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Dynamic centrifuge modeling of a shallow founded structure on layered soft clay considering the hard crust layer

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ABSTRACT: The existence of underlying soft soil can considerably impact the dynamic response of the soil-structure system. As one of the most effective physical modeling methods, geotechnical centrifuge modeling has been widely used to study such influences. This paper presents a recently conducted centrifuge test, which thoroughly investigates the dynamic response of layered soft clay with a hard crust layer while considering soil-structure interaction. From the test, it is observed that the soil acceleration is attenuated considerably when the seismic wave is propagating from the lower soft layer to the hard crust layer. At the same depth, the soil acceleration right beneath the mat foundation is smaller than that away from the foundation due to soil-structure interaction. Such differences also exist in the soil pressure response. At the same depth, the excess pore pressure ratio beneath the foundation is larger than that away from the foundation. These experimental results can help us gain insight into the overall seismic response of the layered soft clay with a hard crust layer and provide us with a trustworthy database to validate available numerical codes.

Keywords: centrifuge modeling, layered soft clay, hard crust layer, soil-structure interaction, site response

1 INTRODUCTION

It has been well acknowledged that the existence of underlying soil can profoundly impact the seismic response of superstructures. In recent years, geotechnical centrifuge modeling has been used as an effective emerging tool to study the site response of soft clay deposits and SSI. Afacan (Afacan et al., 2014) investigated the site response of soft clay over a wide strain range. Zhou (Zhou et al., 2017) reconstructed the soft clay soil model using kaolin clay and found significant amplification of displacement regardless of the input seismic intensities. For soil-structure system modeling, some researchers have proposed a new strategy to design more realistic reduced-scale structural models using the numerical method (Olarte et al., 2017). In this method, the prototype structure and model structure are analyzed using the numerical simulation, where main mechanical properties are enforced to follow the scaling law. However, it should also be stressed that the majority of the available SSI tests were conducted on clayey deposits with increasing undrained shear strength with respect to depth (Afacan et al., 2014). For example, Rayhani (Rayhani & El Naggar, 2007) studied the dynamic response of layered soft clay where the upper layer was softer than the lower one. Although this kind of soil profile is predominant in engineering practice, there are still many cases where the lower layer is softer than the upper one, i.e., the hard crust layer. For example, hard crust layers broadly exist in the Jiaxing area of east China. Furthermore, Rayhani (Rayhani & El Naggar, 2007) used glyben as an artificial clay to model the soft clay. However, there is no water in this material. As a result, the accumulation of pore-water pressure, which has a significant influence on the dynamic response of soil, cannot be captured in the experiments.

In this paper, the geotechnical centrifuge test is used to investigate the dynamic response of a soil-structure system where the undrained shear strength of the upper layer is higher than the lower layer. The preparation procedures of stratified clayey deposit with hard curst layer are discussed in detail. Soil acceleration and pore pressure accumulation recorded during the seismic motions have been systematically investigated to reveal the beneficial effects of the hard crust layer. The experiment also provides a trustworthy database to benchmark numerical codes for soil-structure interaction on layered clayey deposits.

2 CENTRIFUGE EXPERIMENTAL SETUP

2.1 Soil model

The prototype soil-structure system is located in the Jiaxing area of east China where deep soft clay and hard crust layer are substantially widespread. The soil model adopted in the experiment has 2 distinct layers. The upper hard crust layer has a consolidation pressure of 300kPa, whereas the lower layer is normally consolidated. The soil deposit is prepared using kaolin clay. The upper and lower layers are consolidated simultaneously by the two large consolidometers in two separate but identical model containers. The lower layer is consolidated in container #2 with 2 consecutive lifts. Each lift is completely in 5 stages to avoid possible shear failure or oozing of clay. Sensors like PPTs and accelerometers are placed at the designated positions by digging a hole in the clay deposit. The clayey slurry is then poured around the transducers, and the consolidation process is repeated.

For the upper layer, a sheet of high-strength geotextile is placed at the bottom of container #1 in the beginning. This layer is consolidated in just 1 lift. After consolidation, the over-consolidated upper layer is then moved from container 2 to container 1, as shown in Fig. 1(a). Note that a steel plate is used in the experiment to average the lifting force and reduce possible stress concentration on the clay sample. The surface of the lower layer has been carefully scotched before placing the upper layer deposits. As the ultimate step, a final lift is applied to the soil specimen with the maximum force equaling to the last lift of the lower clay layer to prevent the loss of stress history, as shown in Fig. 1(b). The obtained undrained shear strength profile is measured using the in-flight T-bar, as shown in Fig. 1(c). The centrifugal acceleration is 40g.

