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Investigation on the performance of walls reinforced by helical nails under strip footing loading using physical model test

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ABSTRACT: In the current study, the performance of helical soil-nailed walls (HSNWs) was evaluated under footing loading using reduced-scale model tests. For this purpose, sixteen soil-nailed wall models were constructed with different lengths, patterns, and inclinations of the helical nails and then were loaded to failure using the strip footing. The quantitative and qualitative responses of the models to footing loading were identified in terms of the wall displacements, the deformation modes, and the bearing capacity of footing. Particle Image Velocimetry (PIV) technique was also used to trace shear bands and identify the failure mechanism. PIV results showed that increasing the nail length, as well as using a square pattern and a 15° angle to install the nails, could be three effective solutions to reduce the penetration depth of the slip surface and, consequently, to limit wedge failure dimensions. Findings also indicated that 15° can be introduced as the optimal inclination for installing helical nails in walls under strip footings to achieve the maximum bearing capacity and minimum lateral wall displacements.

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1- Introduction

A novel nail element was introduced in 1996 in which the cement grout as the bonding agent has been removed and a series of flights have been employed to provide interaction with the soil mass. This novel nail, which is known as the helical nail, typically consists of a longitudinal shaft with helical flights that are attached to the shaft at equal intervals. These nails are installed in the soil mass by application of torque and the passive pressure mobilized in front of the flights provides the required resistance against pulling out. Due to the lack of need to drill hole for installing helical nails, their installation process is very fast and causes minimal site disturbance.

Although the use of helical nails dates back to 1996, the investigation on the performance of these walls began in 2010 with studying on two instrumented helical soil-nailed walls (HSNWs) by Deardorff et al. [1]. This investigation is one of the few studies that has been done on these structures. They found that the forces mobilized in the helical nails were within the range of values provided by FHWA [2]. The numerical study conducted by Sharma et al. [3] is the only seismic investigation on the performance of helical soil-nailed walls. It was found in this study that the seismic stability of HSNWs decreased by increasing nail inclination and the ratio of helix spacing to helix size. Using numerical study, Zahedi et al. [4] found that helical nails are more efficient than grouted ones for reducing wall displacement under service loading.

Despite the widespread use of helical soil-nailed walls, the studies conducted on them are limited to these few studies. Hence, an attempt was made in the current study to investigate the performance of helical soil-nailed walls under footing loading using reduced-scale model tests. For this purpose, sixteen soil-nailed wall models were constructed with different lengths, patterns, and inclinations of the helical nails and were loaded to failure using the strip footing. The quantitative and qualitative responses of the models to footing loading were identified in terms of the facing displacement, the load of the nail head, the crest settlement, and the failure mechanism, and the load–deformation behavior of models was evaluated.

2- Physical Model Tests

The footing loading simulator located at the Geotechnical Center at the Science and Research Branch of Islamic Azad University was used to perform the physical model tests. The main components of this 1-g simulator included a testing tank, a loading system, and a reaction frame, as seen in Fig. 1. Given that the height of helical soil-nailed walls is practically limited to 6 to 9 m, a 0.6 m-high model with a geometric scaling factor of 1:10 (N = 10) was selected as representative

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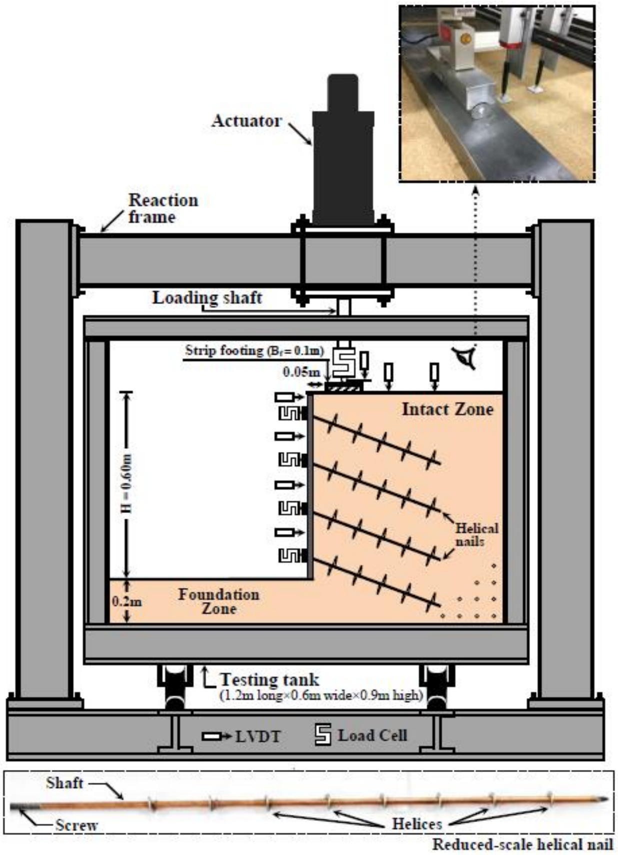


