Distribution of fiberglass anchors related to the stability of soil tunnel faces

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Abstract: Tunnel face stability is significant to the safety in constructing soil tunnels. Based on the analysis of controlled deformation in rocks and soils (ADECO-RS), a quantitative method was developed to determine the required number of fiberglass anchors (FGA) for the soil tunnel utilizing both analytical and numerical methods. As an application example, the tailrace tunnel in the Israel K project employed 25 fiberglass anchors based on an analytical method to increase the safety factor of the tunnel face to 1.5, which is close to the result of the numerical method by FLAC3D. The effects of fiberglass anchor type and construction equipment on the required number of fiberglass anchors in the tunnel face were also analyzed. The results benefit the optimized support design of the tunnel face for similar tunnels in soil.

1. Introduction
Analysis of controlled deformation in rocks and soils (ADECO-RS) was developed by Professor Pietro Lunardi in the 1970–1980s in Italy based on hundreds of tunnel cases. Excavation and deformation responses of tunnels were analyzed with 3D models instead of 2D models in cross-sections (Pietro Lunardi, 2008). It was found that the deformation response starts ahead of the tunnel faces in the advance core and develops backward to the cavity. It is not only the convergence but the combination of extrusion, pre-convergence, and convergence that affect the deformation response. Convergence is only the last stage of an extremely complex stress–strain process (Lunardi, 2000; Vydrova, 2015).

“Tunnels should be driven full face whenever possible”, as emphasized in the paper of NATM by Rabcewicz (1964; 1965). Rabcewicz realized that tunnels should be driven full face using large equipment at the face for faster advances and reduced costs (Tonon, 2010). Unfortunately, due to limitation of construction equipment at that time, Rabcewicz ignored the positive effects of tunnel face to the stability of tunnels, and, instead, proposed the bench and partitioned excavation methods for tunnels in poor geological conditions as opposed to supporting the tunnel face.

2. Tunnel face stability evaluations with analytical and numerical methods
According to Prof. Pietro Lunardi’s research, tunnel face stability is the key factor for overall tunnel stability. Analytical and numerical methods are commonly used to evaluate tunnel face stability and design the support in the tunnel face.

2.1. Analytical methods
For analytical methods, potential failure mechanisms of the tunnel face based on the limit equilibrium state are typically assumed, and many scholars have conducted significant research in this area. Anagnostou & Kovári (1996) proposed that the effective support pressure on the tunnel face can be calculated using Formula (1) when the tunnel face is at the limit of its equilibrium conditions. The failure wedge is schematically shown in Figure 1. It should be mentioned that the strength parameters should be reduced by the design factor of safety (FoS).

\[
s' = F_0 \gamma' D - F_h c + F_2 \gamma' \Delta h - F_3 c \frac{\Delta h}{D}
\]

where,
- \(s'\), effective support pressure, kPa;
- \(D\), tunnel diameter, m;
- \(H\), overburden of the tunnel, m;
- \(h_k\), piezo-metric head, m;
- \(h_0\), elevation of the water table, m;
- \(c\), effective cohesion, kPa;
- \(\varphi\), effective friction, degrees;
- \(\gamma'\), submerged unit weight, kN/m\(^3\);
- \(\gamma_d\), dry unit weight, kN/m\(^3\);
- \(F_0\) to \(F_3\) coefficients related to the friction angle \(\varphi\), according to Anagnostou & Kovári (2006).

![Figure 1. Sliding mechanism and forces acting on the wedge in front of the tunnel face](image)

2.2. Numerical methods

Several numerical methods (Zdenek, 2016; Perazzelli, 2012) have been commonly used to evaluate tunnel face stability, and two of them can be used in this analysis with FLAC3D:

Load reduction method: support pressure on the tunnel face is reduced to the design FoS and the required support pressure can be obtained.

Strength reduction method: reducing the strength parameters until instability failure occurs, where the FoS of the tunnel face can be obtained by the reduction ratio.

If the required face support is larger than zero or the FoS of the tunnel face is less than the design FoS, supports should be added in the tunnel face to increase stability and safety.

3. Tunnel face support with fiberglass anchors

Fiberglass anchors possess high tensile strength, low shear strength, and ease of excavation. It is suitable for temporary supports in tunnel faces to improve the construction efficiency and safety. For
potentially unstable tunnel faces, the design of tunnel face reinforcement includes two important parameters: overlap length and the number of fiberglass anchors required.

