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Application and research of soil tunnel face stability and reinforcement in Israel K project

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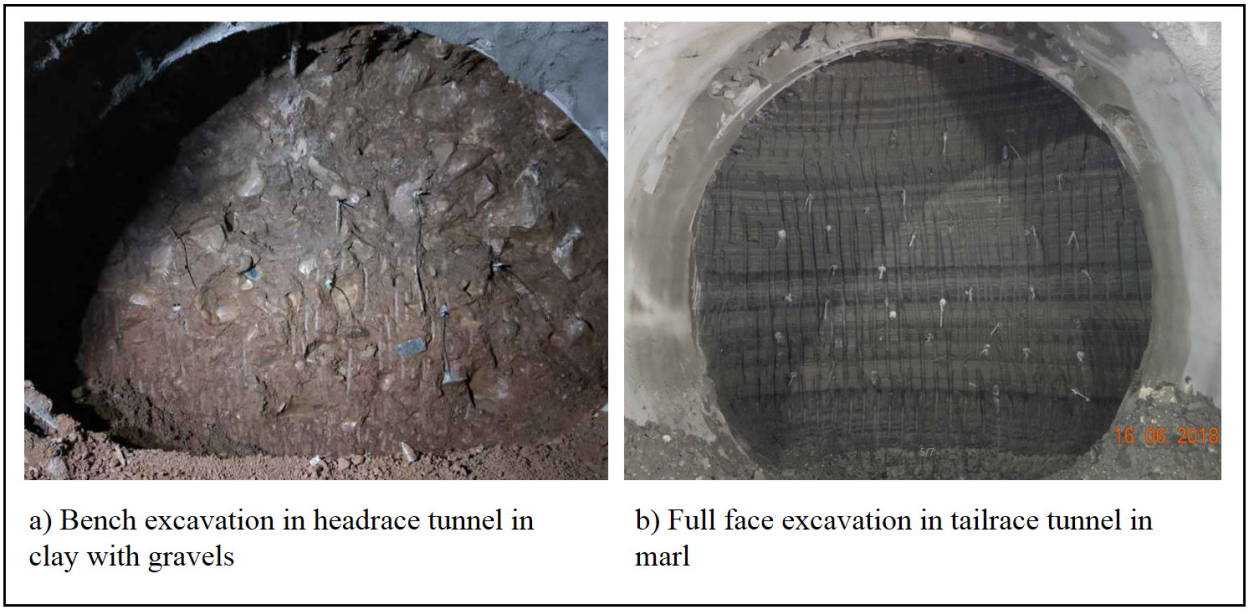
1 INTRODUCTION

Tunnel face stability has great significance on construction safety for soil tunnels. For the Israel Kokhav Hayarden pumped storage power station project, the length of soil section of the headrace tunnel is about 200m in clay with gravels above the underground water level, while that of the tailrace tunnel is about 500m in marl and clay with gravels below the underground water level. Tunnel face stability problems can be very serious in clay with gravels under seepage. The complexity of geological conditions in soil tunnels bring great challenges to construction safety and project completion. Photographs of the tunnel faces are shown in Figure 1.

According to the design guide, full face excavation is applicable to these tunnels. Because the drilling holes are hard in clay with big gravels and bench excavation method is capable of reducing drilling time with less fiberglass anchors, bench excavation method with fiberglass anchors reinforced in the top heading is used in several parts of these tunnels. The soil section of the headrace tunnel was completed on time, and half of the tailrace tunnel had been excavated as of April 2019.



a) Bench excavation in headrace tunnel in clay with gravels

b) Full face excavation in tailrace tunnel in marl

Figure 1. Photographs of the tunnel faces reinforced with fiberglass anchors.

2 DESIGN AND ANALYSIS

Fiberglass anchors have the characteristics of high tensile strength, low shear strength, and are easy to excavate. For these reasons they are very suitable for temporary support in tunnel face and improve the construction efficiency and safety. Design factor of safety (FoS) of the tunnel face is set to 1.5 considering the heterogeneity of the soils, uncertainty of construction safety, the severity of potential accidents, etc.

2.1 *Evaluation of tunnel face stability*

Analytical and numerical methods are mostly used to evaluate the tunnel face stability. Analytical methods always assume a possible failure mechanism of the tunnel face based on limit equilibrium state.

