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STUDY ON PERFORMANCE OF PILE WALLS USING LAMINAR SHAKE BOX

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SUMMARY

Laminar shake box tests have been carried out to study the performance of pile walls embedded in sandy soil layers. Series of tests were carried out on flexible and rigid pile walls embedded in dry loose and saturated sandy layers under different magnitude of static loads applied on top of the pile walls. Sand is filled in laminar shake box with size 0.4 x 0.3 x 0.5 m at a relative density of 15 and 23% to achieve loose condition. Series of model tests are conducted with initial displacement amplitudes of 1, 2, 4 and 8 mm to simulate low, moderate and strong earthquakes. The induced base acceleration varies from 0.04g to 0.3g. The maximum acceleration is observed at the surface and it varies from 0.05g to 0.4g. The maximum pile wall displacement in saturated loose state varies from 2.5d to 18.5d (where 'd' is thickness of pile wall) depending on the intensity of shaking and relative stiffness of the soil-pile wall system. The maximum pile wall displacement in liquefied state is about 30 to 40% higher than the loose dry state.

INTRODUCTION

Earthquake induced liquefaction of loose saturated sandy soil is a major cause of damage to various Geotechnical structures, sheet pile walls, diaphragm walls, retaining walls and pile supported structures etc. Shake boxes differ in the construction of their walls. The walls of a box can be rigid (Rigid box) or consist of movable segments (Laminar box). The main advantage of laminar shake box is that the realistic boundary conditions can be achieved through plane shear waves by permitting single lamellas, which not only translate but also rotate with the consequence that plain shear waves can be propagated easily.

At present, the behaviour of pile foundations during earthquakes in loose sands has not been clearly understood but there is very limited information regarding such behaviour among pile walls. Nishizawa et al. [1] observed the pile damage due to seismic shaking in numerous post-earthquake investigations. Large pile movements occur due to liquefaction and subsequent lateral soil spreading. Mizuno [2] reported that the buildings supported by friction piles driven in loose fluvial deposits suffered severe damage during 1964 Niigata earthquake. Kagawa [3] studied the dynamic response of pile foundations and concluded that the pile-head acceleration may be amplified or de-amplified due to liquefaction, but the pile-head displacement and pile bending moment will be greatly amplified in most cases. In addition, these trends are expected to be more significant when there is a lateral spreading of liquefied soils, which impose additional lateral load to piles. Kobayashi et al. [4] conducted shaking table tests to obtain the dynamic behaviour of the soil-pile-structure system in a liquefied sand layer. It was found that large bending moments are generated in the pile in a liquefied sand layer in the middle of the soil.

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Tokida et al. [5] reported a case study on liquefaction potential and drag force acting on piles in flowing soils. In most major earthquakes, lateral spreading has caused great damage to piled foundations. Ghalandarzadeh et al. [6] conducted shaking table test on seismic deformation of gravity quay walls. It was observed that the occurrence of significant deformation of walls due to the combined effects of shaking and the development of pore water pressure in sand underlying the wall. Sasaki et al. [7] reported case studies on damage of pile foundation of Higasluida sewage treatment plant by the 1995 Hyogoken-Nanbu earthquake. Based on the results of back analysis, the main cause of damage to the piles was found to be both the inertia force of the superstructure and the reduction of subgrade reaction in the almost completely liquefied soil layers. Finn et al. [8] studied the seismic analysis and design issues of piles in liquefiable soils. It was concluded that damage occurs primarily in liquefiable soils and is concentrated in critical areas such as at the pile head when it is fixed against rotation and the boundary between and non-liquefied layers. When the soil liquefies, there is large reduction in stiffness and strength that can result in substantial moments from increased displacements.

Spyrakos et al. [9] studied the seismic response of massive flexible strip-foundations embedded in layered soils and subjected to seismic excitation. It was concluded that when the excitation frequency exceeds the fundamental frequency of the soil-foundation system, the response of soft foundations shows considerable difference from that of stiff foundations. Ashour et al. [10] presented the undrained response of a laterally loaded pile in liquefiable soil incorporating the influence of both the developing excess pore water pressure in the free-field (due to ground acceleration) and that additional near-field pore pressure (due to the lateral load from the superstructure). The author [10] also compared the pile response under drained conditions and proposed the approach, which shows a dramatic reduction in pile-head capacity and stiffness due to developing liquefaction. This includes the response of a completely liquefied soil that regains the resistance due to shear strain.