3.1. **Overlap length of fiberglass anchors**

Overlap length represents the minimum length of fiberglass anchors able to maintain the stability of the tunnel face as excavation progresses. When the length of fiberglass anchors is equal to this value, new rows of anchors should be installed.

According to E. Leca and L. Dormieux (1990)’s research regarding the collapse mechanism of tunnel faces in cohesionless soil, the angle of the critical failure surface to the horizontal is defined as

\[
\delta^{+} = 49^\circ + \frac{\varphi'}{2}
\]

where

\( \delta^{+} \), angle of critical failure surface to the horizontal, degrees;  
\( \varphi' \), effective friction angle of the soil, degrees.

The overlap length of fiberglass anchors should pass through the critical failure surface by at least 1–2 m.

3.2. **Number of fiberglass anchors**

The support pressure of bolts can be evaluated with the following formula (Bischoff and Smart, 1975; Bustamante and Doix, 1975):

\[
P = \min \left\{ \frac{N \cdot A \cdot \sigma_b}{S}, \frac{N \cdot s_f \cdot \tau_a}{S} \right\}
\]

where

\( P \), support pressure offered by fiberglass anchors, kPa;  
\( N \), number of bolts;  
\( A \), cross-sectional area of the bolt, m²;  
\( \sigma_b \), yield strength of the bolt material, MPa;  
\( S \), area of tunnel face, m²;  
\( s_f \), contact surface area of the bolt with soil, m²;  
\( \tau_a \), maximum shear stress along the soil/bolt interface, kPa. This value can be determined according to Bustamante & Doix’s graph valid for clays, as shown in Figure 2.
Figure 2. Shear resistance (bond strength) graph for clay with gravel (where red indicates the value for clay with gravel in the tailrace tunnel at an overburden of 50 m in the Israel K project).

According to Formula (3), it was found that the support offered by fiberglass anchors is controlled by the failure of fiberglass anchors of the grouting, which can be analyzed with pull-out resistance and tensile resistance.

The pull-out resistance offered by one fiberglass anchor is given as follows:

\[ F_{1\text{bar}} = \tau_a \cdot \pi \cdot \phi_{\text{drill}} \cdot L_{\text{overlap}} \]  

(4)

where

- \( \phi_{\text{drill}} \), diameter of the drilling hole, m;
- \( L_{\text{overlap}} \), overlap length, m.

The tensile resistance offered by the grouting is given as follows:

\[ F_{2\text{bar}} = \pi \cdot r_{\text{fb}}^2 \cdot \frac{\sigma_b}{1.15} \]  

(5)

where

- \( r_{\text{fb}} \), radius of the fiberglass anchor, m;
- 1.15 is the material factor for fiberglass anchors.

According to Formulas (3–5), the required number of fiberglass anchors can be obtained with the required face support and available support pressure by one anchor.

3.3. Tunnel face support design with fiberglass anchors in the Israel K project

In the Israel K project, the length of the soil section of the tailrace tunnel is approximately 500 m in marl and clay with gravel, which is below the underground water level. Tunnel face stability problems can be critical in clay with gravel under seepage. With the support of fiberglass anchors in the tunnel face, tailrace tunnel had been already through safety and punctually until now. The cross section and excavation method of the tailrace tunnel are shown in Figure 3. The bench excavation method was used, and the height of the upper bench was approximately 5.96 m, where the fiberglass anchors are installed. The FoS for the tunnel face was assumed to be 1.5 for design safety.

![Figure 3. Cross section and excavation method of the tailrace tunnel](image)

Parameters of clay with gravel of the tailrace tunnel are shown in Table 1.

| Soil type | Unit weight | Permeability coefficient | Effective cohesion c' | Effective friction angle \( \phi' \) | Young’s modulus E | Poisson ratio \( \mu \) |
|-----------|-------------|--------------------------|-----------------------|--------------------------|------------------|------------------|
|           | kN/m³ | m/s | kN/m² | degrees | MPa |

Table 1. Parameters of the clay with gravel of the tailrace tunnel
Analytical and numerical methods were both used to evaluate the stability and design of the support of the tunnel face based on Anagnostou & Kovári’s solution. An analytical tool was developed (Figure 4) for the tailrace tunnel in clay with gravel with design FoS = 1.5 at a maximum overburden of 50 m, and the required numbers of fiberglass anchors was 25.

