Dynamic Analysis of Geosynthetic-Reinforced Soil (GRS) Slope Under Bidirectional Earthquake Loading

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Abstract. For the past few decades, geosynthetic-reinforced soil slopes (GRS slopes) have been increasingly used in geotechnical, hydraulic and geoenvironmental engineering applications, due to their great earthquake resistance. Near-field strong ground motion usually involves a vertical component, which is very large in some cases. However, existing design guidelines do not provide a clear approach of earthquake resistant design for GRS slopes subjected to combined horizontal and vertical accelerations. In this study, a nonlinear Finite Element procedure was further validated by a centrifuge shaking table test, and then employed to investigate the seismic responses of a GRS slope model considering a large range of bidirectional earthquake loadings, based on a highway project located in Xinjiang. The results showed that the vertical acceleration had a great effect on permanent displacement, if the corresponding horizontal acceleration was large, and it also played an important role on the stiffness and natural resonant frequency of the soil due to soil compaction. There existed good correlations between the earthquake intensity parameter a_{rs} at the center of gravity of active wedge and seismic responses of the GRS slope after horizontal earthquake loading.

Keywords: GRS slope · Bidirectional ground motion · Finite element analysis · Ground motion intensity parameter

1 Introduction

China is a country with frequent earthquakes, and geosynthetic-reinforced soil (GRS) slopes have a great potential of extensive application in areas of high seismicity. Near-field ground motions containing vertical components are of interest in the fields of earthquake engineering. However, vertical acceleration is rarely taken into account in the existing design of reinforced soil structures.

There exist limited studies aiming to analyze the seismic responses of GRS structures under bidirectional earthquake loadings. It was reported that several GRS retaining walls failed during near-field earthquakes, in which the ratio of vertical to horizontal acceleration was very large [1, 2]. A series of large-scale shaking table tests of GRS

retaining walls were carried out by Ling et al. [3], and actual records of bidirectional ground motion from the 1995 Kobe earthquake was considered in one of these tests. It was found that the vertical ground motion had little influence on the facing displacement, but led to higher reinforcement loads. Using the Finite Element procedure validated against the aforementioned test [3], Fan et al. [4] analyzed the influence of bidirectional earthquake loadings on the seismic response of GRS retaining walls, and the interplay between the wall responses with the Arias intensity of the horizontal seismic motion was also shown, a transfer function defining the reinforcement loads based on the Arias intensity was proposed. Ling et al. [5] analyzed the residual displacement of a GRS slope subjected to combined horizontal and vertical earthquake loadings with a log-spiral failure mechanism, the importance of vertical excitation to the sliding displacement analysis was discussed.

The objective of this study is to investigate the seismic performance of GRS slopes subjected to combined horizontal and vertical accelerations. With a nonlinear Finite Element procedure validated by a centrifuge shaking table test, a series of numerical models of a GRS slope considering a large range of bidirectional earthquake loadings were established, based on a highway project located in Xinjiang. The influence of vertical acceleration on the seismic response of GRS slopes was analyzed. A good correlations between the earthquake intensity parameter a_{rs} at the center of gravity of active wedge and seismic responses of the GRS slope was proposed, and the intensity parameter a_{rs} can be employed in a pseudo-static analytical method to determine the maximum reinforcement load.

2   Finite Element Procedure and Its Validation

PLAXIS [6] (Finite Element method) is widely used in geotechnical engineering applications including GRS structure systems. In this study, The backfill soil was modeled by Hardening Soil model with small-strain stiffness(HSS model) [6]. A parameter of 0.67 was considered to describe the reduced shear strength and stiffness of the reinforcement-soil interface. The geosynthetic reinforcements were modeled by one-dimension linear elastic elements. The acceleration time-history of the ground motion was input at the base of the model. The viscous damping was set as 5% in the dynamic analysis. Further details can be found in Cai [7].