The present paper discusses on the performance of pile walls embedded in loose dry and saturated sand through laminar shake box tests. The effect of parameters such as base acceleration, stiffness of the soil-pile system and static load applied on the pile wall on the response of pile walls are investigated.

MATERIALS

Sand

The sand used in the present investigation is poorly graded Stuttgart river sand. It has a specific gravity of 2.65, a mean particle size of 0.25 mm and a uniform coefficient of 2.35. The maximum and minimum void ratios are 0.975 and 0.575 respectively.

Pile Wall

The aluminum pile wall is selected as model pile material. The dimensions of the rigid pile wall are 390 × 458 mm and thickness is 2 mm. The dimensions of the flexible pile wall are 390 × 458 mm and thickness is 0.75 mm.

EXPERIMENTAL SETUP

Experiments have been carried out using a shaking table test setup at Institute of Soil Mechanics and Rock Mechanics, University of Karlsruhe, Germany as shown in Figure 1. A laminar shake box of size 400 × 300 × 500mm is used. The Shake box consists of movable wall segments (Lamellas) in the direction of excitation. Aluminium pile walls of thickness of 0.75 and 2 mm are embedded in sandy soil layers perpendicular to the direction of excitation and static loads of 14 N and 28 N magnitudes are applied on top of the pile wall. Eight displacement transducers fixed to the lamellas of the laminar shake box are used to measure the lateral displacement of soil over the height of the shake box. The deflection at top of the pile wall is measured by using a laser displacement meter. Pore pressure transducer fixed at the bottom of the shake box is used to measure the excess pore pressure developed in the soil.

TEST PROCEDURE

The laminar box is fixed to the base plate of the shaking table setup, lamellas are adjusted in straight position with help of clamped screws, and small vertical springs. Pile wall is embedded in the sandy soil layer perpendicular to the base excitation. The laminar shake box is filled with sand up to a height of 0.39 m at different relative densities using sand raining technique. After filling the sand the displacement transducers are fixed to the sides of lamellas of the laminar shake box. All receivers are attached and adjusted in their described position. A wire is fixed to the moving device of the laminar box and the vibration is induced to the shake box by means of springs attached to the base of the laminar box. The wire is cut so that laminar box vibrates freely and all the data are acquired using the data acquisition system. The tests are carried out at a relative density of 15% in loose dry state and 23% in loose saturated state. At each test, excitation is induced with the initial displacement amplitudes of 1, 2, 4 and 8 mm. Tests are carried out under the static load of 14 N and 28 N, which are applied on top of the pile wall. During the tests, lateral displacement of soil, vertical settlement of soil, pore water pressure developed in the soil and deflection at the top of the pile wall are observed and measured.

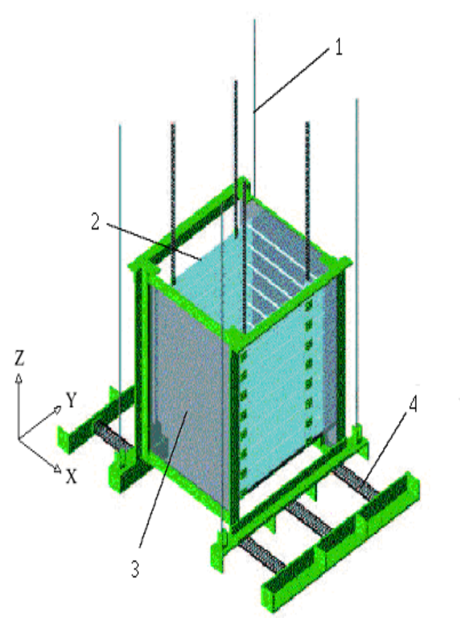

Figure 1. Experimental Setup

1.Tension rope adjusters 2. Movable wall segments (Lamellas) in excitation direction
3. Rigid wall of the laminar shake box 4. Springs for inducing initial vibration

