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Study on the Rapid Drawdown and Its Effect on Portal Subsidence of Heybat Sultan Twin Tunnels in Kurdistan-Iraq

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Abstract

The excavation of tunnels below the water table causes variations in the hydraulic level, pore pressure and effective stresses. In this regard, rapid drawdown is considered as a destructive phenomenon as to the change in the flow regime which has mostly been studied for the reservoirs of embankment dams. The rapid drawdown occurred at the upstream shell of the dam gives rise to increase in the pore pressure at the upstream shell. This is as a result of the incompliance between the water loss inside the shell and the reservoir water level. Hence, it would be more likely to have instability and sliding at the upstream slope on account of decrease in the effective stress. Lack of sufficient studies performed on this matter in tunnelling projects on the one hand and the knowledge on the most important parameter for decreasing the destructive effects of this phenomenon on the other hand necessitates performing further studies on this matter. To this end, the reasons for the occurrence as well as the affecting parameters were studied by modelling the large subsidence of the inlet portal of Heybat Sultan twin tunnels located in Kurdistan-Iraq making use of the variations of the groundwater boundary conditions under Phase2 code. The modelling results depict the importance of the drawdown rate and the permeability coefficient of the surrounding rock mass. In the interim, the rapid loss in the hydraulic gradient caused by the drainage of a considerable volume of precipitations into the tunnels led to the rapid decrease in the pore pressure and increase in the effective stresses up to total stress. This has resulted in the consolidation settlement in the tunnel portal.

Keywords: Rapid Drawdown; Subsidence; Pore Pressure; Effective Stress; Tunnelling.

1. Introduction

The construction of underground structures considerably affects the groundwater flow regime. The presence of water affects the structure stability in view of the induced deformation caused by the decrease in the effective stress, the shear strength and the seepage force applied on the tunnel boundaries and creates different kinds of failures in the tunnel [1]. Rapid drawdown is considered as a destructive phenomenon related to the rapid decrease in the water table. This phenomenon takes place mostly in embankment dams due to the incompliance between the water loss inside the core and the reservoir water level during the rapid drawdown. In this case, the hydrostatic pressure existing in the exposed face of the upstream slope (when the reservoir is impounded) disappears. Nevertheless, it is likely to come up with sliding at the upstream slope allowing for the presence of the regulating hydrostatic pressure inside the dam body. In general, there are various groundwater flow regimes into the tunnel relying upon two controlling factors of the tunnel long-term behavior including the permeability of the surrounding rock and the permeability of the tunnel lining [2]. There might be encountered two cases, if the lining is permeable and water flows into the tunnel: (a) fixed groundwater table as a result of the surface runoff recharge with the same volume as the water flowing into the tunnel, and (b) loss in the groundwater table in view of the insufficient surface runoff recharge and more water flowing into the tunnel. The second case causes rapid drawdown and is expected to have high void ratio and permeability ground, low water storage

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capacity and recharge. The rapid drawdown gives rise to decrease in the pore pressure and increase in the effective stresses. This may result in the consolidation settlements in the upper layers (Figure 1).

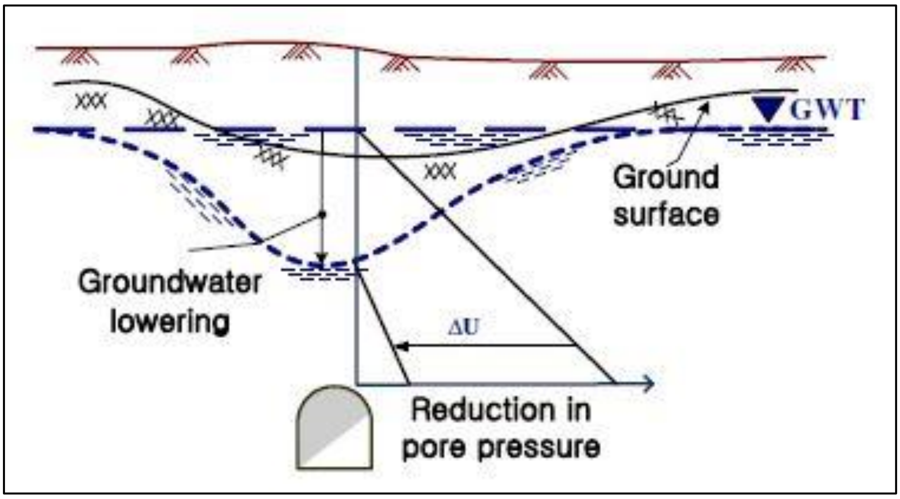


Figure 1. Ground settlement affected by rapid drawdown during tunneling [3]

Studies have mostly focused on the rapid drawdown corresponding to embankment dams and slopes rather than the occurrence of this phenomenon in tunneling projects. Researches regarding the effects of water drawdown on the stability of slopes and dams have been done by Viratjandr and Michalowski [4], Yan et al. [5], Wang et al. [6], Gao et al. [7], Song et al. [8] Brinkgreve et al.[9] and Zieba et al. [10]. The limited number of studies on this subject include Atkinson and Mair [11], Bowers et al. [12], Addenbrooke [13], Shin et al. [2], Anagnostou [14,1], Yoo et al. [15], Moon and Fernandez [16], Wanga and Wang [17], Yoo et al. [18], Shen et al. [19] Xu et al. [20], Alonso and Pinyol [21] and Yoo [3, 22]. Yoo et al. [18] reported an important case study about ground surface settlements during tunnelling. Yoo [22] focused on the interaction between tunneling and groundwater during tunneling in water-bearing ground. He stated that the groundwater drawdown induces a wider and deeper settlement trough than that without the groundwater drawdown, and the optimum pattern of pre-grouting that minimizes the groundwater drawdown during tunnelling. Shen et al. [19] conducted a comprehensive study on long-term settlement behavior of the metro tunnel in Shanghai. They stated that the long-term tunnel settlement is mainly due to urbanisation-induced ground subsidence and groundwater infiltration is responsible for the long-term settlement of the tunnel. Alonso and Pinyol [21] studied different approaches available for calculating pore water pressure distributions during and after a drawdown. They stated that the pore water pressure distribution in a slope after a rapid drawdown requires a coupled flow-deformation analysis in saturated and unsaturated porous media. Raymer [23] said that "during a shallow tunnel excavation, the groundwater level drawdown reaches the tunnel crown, and the groundwater flow pattern into the tunnel is similar to that into a trench". The groundwater inflow rate into a tunnel can be estimated using the trench inflow equation. Insufficient studies performed on the rapid drawdown in tunneling projects as well as the study on the parameters, effective factors and their analysis method necessitate performing more studies on this phenomenon. Following the collapses taken place in the Heybat Sultan tunnel inlet portal in Kurdistan-Iraq, it was found necessary to assess the main parameters that play important role during the ground settlement.

