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Investigating the Nail Walls Performance in Jointed Rock Medium

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***Abstract*—**Evaluation of the excavation-induced ground movements is an important design aspect of support systems in urban areas. Geological and geotechnical conditions of an excavation area have significant effects on excavation-induced ground movements and the related damage. This paper is aimed at studying the performance of excavation walls supported by nails in jointed rock medium. The performance of nailed walls is investigated based on evaluating the excavation-induced ground movements. For this purpose, a set of calibrated 2D finite element models are developed by taking into account the nail-rock-structure interactions, the anisotropic properties of jointed rock, and the staged construction process. The results of this paper highlight effects of different parameters such as joint inclinations, anisotropy of rocks and nail inclinations on deformation parameters of excavation wall supported by nails.

***Keywords*—**Finite element, jointed rock, nailing, performance.

I. Introduction

In recent years, a significant rise has been reported in use of soil nail walls as a cost-beneficial alternative to conventional retaining walls executed in top down excavations. The construction procedure for soil nail walls is well-described in the literature [1]. The process involves installation of the closely spaced steel bars (i.e., nails) in pre-drilled holes, which are subsequently encased in grout. Similarly the nailing method is also used to stabilize excavation walls in jointed or weathered rock medium. This stabilization process is known as “Rock Nail Wall” (RNW) [2].

According to literature, rock nailing refers to a procedure of installing reinforcing elements into a rock mass exposed by an excavation in order to form an internally supported structure. Similar to soil nail walls, in rock nailing construction reinforcing elements are installed in a systematic array as the excavation progresses: Each row of elements is installed into natural material before the next increment of excavation [2].

Under both ground conditions, steel bars act as passive elements in response to the deformation of the reinforced ground during subsequent excavation activities [3]. The supported ground should be active to develop tensile and shear capacity in the steel bars. In other words, movement must occur in the supported ground for creating tensile and shear stress in steel bars. This movement is a potential source for excavation-induced building damage and can lead to legal disputes in urban area.

Performance assessment of RNW seems to be a central and yet difficult issue to be addressed by researchers. Considering the similarity between RNW and soil nail wall in terms of construction sequence, applications, load transfer mechanisms, and deformability response, the concept of soil nail wall performance can be extended to RNW performance. Performance studies of soil nail walls have been a long-standing issue in geotechnical engineering. Over the past decades, significant studies have been conducted to assess the performance of soil nail wall in the framework of experimental and numerical methods.

In stabilizing the excavation wall by the nailing method, Excavation-Induced Ground Movements (EIGM) and excavation wall deformation and ground settlement are unavoidable. In soft soil, the value of maximum horizontal deformations of the wall face can increase up to 0.5% of the wall height [4]. The settlement profile in surrounding area and mode of wall deformation are also evaluated for types of soil conditions [5]-[8]. Some guidance in the estimation of EIGM is referred in literature [9]-[11].

The importance of EIMG estimation increases when buildings are in close proximity to the excavation area. Prediction of building damage resulting from EIGM is another subject that has recently received much attention by many researchers. To characterize the damage that structure frame has experienced during excavation progress, the term “damage level” is generally used. As a term defining the limiting conditions of expected damage in structure according to EIMG, damage level has been investigated and developed by performing physical scaled model tests [12], [13], field observations and case studies [14]-[16], and numerical analyses [17], [18].

II. Effect of Discontinuities on the Jointed Rock Behavior

In the jointed rock, the planes of discontinuity control the strength, deformational and hydraulic properties, and general behavior of rock masses. These discontinuities make the rock mass discontinuous and anisotropic, resulting in different strength and deformability in various directions. The term discontinuity, with its probable sedimentary (bedding or lamination planes), digenetic, or tectonic (joints and faults) origin, refers to any plane of separation or weakness in a rock mass. The stability of the excavations in jointed rock depends on the direction and strength of the discontinuities. The relative orientation of discontinuities may determine whether the excavation wall is stable or not, Fig. 1 [19].

The effects of joints relative orientation and influence of rock nail in enhancement of excavation stability in excavation

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wall stability is well described in literature [2]. Fig. 2 illustrates the influence of nail in stabilizing the jointed rock. As shown in the figure, both "nail angle" and "joint inclination" parameters might affect the stability mechanism of RNW.

