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# FINITE ELEMENT ANALYSIS OF WEAK ROCK UNDERCUT REINFORCED WITH SOIL NAILS

***Summary:***

*A hard rock cavern is usually self-standing and stable with a full crown. However, for an undercut in very weak to weak limestone, additional support was required to make it stable and safe.*

*This paper presents a case study of using soil nails to stabilize an undercut in weak sedimentary rock supporting a traffic deck foundation. The undercut behavior was analyzed with a finite element program for both Ultimate Limit State stability and Serviceability Limit State taking into account the soil nails. The analyses confirmed the need for soil nails to stabilize the undercut under traffic loads applied at the top and was used to adopt soil nail pattern. Modelling aspects, undercut behavior and movement monitoring results are presented and discussed in this paper. Total monitored movements after 2 years were about 40% of predicted movements.*

*Effect of flexural and axial stiffness of plate elements onto soil nail axial load was also investigated. Neglecting flexural stiffness resulted in slight load redistribution with load reduction in heavier loaded nailsof less than 5%, which is not significant for practical purposes. Further parametric analysis of influence of flexural and axial stiffness on the axial force indicated changes in the axial force of up to 5% which is also not significant for practical purposes. This is in agreement with methodologies for soil nail design adopted in standards and engineering manuals.*

***Key words:***

*Undercut, Finite Element Analysis, Weak Rock, Soil Nails.*

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## 1. INTRODUCTION

A deep underground station for the Riyadh Metro Project had been excavated to a depth of 15 m before the station footprint was revised. One of the station egress shafts had to be longitudinally shifted by 3m. As the station box and egress shaft had already been excavated with temporary traffic deck installed over the egress shaft, an undercut had to be formed in weak rock to facilitate the subsequent construction work. Figure 1 shows the excavated egress shaft before the undercut was excavated and indicates the undercut profile.

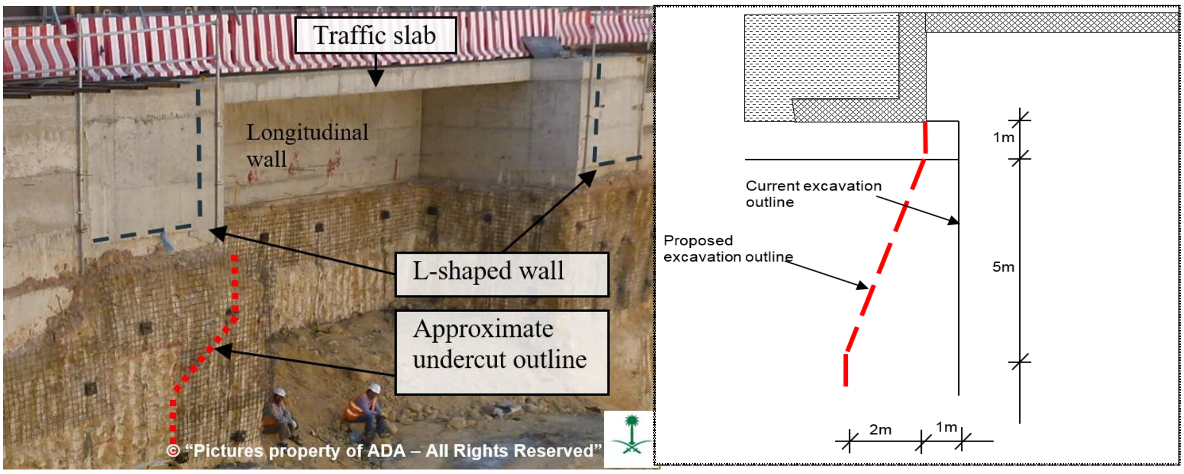


*Figure 1: Proposed undercut profile and its dimensions*

It is well established that a hard rock cavern is usually stable with a full crown. For a full crown, surface vertical loads and ground gravity loads are transferred through the crown and side walls creating arching effect prior to being supported by the ground below. But for an undercut in rock, such load transfer path does not exist and tensile stresses develop above the undercut, with potential to result in a failure in weak materials. Development of tensile stresses due to undercutting is illustrated in Figure 1 where minor principal stress, if in tension, was contoured for a homogenous section and ideally elastic material.

