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Physical Modelling in Geotechnics

Nonlinear site response of soil-cement grid improved ground by centrifuge models

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ABSTRACT: The soil-cement gird has been widely used as soil improvement, liquefaction countermeasure or retaining structure for port facilities in practice. The nonlinear soil-grid interaction was studied by two centrifuge model tests carried out on a soil-cement grid improved model in dry sand. Three soil-cement grids with different internal spacing and an unimproved soil profile were adopted in these two tests. Under the different geometric parameters of soil-cement grids and shaking intensities, the soil-grid kinematic interaction and shear strains of the improved ground were investigated and critically discussed in this paper. It was found that the horizontal displacements of the enclosed soil, especially for the upper half, were largely decreased by soil-cement grids due to the kinematic interaction. And the reduction of soil-cement grid internal spacing can significantly increase the restriction effect on shear strains of the enclosed soil. In addition, the "waist effect" of shear strains along the depth direction in each cell was observed, which means the shear strains of the enclosed soil were least at the middle height and larger on both ends. Moreover, The underlain layer of the soil-cement grid improved ground may experience larger shear strain compared with the unimproved ground.

Keywords: Centrifuge test, Soil-cement grid, Ground improvement, Dry sand

1 INTRODUCTION

The ground improvement technologies are always applied to the original ground in engineering practices to achieve better stability under various external loadings. The soil-cement grid, made up of overlapped soil columns stabilized by the deep mixing method, has been widely developed as a ground improvement for clayey soils or loose sand deposits (Khosravi et al., 2016; Ishikawa and Asaka, 2006), which may experience serious soil liquefaction under seismic loadings.

Different from other ground improvement technologies, such as replacement, densification and drainage, the deep mixing method could largely increase the stiffness of the stabilized soil using lime or cement as the binders. In the meantime, the grid-type shape makes the improvement behave more like an underground structure or foundation, which has a significant stiffness contrast to the enclosed soil. The modern seismic codes, such as Eurocode 8 (2004), recommend that the kinematic interaction between the soil and foundation should be accounted for in the seismic design. The recent studies also demonstrated the significant role of the kinematic soil-foundation interaction in the dynamic responses of the ground (Boulanger et al., 1999; Dezi et al., 2010). And most of them mainly focused on its effects on the internal forces of the foundation.

Similarly, the soil-grid interaction should also be carefully studied to figure out its effects on the seismic responses of the improved ground, and more attention needs to be paid to the enclosed soil inside the soil-cement grid. It is because the purpose of this kind of ground improvement is to prevent the enclosed soil from liquefaction. Taya et al. (2007) proposed a design method for the soil-cement grid, and Nguyen et al. (2013) evaluated the distribution of shear strain within enclosed soil, both of which were based on the elastic finite-element analyses. However, the soil, soil-grid interface and often the soil-cement grid exhibit strongly nonlinear responses under seismic loadings. Several advanced elastoplastic models were applied in numerical simulations (Namikawa et al., 2007; Koseki and Namikawa, 2010; Bradley et al., 2013). In the meantime, dynamic centrifuge model tests provide an effective way to investigate the nonlinear responses of soil-cement grid improved ground (Ishikawa and Asaka, 2006; Tamura et al., 2018).

In this study, two dynamic centrifuge model tests with four different soil profiles were performed, including three soil-cement grid improved soil profiles and an unimproved soil profile. The nonlinear dynamic responses of the enclosed soil were presented together with that of the unimproved soil to show the effect of the soil-grid interaction. In order to simplify the model condition in the preliminary study, the centrifuge models were prepared in dry condition to avoid the soil softening due to the excess pore pressures.

2 CENTRIFUGE TESTS

Two centrifuge model tests were performed using the 4.5-m-radius centrifuge with an in-flight uniaxial shaker at Zhejiang University, the details of which could be referred to Zhou et al. (2018). The dry sand models were prepared in a laminar container with internal dimensions of 595 mm (length)×350 mm (width)×500 mm (height) and tested under centrifugal acceleration of 60 g. All data are presented in prototype unless otherwise specified.

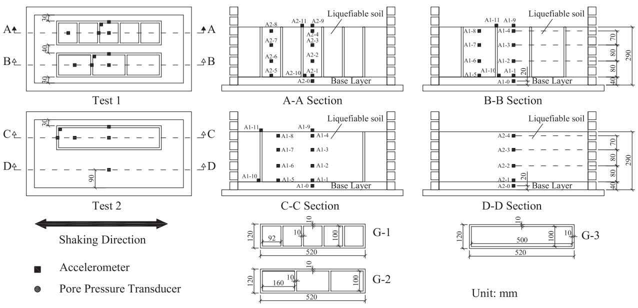

Fig. 1. Model configurations.