Discontinuity in rocks results in different strength and deformability properties in various directions of jointed rock, leading to different response under different load conditions. This so-called "anisotropy" response in jointed rock is considered in the developed FE model by defining of the joints directions and using the jointed rock constitutive model.

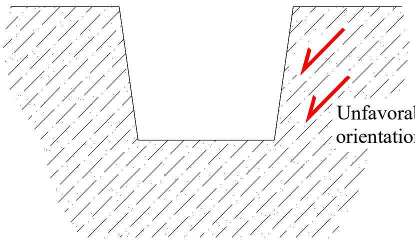

Fig. 1 Effect of the relative orientation of discontinuities in relation to excavation wall stability

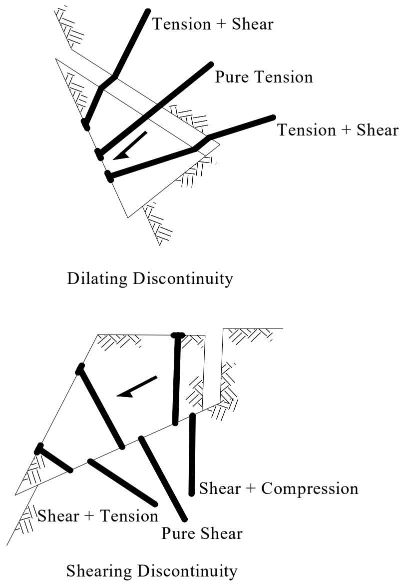

Fig. 2 Reinforcement behavior at discontinuity [2], [20]

III. Numerical Modeling

The present research seeks to provide a better understanding of RNW performance in jointed rock. In this regard, 2D FE models of nail supported excavation have been developed. Fifteen-node triangle plain strain elements were used to model the jointed rock; beam elements were used to model structure frames and rock nails. In order to take into account the interaction between joints, nail and rock, foundation of structure and rock, interface elements were employed using Mohr– Coulomb failure criterion.

The dimensions of models, the size of elements, and the number of nodes were decided after performing a number of sensitivity analyses. The side faces of the model were restrained by rollers, while its bottom was assumed as fixed. The dimensions of RNW in FE model are shown in Fig. 3, for layer inclination equal to +15 degree.

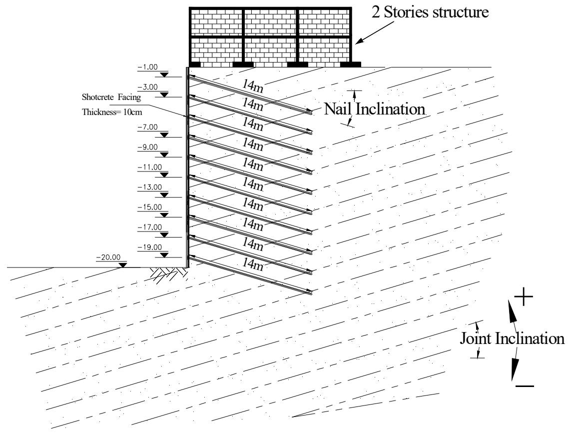

Fig. 3 Schematic of FE model and dimensions of RNW

IV. Numerical Results and Discussion

The developed and validated model was used to evaluate the deformation parameters of rock nail supported ground to assess the performance of RNW in plastic and anisotropic half-space.

As mentioned in introduction section, the majority of recent studies are performed on soil nail wall performance and have paid less attention to the performance of rock nail wall (RNW), despite the existing differences between nails response in soil and rock (spatially in jointed or weathered rock). Numerical studies on soil nail wall indicated that several factors including the nails inclination, nails length, and nails spacing affect performance of the soil nail wall. In the present work an attempt was made to examine the effects of these well-known parameters as well as some other important parameters such as Joint Inclination, Joint Spacing and Rock Anisotropy.

To investigate the rock nail performance, various deformation parameters including cantilever deflection (CD), lateral bulging (LB), and maximum settlement (MS) are defined and used in parametric study (Fig. 4).