2. Research Methodology

This research mainly focuses on the use of numerical simulation procedures based on FEM to model and analyze the causes of failure of inlet portal at Haybat Sultan Twin Tunnels project to determine the main parameters which have affected the ground settlement. The research is carried out using commercially available software i.e. Rocscience Phase2. Firstly, the geo-mechanical properties of the host rock were determined by use of the laboratory tests conducted on the intact rock samples. Then the experienced rapid drawdown scenarios were analyzed by means of finite element code and numerical results were compared with field observation. The results were discussed subsequently. A powerful 2D non-linear finite element program Phase2 is preferred for numerical simulation, since the program has been specially designed to handle a wide range of mining and civil engineering problems in a user friendly way. The modelling was carried out in four stages as following:

1. Stress initialized in the model,
2. Model verifying,
3. Excavation of top heading and complete stress release, and
4. Installation of the supporting system and applying groundwater through changing the boundary conditions.

3. Project Description

Heybat Sultan Twin Tunnels are being constructed in Kurdistan-Iraq along the highway of Erbil - Koya - Suleymanieh in the Northeast of this country (Figure 2). They are 2×2600 m long with horseshoe shape section with an excavation area of 110 m^2. The most outstanding objectives of this project are to remove Heybat Sultan defile, decrease driving casualties and construction of an access road between Erbil and Suleymanieh through Dukan. The distance between axes of two adjacent tunnels is about 40 m. Due to low strength properties of surrounding rocks in the tunnels path, mechanical method has been applied for excavating the tunnels.

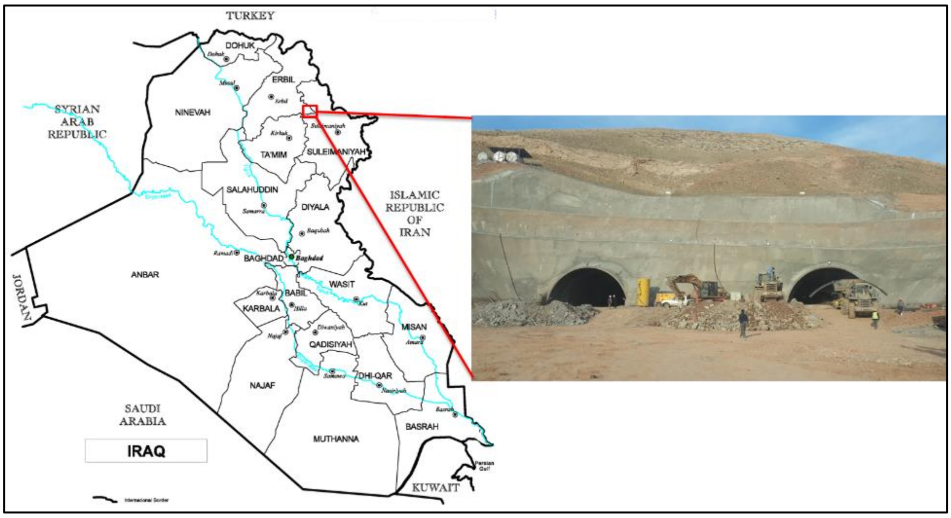


Figure 2. A close up view of Heybat Sultan twin tunnels

3.1. Geological and Geotechnical Setting

The lithology of the tunnels mostly consists of shale, siltstone, marly limestone, gypsum and sandstone with strength ranging between poor and fair which are classified as IV and V from geo-mechanical points of view. The tunnels supporting system are mostly composed of I-160 steel sets at 1 - 1.5 m intervals, embedded in 25 cm shotcrete applied in two passes of 5 cm and 20 cm thickness with 6 m long rock bolts installed with 1 × 1 m grid and diameter of 28 mm. Since the in-situ tests are so costly, the geo-mechanical properties of the rock masses were determined by use of the laboratory tests conducted on the intact rock samples taken from the boreholes drilled in the longitudinal axis of the tunnels. Then, the rock mass parameters were obtained utilizing the RocData software which has been coded based on generalized Hoek–Brown criterion. Taking into consideration the geo-mechanical characteristics of the surrounding rocks, the tunnel route was divided into six blocks in which the inlet portal comprises gypsum rock masses in the upper part and siltstone and marly limestone in the middle and lower parts (Figure 3) in block I. The rock mass properties have been presented in Table 1.

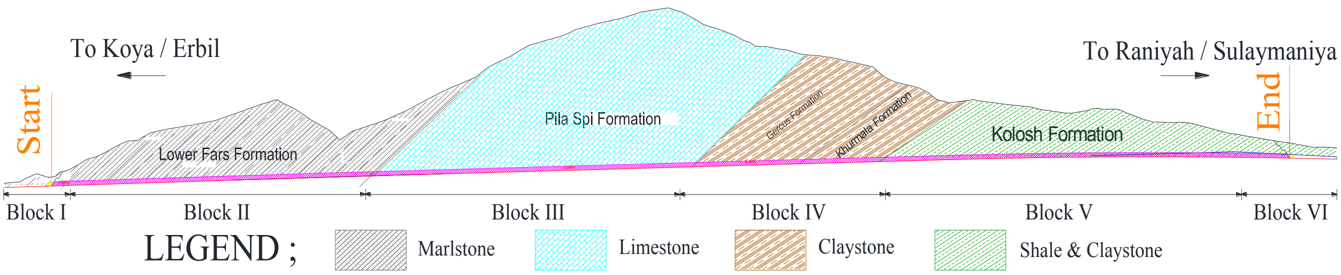


Figure 3. Longitudinal section of Heybat sultan twin tunnels

Table 1. Rock mass properties

Block	Lithology	C (KPa)	φ (Deg)	E (MPa)	GSI	UCS (MPa)	Permeability (m/s)
I	Gypsum	45	41	562	20	10	1×10^{-9}
I	Marly limestone	34	51	918	25	15	1×10^{-5}
I	Siltstone	35	39	562	20	10	1×10^{-6}