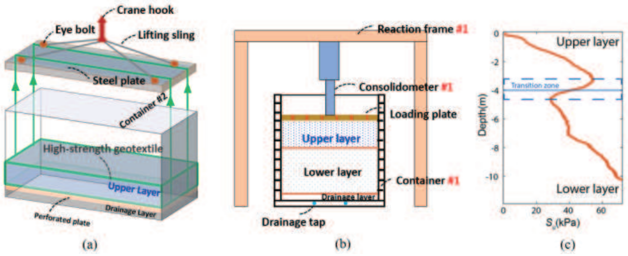


Fig. 1 (a) Lifting the upper layer from container #2 (b) final consolidation (c) undrained shear strength measured using the in-flight T-bar test

2.2 Structural model

The prototype in this test is adopted from an existing real structure in the Jiaxing area, which is a 5-story moment-resisting frame structure with a mat foundation. To convert the prototype structure to the scaled model structure, the similarities of the geometry, natural frequency, lateral stiffness, and foundation pressure (structural mass) are thoroughly investigated in the design process. The total height and the plan dimensions of the model structure were determined following the geometric similarity requirements. To ensure similarities of the natural frequency, lateral stiffness, structural mass, the prototype and model structures have been simulated using OpenSees to determine the cross-section area of the beams and columns in a trial-and-error manner. The properties of the prototype and model structure are shown in Table 1.

Table 1. Parameters for prototype and model structures.

Properties	Prototype	Scaled structure
Number of floors	5	3
Footprint (cm)	800 × 600	20 × 15
Foundation type	Mat	Mat
Total weight(kN)	880	0.0125
Total height(mm)	14000	350
Beam section(mm×mm)	200 × 400	6 × 6
Column section(mm×mm)	200 × 400	7 × 7.5
Natural frequency(Hz)	1.05;3.5;6.7	41;144;270

2.3 Earthquake motion and instrumentation

Two artificial earthquake motions, including a far-field motion and near-field motion, are adopted in the centrifuge test. These motions are simulated considering the 3D velocity profile of the local geological conditions. The motions have been scaled into 3 different intensities during the experiment, as shown in Table 2, where PBA, PBV and I_a are peak base acceleration, peak base velocity and Arias intensity, respectively. The instrumentation details of the experiment can be found in Fig. 2. The accelerometers A7 and A8 malfunctioned during the test.

Table 2 Input earthquake motions (prototype scale).

Name	PBA (g)	PBV (cm/s)	I_a (cm/s)
Step wave	0.02	-	-
NR-L	0.07	4.8	14.4
FAR-L	0.07	6.6	58.7
NR-M	0.13	7.5	43
FAR-M	0.16	11.2	185.1
NR-H	0.23	14.1	210
FAR-H	0.22	18.5	643.4

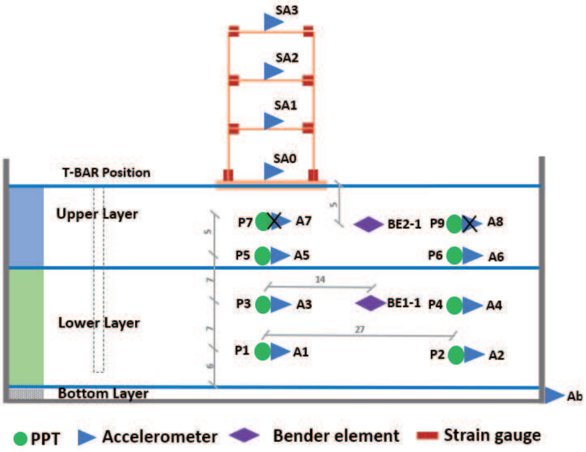


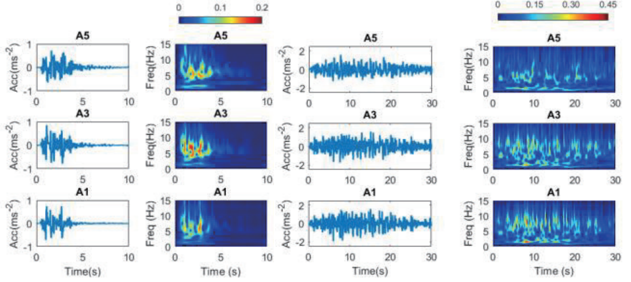
Fig. 2. Instrumentation details of the experiment.