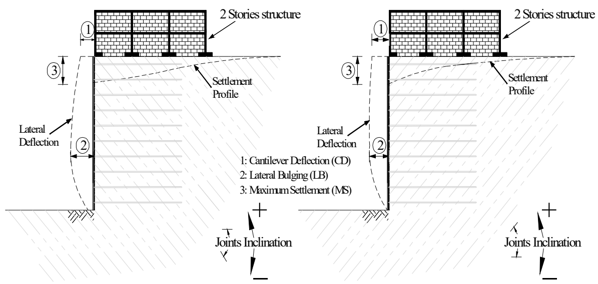

Fig. 4 Definition of wall deformation parameters used in the parametric study presented in this paper

V. Effect of Joints Inclination on Deflection Mode of RNW

Deflection mode of excavation wall influences the damage level in the structures in its vicinity. In Cantilever deflection causes horizontal strain, on the other hand, lateral bulging, and settlement leading to the angular distortion in adjacent structures [21].

In jointed rock medium, joint direction dominantly affects the mode of wall deflection. The influence of joints direction on the CD and LB are shown in Figs. 5-7 for nail angles 0°, 15°, and 30°, respectively. Here, the jointed rock is considered as isotropic (E1/E2=1) and joint space (JS) is assumed to be equal to 2m. The vertical axis indicates the value of displacement in millimeters. The direction of negative and positive joints inclination is shown on both sides of graphs.

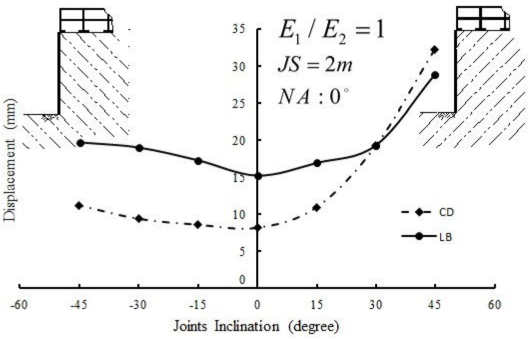

Fig. 5 Effect of joints inclination on cantilever displacement and lateral bulging, nail angle: 0^0

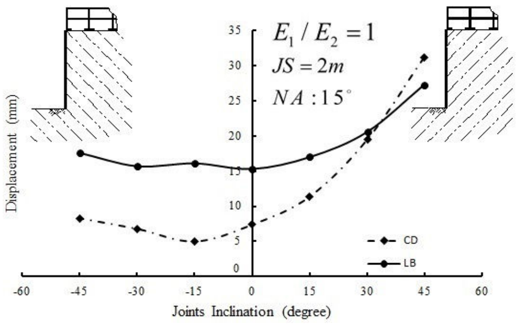

Fig. 6 Effect of joints inclination on cantilever displacement and lateral bulging, nail angle: 15^0

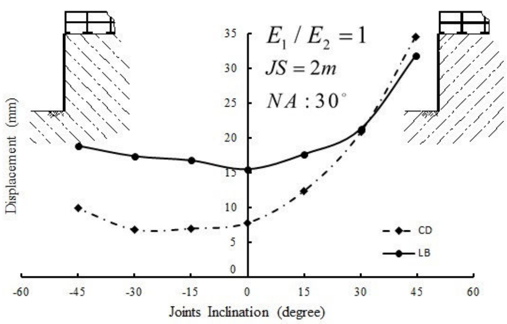

Fig. 7 Effect of joints inclination on cantilever displacement and lateral bulging, nail angle: 30^0

As shown in the figures, both CD and LB values have small changes in joint inclination range of -45 to 0; however, the values increase significantly as joints inclination varies from 0 to 45. This trend is similar for all examined nail angles. An important result observed from these figures is the variability of dominant deflection mode by variation of joints inclination. Based on these results, by an increase in joints inclination value, the RNW has a tendency to behave as a cantilever wall.

VI. Effect of Joints Inclination on Deformation Parameters of RNW

In the previous subsection, the effect of joints inclination on wall deflection mode was investigated by assuming jointed rock as an isotropic medium. In order to obtain a better insight into nail wall response in jointed rock medium, the anisotropy equal to 3 was considered for rock medium. By taking into account the anisotropy effect, the influence of joints inclination on CD and LB for different nail angles is shown in Figs. 8 and 9, respectively.