4. Inlet Portal Subsidence

The inlet portal has been constructed as three berms with heights of 7 m, 8 m and 15 m, slope of 1:1 (45 degrees) and widths of 5 m. The supporting system of the inlet portal includes a 15 cm shotcrete reinforced by a layer of Q221/221 welded wire mesh, drilling of 3-6 m long with 6×4 and 3.5×3.5 m grid weep holes drainage. In view of the presence of dissolvable formations in some parts of the inlet portal and high precipitations, there can be seen some sinkholes in some parts of the ground. The subsidence of the inlet portal has occurred in an approximate distance of 15 m from the tunnels inlet in an area with the overburden depth of about 28 m and dimensions of 30 m × 15 m × 5 m after heavy continuous precipitations (Figure 4).

Figure 4. Subsidence of the Inlet Portal of Heybat Sultan Twin Tunnels

The most important reasons for the occurrence of the foregoing subsidence comprise: (a) laying out the inlet portal in the thalweg of the region waterways and easy accessibility of the surface runoffs to the inlet portal, (b) the presence of the dissolvable rock masses of gypsum in the area (c) lack of drilling weep holes drainage and increase water pore pressure in the surrounding rock, and (d) lack of monitoring during construction for recognizing the displacements in the tunnels crown and walls before the occurrence of subsidence (Figure 5).

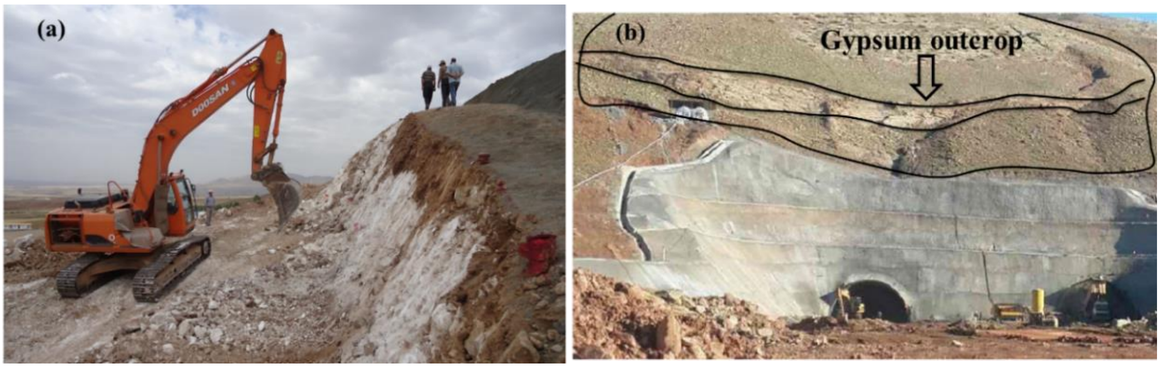


Figure 5. (a) Outcrop of Gypsum Layers during the Excavations of the First Berm (b) Location of Inlet Portal in the Thalweg of the Region Waterways

5. Numerical Modeling

5.1. Introduce the Numerical Model

Numerical models are widely used in Geotechnical fields; i.e., underground structures, dam, slope stability and foundation works. This method is widely used due to development in analysis software and powerful computing devices. Palmström and Nilsen [24] define numerical modeling as discretization of the rock mass in consideration into a large number of individual elements which are analyzed by use of computers basically for the evaluation of rock stresses and deformations. The FEM has been the most popular numerical method in engineering sciences due to its flexibility in handling material inhomogeneity and anisotropy, complex boundary conditions and dynamic problems, together with moderate efficiency in dealing with complex constitutive models and fractures [25]. Basically, three steps are required to complete an FEM analysis: domain discretization, local approximation, and assemblage and solution of the global matrix equation. The domain discretization involves dividing the domain into a finite number of internal contiguous elements of regular shapes defined by a fixed number of nodes. A basic assumption in the FEM is that the unknown function over each element, can be approximated through a trial function of its nodal values of the system unknowns in a polynomial form. According to crushed host rocks of the Heybat sultan tunnel's portal and being classified as pseudo-continua media from geo-mechanical point of view, Phase2 Code, a finite element program developed by Rocscience, was used for simulation of portal subsidence. This code is a powerful 2D program for soil and rock applications which can be used for a wide range of engineering projects and includes excavation design, slope stability, groundwater seepage, probabilistic analysis, consolidation, and dynamic analysis capabilities.

5.2. Rapid Drawdown Simulation

The model dimensions to dissipation effect of boundary condition on displacements 152 × 68 m, and Mohr - Coulomb failure criterion is assumed for the ground. Method of applying the stress to the model is on gravitational basis and with stress ratios of vertical to horizontal of 1.5 in vertical direction and 2 in parallel direction. At the vertical and bottom boundaries, displacements perpendicular to the boundaries are restrained against "x" and "y", respectively and it free at top, as shown in Figure 6.