Figure 4. Analytical tool for tunnel stability analysis and support design

A numerical model was also built with FLAC3D, which is shown in Figure 5, where the pipe roof and fiberglass anchors are considered in the numerical model. For the tailrace tunnel below the underground water table, drained conditions were considered, and the Mohr–Coulomb constitutive model was used for analysis. To avoid secondary effects and directly focus on tunnel face behavior, the details of the excavation and support sequence of the tunnel were not simulated step by step. Instead, a simplified excavation scheme was adopted, where the position of the tunnel face remained fixed in the model and the excavation sequence was simulated by a gradual reduction in the longitudinal stress acting on the face. Cable elements are used to simulate the pipe roof and fiberglass anchors.

A strength reduction method was used to analyze the FoS of the tunnel face of the tailrace tunnel in clay with gravel with a maximum overburden of 50 m. With 25 fiberglass anchors, the FoS was 1.59, which is close to the result of the analytical method.
4. Distribution of fiberglass anchors to the stability of the tunnel face

According to the analysis above, support pressure offered by the fiberglass anchors is affected by the properties of soils, fiberglass anchors, the interaction between the fiberglass anchors and soil, construction machinery, etc. For a special engineering project, it is relatively easy to change the design of the fiberglass anchors or construction machinery for an optimized design. The effect of overlap length and the types of fiberglass anchors on the number of fiberglass anchors at the designed FoS were analyzed in the following.

For the tunnel face of the tailrace tunnel in a maximum overburden of 50 m, the fiberglass anchor parameters are shown in Table 2.

| Fiberglass anchor parameters | Value |
|-----------------------------|-------|
| Overlap length, L (m)       | 7.0   |
| Diameter of fiberglass anchors, Ø (mm) | 24.0 |
| Drilling borehole diameter, Ø' (m) | 140  |
| Dowel young’s modulus, E (MPa) | 4500 |
| Tensile strength of fiberglass, (MPa) | 800  |

As shown in Table 2, the required number of fiberglass anchors is affected by these factors. The effects are shown in Figure 6 with the analytical method at a design FoS = 1.5.

According to Formulas (3–5), once the fiberglass anchor (FGA) of the grouting is in failure mode, support pressure is not further provided by the anchor. As shown in Figure 6 (a), 111 fiberglass anchors are required with an overlap length of 1 m. As the length increases, the required number

![Figure 6](image-url)

**Figure 6.** Required numbers of fiberglass anchors with design FoS = 1.5. Effects of (a) overlap length, (b) diameter of fiberglass anchors, (c) diameter of drilling hole, and (d) strength of fiberglass anchors.
gradually decreases. There is no further decrease when the number is 25 FGA and the overlap length is larger than 5 m. The reason is that the failure mode changes from grouting failure to anchor failure. The same change in the failure mode occurs in Figure 6 (c) due to the diameters of drilling boreholes. It was found that a large drilling diameter requires less fiberglass anchors. When the drilling diameter reaches 100 mm, the failure mode is changed from grouting failure to anchor failure, which implies that if the construction equipment allows larger diameters for drilling boreholes, at the same design FoS, the number of fiberglass anchors can be decreased. The most economic drilling diameter is 100 mm for the tailrace tunnel in clay with gravel with an overburden of 50 m. For Figures 6 (b) and (d), a new type of fiberglass anchor was considered with incremental differences in strength or diameters of fiberglass anchors, and the grouting failure becomes the controlling factor, which is also useful in optimizing the support in the tunnel face.

In practice, less fiberglass anchors can improve construction efficiency and save cost, but it is less conservative. It is strongly suggested to check the design with monitoring. Monitoring is also important for examining reinforcement and targeting optimization of the design.

5. Conclusions

Using analytical and numerical methods, a quantitative method to determine the required number of fiberglass anchors for the soil tunnel was presented according to ADECO-RS. For the tailrace tunnel in the Israel K project, the stability of the tunnel face was evaluated, and face reinforcements were designed with these methods. The effects of factors controlled by fiberglass anchors and construction equipment were analyzed, which are helpful when optimizing the support design for the tunnel face.

6. References

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