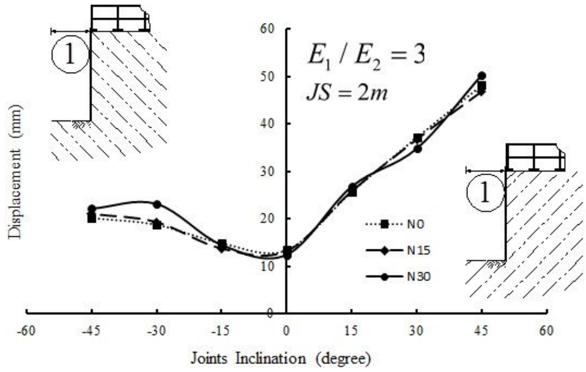

Fig. 8 Effect of joints inclination on cantilever deflection where anisotropy equals to 3

When the joint inclination is almost zero, the least value for wall deformation occurred. In other words, the value of CD and LB of nail wall in jointed rock with horizontal joints is less than the corresponding values in jointed rock with oblique joints. This trend can be attributed to the joint slippage and anisotropic properties of jointed rock. It should be noted that based on the defined anisotropy properties, the elastic modulus perpendicular to the joint direction is less than the elastic modulus along the joint direction. So, for negative values of joint inclination, the deformation of nail wall in jointed rock will be more than the corresponding values in jointed rock with horizontal joints. It can also be observed that the variation of LB is less than the variation of CD in the range of investigated parameters. The trend of curves is the same for all of examined nail angles. Similar to the isotropic situation, an increase in joints inclination value, the RNW has a tendency to behave as a cantilever wall.

The effect of joints inclination on maximum settlement is examined and shown in Fig. 10. The vertical axis shows the value of maximum settlement in millimeters.

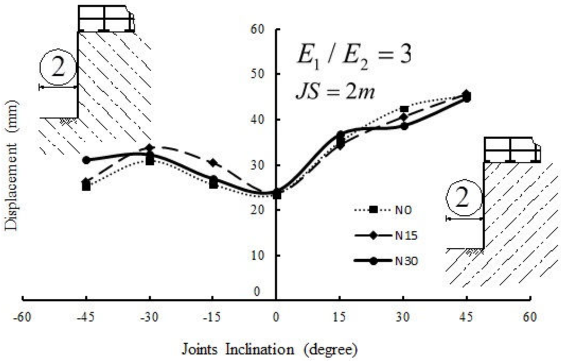

Fig. 9 Effect of joints inclination on lateral bulging where anisotropy equals to 3

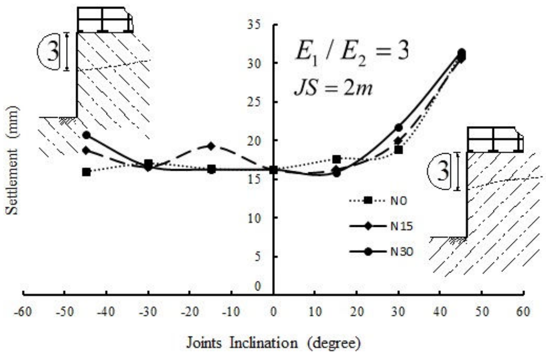

Fig. 10 Effect of joints inclination on maximum settlement where anisotropy equals to 3

As indicated in Fig. 10, the maximum settlement for positive values of joints inclination can increase up to twice as compared to the zero and negative values of joints inclination. The mentioned parameter had negligible variation for negative values of joints inclination.

If the generated settlement under the structure is uniform, the structure encounters less damage in comparison with the structure with non-uniform settlement. So, effect of joint inclination on settlement ratio was investigated. Settlement ratio was defined as the ratio between maximum and minimum settlement under adjacent structure. Fig. 11 shows the effect of joint inclination on settlement ratio where anisotropy is 3.