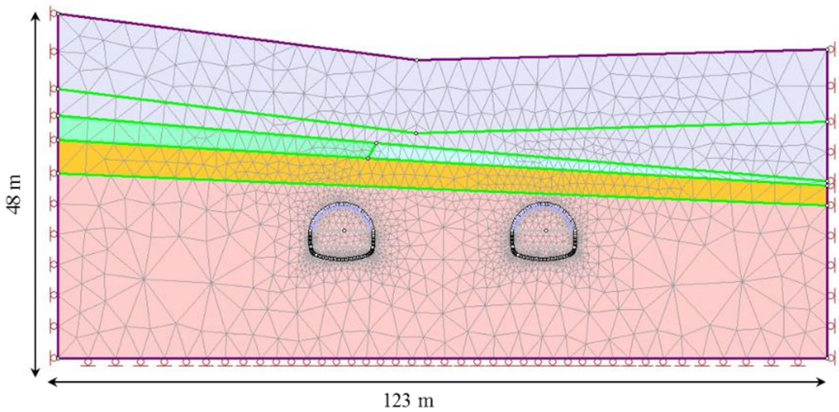


Figure 6. Numerical model

Taking into account the development of the failure area to the ground surface in the shallow tunnels located in soft rocks, the rock load was completely applied without the stress release effect on the support system during the heading excavation [26]. The design of a suitable mesh depends on the purpose of the simulation. If the process of localization, i.e. the deformation in the material is non-uniform and concentrated in narrow bands, is to be studied, then the finest possible mesh should be used. Plain strain conditions were taken with maximum number of iterations as 500. A three nodded triangular graded mesh was used with 65 nodes on external boundary. In model, the total number of elements and the number of the nodes were about 4542 and 2322, respectively. The main numerical model properties have been illustrated in Table 2. The variations of the groundwater table and the permeability of the inner concrete lining are considered as the most outstanding issues in simulation of the groundwater. In this regard, three cases can be considered including the permeable lining with fix groundwater table, the permeable lining with water rapid drawdown and the impermeable lining with fix groundwater table. The second case was used for numerical simulation according to Anagnostou [14] related to the function of the surrounding rock with permeability coefficients of more than 10-6 m/sec. to 10-7 m/sec. as drainage as well as the water flow from the weep holes drainage installed inside the tunnel after the subsidence event.

Table 2. Numerical model properties

Model Dimension (m)	Mesh Type	Number of stage, element and node	Poor quality element define as	Boundary conditions
Length :123	Graded	4	Side length ratio (Max/Min) >30	Top : free
Width : 48	3 noded	4542	Minimum interior angle < 2 °	Bottom : restrain Y
---	Triangles	2322	Maximum interior angle > 175 °	Sides : restrain X

Having modelled the aforesaid stages and excavated the top heading, flow lines and the rapid drawdown was achieved as Figure 7.

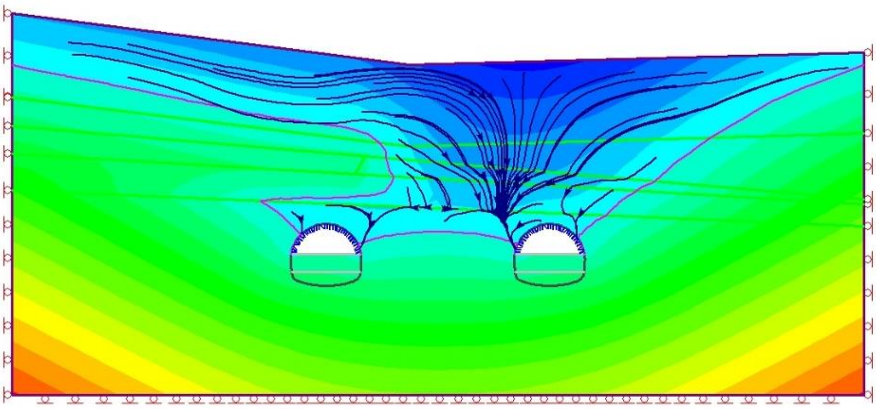


Figure 7. Flow lines and the water table after top heading excavation

5.3. Calibration and Verification of Model

The tunnel monitoring results obtained using geodetic points round the tunnel as well as the data back analysis results have been used to evaluate and calibrate the numerical model. The numerical model was found acceptable when the tunnel walls had an approximate difference of 10% with the monitoring results after excavating the heading. Such a difference is negligible due to the inevitability of errors in the numerical methods.

6. Analysis of the Parameters Affecting Subsidence

Ground water in side slopes is often a primary or contributory cause of instability, and a reduction in water pressures usually improves stability. In accordance with the principles of soil mechanics and Terzaghi theory on consolidation phenomenon, the pore pressure and effective stresses are considered as the most important parameters in the settlement of the surrounding rocks as a result of loading. Hence, the variations in these two parameters in the tunnel crown to the ground surface were monitored in 8 m spacing between tunnels pillar (Figures 8 and 9). The monitoring results depict increase in the effective stresses and decrease in the pore pressure proportionate to the depth during the water rapid drawdown.