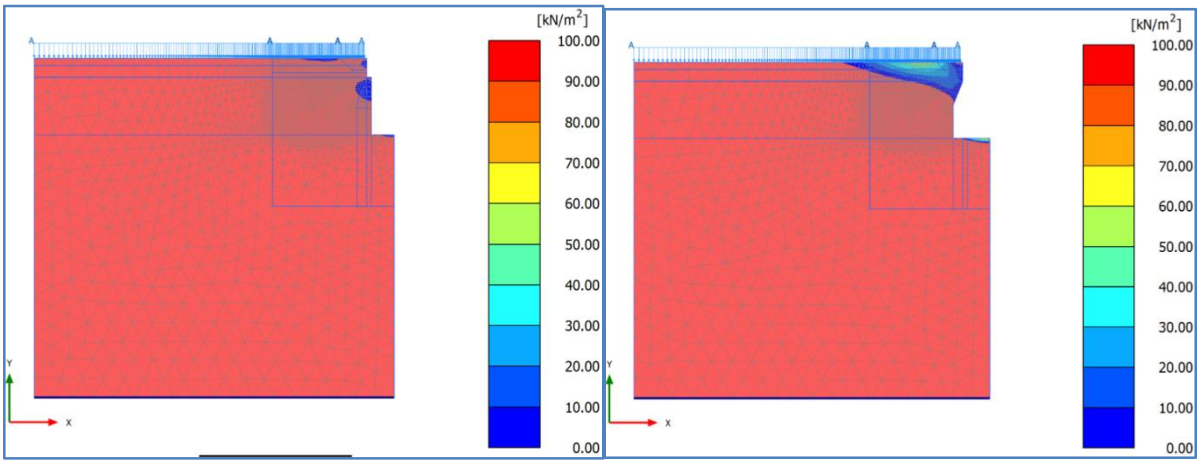


*Figure 2: Zone of minor principle stress in tension – vertical excavation and excavation with undercut*

Assessments carried out indicated that additional support was needed in order to transfer the vertical loads and to maintain adequate stability of the excavation. Soil or rock nails are widely used for this purpose and were applied in this case. This paper used term "soil nails", although both terms could be used given subsurface conditions that included completely and highly weathered rock, with completely weathered rock having soil like properties.

Soil nails systematic research started in 1970's in Germany [1], followed by development of design methods in France [2] and United States [3] in early 1990's that have been used as basis for design methodology [4, 5] over the last 30 years. Large number of papers have been published about numerical methods of soil nail analysis including references [6] to [9] and [11]. Conventional soil nail design is often carried out using limit equilibrium methods such as method of slices. Available software for method of slices cannot deal with undercut geometries and could not be used.

Finite element (FE) or finite difference numerical modelling of continuum is commonly used when it is necessary to consider more complex geo-structures. In this paper, FE program PLAXIS 2D (2010) was used to model the weak rock undercut reinforced with soil nails. Of particular interest for cut behavior was interaction between the grouted nail bar and the soil surrounding the nail [6, 8].

PLAXIS 2D [4, 12] can model soil nail by "node to node anchor element", or "geogrid element" or "plate element". For the "node to node anchor element", it is sufficient to model the structural capacity of nail tendon, but such method does not include the characteristics of bond between the grouted nail tendon and surrounding soil. The "node to node anchor element" was not therefore used in this exercise. When the flexible "geogrid element" is used, the bond properties are included in the modelling, but flexural stiffness of the nail is not modelled. We adopted the "plate element" to model flexural and axial stiffness of nails and PLAXIS"interface element" to model bond properties and interaction between soil nail and surrounding weak rock. A geometrical conversion was adopted to take into account bond strength of the circular shape of soil nail modelled with rectangular 2D "plate element" of unit width.