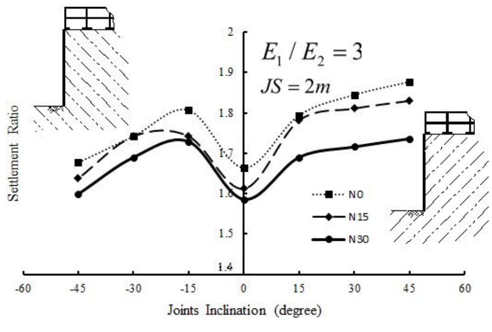

Fig. 11 Effect of joints inclination on settlement ratio where anisotropy equals to 3

The results show that settlement ratio increases by the increase in joints inclination for its positive values. On the left side of the figure, there exists a peak in curves at joints inclination -150. Fig. 11 also demonstrates that the settlement is more uniform for greater nail angles.

VII. Effect of Joint Spacing on Deformation Parameters of RNW

Spacing is defined as the average perpendicular distance between discontinuity planes in the same set. It controls the size of blocks of intact rock and affects the overall behavior of a rock mass. With small spacing, the strength of the rock mass is considerably reduced, and in extreme cases a granular-like behavior is observed in non-cohesive materials.

To evaluate the effects of joints spacing in the study of excavation wall performance or stability, the relative dimensions of the both the rock mass structure and the separation between discontinuities to the excavation depth should be considered. The RNW performance is studied in the jointed rock medium with the joints spacing 0.5, 1, 1.5, 2, and 2.5m. The mentioned values are corresponding to 0.025, 0.05, 0.075, 0.1, and 0.125 of the excavation depth, respectively. To investigate the effects of spacing on wall performance, the variations of cantilever displacement and maximum settlement respective to joints spacing were plotted in Figs. 12 and 13.

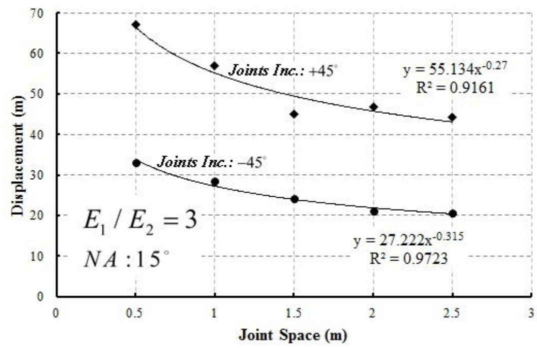

Fig. 12 Effect of joints inclination on CD

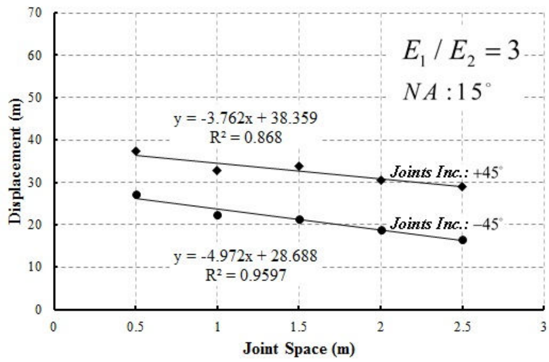

Fig. 13 Effect of joints inclination on MS

The power and linear functions are defined to characterize the variation of cantilever displacement and maximum settlement, respectively. Here, the excavation-induced deformation and related damage decreases with the increasing joints spacing.

VIII. Summary and Conclusion

The paper presents the results of a comprehensive numerical analysis carried out to investigate the performance of nail walls in jointed rock media. Taking into account joint-rock-structure interaction and anisotropic properties of jointed rock, the deformation parameters of excavation zone supported by RNW were investigated for different conditions of joints inclination and spacing. The most important findings of this study can be summarised as follows:

1) The dominant deflection mode of RNW was evaluated for a range of joints inclination values. Results showed that RNW has a tendency to behave as a cantilever wall by increasing the joints inclination value.
2) The power and linear functions can be defined to characterise the variation of cantilever displacement and maximum settlement versus joints spacing variations.
3) For jointed rock media with negative joints inclination, the deformation and related damage level is higher as compared to the jointed rock medium with horizontal joints; despite the fact that stability is higher for jointed rock medium with negative joints inclination. This response can be attributed to the anisotropic specifications of jointed rock medium. Also, the quantified analogy between the results was presented in this paper.

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