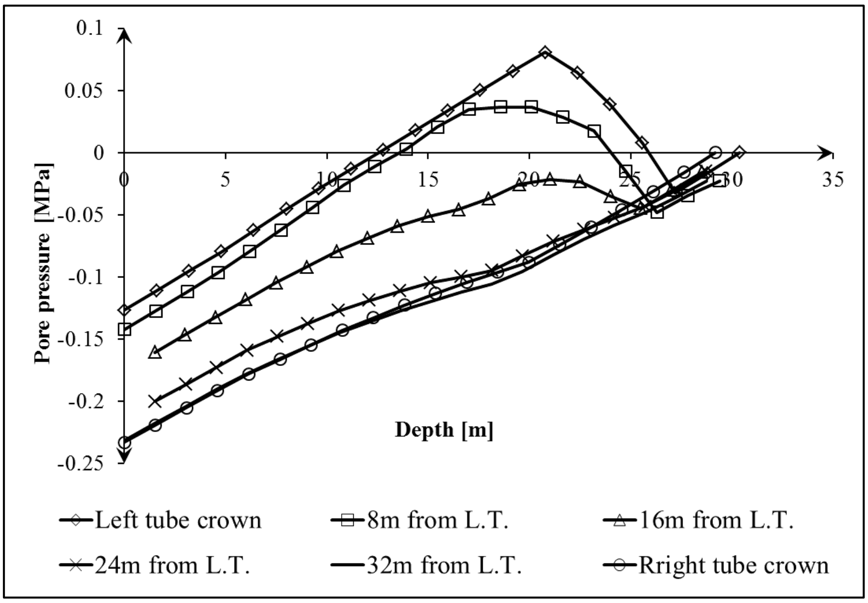


Figure 8. Pore pressure variation between tunnels pillar and the ground surface

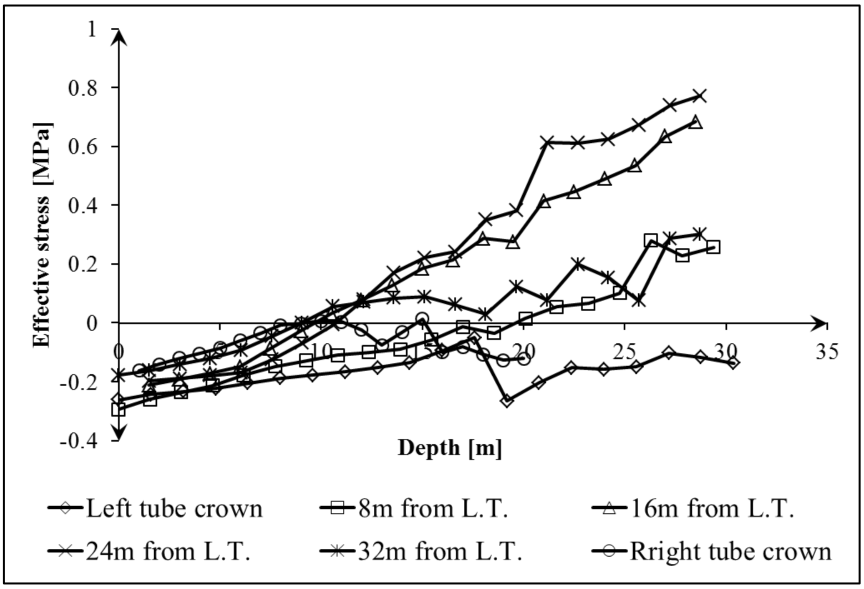
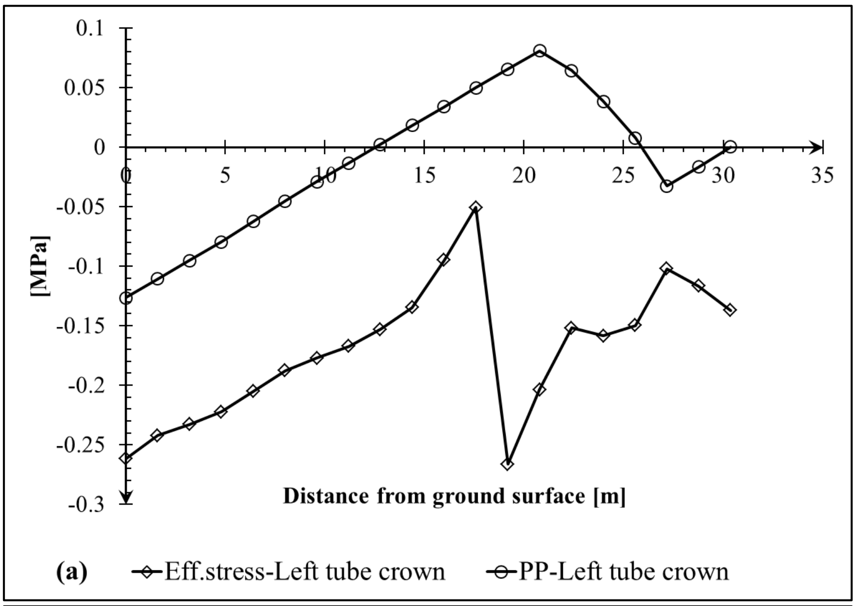
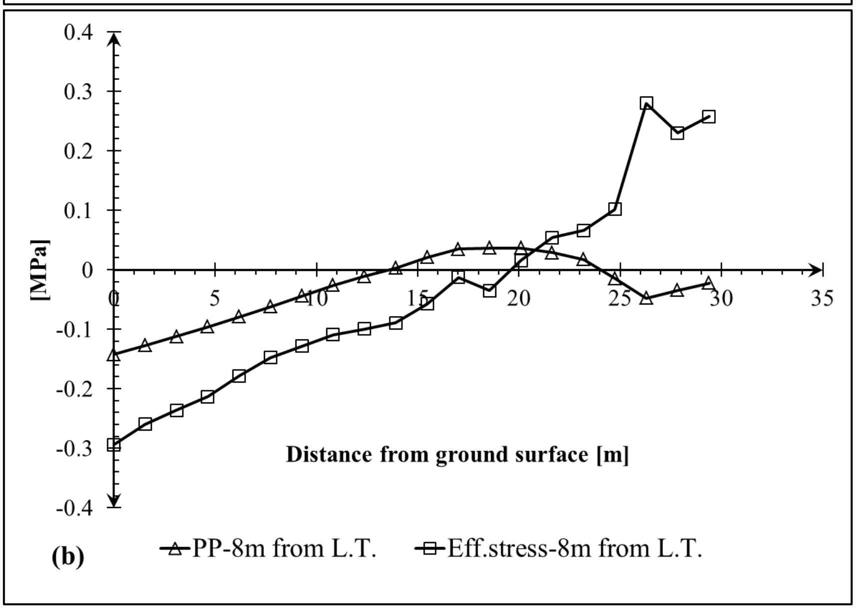
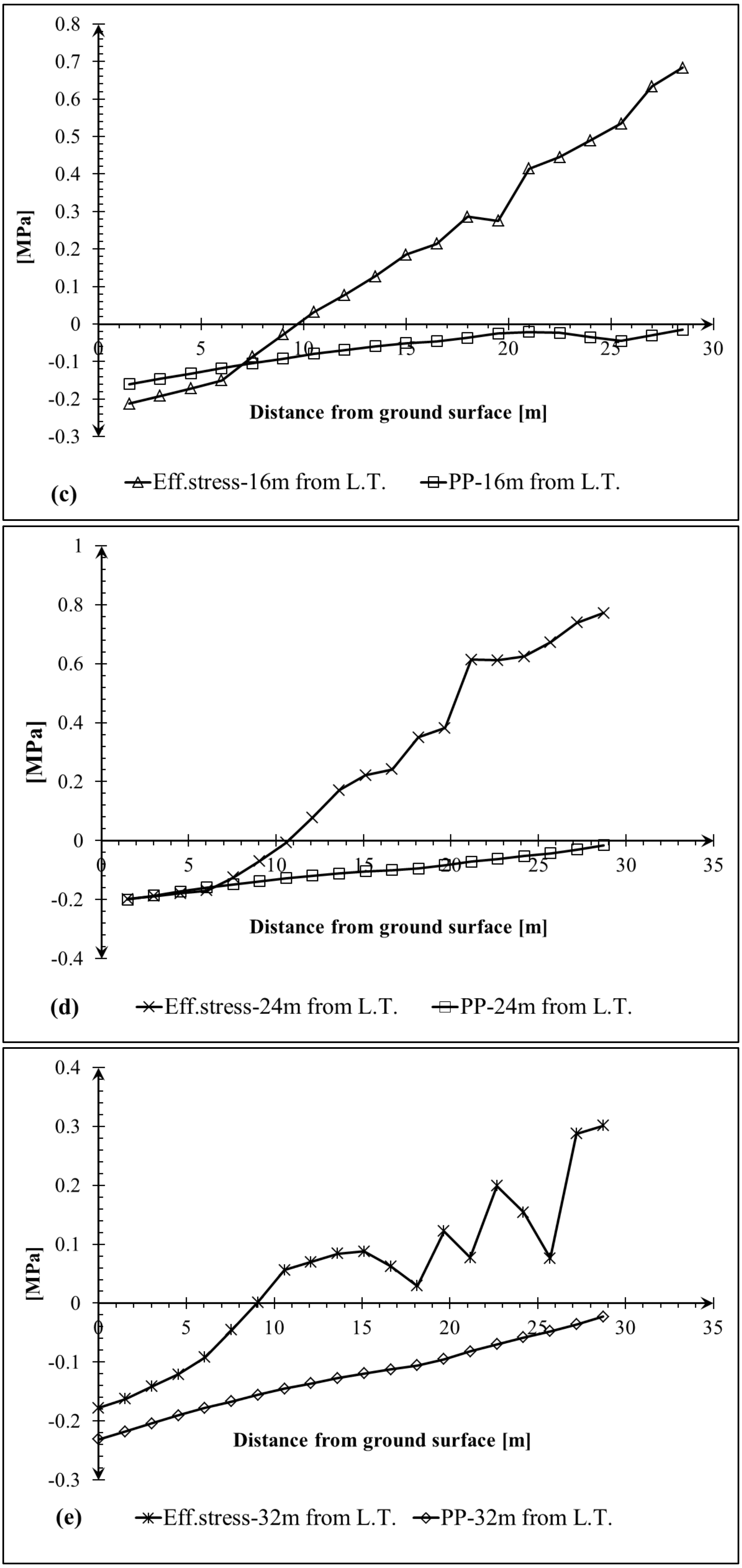