We also carried out investigation of the effect of the nail flexural stiffness on the nail axial load. This part of investigation was undertaken, first by using "geogrid element" which has no flexural stiffness, and, additionally, by varying axial and flexural stiffness for "plate element". Corresponding axial load changes were then examined and compared.

## 2. NUMERICAL MODEL AND INPUT PARAMETERS

PLAXIS elasto-plastic Mohr-Coulomb constitutive model was adopted to assess the undercut performance. Staged construction sequence was simulated, i.e. excavation to about 1.0m depth below the planned nail elevation was simulated prior to application of soil nails by activating corresponding plate elements and interface elements. Plastic analysis was carried out for each stage followed by further excavation.

### 2.1. Numerical Model

A reinforced concrete traffic slab bridged between its foundation above the undercut and at the other side of the excavation, as shown in Figure 1. The traffic slab was supported by an L-shaped retaining wall, both sides. A longitudinal retaining wall spanning between the two L-shaped walls supported soil pressures between the two foundations.

The lateral support of the traffic slab provided to the undercut was not considered in the modelling as the connection between the traffic slab and its foundation above the undercut was not designed to transfer horizontal loads. Similarly, the lateral support of the longitudinal wall was not considered in the original design nor in the numerical modelling. It is however noted that both most likely provided some lateral restrain.

The vertical load from traffic and slab self-weight was represented by a line load of 190kN/m' (SLS) applied on the L-shaped retaining wall foundation, and surface traffic load by uniformly distributed load of 20 kN/m$^2$ (SLS). The foundation was modelled using 2D elastic mesh elements, in the same way as soil and rock. Figure 3 shows the adopted numerical model which comprised 6749 of 15 nodded triangular elements.

Soil nails were modelled by "plate element" with "interface element" on both sides to simulate the interaction between soil nail and the surrounding soil or weak rock [11].

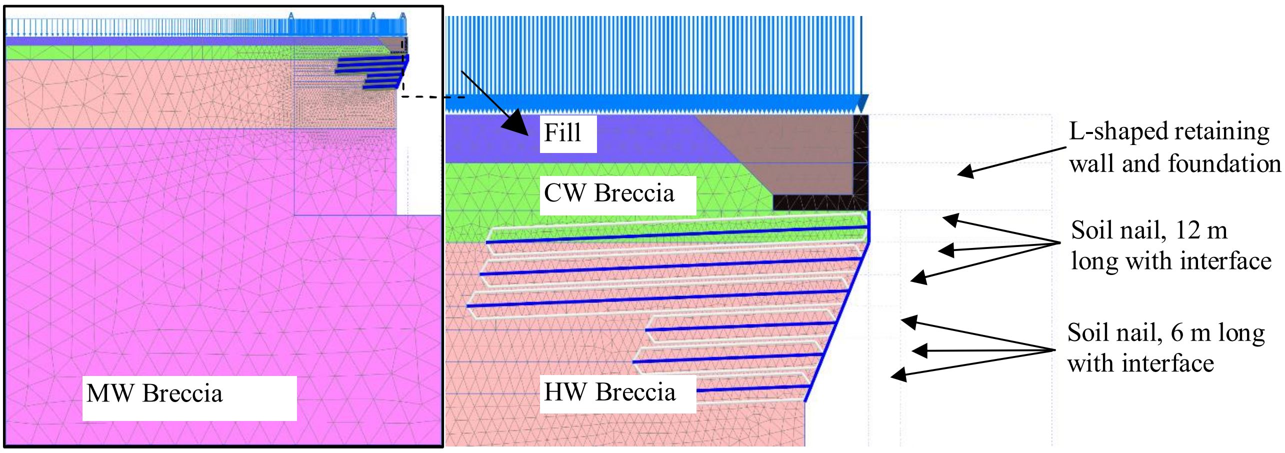


*Figure 3: Adopted numerical model*

### 2.2. Geotechnical Unit Parameters

There was no site specific geotechnical investigation for the undercut. The geological units were identified, and properties verified, by field geotechnical inspections of the excavation. The subsurface conditions comprised granular uncontrolled fill to 1.5m depth, overlying completely weathered (CW) Limestone Breccia from 1.5m to 4 m depth, over highly to moderately weathered (HW/MW) Limestone Breccia to 16m depth, over moderately weathered (MW) Breccia to the bottom of the bottom of the model at 70m depth. The excavation was 31 m deep.

