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Response of gravity retaining wall with anchoring frame beam supporting a steep rock slope subjected to earthquake loading

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ABSTRACT

Shaking table test and dynamic numerical analysis are carried out to study the seismic behavior of the gravity retaining wall with anchoring frame beam supporting a steep rock slope (inclined at an angle of 40° with the horizontal) by applying one-directional and bi-directional excitations of Wenchuan motion with different intensities. The horizontal and vertical acceleration responses, the dynamic earth pressure are investigated in shaking table test. A comparative and extensive study is performed in terms of the horizontal and the vertical acceleration responses, the dynamic earth pressure, the axial stress of anchor by means of dynamic numerical analysis with Flac3D code. Results show that both the horizontal and the vertical acceleration amplifications present a dramatic increase at the base of the anchoring frame beam, where the acceleration response is greatly amplified. The bi-directional excitation of Wenchuan motion causes a more intensive acceleration response than the one-directional excitation. The nonlinear behavior of anchoring frame beam is much more obvious than that of gravity retaining wall under earthquake loading. The response of dynamic earth pressure is not in phase as that of the inertial force, and quite a big value of residual earth pressure is induced by earthquake loading. The earthquake loading greatly increases the axial stress of anchor in the free zone. The axial stress of anchor decreases rapidly in anchorage zone and tends to zero within a short length.

1. Introduction

The engineering construction in the southwest of China has to overcome the issues including the support of high-steep slope, the seismic resistance of structure, and so on. For example, the under construction Da-Rui railway (from Dali city to Ruili city), which is regarded as a national main-line with a design speed of 140 km/h, lies in Yunnan province, China with a total length of about 330 km. The railway line goes across the mountain area with high seismic intensity, and the gravity retaining wall with anchoring frame beam is a widely used structure for supporting the high-steep slopes. Consequently, a comprehensive understanding on the seismic behavior of the gravity retaining wall with anchoring frame beam is required for the engineering safety of railway line in seismic zone.

The present seismic method related to the stability of retaining structure mainly takes the pseudo-static method [1–4], which applies the static equilibrium by simplifying the earthquake loading as an inertial force without regarding for some important issues about the dynamic characteristics of retaining structure. To compensate the shortcomings in pseudo-static method, many scholars repeated the earthquake loading by means of dynamic test system (mainly includes shaking table test and dynamic centrifuge test) and dynamic numerical analysis with an attempt to reveal a more real seismic behavior of retaining structure [5-8]. Wilson and Elgamal [9] investigated the dynamic lateral earth pressure on retaining wall by shaking table test and highlighted the influence of the soil cohesion and the small wall movements on the distribution of earth pressure. Guler and Selek [10] performed reduce-scaled shaking table tests on eight different configurations of geosynthetic-reinforced earth walls to investigate the effects of the change in peak ground acceleration on the acceleration responses of the wall face. Jo et al. [11] conducted two dynamic centrifuge tests to reexamine the Mononobe-Okabe method and to evaluate the seismic lateral earth pressure on an inverted T-shape flexible retaining wall filled with dry medium sand. Deyanova et al. [12] performed the time-history analyses on gravity retaining walls by establishing a numerical model with different soil parameters and varying wall geometries, and the results were compared with the Newmark sliding block procedures and the recommendations in

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However, most of the existing studies in literature were mainly concentrated at the research of a single-formal retaining structure. The gravity retaining wall with anchoring frame beam, as a composed retaining structure, may behave with a more complex response under earthquake loading. In view of this, shaking table test and dynamic numerical analysis are carried out to study the seismic behavior of the gravity retaining wall with anchoring frame beam by applying one-directional and bi-directional excitations of Wenchuan motion with different intensities. The paper is structured as following. Section 2 introduces the setup of the shaking table model of the gravity retaining wall with anchoring frame beam. The results of the horizontal and the vertical acceleration response, and the dynamic earth pressure derived from shaking table test are analyzed in Section 3. Where, all of the shaking table test results are presented in terms of the prototype units. Section 4 interprets the establishment of dynamic numerical model with Flac3D code, and the horizontal and the vertical acceleration response, the dynamic earth pressure and the axial stress of anchor derived from dynamic numerical analysis are compared and discussed here. Finally, the conclusions are drawn in Section 5.

2. Setup of shaking table test

2.1. The prototype structure and instrument arrangement

The prototype of retaining structure was derived from the construction site in Dali-Ruili railway line. A gravity retaining wall with anchoring frame beam was supporting the soil mass covering on a steep rock slope that was inclined at an angle of 40° with the horizontal surface. Besides, an inclined rock layer lay between the soil mass and the rock body, as shown in Fig. 1. The gravity retaining wall was fixed on rock body with an embedded depth of about 1.2 m. The heights of the gravity retaining wall and the anchoring frame beam were both 6.0 m. Two rows of anchors, which were upwards named as Anchor 1 and Anchor 2 respectively, were fixed at the frame beam with an inclined angle of 30° with the horizontal surface. The distance of adjacent anchors was about 4.8 m along the inclined slope surface, and the horizontal spacing was about 4.0 m.