Figure 9. Effective stress variation between tunnels pillar and the ground surface

In order to study on the failure depth development, the variations of the pore pressure and effective stresses were drawn according to Figure 10.






[MPa]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0
5
10
15
20
25
30
Distance from ground surface [m]
Eff.stress-16m from L.T.
PP-16m from L.T.
(c)
[MPa]
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
5
10
15
20
25
30
35
Distance from ground surface [m]
(d)
Eff.stress-24m from L.T.
PP-24m from L.T.
[MPa]
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0
5
10
15
20
25
30
35
Distance from ground surface [m]
(e)
Eff.stress-32m from L.T.
PP-32m from L.T.

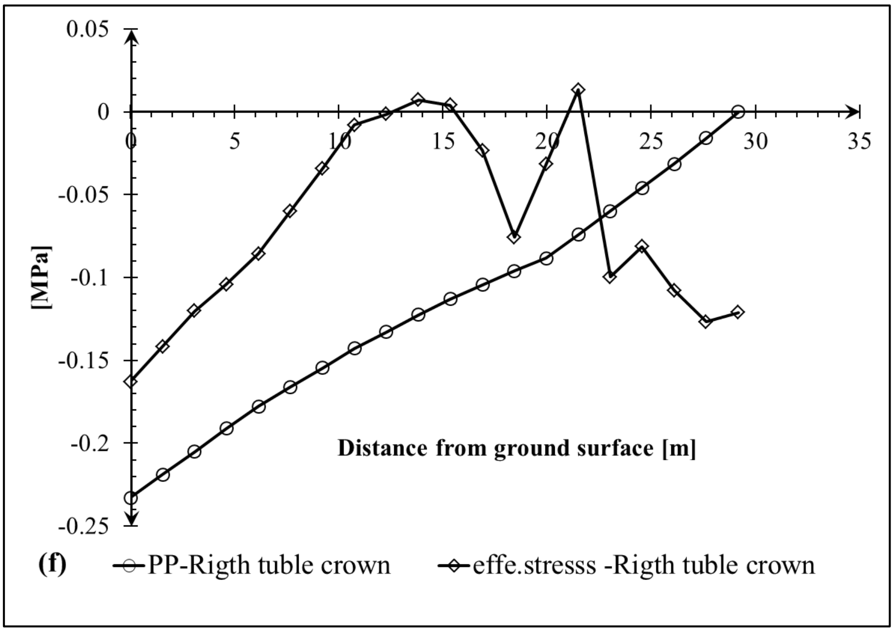


Figure 10. Variations of the effective stress and pore pressure vs. distance from ground surface, (a) Left tube crown, (b) 8 m from left tube, (c) 16 m from left tube (d) 24 m from left tube (e) 32 m from left tube (f) Right tube crown

7. Discussions

Taking into consideration the graphs, the subsidence process in the inlet portal can be expressed in four stages as per Figure 11. At the first stage, the groundwater level was below the tunnels level prior to the precipitations and occurrence of subsidence. After uninterrupted precipitations, the groundwater level raised and saturated the surrounding rock. At the second stage, the upper gypsum layer had no resistance and was demolished by dissolution and piping. At the third stage, the groundwater table raised during stage 1 gave rise to increase in the pore pressure in the surrounding rocks. At the fourth stage, the hydraulic gradient created for decreasing the pore pressure should be decreased by evacuating the water. In this case, water needs to find the shortest possible way to decrease the hydraulic gradient. Nevertheless, due to the lack of weep holes drainage in the portal, water has to flow longer distance to discharge from the tunnel excavated area which function as a large drainage in the lower part. Besides, in view of the fact that the penetration of surface runoff recharge is less than the flow penetrated into the tunnel, the pore pressure decreases rapidly followed by rapid drawdown. Consequently, the effective stresses increase up to the total stress value and give rise to the consolidation settlement in the inlet portal. In view of the presence of the more permeable strata adjacent to the right tube, the flow lines tend towards this tunnel and caused asymmetric settlement.