The fill material was placed during earlier road and utility construction for which details were not known. Most of the fill in the area was gravel mixed with sand and silt associated with road construction, but there was also some loose sand backfill of utility trenches. Conservatively, shear strength for the un-compacted sand was adopted.

Shear strength propertiesfor Breccia (CW and HW/MW) were adopted fromconsiderationsof project wide properties across the city and findings during geotechnical inspections of the excavation. The adopted shear strengths were necessarily somewhat conservative. Deformation properties mostly relied on results of seismic refraction testing, but used lower bound values.

CW Breccia would crumble under firm blows with geological hammer, or unravel when the hammer was dragged over vertical cut. It was considered to have soil like properties. The shear strength was adopted from a combination of experience based judgment and a few back analyses of cuts in the area, as there was no locally available technique for undisturbed sampling of the soft rock that would enable good quality laboratory testing.

HW/MW Breccia was massive and matrixsupported, rather than clast supported. The clasts were strong and ranged from fine to coarse gravel. The matrix was very weak to weak cemented silt material. Matrix would crumble under firm blows by geological pick, but was too hard to be broken by hand. AdoptedMohr-Coulomb shear strength was based on matrix properties androughly corresponded with Hoek-Brownshear strength [13] for uniaxial compressive strength of 2 MPa, Geological Strength Index (GSI) of 80 and intact rock parameter ($m_i$) of 7 as recommended by Hoek and Brown for siltstone.

Properties of MW Breccia were not considered to influence the results of the assessment. It was clast supported, massive and of medium strength with uniaxial compressive strength of intact rock typically well over 15 MPa. The properties were adopted based on lower bound values that were used project wide.

The groundwater table was below the base of the excavation and not considered. The adopted material parameters are listed in Table 1.

*Table 1. Rock and soil parameters for PLAXIS Mohr-Coulomb Model*

| Property | Geotechnical Unit | | | |
|---|---|---|---|---|
| | Uncontrolled fill | CW Breccia | HW/MW Breccia | MW Breccia |
| Unit weight (kN/m$^3$) | 18 | 22 | 22 | 24 |
| Effective cohesion (kPa) | 0 | 15 | 200 | 400 |

| | | | | |
|---|---|---|---|---|
| Effective friction angle (°) | 30 | 32 | 37 | 46 |
| Dilatancy angle (°) | 0 | 0 | 0 | 0 |
| Tension cut off (kPa) | 0 | 0 | 50 | 80 |
| Modulus of elasticity (MPa) | 50 | 500 | 1000 | 6000 |
| Poisson's ratio | 0.3 | 0.3 | 0.3 | 0.2 |

### 2.3. Soil nails

The undercut was reinforced by top three rows of 12 m long nails, and three lower rows of 6 m long nails at 1.0 m center to center in horizontal and vertical direction. 32 mm deformed steel bars were installed in 100 mm diameter grouted holes. The top row of nails was installed at 0.5 m below the wall. Nail heads were fixed with walers against 100 mm reinforced shotcrete over rock face.

There was a shorter row of nails that was initially installed for the vertical cut only, at about the same level as the top row of the 12 m long nails. The shorter nails were to reinforce foundation of the retaining wall foundation which could not be supported on CW Breccia, but were not adequate to reinforce the undercut. These shorter nails were disregarded in PLAXIS modelling of the undercut.

The structural capacity of soil nails was simulated with "plate element" for the nail structural capacity and interaction between nail and surrounding soil was simulated with "interface element". Compared to the circular shape of soil nail, the "plate element" is continuous and rectangular in the out-of-plane direction as shown in Figure 4. For this 2D modelling, nails stiffness and bond strength of circular shaped soil nail had to be modified to cater for the rectangular plate element and nail spacing.