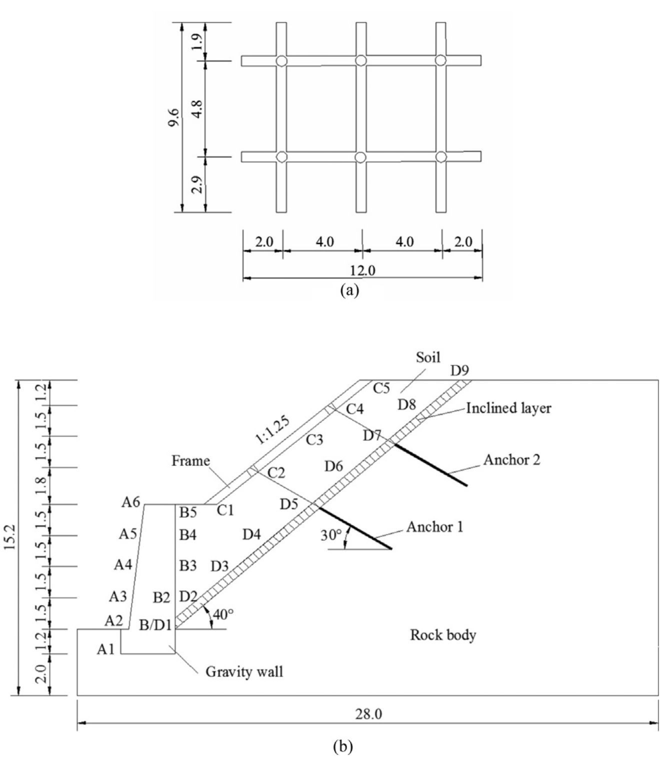

Fig. 1. The full-scale model of the retaining structure: (a) The anchoring frame beam and (b) The gravity retaining wall with anchoring frame beam (unit: m).

Table 1
The instrument arrangement of the test points in shaking table test.

Items	Gravity retaining wall	Supporting frame beam
Accelerometers	A2, A4, A6, B1, B3, B5	C1, C3, C5
Dynamic earth pressure cell	B2, B3, B5	/

Remark: "/" means that there is no sensor arranged here or the response data is not analyzed in this paper.

Points A1–A6, B1–B5, C1–C5 and D1–D9 are marked at the front-face of gravity wall, the back-face of gravity wall, the face along frame beam and the face along inclined layer, respectively. Several typical test points were arranged with accelerometers and dynamic earth pressure cells to investigate the acceleration response and the dynamic earth pressure response of the retaining structure in shaking table test, as presented in Table 1. The accelerometers were set in both the horizontal and the vertical directions, and the dynamic earth pressure cells were mainly laid in the horizontal direction to investigate the lateral earth pressure on gravity retaining wall. The accelerometer was typed CA-YD-189 with a measuring range of ±5 g and a frequency range of 0.2–1000 Hz. The type of dynamic earth pressure cell was BX-7 whose maximum permitted pressure was 100 kPa. The response data in shaking table test was collected by the Dewetron 2010 Data Acquisition System with a high sampling frequency of 2000 Hz.

2.2. Shaking table test equipment and similitude law

The earthquake loading was applied with the help of the large-scale shaking table system in China Merchants Chongqing Communications Research and Design Institute Co. Ltd. The dimensions of the shaking table were 6.0 m×3.0 m. The shaking table equipment could produce a 3-D ground motion with the maximum permitted acceleration of 1.0 g in each dimension. The carrying capacity of shaking table equipment was 350 kN with an input frequency range of 0.1–50.0 Hz. The maximum overturning moment of shaking table facility related to the rotation with respect to x or y axis was 700 kN m, and the maximum turning moment with respect to z axis was 350 kN m.

The law of similitude should be applied to simulate the prototype in a reduce-scaled model in shaking table test. However, it is difficult to make a complete similar relationship between the prototype and the model for a reduce-scaled model in 1.0 g gravity field. The law of similitude is mainly developed based on the factors considered as the most important in the simulation. As for granular soil, one of the rational method of similitude law is derived from the equation between the shear modulus G and the effective stress σ, which is empirically expressed as $G \propto (\sigma^{0.5})$ when the shear strain is rather small. If the soil density is kept the same for both the prototype and the model, the similitude ratio of the loading duration can be deduced as [13–15]:

$$S_t = t_m/t_p = S_l^{0.75} \tag{1}$$

where S_t and S_l refer to the scaling ratios of loading duration and geometry length respectively; t_m and t_p refer to loading durations of the model and the prototype respectively.

In this study, the above similitude law is not adopted in shaking table test. The gravity retaining wall with anchoring frame beam is considered as a composed structure in shaking table test. The behaviors of the gravity wall, the frame beam and the anchor are quite different from that of the granular soil, which will subsequently results in the invalidity of the scaling ratio of $S_t = S_l^{0.75}$. Besides, the empirical relationship of $G \propto (\sigma^{0.5})$ is applicable for granular soil only when the shear strain of granular soil is rather small. The seismic ground motions with high intensity are applied in shaking table test, which may lead to a great plastic deformation in soil mass. Subsequently, the