RESULTS AND DISCUSSION

Soil-Pile Wall Behaviour in Loose Dry Sand

Lateral Displacement of Soil

The variation of lateral displacement of soil over the height of the box at different excitation levels for flexible pile wall is shown in Figure 2. It can be observed from Figure 2 that the lateral displacement of the soil is uniform throughout the depth at low intensity of shaking but it is substantially higher at surface level than the base level at high intensity of shaking. Figure 2 also indicates that increase of lateral displacement with an increase of static load due to low flexural stiffness of pile wall. Figure 3 shows the variation of lateral displacement of soil over the height of the box for rigid pile wall. In this case, the displacement pattern is practically identical under both magnitudes of static loads.

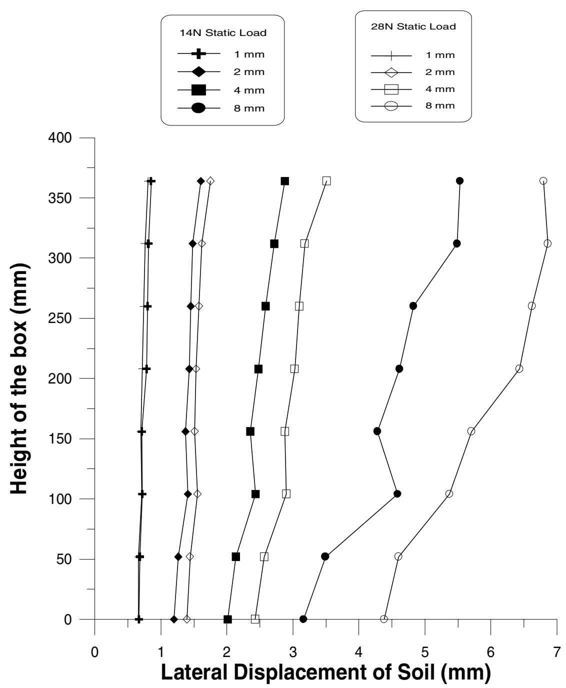

Figure 2. Lateral soil displacement with height of the box for flexible pile wall

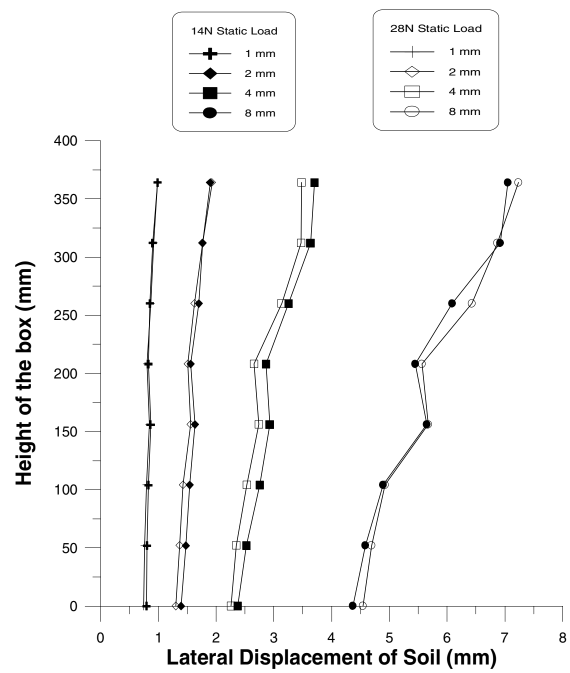

Figure 3. Lateral soil displacement with height of the box for rigid pile wall

It can be easily noticed from Figure 3 that the lateral displacement of the soil pattern of rigid pile wall is similar under low intensities of shaking but it is about 20 to 30% higher than the flexible pile wall case under high intensity of shaking.