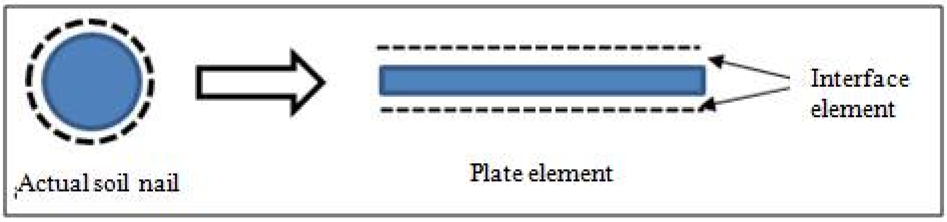


*Figure 4: Circular shaped soil nail modelled with rectangular plate element*

The plate equivalent axial stiffness EA and its flexural stiffness EI, for the unit width of 1m in the out-of-plane direction, were calculated as below with consideration of the circular shape of soil nails and its spacing:

$$EA_{(plate)} = \frac{EA_{(nail)}}{S} = \frac{E_{steel}}{S}\left(\frac{\pi d^2}{4}\right) \quad (1)$$

$$EI_{(plate)} = \frac{EI_{(nail)}}{S} = \frac{E_{steel}}{S}\left(\frac{\pi d^2}{64}\right) \quad (2)$$

Where, $E_{steel}$ is the soil nail elastic modulus, S is the soil nail horizontal spacing and d is the soil nail diameter. The stiffness of grout is relatively small compared to the steel tendon, and therefore not considered for the equivalent stiffness of the plate element.

As the contact area of the circular soil nail is changed to two planar interfaces, the equivalent bond strength of interface elements (2 sides) was calculated as below:

$$\left(\frac{\sigma_b \pi D L}{S}\right)_{nail} = (2\sigma_b' L)_{plate} \quad (3)$$

The equivalent bond strength of interface elements is therefore calculated as:

$$\sigma_b' = \frac{\sigma_b \pi D}{2S} \quad (4)$$

The bond strengths were adopted based on limited number of pull out tests from other areas of the project. Table 2 lists the parameters used for the 2D soil nail modelling:

*Table 2. Equivalent soil nail parameters used in FE modelling*

| | | |
|---|---|---|
| Soil nail property | Steel elastic modulus, Esteel (GPa) | 20 |
| | Soil nail tendon diameter, d (mm) | 32 |
| | Soil nail spacing, S (m) | 1 |
| | Soil nail hole diameter, D (mm) | 100 |
| | Characteristic bond strength of CW Breccia (kPa) | 160 |
| | Characteristic bond strength of HW/MW Breccia (kPa) | 275 |
| Equivalent property for modelling | Equivalent axial stiffness of plate element (kN/m) | 160850 |
| | Equivalent flexural stiffness of plate element (kNm2/m) | 10 |
| | Equivalent interface strength in CW Breccia (kPa) | 25 |
| | Equivalent interface strength in HW/MW Breccia (kPa) | 43 |

# 3. MODELLING RESULTS AND DISCUSSION

## 3.1. Overall stability

For the unreinforced undercut, two Ultimate Limit State (ULS) combinations per Eurocode 7 were first assessed – Combination 1 (C1) for actions, and Combination 2 (C2) for material strengths, and both had ULS factor of safety of less than 1.0 as PLAXIS plastic analysis could not reach equilibrium. Furthermore, Serviceability Limit State with unfactored loads was analyzed and alsofound not be stable.

PLAXIS runs of the reinforced slope indicated factors of safety greater than 1 both for Combination 1 and 2. For Serviceability Limit State (SLS), PLAXIS indicated factor of safety of 1.5 which is in general accordance with traditional guidance for factors of safety of permanent structures. Given that majority of the project slopes were designed using traditional method of slices and factors of safety between 1.3 and 1.5, that those slopes performed satisfactory, that the excavation was meant to be open between 1 and 2 years and that the bridge supported a major road artery, the factor of safety of 1.5 was considered adequate and the design was adopted.

