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Experimental and numerical study on the seismic behavior of anchoring frame beam supporting soil slope on rock mass

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ABSTRACT

The anchoring frame beam is a widely used supporting structure in slope engineering. In this work, the dynamic behavior of anchoring frame beam under earthquake loading was studied by means of shaking table test and dynamic numerical simulation. The results of numerical simulation were compared with the test results in terms of the horizontal acceleration amplification, the vertical acceleration amplification, and the time history of displacement response. The behavior of axial stress of anchor was mainly studied by dynamic numerical simulation. The numerical results are generally consistent with those apparent in shaking table test. The results show that the natural frequency of the supported soil slope presents a decreasing trend during the shaking table test. The soil slope performs an amplification effect on input horizontal acceleration in time domain, and the energy within a frequency range that is around the natural frequency of soil slope is also amplified. Both the horizontal and the vertical acceleration amplifications present an increasing trend with the increase in input acceleration. The acceleration amplification differs greatly under different seismic motions. The frame beam presents a translation displacement together with a rotation around the vertex of frame beam. The residual deformation of frame beam increases obviously with the increase of input acceleration. A larger value of axial stress is observed at the anchor located at the bottom of frame beam. The axial stress of anchor decreases rapidly in anchorage segment, and it tends to zero within a short length under Wenchuan shaking event. The distribution curve of axial stress along the length of anchor presents two peak values after earthquake loading, which is much different from that induced by the self-weight.

1. Introduction

Most of the geotechnical structures existing or under construction in China are located in the areas of high seismic intensity. For example, the Da-Rui (from Dali city to Ruili city) Railway Line, with a total length of 350 km, is now under construction in Southwest China with high seismic intensity. The railway line goes across the mountain areas, and the cutting slope is widely supported by anchoring frame beam structure in the whole railway line. It is important to get a comprehensive understanding on the dynamic behavior of anchoring frame beam structure under earthquake loading.

The pseudo-static method is now widely adopted in seismic codes, which simplifies the earthquake loading as an inertia force in static equilibrium [1–4]. The crude assumptions in pseudo-static method neglect many important characteristics of structure including the dynamic behavior of the soil, the dynamic response of the structure as well as the coupling effect among the sub-structures. Consequently, many scholars attempted to perform shaking table test or dynamic centrifuge test to reveal the seismic behavior of supporting or retaining structures in a real stress-strain condition [5–9]. Due to the limited carrying capacity of dynamic centrifuge system, the dimension of shaking table model is generally larger than that of dynamic centrifuge model, which means that more space is available in shaking table model for instrumentation and investigation. Kloukinas et al. [10] compared the earthquake response of the cantilever retaining walls in shaking table test with that determined by limit analysis to provide a better understanding on the complex mechanics of the cantilever retaining structure. Mojiri et al. [11] studied the seismic performance of lightly reinforced fully grouted masonry shear wall by shaking table test with a conclusion that the displacement ductility capacity of reinforced masonry wall and the capability to dissipate energy are higher than what are recognized by Canadian code. Guler and Enunlu [12] conducted shaking table tests on two reduced-scale geotextile-reinforced soil retaining walls with different reinforcing lengths, and the

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test results showed that the geosynthetic reinforced retaining structures designed by current specifications behaved safely under earthquake loading.

The numerical simulation, as an economical way to study the complex mechanics of structures in engineering, was widely performed on the seismic behavior of supporting or retaining structures, and the numerical result was commonly used as a comparison or supplement of the test data [13–16]. Wang et al. [17] studied the seismic reinforcement mechanism of geogrid reinforced soil retaining walls by means of numerical simulation and shaking table test with a comparison on the seismic strains of geogrids. Zarnani et al. [18] developed a numerical FLAC model to simulate the dynamic response of two reduced-scale model reinforced soil walls which were constructed on a 1-g shaking table, and the results showed that a simple elastic-plastic model with Mohr-Coulomb failure criterion for the sand gave a satisfactory agreement with the measured results. Koseki et al. [19] applied a simplified numerical procedure to evaluate the earth pressure on retaining walls while considering the effects of negative pore air pressure, and the numerical results qualitatively simulated the measured behavior in terms of the seismic earth pressure and the angle of failure plane in the backfill apparent in 1-g model shaking test.

The above mentioned shaking table tests (or centrifuge test) and numerical analyses were mainly carried out on supporting or retaining structures excluding the anchoring frame beam supporting structure. More recently, Lin et al. [20] studied the response of gravity retaining wall with anchoring frame beam subjected to earthquake loading by means of shaking table test and numerical simulation, where the acceleration response was analyzed by taking the gravity retaining wall and anchoring frame beam as a whole combined retaining structure. However, the seismic behaviors of anchoring frame beam in this paper were much different from those of combined retaining structure as presented by Lin et al. [20]. In this paper, the dynamic modal parameters of anchoring frame beam were obtained successfully, and the acceleration response was analyzed combining with the dynamic modal parameters. Meanwhile, the deformation behavior of anchoring frame beam was studied. The paper is structured as following. Section 2 introduces the structure model of anchoring frame beam in shaking table test. Section 3 explains the dynamic numerical model established in FLAC3D. The results from shaking table test and dynamic numerical simulation, including the dynamic modal parameters, the horizontal and the vertical acceleration responses, the deformation behavior of frame beam and the axial stress of anchor, are presented and compared in Sections 4, 5, 6 and 7, respectively. All the results are presented in terms of prototype units unless specially stated. Finally, the main results are concluded in Section 8.