Pile Wall Response

The variation of deflection at top of the flexible and rigid pile wall embedded in dry loose sand with time for 2 mm initial displacement amplitude is shown in Figure 4. The Figure 4 shows that the deflection at top of the flexible pile wall is very high when compared to the rigid pile wall due to lesser stiffness of the flexible pile wall. The predominant frequency is evaluated using Fast Fourier Transform (FFT) technique for the soil-pile wall system in dry state as 4.2 Hz. It is clearly observed in case of soil-rigid pile wall behaviour that the relative displacement of pile wall and the soil are very less, however in case of soil-flexible pile wall behaviour, the deflection of pile wall is much higher than the soil displacement.

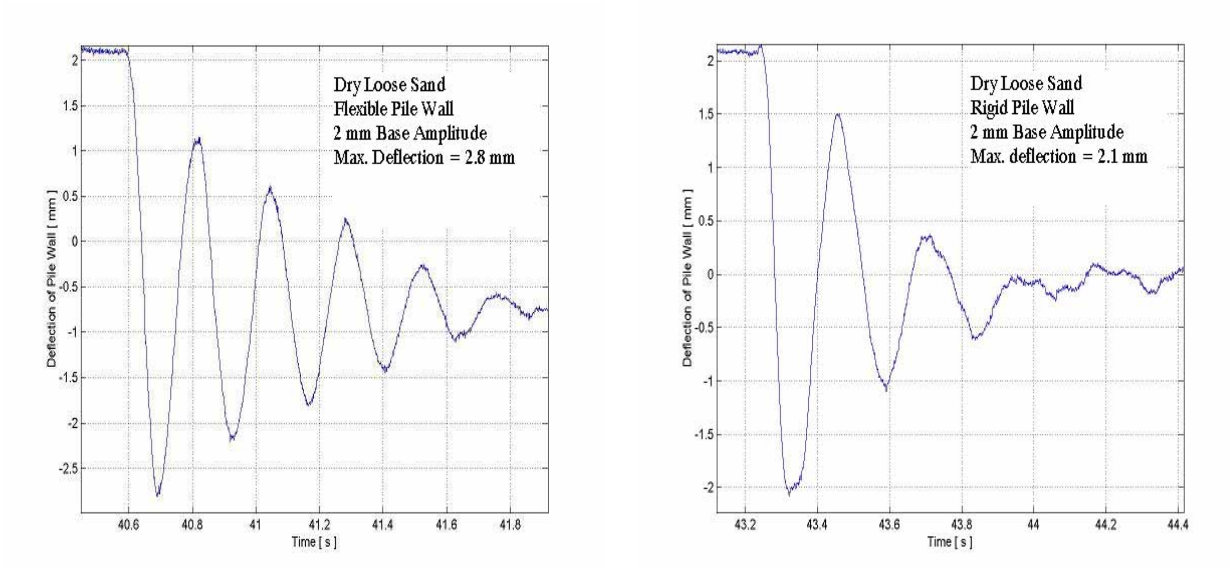

Figure 4. Variation of deflection at top of the flexible and rigid pile walls with time in dry loose sand with 2 mm base amplitude

The results of laminar shake box tests carried out on pile walls embedded in loose dry sand (14N static load) are given in Table 1. It can be observed from Table 1 that soil amplification takes place at all excitation levels and it is moderately lower at low intensity of shaking. The maximum deflection of the flexible pile wall is relatively higher than the rigid pile wall depending on the flexural stiffness. Damping ratio increases with increase in base shaking and is very high at high intensity of shaking.

Table 1. Results of laminar shake box tests carried out on pile walls embedded in loose dry sand (14N static load)

Amplitude (mm)	Base Acceleration (g)	Surface Acceleration (g)	Damping ratio	Max. Deflection of pile wall head (mm)	
				Flexible pile wall	Rigid pile wall
1	0.04	0.05	0.06	1.2	1.0
2	0.08	0.10	0.09	2.8	2.1
4	0.13	0.19	0.10	5.5	4.2
8	0.27	0.37	0.22	11.4	9.0

Soil-Pile Wall Behaviour in Loose Saturated Sand

Pore Pressure Response

Typical variation of pore pressure and pore pressure ratio with time for saturated loose sand at different excitation levels is shown in Figure 5. Excess pore pressure developed in the soil increases with increase of excitation level. It can be observed from Figure 5 that the pore pressure developed in the loose saturated sand at lower excitation level (0.04-0.07g) is about 50% of effective overburden pressure and 100% or above at higher excitation level (0.1-0.3g). It means that soil liquefaction takes place at acceleration above 0.1g.

