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Determination of shear modulus, damping ratio and failure pattern in helical soil-nailed walls

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ABSTRACT

A series of shaking table tests were performed on reduced-scale models of helical soil-nailed walls (HSNWs) to evaluate the effect of the nail arrangement and nail inclination on the failure mechanisms and dynamic characteristics of the retaining structures under seismic conditions. The results of particle image velocimetry (PIV) showed that the potential failure surfaces in the helical soil-nailed walls was a parabolic one with an inflection point and the dimensions of failure wedge increased as the length and inclination of the nails increased. A combination of overturning and base sliding was identified as the predominant deformation mode in the HSNWs and that base sliding faded with an increase in the nail inclination. It was found that horizontal helical nails located in the lower half of the wall played a more effective role in reducing lateral displacement, but the opposite was true for HSNWs with inclined nails. The use of inclined nails instead of horizontal ones was found to be an efficient solution for increasing the shear modulus in HSNWs. The efficiency of this solution decreased with the use of shorter nails in the upper half of the walls and was eventually minimized by increasing the length of the nails across the wall height. It was found that, although the use of helical nails instead of grouted ones reduced wall damping, it could be a good solution for increasing the stiffness of the soil-nailed walls.

KEYWORDS

Helical soil-nailed wall; Failure mechanism, Damping ratio; Shear modulus, Particle image velocimetry.

1. Introduction

The use of cement grout is a common method of installing nails in a soil mass. Because grouted nail performance depends on the grouting quality, this type of nail will be inefficient if the quality of the grouting cannot be assured or the opportunity for stabilization is less than the cement curing time [1,2]. In order to carry out soil nailing under these conditions, a novel nail element was introduced in 1996 in which the cement grout was eliminated as the bonding agent and a series of flights were employed to interact with the soil mass. This is known as a helical nail and typically consists of a longitudinal shaft with helical flights attached to the shaft at equal intervals. In this type of nail, which is installed in the soil mass by the application of torque and the passive pressure mobilized front the flights provides the required resistance against pullout. Because it is unnecessary to drill a hole in order to install a helical nail, the installation process is very fast and causes minimal site disturbance.

Despite the widespread use of helical nails in geotechnical structures, the performance of such structures has been poorly studied and is not completely understood. A literature survey indicates that investigations of the behavior of helical soil-nailed structures are limited to an only few studies, most of which have focused on the pullout behavior of helical soil nails. Deardorff et al. [3] used two instrumented helical soil-nailed walls (HSNWs) to show that the force mobilized in the helical nails was within the range of values provided by the FHWA [4]. A numerical study conducted by Sharma et al. [5] is the only seismic investigation on the performance of helical soil-nailed walls. They found that the seismic stability of HSNWs decreased with an increase in the nail inclination and the ratio of helix spacing to helix size. In another numerical study performed under static conditions, Zahedi et al. [6] reported that helical nails were more efficient than grouted ones for reducing wall displacement and that the efficiency increased as the excavation proceeded. Mahmoudi-Mehrizi et al. [7] used 1g model tests to determine that the nail configuration and number of helices were more effective than the number of nails for increasing the bearing capacity of a footing located on helical soil-nailed walls. In similar study, Yadegari et al. [8] showed that increasing the bearing capacity of strip footing, postponing its collapse and also decreasing the lateral wall displacement were advantages of using helical nails instead of grouted ones.

Lack of sufficient knowledge about the seismic performance of helical soil-nailed walls and the need to achieve a comprehensive understanding of their behavior under seismic conditions prompted the present investigation on the seismic performance of HSNWs using 1g shaking table tests. For this purpose, eight wall models were constructed at 1:10 scale with two nail inclinations (0° and 30°), two nail lengths (0.5H and 0.9H), and two nail arrangements (uniform and trapezoidal arrangements). The models then were subjected to input excitations of different durations. The response of each model to base excitation was identified in terms of the shear band development and failure mechanism. The displacement and acceleration response in different locations in the models were used to produce hysteresis loops and estimate the equivalent shear modulus (G_e) and damping ratio (D) for HSNWs as a function of the shear strain level.