The model configurations are shown in Figure 1 in model scale. The soil profile consists of a 15-m-thick liquefiable layer and an underlying 2.4-m-thick coarse sand layer in both models. Based on the previous research (Ishikawa et al., 2015), the clayey sand (i.e., Fujian sand with 10% of Kaolin clay) with the relative density of 60% was adopted as the liquefiable layer in this study, which was dryly pluviated into each square cell. And the coarse sand was tamped to a dense condition of the relative density of 90% as the base layer. It contributes to the uniform saturation of the upper layer and serves as the underlain non-liquefiable layer corresponding to engineering practices. The physical properties of the adopted soil are given in Table 1.

The soil-cement grid is composed of repeated cells with the same internal spacing. Thus, the grid models adopted in these tests were made of aluminum alloy with the same width and total length while varying internal lengths of the cells to cover different engineering application scenarios. In general, relatively small internal spacing (around 5 to 10 m) are traditionally designed for embankment (Boulanger et al., 2018; Washida et al., 1993), port facilities and high-rise buildings (Suzuki et al., 1996). And much larger width of the cell was adopted when the soil-cement grids were used to strengthen the foundation of the existing building (Ishii et al., 2017).

Table 1. Physical properties of the test soils.

Property	Unit	Clayey sand	Coarse sand
Soil particle density, ρ_s	g/cm^3	2.651	2.648
Maximum void ratio, e_{max}	-	1.14	0.80
Minimum void ratio, e_{min}	-	0.60	0.57
Fines content, *FC*	%	15	0.2
Uniformity coefficient, U_c	-	40	1.4
50% diameter on the grain size diagram, D_{50}	mm	0.16	1.31
Permeability, *k*	m/s	8.04×10^{-6}	7.14×10^{-3}

The soil-cement grids with minimum and intermediate spacing (i.e., G-1 and G-2) were used to reinforce one half and the other half of the model D1, corresponding to sections A-A and B-B respectively. And section C-C of model D2 was improved by the large-spacing soil-cement grid and section D-D represents free field without any improvement. Thus, there were four soil configurations in this series of centrifuge tests, which are summarized in Table 2. The L represents the length of the cell and the H represents the height of the soil-cement grid.

The centrifuge models were subjected to sine waves successively with stepwise increasing peak base accelerations (PBA) of 0.05 g, 0.10 g, 0.15 g, 0.20 g, 0.30 g and 0.40 g. The input sine wave consists of the first four cycles with increasing amplitude, the middle 20 cycles with a constant amplitude at peak acceleration and the last four cycles with decreasing amplitude. The frequency of the input motion was 1.2 Hz in prototype unit.

Table 2. Test conditions of two models.

Test ID	Section	Improvement	L/H
Model 1	A-A	G-1	0.368
	B-B	G-2	0.640
Model 2	C-C	G-3	2
	D-D	Free field	-

3 TEST RESULTS AND DISCUSSIONS

3.1 Kinematic soil-grid interaction

The intensity of kinematic interaction between soil and foundation is always evaluated by the displacement responses of the ground, which are always adopted in pseudostatic approaches for calculating the internal forces of the foundation (Tabesh et al. 2001). It could also be portrayed in terms of the kinematic interaction factor, such as U_p/U_b (Hussien et al., 2016), where U_p is the horizontal displacement of the pile head and U_b is the base displacement. Thus, the displacement responses of the soil enclosed by the soil-cement gird are analyzed in this section.

The acceleration time history data was filtered using a fourth-order bandpass filter allowing frequencies between 0.1 Hz and 20 Hz to pass through. The time histories of the displacement were obtained by double integration of the corresponding acceleration records. Fig. 2 presents the amplification factor, which represents the amplitude of soil displacements at all depths normalized with the input base displacements ($A_u=U_s/U_b$). M1 to M6 correspond to the six shaking events in turn, and the section D-D represents the free field without any improvement. Basically, the displacement amplification factor Au gradually increased as the depth became shallower. However, the increase rate of the displacement amplification factor suddenly decreased in the enclosed soil within a depth range of 5 m to 10 m, especially in the soil-cement grid with minimum spacing, which led to the soil displacement inside the soil-cement grid beginning to be significantly smaller than that in free field. It shows that the soil-grid interaction was strongest in the middle height of the soil-cement grid, and its effect would be exaggerated with the increase of shaking amplitude.