2. Experiment

The shaking table test was carried out by the shaking table system in China Merchants Chongqing Communications Research and Design Institute Co. Ltd, which could simulate 3-dimensional ground motion. The maximum permitted acceleration of shaking table system was 1.0g in each dimension with a carrying capacity of 35 t. The permitted frequency of input motion ranged from 0.1 to 50 Hz. The dimension of shaking table was 6.0 m in length and 3.0 m in width.

The shaking table model was established based on a typical section of anchoring frame beam in Da-Rui Railway Line, China. An anchoring frame beam with an approximate height of 12 m was supporting the soil slope which was covering on the rock mass. According to the geometry size of the prototype and the carrying capacity of shaking table system, the similar ratio of the geometry size was determined as 1:8. Subsequently, the similar law of shaking table model could be established based on Buckingham π theorem, as shown in Table 1 [20–25]. Where, the similar constant of time (C_t) was used as a control quantity for performing the acceleration time histories of different seismic motions.

Table 1
The similarity law in shaking table test.

Quantities	Similar law	Similar constant
Geometry size l	C_l	8
Mass density ρ	C_ρ	1
Gravity acceleration g	C_g	1
Input acceleration a	C_a	1
Elastic modulus E	C_E	8
Time t	$C_t = C_l^{1/2}$	2.83
Frequency f	$C_f = C_l^{-1/2}$	0.35

A large-scale model box with an inner dimension of 3.6 m (length) × 1.5 m (width) × 2.0 m (height) was used in shaking table test to reduce the boundary effect [26]. The model box was rigidly supported on both sides to distance its natural frequency from that of the structure model. Additionally, the polystyrene foam was laid along the inner side of model box to reduce or avoid the wave reflection in shaking table test [27,28]. The model of anchoring frame beam in shaking table test was shown in Fig. 1. The C25 concrete with an arc-surface was constructed at the bottom of model box to simulate the rock mass of the prototype. The cohesion and the internal frictional angle of the soil used in shaking table test were 6.2 kPa and 34° respectively. The non-uniform coefficient and the curvature coefficient of soil were 11.5 and 1.04 respectively. The optimum water content and the maximum dry unit weight of the soil mass were 5.34% and 21.8 kN/m^3 based on modified Proctor compaction test, by which the soil slope of shaking table model was artificially compacted at a 90% compaction degree. The frame beam was shaped by aerated concrete whose elastic modulus and compressive strength are about 2.20 GPa and 5.0 MPa respectively. The steel wire with a diameter of 4 mm was used to simulate the anchor in shaking table model, and it was inclined at an angle 30° with the horizontal line. Taking a mid-section for typical study, seven points were marked along the soil slope surface, which were upwards designated as Points 1–7. And the anchors were upwards numbered as Anchors 1, 2 and 3, as shown in Fig. 1. The horizontal and the vertical accelerometers were set at Points 2, 4 and 6 along the surface of soil slope. Another several horizontal and vertical accelerometers were laid on the rock mass and the shaking table to verify the accuracy of input acceleration. The type of accelerometer used in shaking table test was CA-YD-189 with a measuring range of -0.5–0.5g and a frequency range of 0.2–1000 Hz. Three horizontal displacement gauges were arranged at Points 2, 4 and 5 to investigate the deformation behavior of frame beam. Horizontal displacement gauge was a type of laser sensor, which could receive the reflected light from the reflecting-plate that was located at the frame beam. The response data were all collected by Dewetron 2010 Data Acquisition System with a sampling frequency of 2000 Hz. A photograph of shaking table model in shaking table test was shown in Fig. 2.

Three seismic motions with different spectrum characteristics were applied in shaking table test, which were named as the Wenchuan motion, the Da-Rui motion and the Kobe motion. The acceleration time history and the Fourier spectrum of these three seismic motions were shown in Fig. 3. The Wenchuan motion, which was a near-field ground motion, was recorded in Wolong station in M_w 7.9 Wenchuan earthquake of China in 2008. Generally, the structure is more vulnerable under the shaking events of a near-field ground motion [29–32]. The acceleration time history of Wenchuan motion was a long-time pulse with two intensive periods, and its significant frequency concentrated at 2.0–4.5 Hz and 5.0–6.5 Hz. The Da-Rui motion was an artificial seismic motion which was synthesized based on the safety evaluation data in Da-Rui Railway Line. The significant frequency of Da-Rui motion ranged from 0.5 to 8.0 Hz. The Kobe motion, which was another recorded motion in M_L 7.3 Hanshin-Awaji, Japan, earthquake in 1995, presented a wide frequency band. Its significant frequency