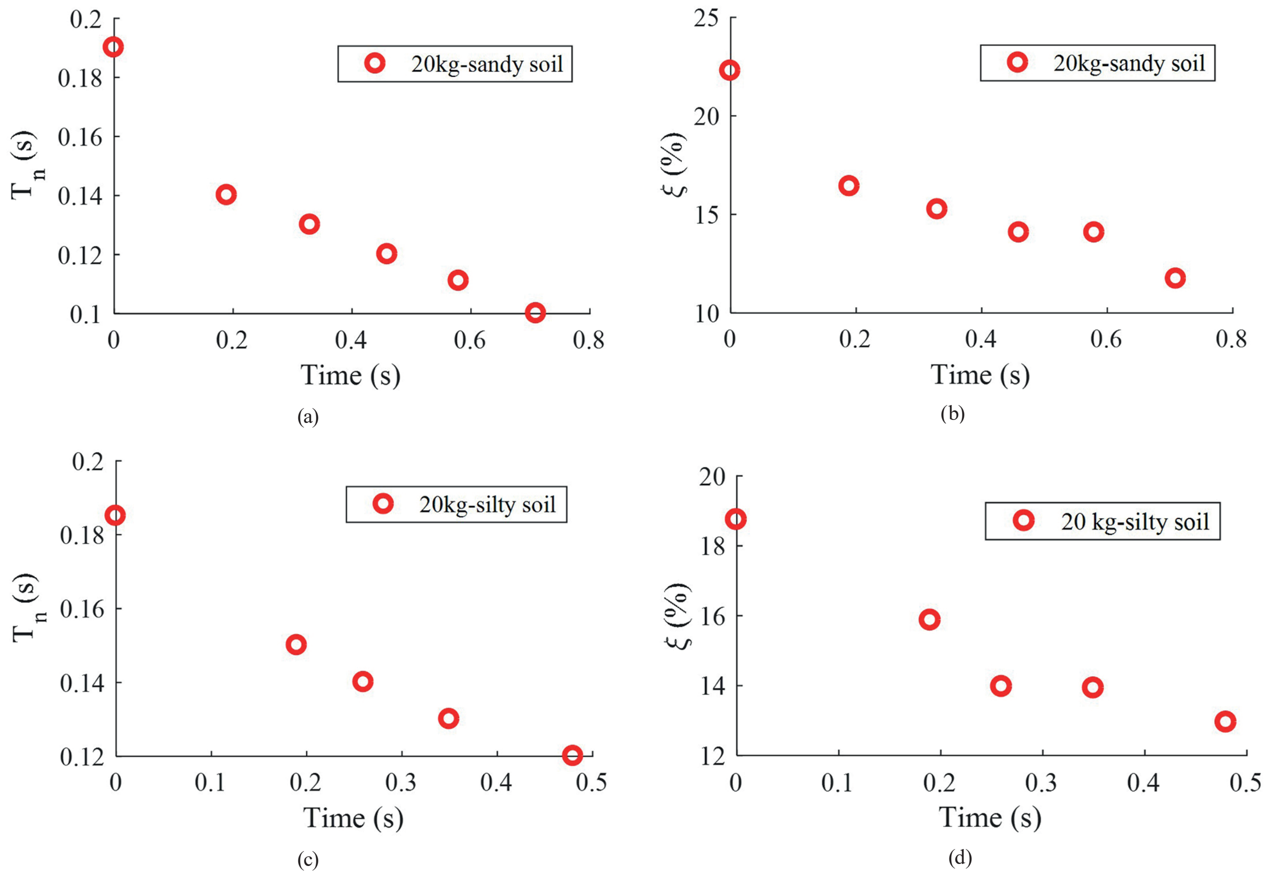

Fig. 15 Free decay motion results for the tests with 20 kg concentrated mass (a) instantaneous period for the tests with sandy soil, (b) variation of instant damping for the tests with sandy soil, (c) instantaneous period for the test with silty soil, (d) variation of instant damping for the test silty soil

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