## 3.2. Movements and nail axial loads

Horizontal movements and settlements for the SLS condition are presented in Figure 5, with maximum settlement of about 12 mm and horizontal movement of 18 mm. These movements were considered acceptable for the bridge performance. Movement monitoring results are presented in Figure 6 with maximum movement towards the excavation and settlement of the order of 3 mm. These movements were recordedfrom the time when the excavation had been advanced to 15 m depth, but before the undercut was carried out, and over a period of 2 years. The station was built and the excavation backfilled after 2 years.

Based on comparison with other prisms in the area where monitoring started earlier, from beginning of the excavation, the total movement towards the excavation was estimated to be about 7 mm, and the total settlement 5mm. This is about 40% of the estimated movements. For the settlement, the difference is attributed to higher in-situ stiffness of the rock comparing with adopted parameters. For movements towards the excavation, besides the rock properties, stiffness of the traffic slab and the longitudinal wall could have also somewhat contributed to the movement reduction.

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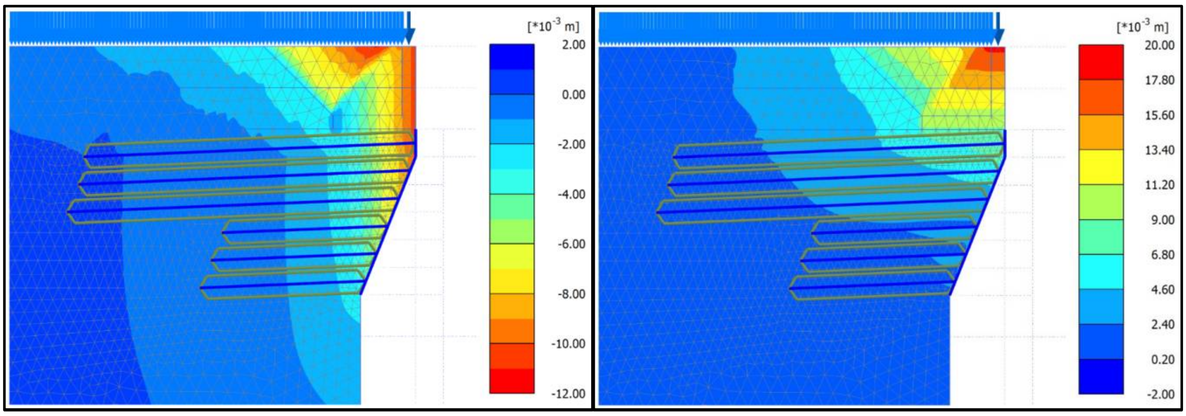


*Figure 5: Contours of settlement (maximum 12 mm) and movement towards the excavation (maximum 18mm)*