3 KEY EXPERIMENTAL RESULTS

3.1 Soil acceleration

Stockwell transform is used to characterize the site response during seismic events (Olarte et al., 2018). Fig.

3 shows the Stockwell spectral of accelerometers of Array 1 during NR-L and FAR-H events, where red and blue represent high and low acceleration intensities, respectively. All of the units presented hereinafter are in the prototype scale unless otherwise stated. It can be observed that in the lower layer, the soft soil amplifies (see A1 and A3) the acceleration signal. This amplification effect is quite common for small seismic motions(Afacan et al., 2014). However, the acceleration signals at A6 exhibit an attenuation effect. This phenomenon is attributed to the relatively large elastic modulus in the transition layer. Since the shear stress must be continuous at the interface, shear strain and acceleration are smaller in the transition layer. For strong peak base motions, soft clay may exhibit softening behavior, which can result in attenuation effects(Afacan et al., 2014). Fig. 3(b) depicts the acceleration signals of Array 1 recorded during the FAR-H event, where attenuation effects are observed in the lower layer.



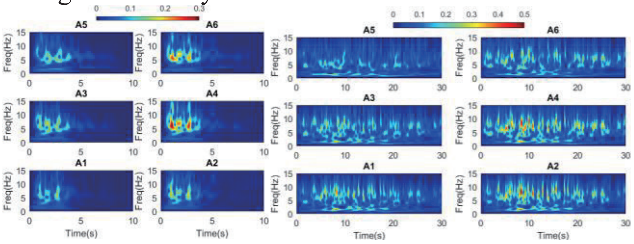
(a) (b)

Fig. 3 Stockwell spectra of acceleration signals of Array 1 during (a) NR-L (b) FAR-H.

To evaluate the inertial effects of SSI, Fig. 4 shows the Stockwell spectra of accelerations in both Array 1 and Array 2 during NR-L and FAR-H motions. From the figure, it can be concluded that at the same depth, the acceleration intensities beneath the foundation are smaller than those away from the foundation, especially in the high-frequency region. This phenomenon can be attributed to dynamic normal and shear stress induced by inertial interaction. Heidarzadeh (Heidarzadeh, 2015) systematically studied the dynamic stress in the foundation soil caused by external loads, where the underlying soil was simplified as a viscoelastic material. The induced dynamic stress tensor is expressed in a dimensionless manner. For example, for the horizontal point load, the induced stress tensor can be calculated using Eq. 1.

$$\frac{\sigma_{ij}R^2}{P} = g\left(\phi,\nu,\xi,\frac{\omega R}{V_s}\right) \tag{1}$$

where R is the radial distance, P is the load amplitude, ϕ is the vertical aperture angle, ν is the Possion's ratio, ξ is the soil damping, ω is the load frequency, V_s is the shear wave velocity of soil. Function g is expressed by graphs of amplitude and phase angle. Since the seismic motions studied in the current experiment are focused on frequencies less than 10Hz. Thus, the dimensionless quantity $\frac{\omega R}{V_s}$ is less than 2. A typical induced shear stress amplitude distribution is plotted in Fig. 5. As can be seen from Fig. 5, the induced shear stress amplitude beneath the foundation is larger than away from the foundation.



(a) (b)

Fig. 4 Comparison of Stockwell spectra of Array 1 and Array 2 (a) NR-M.

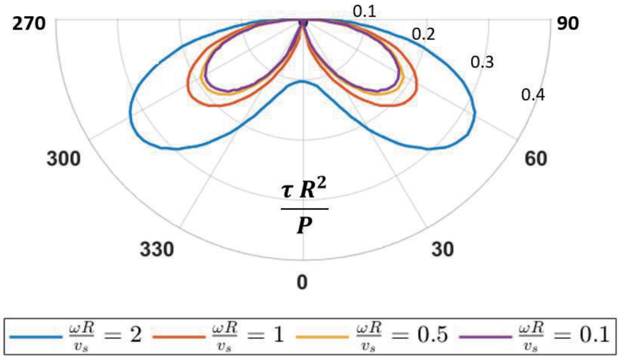
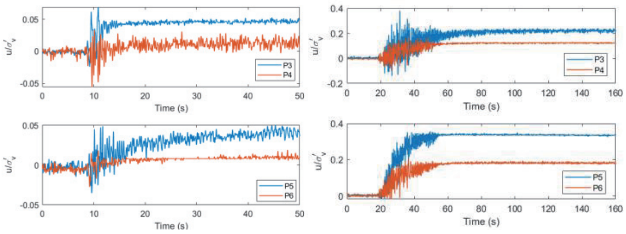


Fig. 5 Shear stress amplitudes induced by dynamic horizontal point loading ($\nu = 0.45, \xi = 5\%$).