2- Shaking table tests

A 0.8-m high model with a geometric scaling factor of 1:10 (N = 10) was selected as representative of an 8-m high helical soil-nailed wall. A 0.2-m thick foundation was considered to provide real conditions for possible settlement and lateral sliding. In order to reinforce the wall models, two different nail arrangements were selected. In the first arrangement, horizontal nails of uniform length were used at L/H ratios of 0.5 (Model 1) and 0.9 (Model 2). These two ratios were, respectively, less than and greater than the optimal value which has been recommended for grouted nails by the FHWA [4] with a conservative view. 0.7H has been recommended by the FHWA [4] as an optimal length for grouted nails in seismic conditions, while numerous studies have shown that walls with nail lengths of 0.5H to 0.9H can have an acceptable seismic performance. In the second arrangement, horizontal nails of non-uniform length were used. In this arrangement, the length of the nails located in the upper and lower halves of Model 3 were selected as 0.9H and 0.5H and of Model 4 as 0.5H and 0.9H. respectively. These two nail arrangements were also used with nails at an angle of 30° (α = 30°) to reinforce Models 5 to 8. This angle was the maximum value recommended by the FSI (2014) for the installation of helical nails and was used to investigate the effect of nail inclination on the behavior of helical soil-nailed walls. In all models, the nail elements were installed on the wall face in a square pattern with a horizontal spacing of 0.15 m and a vertical spacing of 0.2 m. These intervals are within the range recommended for helical nails by the FSI [9].

To excite the models, a series of variable-amplitude harmonic excitations with a constant peak grand acceleration (PGA) of 0.5g and of different durations were applied in sequential steps. In the first step, a base excitation with a duration of 3s was applied to the models, which was equivalent to a real earthquake with a duration of 16.9s in accordance with the similitude rules for time. The duration was increased in increments of 2 s at each step until failure occurred in order to study the effect of changes in the cumulative absolute velocity (CAV) at a constant acceleration on the seismic behavior of the models. Base on the acceleration level (0.5g) and duration of these excitations (16.9s to 95.6s in the real scale), they are classified as strong ground motions. This type of loading was applied using the shaking table system located at Bonab University. The test facility features a uniaxial shaking table device with a rigid box container having dimensions of 182 × 123 × 80 cm and a servo-hydraulic actuator with the ability to shake specimens at 50 kN with a frequency of up to 10 Hz. A frequency of 5 Hz was chosen for input motion so that it was sufficiently distant from the natural frequencies measured for each model during the free-vibration tests. The choice of this frequency caused the models to be evaluated in the same seismic conditions without the occurrence of resonance in all of them. The measured natural frequencies of the models ranged from 16.4 to 25.3 Hz. In accordance with the similitude

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rules for frequency in cohesionless soil, the frequency of the input motion corresponded to the predominant frequency of a real excitation at approximately 1 Hz. It should be noted that to assess the reliability of the results and verify the consistency of the test data, the test on Models 1, 2, 7 and 8 was repeated and measured data were compared with each other.

3- Results and Discussion

Fig. 1 shows the idealized geometry of the slip surface of the HSNWs to clarify the failure mechanism. It is evident that the patterns of failure of the models were defined by the roles played by each row of helical nails. In all models, the nail rows in the upper half held the reinforced-soil mass together, creating a block of reinforced soil (zone I). The nails located in the bottom half rows acted predominantly as an anchoring mechanism (zone II); thus, the pullout capacity of the bottom row of nails played a significant role in the stability of HSNWs. The pullout capacity of the bottom row of nails was eventually reached by shaking, allowing for significant lateral displacement of the reinforced soil mass to occur. After that point, the reinforced soil mass was observed to move outward and downward by sliding on the slip surface. During cyclic lateral movement, a relatively large shear stress developed along the interface between zones I and II, as seen in Fig. 1. This shear stress was formed because of the stability caused by the anchoring mechanism of the nails in the lower half of the wall models, which caused zone I to act on zone II with sufficient shear force to form a failure surface behind zone II. Fig. 1 shows that these loading conditions are analogous to those of a retaining wall acting on a soil backfill by an upward or downward force. Tufenkjian and Vucetic [10] showed that the induced force acted in an upward direction on the backfill (zone I) when very stiff reinforcements were used. This is called a passive failure state with negative wall friction (-δ) and can cause formation of a concave failure surface in the backfill, as seen in the lower half of the wall models.

An attempt was made in the present study to determine the strain-dependent dynamic parameters (G_e and D) of the HSNWs. Parameter G_e versus γ for the upper, middle, and lower third of the models are presented in Fig. 2. Comparison of the trends for G_e in different models indicates that the rate of stiffness reduction versus γ in models with inclined nails was much more pronounced than in ones with horizontal nails. It could be concluded that, under the same seismic conditions, although larger strains formed in HSNWs with horizontal nails, stiffness degradation occurred in HSNWs with inclined nails with more intensity. In other words, the dependence of the shear modulus on the shear strain was greater after installing inclined helical nails. It also was observed that increasing the nail length also increased this dependence, but not as much as increasing its angle. The reduced effectiveness of increasing the nail length relative to increasing the nail inclination can be attributed to the greater distortion of the soil after the installation of longer nails. In addition to the dependence of the rate of hardness on the angle and length of the nails, the dependence of the amount of hardness on these parameters also was observed.