Fig. 1. Schematic representation of the test setup, model geometry, and instrumentation.

of a 6 m-high HSNW.

Two nail arrangements were selected to reinforce the wall models. In the first arrangement, helical nails of uniform length were used at L/H ratios of 0.5 and 0.7. These ratios were less than and equal to the optimal value recommended by FHWA [2], respectively. In the second arrangement, helical nails of non-uniform length were used. In this arrangement, the length of the nails located in the upper and lower halves of the wall were selected as 0.7H and 0.5H, respectively. The nails were installed at two different angles of 0° (horizontal) and 15°. In addition to these two angles, the third angle of 30° was also used in the first arrangement. These angles were based on the minimum and maximum values recommended by the FSI [5] for the installation of helical nails and made it possible to investigate the effect of nail inclination (α) on the behavior of HSNWs. Staggered and square were also used as two different patterns to install the nail elements on the wall face. In both nail patterns, the nails were installed on the wall face with a horizontal and vertical spacing of 0.20 m and 0.15 m, respectively. These intervals are within the range recommended for helical nails by the FSI [5].

Silica sand with a moisture content of 6% was used at a relative density (D_r) of 65% to construct all main parts of the wall models. This soil material, called Firuzkooh #161 sand, was a synthetic soil composed of angular particles with a specific gravity of 2.654 and a fines content of about 6% that