A centrifuge shaking table test at a centrifugal acceleration of 20 g considering bidirectional seismic excitation was employed to validate the Finite Element procedure for the dynamic analysis. The wrap-faced GRS retaining wall model configurations and the test results are shown in scale-down units. Figure 1 shows the Finite Element mesh. The model height was 200 mm, the reinforcement length was 210 mm, and the vertical spacing of the reinforcement layers was 50 mm. The model parameters of the backfill soils are presented in Table 1, which were calibrated from cyclic triaxial compression tests on Fujian standard sand (relative density Dr = 70%) as shown in Fig. 2. The 100 mm thick foundation used the same sand but at a Dr of 90%. The reinforcement layers were one type of PP geogrid with a stiffness of 35 kN/m, which represented the secant stiffness at a strain of 2%. The model wall was subjected to several consecutive

bidirectional sinusoidal shakings. In the first shaking, the peak horizontal acceleration was 1 g, while the peak vertical acceleration was 0.67 g(the vertical to horizontal (V/H) ratio = 0.67), and there was no phase difference. The input accelerations in the later shaking were approximately 2, 4, 8, 10 times of those in the first one with the same V/H ratio. The frequency of input motions was 66.7 Hz. Further details of the input motions can be found in Cai [7].
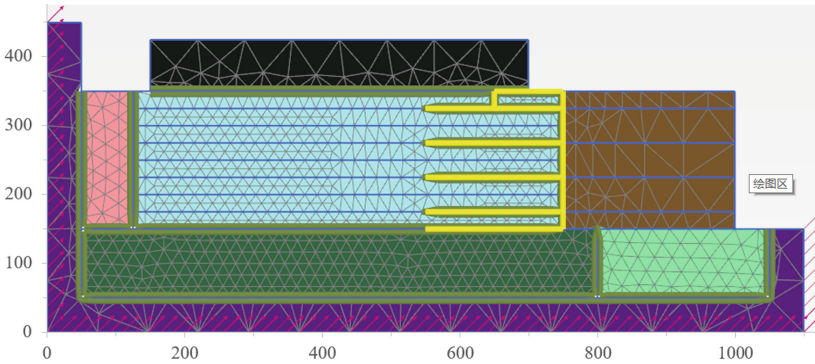

Fig. 1. Finite Element mesh of the centrifuge shaking table test (unit: mm)

Table 1. Backfill parameters of the GRS retaining wall model

Parameter	Unit	Value
Unit weight, γ	kN/m^3	15.1
Cohesion, c	kPa	2
Friction angle, φ	°	36.6
Dilatancy angle, ψ	°	6.6
Secant stiffness in standard drained triaxial test, E_{50}^{ref}	kPa	2.45E4
Tangent stiffness for primary oedometer loading, E_{oed}^{ref}	kPa	2.5E4
Unloading–reloading stiffness, E_{ur}^{ref}	kPa	7.35E4
Power for stress-level dependency of stiffness, m	–	0.5
Shear strain, $\gamma_{0.7}$	–	0.0004
Reference shear modulus at very small strains (e < 10E6), G_0^{ref}	kPa	9E4
Strength reduction factor in the interface, R_{inter}	–	0.67
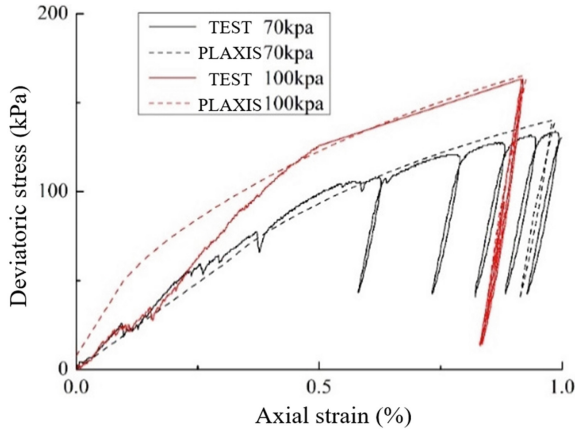
Fig. 2. Cyclic triaxial compression tests on Fujian standard sand (Dr = 70%)
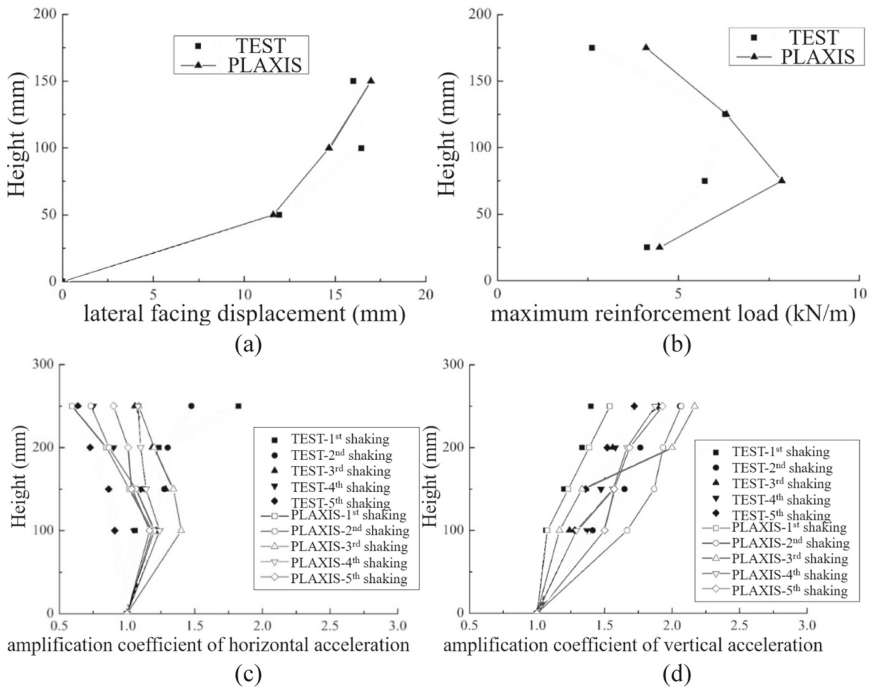
Fig. 3. Comparisons between the results from the test and the Finite Element method: (a) lateral facing displacement (b) maximum reinforcement load of each layer (c) amplification coefficient of horizontal acceleration of the reinforced soil (d) amplification coefficient of vertical acceleration of the reinforced soil

