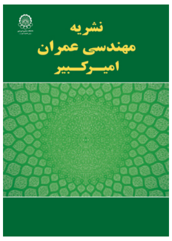

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Numerical and Experimental Study on Seismic Behavior of Soil-Nailed Walls to Introduce the Pseudo Static Coefficient Based on Performance Levels

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ABSTRACT: This study, tries to suggest a design method based on displacement using experimental and numerical modeling in soil nailed walls. In this case, dynamic loading characteristics, geometrical characteristics of reinforced soil mass and type of the site are considered to introduce the pseudo static coefficient as a function of seismic performance level and dynamic loading characteristics. For this purpose, the influence of dynamic loading characteristics, reinforcement length, height of reinforced system and type of the site are investigated on seismic behavior of soil nailed wall by numerical analysis. Furthermore, the performance levels of this structure were determined by experimental studies of shaking table tests. The results illustrate that the seismic response of this type of wall is highly dependent to cumulative absolute velocity, maximum acceleration, height and reinforcement length. The results also indicate that the use of coefficients in this study leads to most efficient designs in comparison with other methods which are generally suggested in codes that are usually based on limit-equilibrium concept. The outputs show the over-estimation of equilibrium design methods in comparison with proposed displacement based methods here. The pattern of the observed failure mechanisms included a moving block and a parabolic failure surface with certain inflection point. Also, irrespective of different nail lengths, a range of $\Delta x/H = 0.5$ % as a transitional level from quasi-elastic to plastic state and based on starting the development of active wedge failure, a range of $\Delta x/H = 3.75\%$ as a transitional level from plastic to failure state were determined.

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1- Introduction

In recent decades, the seismic behavior of soil-nailed walls has been the focus of research [1-3] because these structures have performed well during major seismic events [4, 5]. Pseudo-static analysis is one of the simplest approaches used in earthquake engineering to analyze the seismic response of retaining walls. Selection of an appropriate seismic coefficient is the most important, and difficult, aspect of a pseudo-static stability analysis. In theory, the seismic coefficient values should depend on some measure of the amplitude of the inertial force induced in the wall by the dynamic forces generated during an earthquake. Because retaining walls are not rigid and the peak acceleration generated during an earthquake last for only a very short period of time, seismic coefficients used in practice generally correspond to acceleration values well below the predicted peak accelerations. However, the choice of coefficients used in the retaining wall stability analysis is very subjective and lacks a clear rationale.

In the current study, to present the pseudo-static coefficient as a function of the dynamic loading characteristics, type of the site and the seismic performance levels (seismic permanent displacements), the seismic performance of soil-nailed walls were investigated numerically and experimentally. For this purpose, first, a series of reduced-scale uni-axial shaking table tests were carried out on the five wall models with different nail lengths under different input motion parameters for investigating the performance of soil-nailed walls. The quantitative and qualitative responses of the walls to base shaking in terms of facing displacements, deformation modes, the boundaries of performance levels and the failure mechanisms are studied and identified. Then, based on the numerical analysis, the seismic performance of each of soil-nailed models with different heights and nail lengths was determined under harmonic loading whit different base accelerations and cumulative absolute velocities. Also, using the limit equilibrium method, the pseudo static coefficient values of each models were determined. Finally, based on the results of experimental, numerical and analytical investigations, the pseudo static coefficient value was defined as a function of dynamic loading characteristics and performance levels.

2- Physical Model Tests

A series of 1-g shaking table tests were carried out on soil-nailed walls at the Centrifuge and Physical Modeling Center in Tehran University. In physical modeling of soil-nailed walls, wall height is an important factor in scale effects and