3.3 Pore pressure

Fig. 6 plots the excess pore pressure ratio r_u under different earthquake motions. It can be seen that at the same depth, r_u beneath the foundation is generally larger than the region away from the foundation. The theory proposed by Matsui(Matsui et al., 1980) is used for an explanation. In this theory, r_u is related to the over-consolidation ratio and maximum shear strain magnitude, as shown in Eq. 2, where A_1, B_1 and β are all constants. A finite element model is constructed to investigate the distribution of structure-induced vertical stress σ'. As shown in Fig. 7, inertial SSI results in larger σ'. Therefore the over-consolidation ratio is smaller beneath the foundation. The shear strain time series is obtained from the method proposed in (Brennan et al., 2005) to evaluate the maximum magnitude of dynamic strain. Fig. 7 depicts the shear strain-time series of the near and far fields during FAR-H motion. From Fig. 7, it can be seen that such discrepancy between the strain time series of two is negligible when using Eq. 2. As a result, r_u should also be larger beneath the foundation.

$$r_u = \beta\left[\log\frac{\gamma_{cmax}}{A_1(OCR-1)+B_1}\right] \tag{2}$$



(a) (b)

Fig. 6 Pore water pressure accumulated in seismic events (a)NR-L; (b)FAR-H.

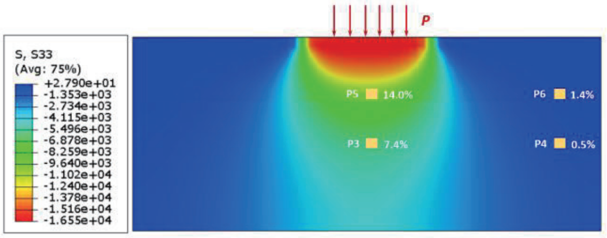


Fig. 7 Distribution of foundation-induced vertical stress σ'.

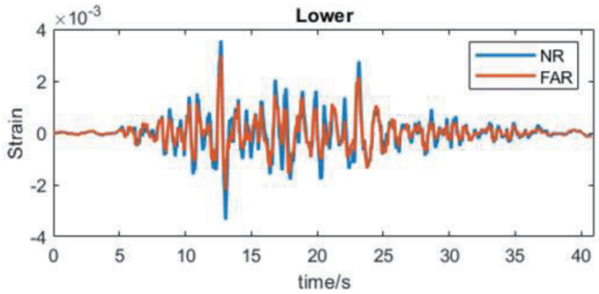


Fig. 8 Strain histories of the near-field and far-field regions during FAR-H motion.

4 CONCLUSIONS

In this paper, the geotechnical centrifuge is used to investigate the seismic response of layered soft clay with a hard crust layer while considering soil-structure interaction. The model structure and soil sample are designed and prepared in accordance with the prototype structure and typical soil stratification in the target area. The upper hard crust layer has larger stiffness and shear strength than the lower soft layer. The input earthquake motions, which can reflect the characteristics of local geological structures, are applied through the in-flight uniaxial hydraulic shaker.

The site response of soft clay is thoroughly investigated. Under seismic motions with low intensities (PBA<0.16g in the experiment), amplification of accelerations is observed in the lower soft layer. However, when the acceleration exceeds 0.20g, accelerations are attenuated because of softening of soft clay. Due to the larger modulus of the upper layer, acceleration will attenuate in the transition zone between the upper and lower layers regardless of seismic intensities. Therefore, hard crust layers are beneficial in terms of decreasing the dynamic acceleration of soil and superstructures.

Soil-structure interaction is found to impact the underlying soil deposit's dynamic response profoundly. Due to the dynamic force induced by the vibrating superstructure at the soil-foundation interface, the accelerations away from the foundation were relatively larger than that close to the foundation. The excessive pore pressure ratio, however, has the opposite trend because of the larger effective stress and over-consolidation ratio beneath the foundation.

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