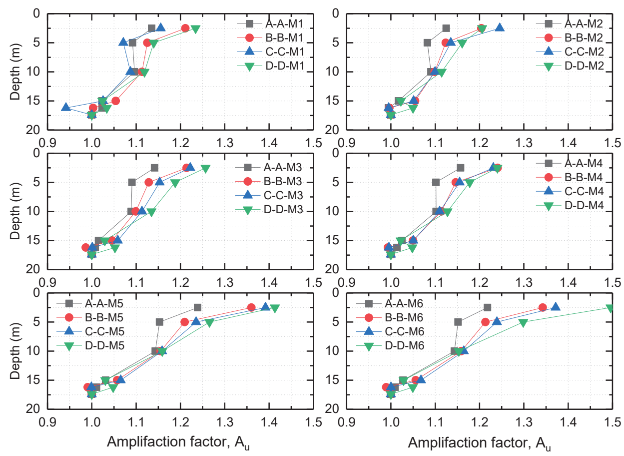

Fig. 2. Displacement amplification factor of the enclosed soil.

3.2 Shear strain

The dynamic shear strains were computed at different depths using the recorded data from the vertical array of accelerometers at the center of each section. The procedures were proposed in Zeghal et al. (1999) with the assumption of a one-dimensional shear beam condition. Fig. 3 presents the peak shear strains of the enclosed soil or free field under sinusoidal waves with amplitude of 0.3 g. When focusing on the clayey sand layer, the shaking-induced shear strains of the unimproved ground (section D-D) gradually increase as the depth becomes shallow, while the remarkable "waist effect" in the shear strains of the soil enclosed by the soil-cement grid was observed in section A-A, B-B and C-C. It shows the restriction effect of the soil-cement grid on the soil deformation was best at the middle height.

In addition, the shear strains of the enclosed soil were reduced significantly with the decrease of cell spacing and evidently smaller than that of the unimproved ground, except for the shallow layer inside the large-spacing soil-cement grid (G-3). It shows that the soil-cement grid with large internal spacing might increase the liquefaction potential of the shallow layer due to the soil-grid interaction. However, the shear strains at the interface of the soil-cement grid bottom and base layer were much larger than that of the unimproved ground, indicating intense relative movement between these two layers. It is worth noting that the underlain layer would experience abnormally large deformation due to the upper improvement, which might lead to undesirable liquefaction or soil softening of the underlain layer.

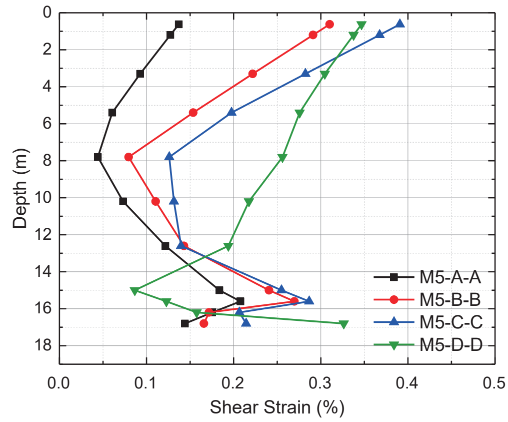

Fig. 3. Peak shear strains of the enclosed soil

4 CONCLUSIONS

Two centrifuge models, including four different soil profiles, were prepared in dry condition. The nonlinear responses of the soil-cement grid improved ground were presented together with that of the unimproved ground to investigate the kinematic soil-grid interaction. Some interesting conclusions could be drawn as follows:

(1) The horizontal displacements of the enclosed soil, especially for the upper half of the model, were largely decreased by the soil-cement grids. And the soil-grid interaction was most significant at the middle of the soil-cement grid.

(2) The "waist effect" of the shear strain along the depth was observed in the soil-cement grid improved ground with different cell spacing, which means the shears strain was the least at the middle height of the soil-cement grid. And such effect is the most significant in the cell with the minimum internal spacing due to the strongest kinematic soil-grid interaction.

(3) The underlain layer of the soil-cement grid improved ground may experience larger shear strain compared with the unimproved ground. The resulting liquefaction or soil softening of the underlain layer should be carefully treated.

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