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the response of the models. Given that the height of traditional soil-nail walls ranges (from 3.0 m to 14.0 m, with an average of 8.0 m) and limitations in the height of the box, a 0.8 m high model with a scale factor of 10.0 is a reasonably representative physical model to reflect realistic seismic behavior. In each of the physical models tested, to construction of the backfill, foundation and reinforced zone, a wet mixture of Firuzkooh 161 sand and Firuzkooh silt with a medium state of density (56%) and a moisture of 6% was used. For selecting the reduced-scale nail element, by choosing the pull-out behavior and flexural capacity as the main criteria for calibration and by taking the similitude rules and scaling factor (1:10), a series of pullout and flexural tests were performed on elements made of different materials and the various surface roughness to find the best kind of element for use in reduced-scale models. In order to construct physical models, uniform nail lengths with the same horizontal and vertical spaces (S_H = S_V = 0.2 m) were used to reinforce the reduced-scale models of soil-nailed wall. Since in seismic conditions, the minimum value of nail length to wall height ratio L/H=0.7 is recommended by FHWA, physical models were constructed with the values of L/H = 0.5, 0.6, 0.7, 0.8 and 0.9. Select this range of values makes it possible to investigate the seismic behavior of soil-nailed walls which have been reinforced with more lengths and less than the minimum recommended value. Given that the strong dependency of soil mechanical parameters on density, during construction, the moist unit weight was controlled to be constant at about 17.1 (kN/m^3). Also, to facilitate the monitoring of displacements and failure patterns, a thin layer of black-dyed sand was placed at the intersection of layers and at discrete spacing vertically. To connect the nail element and the facing, a circular steel plate with 25 mm diameter and 2 mm thick as nail head was placed and held in position by means of key pins. To construct the soil-nailed wall models in accordance with the executive construction process, first, the entire wall with all of the components was constructed completely by using the spatially designed bracing structure. This structure has capability to simulate the construction processes of the soil-nailed wall by releasing the restrained layers, step by step and top-down such as executive construction process of actual soil-nailed walls. With this method, the stress distribution in the soil mass of models due to excavation process is simulated correctly. Then, after the completion construction process of the main body wall, excavation process was simulated by using the supporting structure. To measure the deformations and accelerations of the models, four displacement transducers (LVDT sensors) and thirteen accelerometers were installed in the models. In order to apply dynamic loading, a variable-amplitude harmonic excitation was used to simulate the actual earthquake records. This harmonic loading has two main features. First, it simulates the rise and time decay of an idealized accelerogram. Secondly, it involves basic parameters which can control the earthquake parameters in model testing and can change easily at different steps of tests. These advantages lead to generate closer simulation of actual earthquake records. The pictures of the experimental models have been shown in Figure 1.

Figure 1. Finished soil-nailed wall model in shaking table box

3- Numerical studies

In order to perform numerical studies, FLAC software was used. All of numerical models were prepared by selecting five categories including 4, 6, 8, 10 and 12 meters for height of the wall and five categories including 0.6H, 0.7H, 0.8H, 0.9H and 1.0H for length of nails. For the sake of omitting the influence of defined boundaries on analysis results, and based on implemented sensitivity analysis, height of the soil bulk at the back of the wall is considered 5 times of wall height and 2 times of wall height in front of the wall in each model. In addition, regarding to considerable effect of foundation dimensions on system deformations, and for considering this effect and omitting the influence of soil type, a foundation with a height equal to 0.25 times of the structure height is utilized by sensitivity analysis. To select the geotechnical parameters, it has been tried to consider soil type effects by introducing 3 kinds of soil profiles, which are represented as 1 to 3 in 2800 standard of Iran. Considering and using geotechnical parameters from many boreholes representing 3 kinds of soil type in different regions of Iran, geotechnical parameters for modeling the different parts of the model were chosen. After preparing the numerical models, harmonic loads were applied to the foundation level and the dynamic analysis were performed. During each of the dynamic analyses, the history of horizontal wall displacements as a representative of the seismic performance were recorded. Regarding to the studies investigated by Yazdandoust (2013), harmonic load frequency, maximum acceleration and cumulative absolute velocity instead effective time were considered in based of soil type and regions seismic risk categories.

4- Results and Discussion

From the observations of the seismic behavior of shaking table and numerical models, it was evident that the pattern of failure mechanism in all models was a parabolic failure surface with certain inflection point, so that the geometry of the failure mechanism was a function of the nail length (Figure 2).

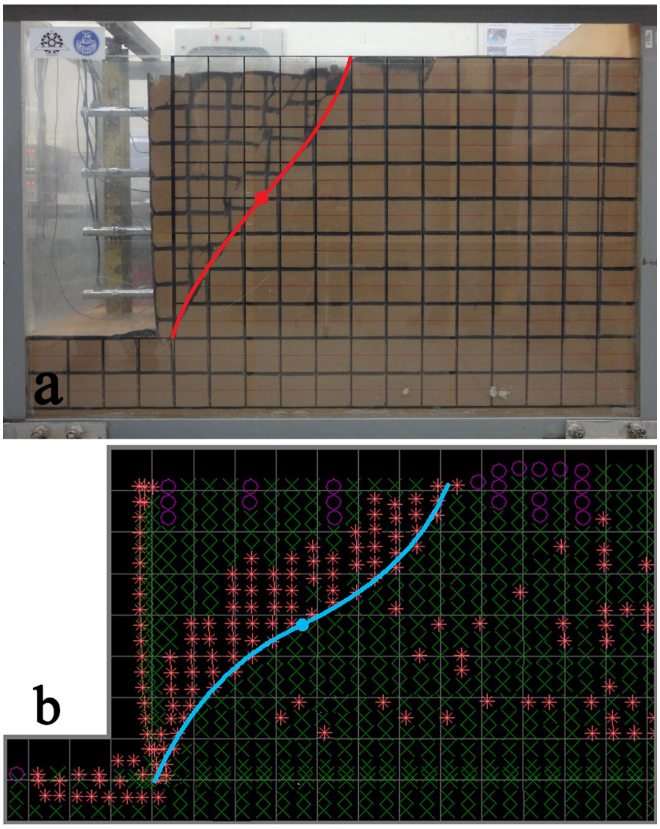

Figure 2. Geometry of the failure mechanism and deformation modes during shaking: (a) physical model; (b) numerical model