Carlos Carranza-Torres (2004) revised the Caquot's Lower Bound Solution (Caquot et al. 1954) of the problem of cavity collapse. Carranza's solution defines the value of face-stabilizing pressure as the minimum or critical pressure below which the tunnel will collapse (Javad Mohammadi et al. 2011). Carranza's solution can be applied to both dry and drainage conditions. Anagnostou & Kovari (1996) performed the tunnel face stability analysis under drainage condition and considered the difference between the stabilizing water pressure and the effective pressure. Drainage conditions are to be expected when the permeability is higher than 10^{-7}~10^{-6} m/sec and the net excavation advance rate is 0.1-1 m/hr or less. The formulas for calculating the required face support pressure are given in these analytical methods, and the strength parameters in the formulas are reduced with design FoS for obtaining the required face support pressure.

Several numerical methods (Zdenek Zizka et al. 2016, Perazzelli et al. 2012) are commonly used to evaluate tunnel face stability, and two of them are used in this analysis with *FLAC3D* (Itasca 2017):

- Load reduction method – the support pressure on the tunnel face is reduced to design FoS until the required support pressure is obtained.
- Strength reduction method – reducing the strength parameters until instability failure occurs, FoS of tunnel face can be obtained by the reducing ratio.

2.2 *Reinforcement of tunnel face*

When the required face support pressure is larger than zero or the FoS of the tunnel face is less than the design value, fiberglass anchors should be installed to reinforce the tunnel face. For the potential unstable tunnel face, the design of the fiberglass anchors includes two important issues: (i) design overlap length, and (ii) the required number. If the fiberglass anchors are too short, increasing the number may still not guarantee the stability of tunnel face. The overlap length of the fiberglass anchors is designed according to Leca's (1990) research on the collapse mechanisms of the tunnel face. The results show that the overlap length of the fiberglass anchors should pass through the failure surface at least 1-2 m.

The required number of fiberglass anchors used to reinforce the tunnel face is determined according to the mechanism between anchor and soil (Bustamante 1985), and the FoS of the tunnel face reinforced with fiberglass anchors is also checked with the *FLAC3D* model.

3 RESULTS AND DISCUSSION

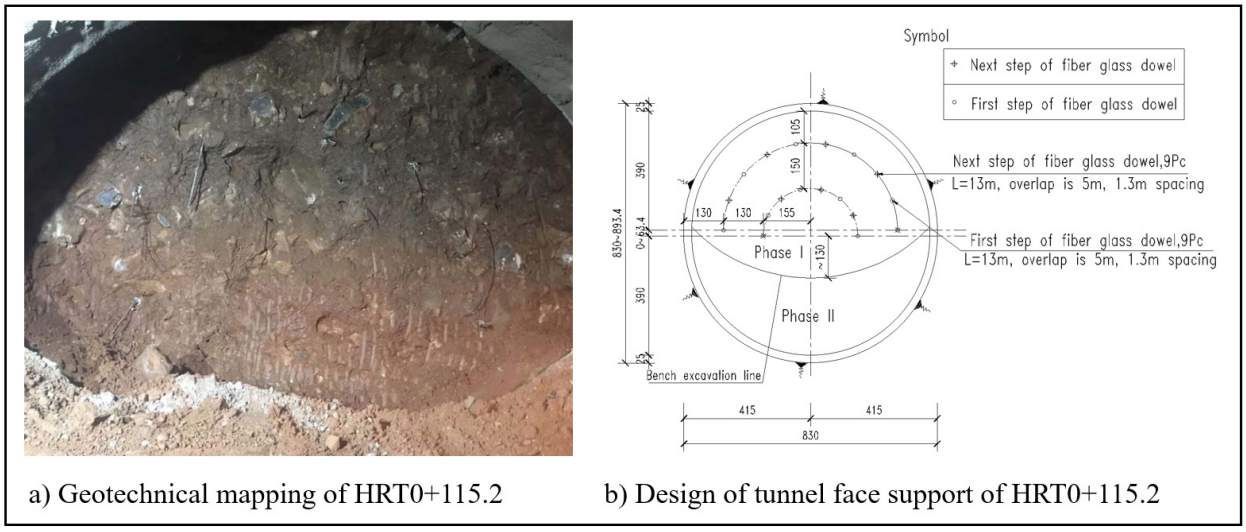
3.1 *Comparison between analytical and 3D numerical approaches on a tunnel face under construction*

Excavation of headrace tunnel has been completed. The geotechnical mapping and design of the tunnel face support of a typical section HRT 0+115.2 are shown in Figure 2.