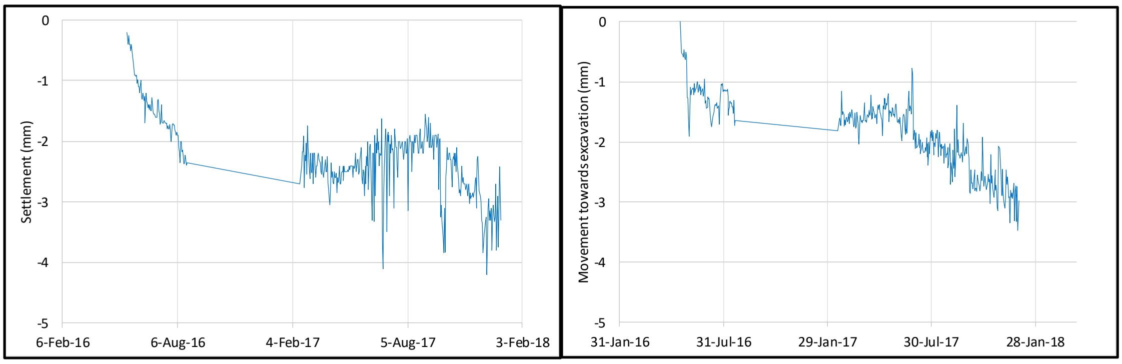


*Figure 6: Monitoring results (prism mounted about top of l-shaped wall)*

Relative movements between soil nails and rock are presented as relative movements of the “interface elements” each side of the nail on Figure 7.Soil nail forces are illustrated graphically in Figure 8 and magnitudes are shown in Table 3. The top 3 rows played major part in the stabilization of the undercut which was indicated both by the magnitude of the nail load and by the force distributed through the full length of the nails. The force in the top 2 nails gradually increases along the nail length, while the lower 3 nails are engaged only in the front two thirds.

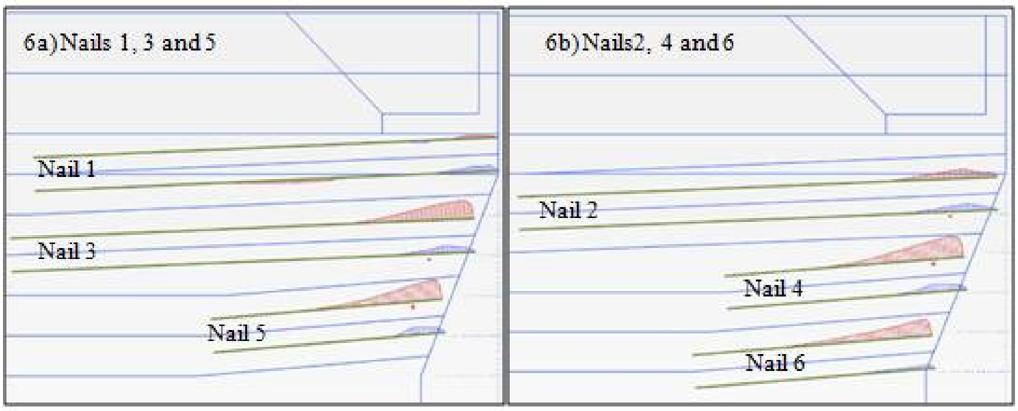


*Figure 7: Relative movement on interface elements between nails and surrounding rock (maximum 2.5 mm)*

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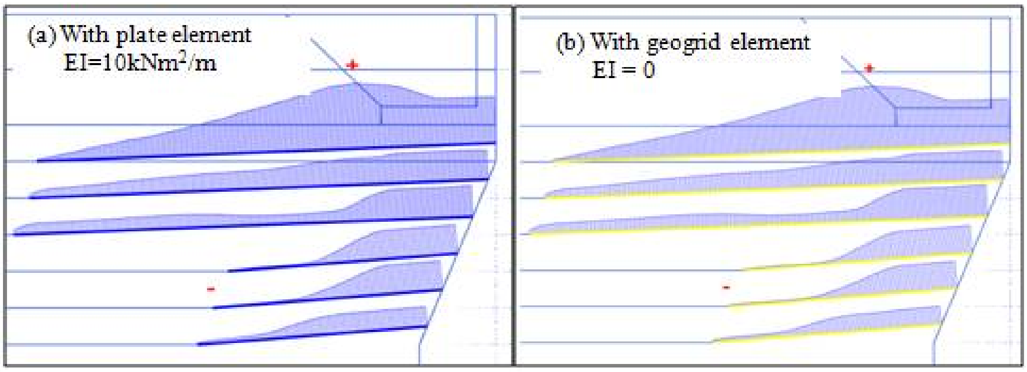


*Figure 8: Soil nail axial load with "plate element" and with "geogrid element"*

### 3.3. Effect of nail stiffness

Comparison of the nail axial forces for the "plate element" and "geogrid element" is presented graphically in Figure 8and for force magnitude in Table 3. The change to modelling with "geogrid elements" resulted in slight force redistribution, with nails that are in the slope active zone, and more heavily loaded, attracting less axial load. I.e., there was force reduction in nails 1 to 3, and force increase in nails 4 to 6. The force difference was relatively small, between 1% and 5%. Overall, the conclusion is that neglecting nail flexural stiffness does slightly underestimate nail forces for heavily loaded nails, but that this underestimate is not significant from practical point of view.This findingagrees with finding of Sing and Sivakumar [11] from numerical simulations, with findings of the early soil nail research [1 to 3] and design methodologies [4, 5] that allowto disregard soil nail bending and axial stiffness.