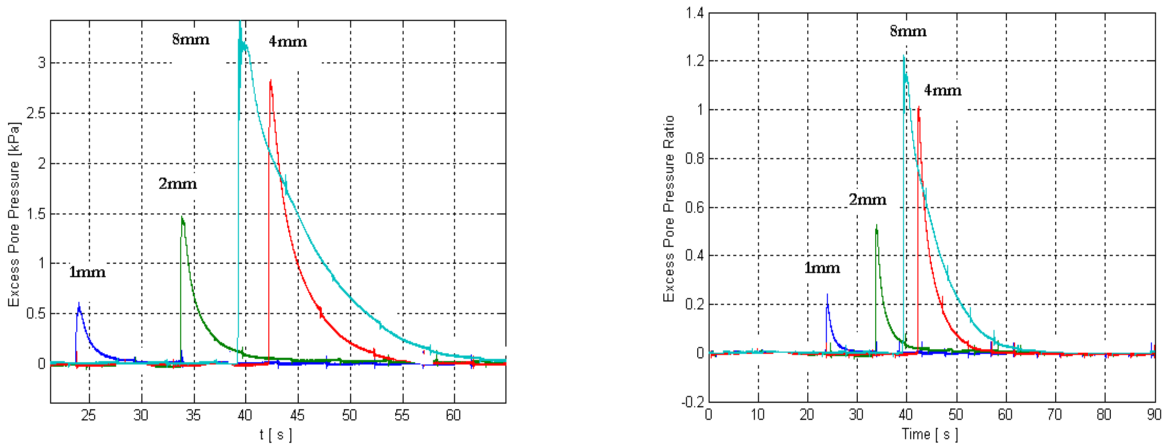

Figure 5. Variation of excess pore pressure and pore pressure ratio with time

Lateral Displacement of Soil

The variation of lateral displacement of soil over the height of the box at different excitation levels for flexible and rigid pile walls are shown in Figure 6 & 7 respectively. It can be observed from Figure 6 & 7 that the lateral displacement of the soil is substantially increasing through out the depth at all intensities of shaking. It is also evident from Figure 6 & 7 that the static load on pile wall is not affecting the lateral displacement pattern for both flexible and rigid pile wall.

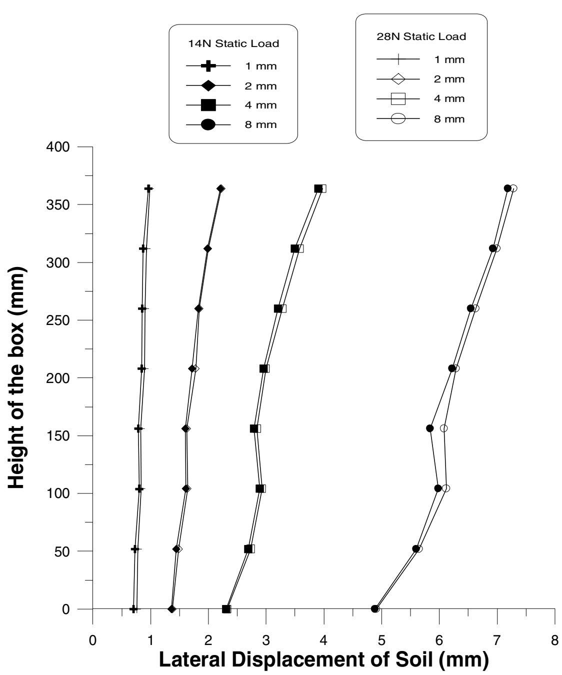

Figure 6. Lateral soil displacement with height of the box for flexible pile wall