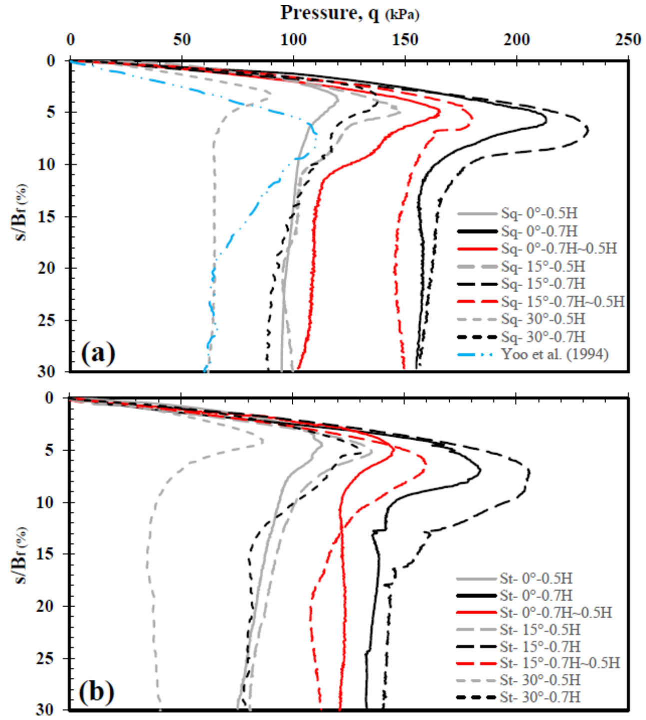


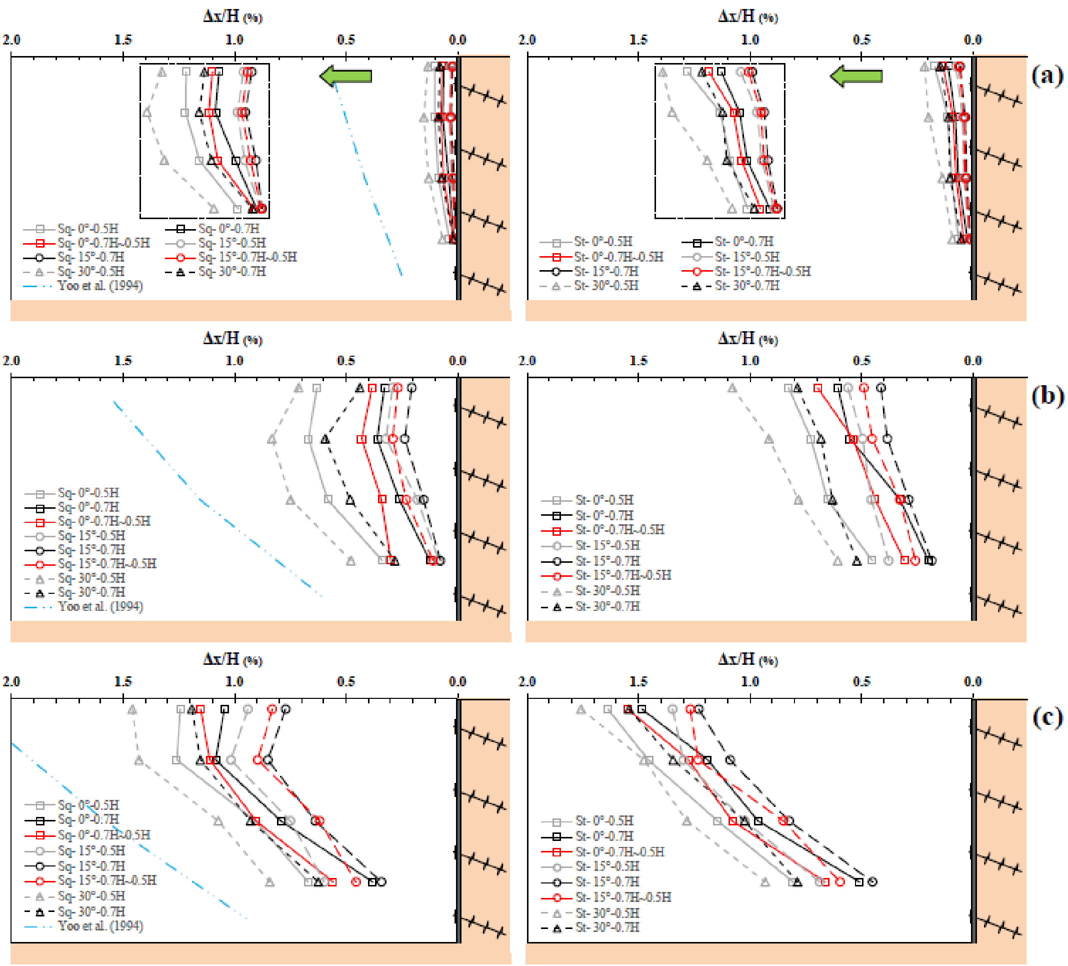
Fig. 2. Pressure-settlement relationships for HSNWs with: (a) a square pattern; (b) a staggered pattern.

had the minimum and maximum dry unit weights of 14.6 kN/m^3 and 16.6 kN/m^3, respectively. Based on the axial stiffness relationship and the similitude rules for axial stiffness, a 2.5 mm diameter rod composed of phosphor bronze was selected as the nail shaft which was equivalent to a real helical nail with a 38 mm diameter steel shaft. Moreover, a series of pull-out tests were carried out on reduced-scale models of helical nails with different ratios of helix spacing to helix diameter (S_{hx}/D_h) to determine the appropriate arrangement of helices in reduced-scale helical nails. Based on these tests, helices with a diameter of 10 mm and distances of 33 mm were selected to make helical nails with a geometric scale of 1/10, as shown in Fig. 1. A facing panel with a thickness of 10 mm, which was composed of steel wire mesh surrounded by cement grout, was selected for use in the reduced-scale models. The specifications of steel wire mesh and cement grout were selected using the results of flexural tests and considering the scaling relationship for flexural resistance.

After constructing the wall models according to a real construction process of helical soil-nailed walls, the models were loaded using a stiff steel plate with a width of B_f =0.1m that was located 0.05m from the wall crest (Fig. 1). This steel plate corresponded to a real strip footing with a width of 1.0m.