Figure 3 shows the comparisons between the results of the centrifuge shaking table test and the Finite Element method. It shows that the Finite Element procedure satisfactorily reproduced the seismic responses of the wrap-faced GRS retaining wall model. The validated procedures can then be used for analyzing the seismic responses of a GRS slope model considering bidirectional earthquake loadings.

3   Finite Element Models

The seismic responses of a gabion-GRS slope model with a height of 10.1 m were investigated, based on a highway project located in Xinjiang, as shown in Fig. 4. The gradient of the slope facing and its back were 1:0.75 and 1:1.5, respectively. The vertical spacing of the reinforcement layers was 0.6 m. The foundation soil was assumed to be stiff rock, hence fixed boundaries were used on the base, and roller boundaries were used on the sides. The unit weight of gabion facings was 24 kN/m^3, which was the same as Xu [8]. Parameters of the backfill soil are shown in Table 2, and further details can be found in Xiong [9]. The reinforcements were modeled by one-dimension linear elastic elements with a stiffness of 4000 kN/m. The other parameters of the Finite Element model can be found in Cai [7].

Table 2. Backfill parameters of the Gabion-GRS slope model

Parameter	Unit	Value
Unit weight, γ	kN/m^3	20
Cohesion, c	kPa	12
Friction angle, φ	°	41.7
Dilatancy angle, ψ	°	0
Secant stiffness in standard drained triaxial test, E_{50}^{ref}	kPa	5.421E4
Tangent stiffness for primary oedometer loading, E_{oed}^{ref}	kPa	5.421E4
Unloading–reloading stiffness, E_{ur}^{ref}	kPa	1.63E5
Power for stress-level dependency of stiffness, m	–	0.5
Shear strain, $\gamma_{0.7}$	–	4.5E−4
Reference shear modulus at very small strains (e < 10E6), G_0^{ref}	kPa	1.05E5
Strength reduction factor in the interface, R_{inter}	–	0.67

After construction simulation, the base excitations were input from bottom of the model. Altogether 30 strong bidirectional ground excitations taken from the records of 8 actual earthquake were employed in the dynamic analyses. The peak acceleration of all the input horizontal excitations were scaled to be 0.4 g, and the corresponding vertical excitations were scaled proportionally according to the actual vertical to horizontal (V/H) ratio.

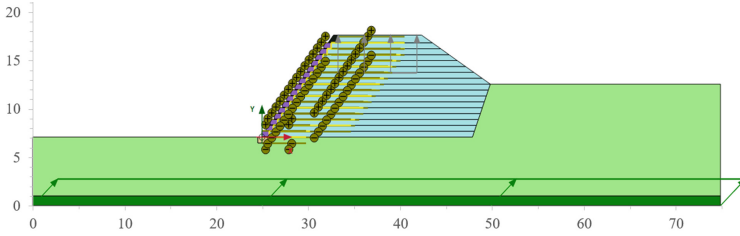Further details can be found in Cai [7].