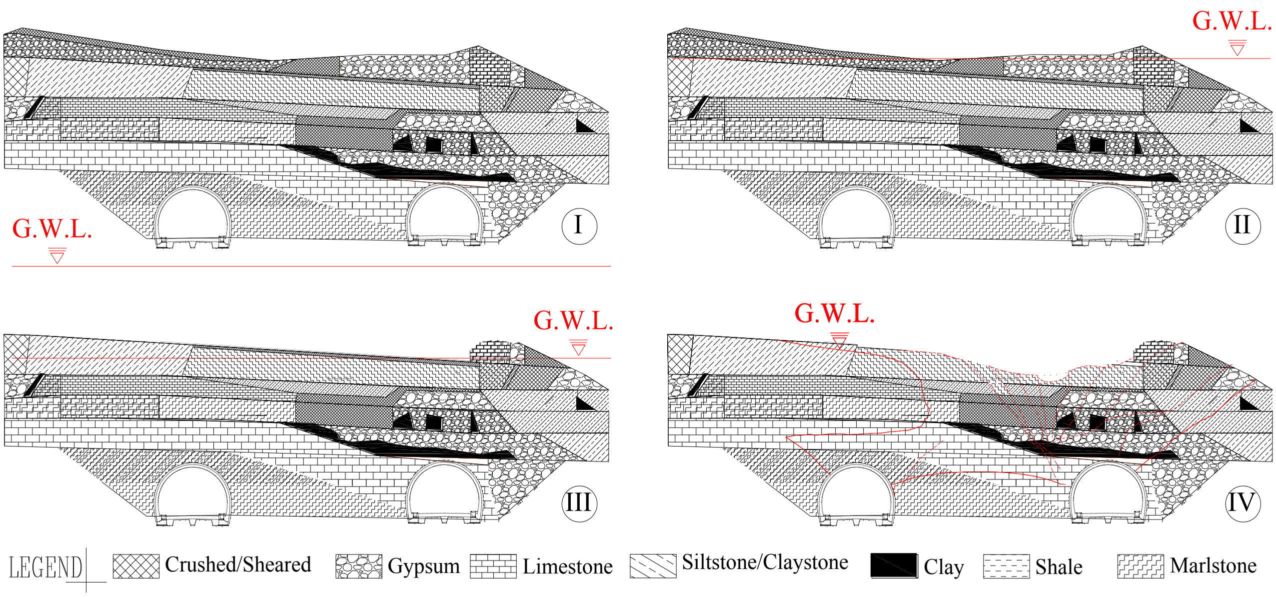


Figure 11. Subsidence Stages at inlet portal

A review on graphs of Figure 10. depicts that the subsidence of the portal has given rise to the development of failure only on the surface rather than deeper levels of the upper part of the left tube. But, in 32 m away from the axis of the left tube, in view of the fact that the effective stress between the surfaces to the axis between tunnels in depth is more than the pore pressure, it can be concluded that the subsidence has caused failure in the layer and strata of this area. The point is the loss of the effective stress in approximate depths of 10 m to 12 m that can be due to the presence of fine-grained soils in this zone resulted from the uplift phenomenon while running into rise in ground water table (transition between stage 1 and stage 2). The increase in the pore pressure and decrease in the effective stress during the rise in the groundwater table cause increase in the hydraulic gradient allowing for the fixed area of the joints and permeability coefficient of the surrounding rocks; on a way that the effective stress and pore pressure values in this zone are equal. This has caused loss in the strength of the surrounding rocks. The surface evidences of the sediments in the cracks existing in the upper part of the subsidence area verify the above issue as well. Figure 12. depicts that the pore pressure is mostly concentrated in right tunnel and in the pillar between the two tunnels on account of the presence of more permeable layers.

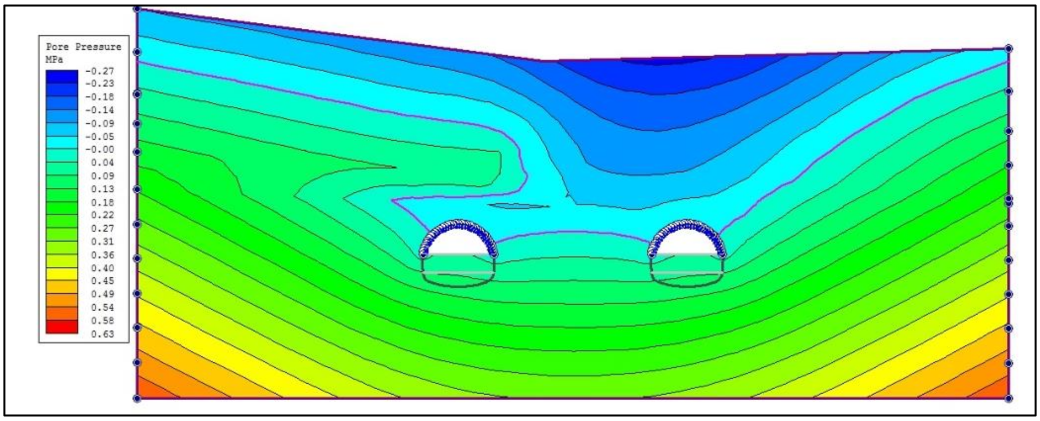


Figure 12. Pore pressure contour

Higher hydraulic gradient in the right tunnel causes more damage resulted from the rapid drawdown in this section (Figure 13). The presence of more discontinuities in this section is the main cause for the increase in the hydraulic gradient. The piping phenomenon and decrease in the joint infilling rate have given rise to increase in the permeability value over time.