Also, to determine the boundaries of performance levels of soil-nailed walls for use in the performance base design method, based on the formation of initial cracks and failure surface, a range of Δx/H' = 0.33 - 0.56 % as a transitional level from quasi-elastic to plastic state and based on starting the development of active wedge failure, a range of Δx/H' = 3.3% - 4.3 % as a transitional level from plastic to failure state were determined and recommended.

Moreover, by tracing seismic behavior it can be seen that in all models, the maximum lateral displacement occurred at the top of the wall and a part of reinforced zone moved outwards and rotated similarly to a rigid block about the toe. Then, the combination of a base sliding and rotating deformation mode were observed in all models such that with increasing nails length from 0.5H to 0.7H, the base sliding deformation mode faded gradually.

In the other hands, given the proper convergence between the maximum normalized horizontal displacement and CAV, this parameter can be defined as a suitable seismic parameter for selecting design earthquake in performance base design method. (Figure 3).

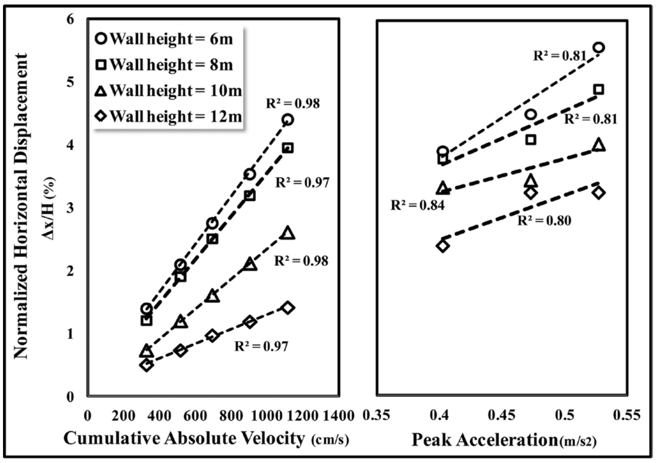

Figure 3. The variation in maximum normalized horizontal displacement with CAV and peak acceleration

According to the results, L/H= 0.7 can be presented as the critical ratio in seismic conditions so that in specified seismic situation, the reduction in L/H of 0.7 leads to significant horizontal displacement of the soil-nailed walls. This ratio is the key criteria in the performance-based design for the selection of the appropriate nail length (Figure 4).

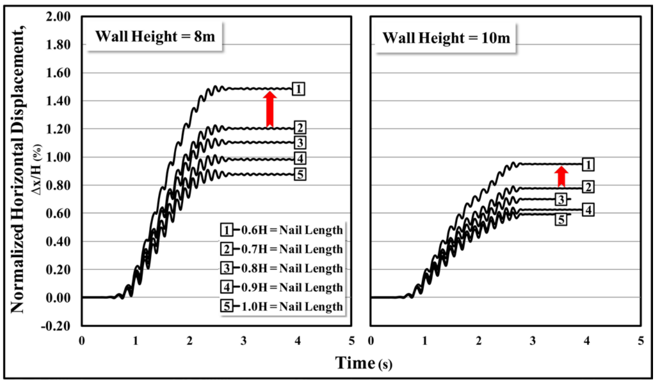

Figure 4. History of normalized horizontal displacements at crest of the wall with different nail length

5- Conclusions

The main conclusions regarding physical and numerical models can be summarized as follows:

1. The pattern of the observed failure mechanisms in all models was similar regardless of the nail length, so that this failure pattern includes a moving block and a parabolic failure surface with certain inflection point.
2. Irrespective of different nail lengths, a range of Δx/H = 0.5 % as a transitional level from quasi-elastic to plastic state and based on starting the development of active wedge failure, a range of Δx/H = 3.75% as a transitional level from plastic to failure state were determined.
3. According to the sudden increase in wall displacements caused by decreasing the nail length from 0.7H to 0.5H, the L/H ratio of 0.7 was presented as the critical ratio in seismic conditions.
4. Based on the experimental and numerical results, the

pseudo static coefficient value was defined as a function of dynamic loading characteristics and performance levels.

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