For HRT 0+115.2 with Design FoS=1.50:

- With Carranza's solution, 27 fiberglass anchors are required with equivalent circular area of top heading, 16 fiberglass anchors are required for FoS=1.00.
- With 3D numerical method by *FLAC3D*, 8 fiberglass anchors are required with the overlap length of 5 m.

During construction, the face of the headrace tunnel is supported with 9 fiberglass anchors in chainage HRT 0+087.240 ~ HRT 0+139.322, which is safe and efficient. The comparison shows that the result from the numerical method is more reliable and economical.



a) Geotechnical mapping of HRT0+115.2 b) Design of tunnel face support of HRT0+115.2

Figure 2. Geotechnical mapping and design of tunnel face support of HRT0+115.2.

3.2 *Design for tailrace tunnel without excavation*

For the tailrace tunnel, the results of the analytical and numerical methods with full face excavation are shown in Table 1. As shown in Figure 3, for marl layer with cover depth of 40 m, and 31 fiberglass anchors with full length 15 m by *FLAC3D*, the FoS is 1.68.

Table 1. Results of tailrace tunnel face reinforced with fiberglass anchors.

Condition	Cover depth	Numerical Calculation results				Analytical Calculation results		
		Fiberglass anchors		FoS	Density	Required support pressure	Fiberglass anchors*	FoS
	(m)	Length (m)	Number		b/m^2	kPa	Number	
Drainage condition	marl							
	40	15	31	1.7	0.52	67.96	/	1.5
		7		1.5			13*	
	clay with gravels							
	45	15	31	1.8	0.52	192.17	/	1.5
		7		1.5			37*	

*Analytical methods only show the results with the overlap length of 7 meters of fiberglass anchor.

3.3 *Discussion*

There are some difference between the analytical and numerical method. The collapse mechanism of the tunnel face in the soil is complex and influenced by many factors, such as the soil's physical and mechanical parameters, overburdens, excavation profile, tunnel face areas, underground water, reinforcement parameters, etc. Influence of these factors on tunnel face stability can be analyzed further.

Monitoring is also very important for examining the reinforcement and optimizing the design.

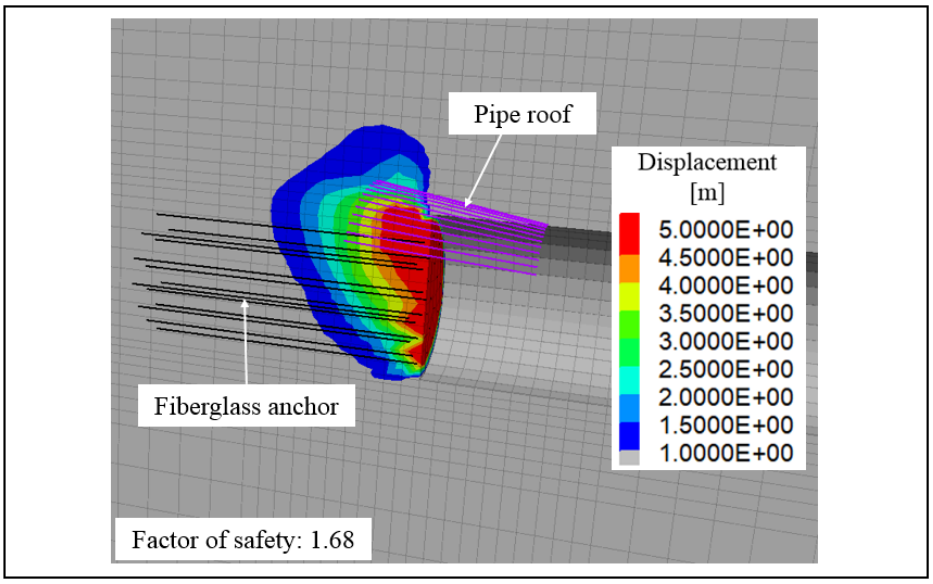


Figure 3. FoS of reinforced tunnel face in tailrace tunnel with cover depth of 40 m, 31 fiberglass anchors and overall length of 15 m.

4 CONCLUSIONS

Using analytical and numerical methods, tunnel face stability is evaluated and the required face reinforcement is obtained. A quantitative method to determine the required number of fiberglass anchors for the soil tunnel with different excavation methods can be used in the design.

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