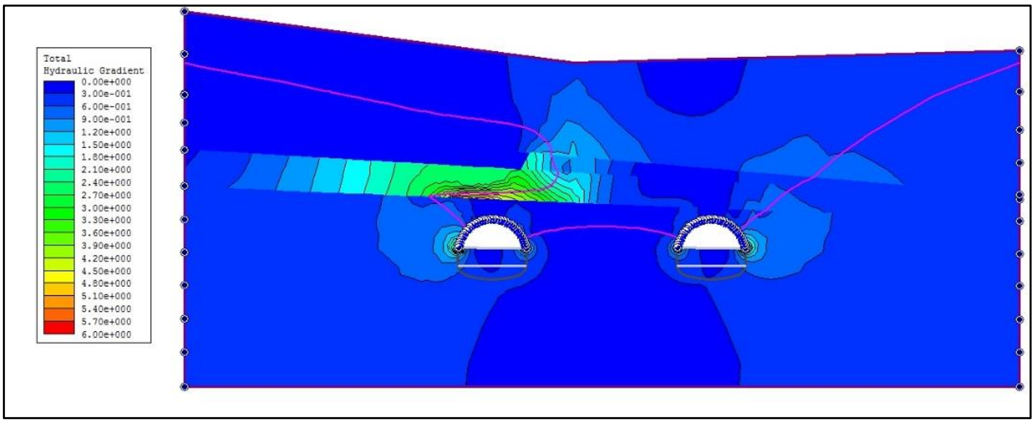


Figure 13. Hydraulic gradient contour

Having controlled the strength factor graph (strength/ stress ratio), it was realized that the portal has had stable conditions prior to being saturated followed by the rise in the groundwater table and (Figure 14). Nevertheless, after heavy precipitations when the portal inflow was less than the outflow, the surrounding rock strength decreased rapidly and resulted in collapse condition in the portal.

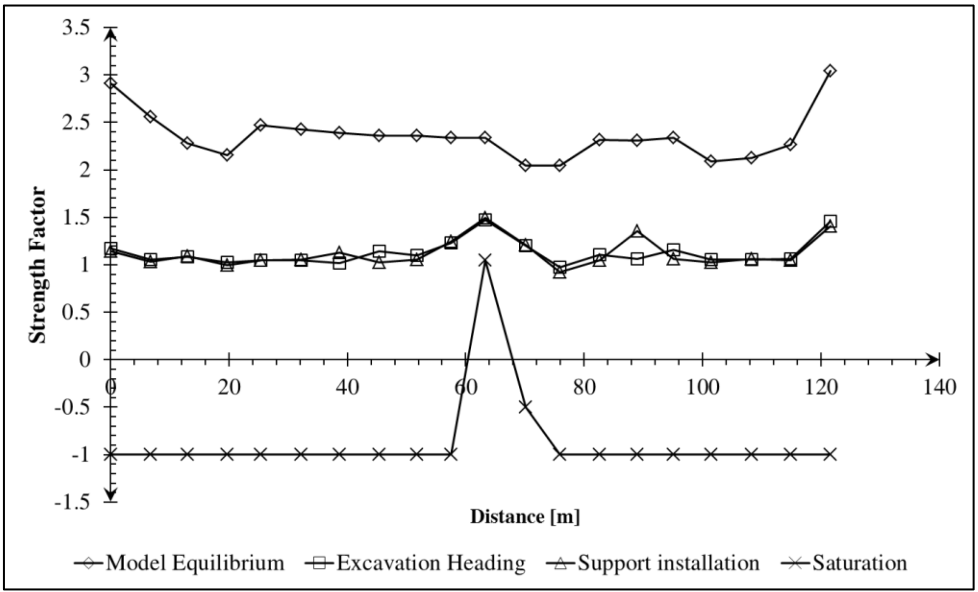


Figure 14. Strength factor between tunnel's pillar during different stages

8. Conclusion

The excavation of the tunnel result in changes in the groundwater conditions in the inlet portal. These changes have a significant impact on the effective stresses in the rock mass surrounding the tunnel. The numerical modelling results of the large subsidence occurred in Heybat Sultan inlet portal depict rapid drawdown, decrease in the pore pressure and increase in the effective stresses. This can be considered as the main cause for the consolidation settlement in the inlet portal. The dissolution of the gypsum rock masses in the upper part of the area has created more suitable topography for the penetration of the surface runoffs and further damages therein. Weep holes drain of the portal plays an important role for creating a steady-state flow as a system devised to decrease the pore pressure and maintain the groundwater table at a certain level. When weep holes drain are installed, no rapid drawdown would occur. The damage to the portal can considerably be decreased by balancing the volume of penetrated surface runoff and the water discharge via weep holes drain. Weep holes have two main permanent function: (1) Decreasing gradually pore pressure, (2) Increasing shear strength of surrounding rock & soil by discharging water in the media. The effectiveness of weep holes strongly depends on the surrounding media permeability. Since most of the ground water is contained in discontinuities, the holes should be aligned so that they intersect the discontinuities that are carrying the water. Permeability is the critical geomaterial parameter governing the post-construction behaviour. It is usual to assume that geomaterial permeability remains constant through an analysis. However, it is known that permeability depends on void ratio, which is dependent on mean effective stress, and hence seepage flow is non-linear. When the tunnel lining is permeable, surface settlements increase with time during the equilibration period and the changes in ground loading with time is neglected. An increase in settlement and lining load with time was achieved only with the finite permeable lining analysis. Under drawdown flow conditions, the drawdown of the water table causes larger surface settlements than under maintained phreatic surface flow. The main influencing factors on settlement are the thickness and stiffness of the host geomaterial layer, void ration and permeability of host media. In general, as the flow lines mainly tend toward the right tunnel, the weep drainage holes should mostly be devised in this section so as to dewater the surrounding rocks and decrease the pore pressure. The determination of the permeability rate of the surrounding rocks, knowledge on the groundwater and the supporting system behaviour are the most important parameters in the optimal design of underground structures located below the groundwater table.

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