*Table 3. Soil nail axial load (kN) - "plate element" and "geogrid element"*

| Axial load | Plate element EI = 10 $kNm^2$/m' | Geogrid element EI = 0 | Change |
|---|---|---|---|
| Top row | 178.7 | 175.3 | -2% |
| 2nd row | 82.1 | 82.8 | -1% |
| 3rd row | 85 | 88.7 | -4% |
| 4th row | 78.4 | 75.4 | +4% |
| 5th row | 79.0 | 75.6 | +4% |
| 6th row | 54.0 | 51.2 | +4% |

The effect of flexural stiffness was further investigated by parametric method. Both axial stiffness, EA and flexural stiffness, EI were varied for plate elements and the axial load variation was normalized against a bench mark value. The benchmark value was EI = 10kNm2/m, $(EI)_0$. Sensitivity analysis was undertaken by increasing EI to $2(EI)_0$, $5(EI)_0$, $10(EI)_0$, $20(EI)_0$ and $50(EI)_0$. The change of the nail axial load was examined and plotted in Figure 9. The change was typically within 5% which is not considered significant from practical point of view. This finding from the numerical analysis agrees with findings of the early soil nail research [1 to 3] and adopted design methodologies [4, 5] that typically don't take into account stiffness of soil nails for estimate of soil nail forces.

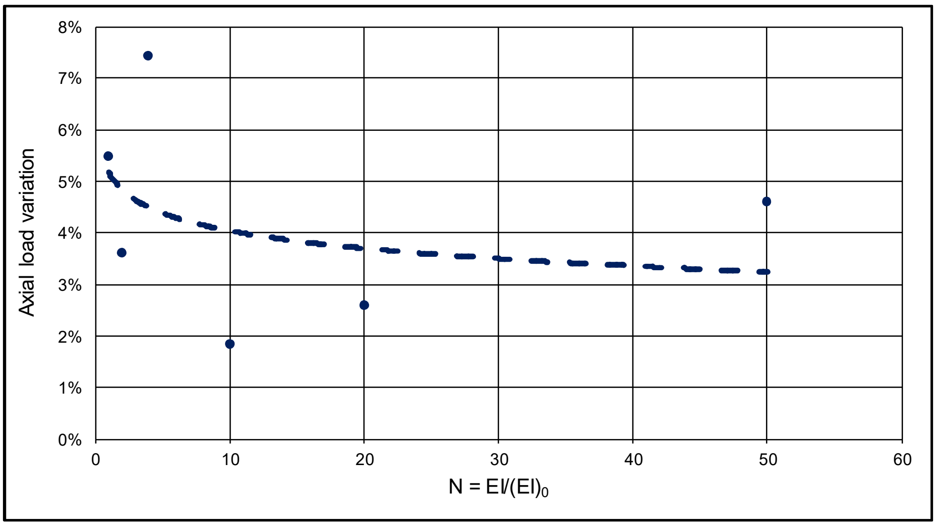


*Figure 9: Correlation between flexural stiffness and axial load change*

## 4. CONCLUSION

A case study has been presented for a weak rock undercut stabilized by soil nails. PLAXIS 2D was used to numerically model, analyze and assess the undercut behavior. The analyses found that additional support was needed to maintain stability of the undercut and that it would perform adequately if reinforced with soil nails. The soil nails were modelled using PLAXIS "plate elements". Total monitored movements after 2 years were about 40% of the movements predicted by the numerical model.

Parametric analyses found that nail axial load is not significantly influenced by either its flexural or axial stiffness and that it can, therefore, be modelled using"geogrid elements".

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