Fig. 4. Gabion-GRS slope model (unit: m)

4   Results and Discussions

Figure 5(a) shows the comparisons between the maximum residual lateral facing displacement δ_{max} after bidirectional earthquake loading and that after horizontal loading only. It can be seen that the vertical acceleration had a great effect on permanent displacement, if the corresponding horizontal acceleration was large.

The comparisons between the sum of maximum reinforcement loads $\sum T_{max}$ after bidirectional earthquake loading and that after horizontal loading only are summarized in Fig. 5(b). It shows that the vertical acceleration led to smaller reinforcement loads with larger corresponding horizontal acceleration, which mean it played an important role on the stiffness and natural resonant frequency of the soil due to soil compaction.
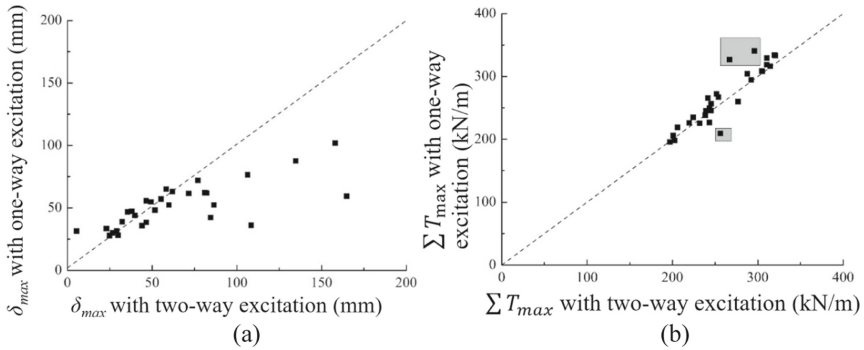

Fig. 5. Influence of vertical acceleration on (a) the maximum residual lateral facing displacement δ_{max} (b) the sum of maximum reinforcement loads $\sum T_{max}$

The earthquake intensity parameter a_{rs} is defined as:

$$a_{rs} = \left(\frac{1}{t_0} \int_0^{T_d} a(t)^2 dt \right)^{0.5} \tag{1}$$

Here t is time, $a(t)$ is the time history of the horizontal excitation, T_d is the duration of the horizontal earthquake motion, and t_0 is a unit time.

Figure 6 shows that there existed good correlations between the earthquake intensity parameter a_{rs} at the center of gravity of active wedge and reinforcement loads of the GRS slope after horizontal earthquake loading. The intensity parameter a_{rs} can be employed in a pseudo-static analytical method to determine the maximum reinforcement load.
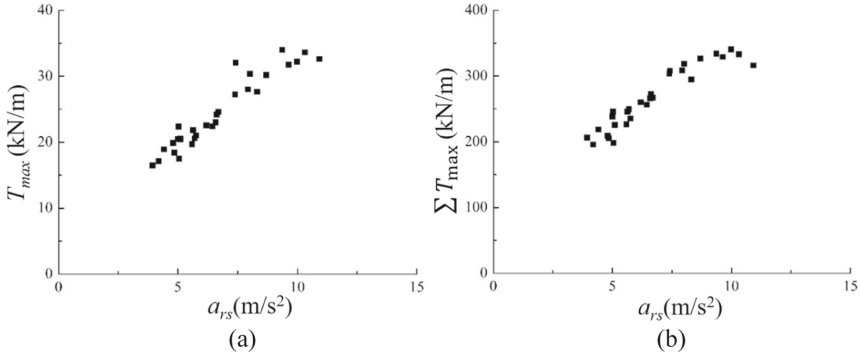
Fig. 6. Relationship between a_{rs} and (a) maximum reinforcement load T_{max} (b) the sum of maximum reinforcement loads $\sum T_{max}$ after horizontal earthquake loading

5   Conclusion

In this study, a nonlinear Finite Element procedure was further validated by a centrifuge shaking table test, and then employed to investigate the seismic responses of a GRS slope model considering a large range of bidirectional earthquake loadings, based on a highway project located in Xinjiang. The results showed that:

(1) The vertical acceleration had a great effect on permanent displacement if the corresponding horizontal acceleration is large, and it also played an important role on the stiffness and natural resonant frequency of the soil due to soil compaction;

(2) There existed good correlations between the earthquake intensity parameter a_{rs} at the center of gravity of active wedge and seismic responses of the GRS slope after horizontal earthquake loading; The intensity parameter a_{rs} can be employed in a pseudo-static analytical method to determine the maximum reinforcement load.

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