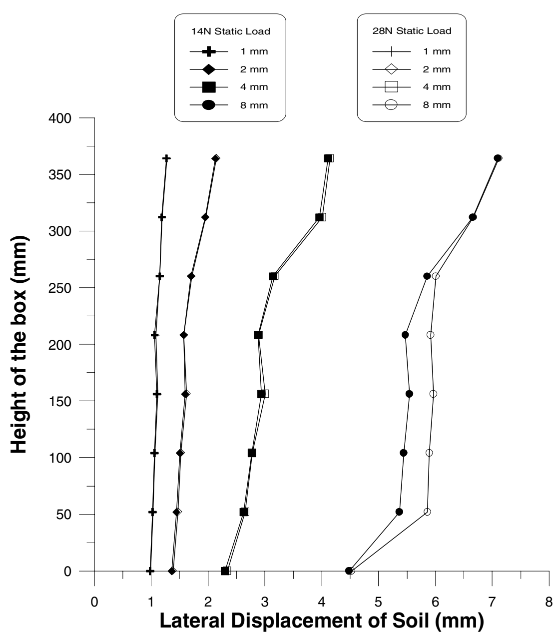

Figure 7. Lateral soil displacement with height of the box for rigid pile wall

Pile Wall Response
The variation of deflection at top of the flexible and rigid pile wall embedded in saturated loose sand with time for 2 mm base amplitude is shown in Figure 8. The Figure 8 clearly reveals that the deflection at top of the pile wall is maximum in flexible wall case as compared to rigid wall. The predominant frequency is evaluated using FFT for the soil-pile wall system in loose saturated state as 3.3 Hz. The deflection of the pile wall in saturated state due to liquefaction is about 30 to 40% higher than the dry state.

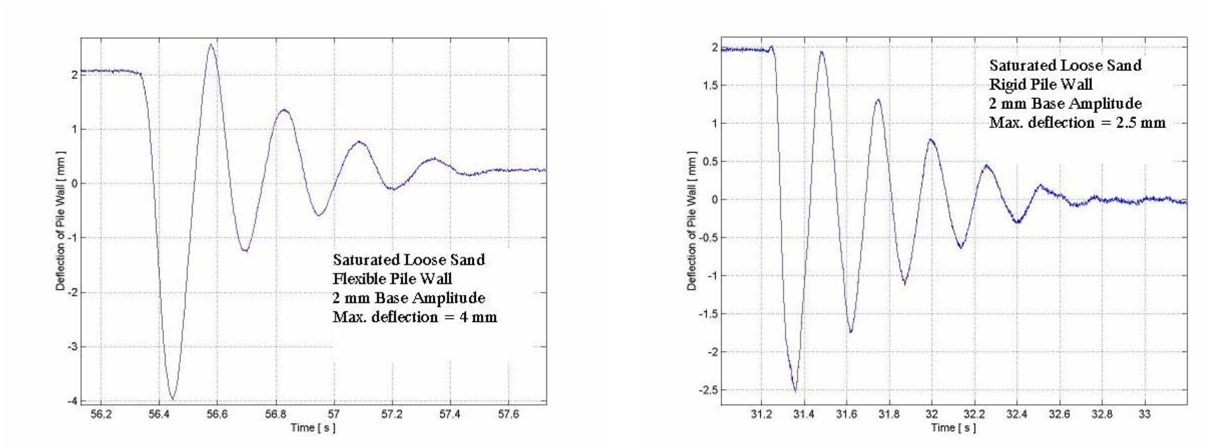

Figure 8. Variation of deflection of the flexible and rigid pile walls with time in saturated loose sand with 2 mm base amplitude

The results of laminar shake box tests carried out on pile walls embedded in loose saturated sand (14N static load) are given in Table 2. It can be observed from Table 2 that soil amplification takes place at all excitation levels but it is moderately low at lower intensity of shaking. The maximum deflection of the pile wall is relatively higher than the dry state. Damping ratio increases with increase in base shaking.