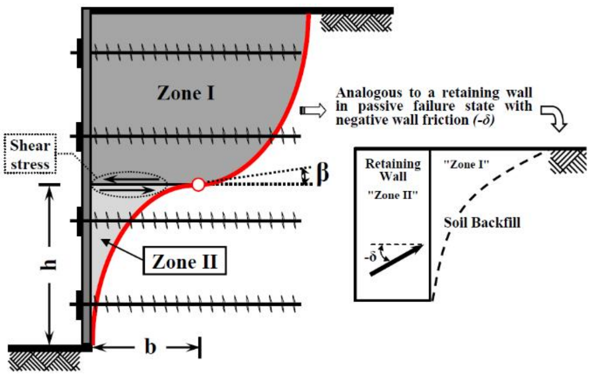

Fig. 1. Illustration of failure surfaces and soil zones involved in failure mechanism.

It was also found that the reinforcement type had a significant effect on the amount of wall damping. This effect was observed as a 25% decrease in damping when using helical nails instead of grouted ones. It also was observed that the noticeable deformability of MSE walls caused the damping ratio of these structures to be about 50% higher than the damping of the soil-nailed walls. Comparison of the damping ratios obtained from the model tests and those from the cyclic triaxial tests showed that the damping ratio of the HSNWs could be estimated with only a slight difference from the element tests conducted on the soil used in the soil-nailed walls using helical nails. This slight difference was due to the low confining pressure associated with the reduced-scale models and caused the element test results to be the lower bound of the damping ratios of HSNWs.

4- Conclusion

The main conclusions regarding shaking table tests can be summarized as follows:

1) The results of particle image velocimetry showed that the potential failure surface in the helical soil-nailed walls was a parabolic one with an inflection point and the dimensions of failure wedge increased as the length and inclination of the nails increased.

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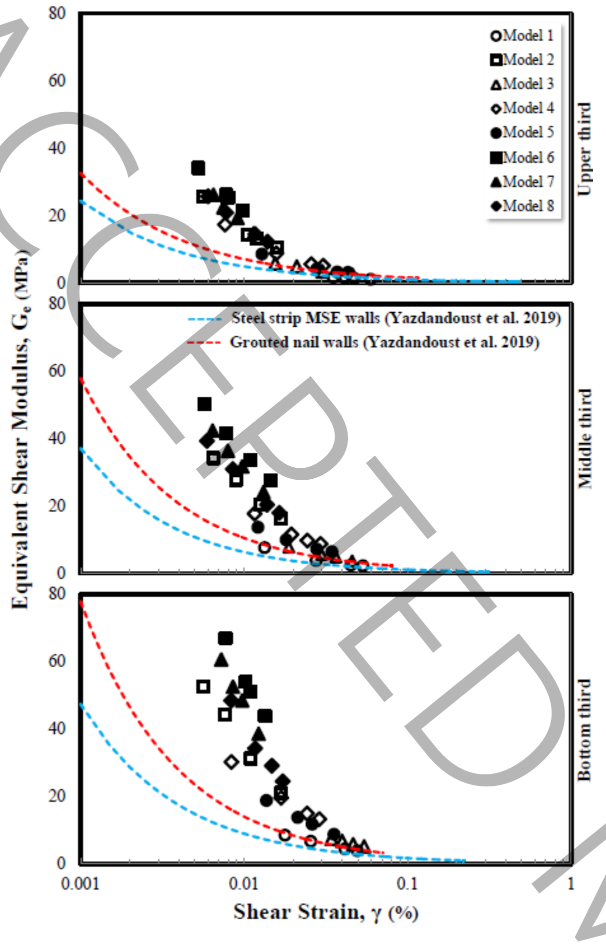

Fig. 2. The variation of equivalent shear modulus versus γ at three different parts of the wall models.

2) It was found that the use of inclined nails instead of horizontal ones was an efficient solution to increase the shear modulus of the HSNWs. The efficiency of this solution decreased with the use of shorter nails in the upper half of the wall and was eventually minimized by increasing the length of the nails across the wall height.

3) The strain-dependent dynamic parameters showed that, although the use of helical nails instead of grouted ones reduced wall damping, it also was a good solution for increasing the stiffness of the soil-nailed walls.

4) A combination of overturning and base sliding was identified as the predominant deformation mode in helical soil-nailed walls were the base sliding faded with an increase in the nail inclination.

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