3- Results and Discussion

The pressure–settlement (q–s/B_f) responses of the strip footing located on HSNWs with different arrangements, inclinations, and patterns of helical nails are presented in Fig. 2. Comparison of the q–s/Bf curves for the wall models with different nail patterns in Figs. 2(a) and 2(b) show that



Note: Δx is the lateral wall displacement

Fig. 3. Lateral deformations of the wall facing at different footing settlements: (a) s/Bf = 2%; (b) s/Bf = 8%; (c) s/Bf = 14%

the use of a square pattern to install helical nails not only increased the ultimate bearing capacity of the footing but also decreased the settlement needed to reach failure $(s/B_f)_f$. This means that the bridge footings located on HSNWs with a square pattern experience a pressure–settlement behavior in a rigid manner before reaching ultimate bearing capacity. On the other hand, because the ultimate bearing capacity can be used in the footing design when it occurs within the range of allowable settlements, the reduction of $(s/B_f)_f$ can be considered an advantage for the square pattern. As seen in Fig. 2, the bearing capacity improvement due to the square pattern is more evident in long nails and gradually fades with an increase in the nail inclination so that the effect of nail pattern in calculating the bearing capacity can be ignored in HSNWs with 30-degree nails.

A comparison of the lateral displacement profiles in Fig. 3 shows that an increase in the nail length played an important role in reducing the lateral displacements of HSNWs subjected to footing loading. This displacement reduction, which was maximized by installing the nails at a 15-degree angle, was greater when the length of the nails increased uniformly along with the wall height. As the nail inclination continued to increase, the wall displacement increased again and reached more than those experienced in the walls with horizontal helical nails. Hence, 15° and 30° can be introduced as the most efficient and inefficient angles for installing the helical nails to control the wall deformation, respectively. The pattern of nail installation was found as another factor affecting the wall displacements. As can be seen in Fig. 10, the use of a square pattern in installing the helical nails not only reduced the wall displacement but also added a bulging to the predominant deformation mode, which was overturning. The change in deformation mode caused the location of the maximum lateral displacement (Δx_{max}) to move from the wall crest to the middle third of the wall. Because limiting the lateral displacement of the wall crest plays an effective role in providing the confining pressure around the footing, moving the location of Δx_{max} to a lower point of the wall can play an effective role in improving the performance of the bridge footings located on HSNWs.

The change in the geometry of the slip surfaces due to the change in the pattern of the nail installation was the first finding obtained from the comparison of the failure mechanism in the HSNW models with the square and staggered patterns. As seen, the slip surface in HSNWs with a square pattern started from the one-side edge of the footing and developed through the nail rows in the form of a convex curve toward the wall and finally led to the deformation of the wall facing, as reported for grouted-nail walls [6] and soil-nailed slopes [7]. the slip surface was developed to form a concave curve in HSNWs with a staggered pattern. The change in the geometry of the slip surface can be attributed to the amount of wall tendency to move outward. Inclination and length of nails were also found to be the other two structural factors to affect wedge failure dimensions in HSNWs. A uniform increase in the nail length along with the wall height, as well as the use of a 15-degree angle to install nails, reduced the penetration depth of the slip surface in all the wall models. The reduction of wedge failure dimensions, which was not observed in the local increase in nail length, can be considered as an advantage in the design of the walls. The failure to change the wedge failure dimensions due to the increase in the length of the nails located in the upper half of the walls indicates that the role of the lower rows of nails in the stability of HSNWs is more prominent than the upper rows. Therefore, it can be concluded that to maintain the performance of HSNWs when using non-uniform nail arrangements, attention to the lower rows of nails should be a priority. It should be noted that this conclusion is for footing loading only and may change under other loading conditions.

4- Conclusion

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

1) 15° and 30° were found to be the most efficient and inefficient angles for installing the helical nails to control the wall deformation, respectively, and vice versa as the inefficient and the most efficient angles for installing the helical nails to reduce the induced lateral pressure behind the facing in HSNWs under footing loading.

2) The use of a staggered pattern to install helical nails was found to be an effective solution to reduce the lateral pressure induced by the footing located on HNSWs.

3) The change in the pattern of the nail installation was recognized as the only factor in causing a fundamental change in the geometry of the slip surfaces. This fundamental change was a change of curvature from convex to concave due to the use of a square pattern instead of a staggered one.

4) The addition of bulging to the predominant deformation mode (overturning) and the change in slip surface geometry from a concave curve to a curve convex were observed as two important consequences of changing the pattern of nail installation from staggered to square.

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