Table 2. Results of laminar shake box tests carried out on pile walls embedded in loose saturated sand (14N static load)

Amplitude (mm)	Base Acceleration (g)	Surface Acceleration (g)	Damping ratio	Max. Deflection of pile wall head (mm)	
				Flexible pile wall	Rigid pile wall
1	0.04	0.06	0.06	1.8	1.5
2	0.08	0.11	0.07	4.0	2.5
4	0.13	0.15	0.16	7.5	5.9
8	0.24	0.38	0.18	13.9	10.9

It is also observed from Table 1 & 2 that the maximum pile wall deflection in saturated loose state varies from 2.5d to 18.5d (where ‘d’ is thickness of pile wall) depending on the intensity of shaking and relative stiffness of the soil-pile wall system.

Soil Settlement

The variation of vertical settlement of soil with amplitude of vibration (1, 2, 4 & 8 mm) for flexible and rigid walls in dry loose sand is shown in Figure 9. The Figure 9 clearly indicates that the vertical settlement of sand is increasing with increased base excitation level. After completing the first series of tests with four base amplitudes, the settlement values with second series of tests were lower because of soil densification. The settlement of the soil with flexible and rigid wall is practically same for both dry and saturated cases. The settlement of sand in saturated loose state is about 40 to 50% higher than the dry loose state because of the liquefaction phenomena under saturated condition.

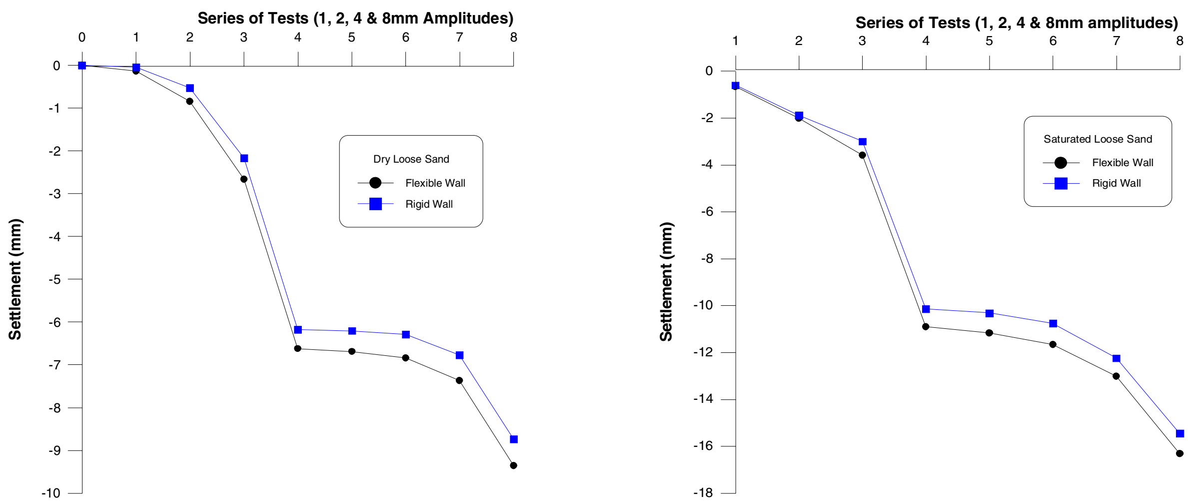

Figure 9. Variation of settlement with series of tests for flexible and rigid pile walls in loose dry and saturated state

CONCLUSIONS

The following are the concluding remarks based on the series of laminar shake box tests carried out on flexible and rigid pile walls embedded in saturated and dry loose sand at different intensity of shaking (corresponding base acceleration of 0.04g to 0.3g), which simulate low, moderate and strong intensity earthquakes.

The soil amplification is observed at all intensity of shaking both at dry and saturated condition. The static load applied on top of the pile wall has practically no effect on lateral displacement pattern in saturated state irrespective of the pile wall stiffness. However, the lateral displacement slightly increases with increase of static load applied in the case of flexible pile wall embedded in dry sand. The maximum deflection of the flexible pile wall is marginally higher than the rigid pile wall at dry and as well as saturated state of soil.

The deflection of pile wall embedded in saturated state of soil is about 30% higher than in the dry state of the soil irrespective of the stiffness of pile wall. The maximum pile wall deflection in saturated loose state varies from 2.5d to 18.5d (where ‘d’ is thickness of pile wall) depending on the intensity of shaking and relative stiffness of the soil-pile wall system.

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