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Preliminary communication

# The Selection of a Suitable Shape for Parallel Tunnels in Case of Changing Surface Conditions

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**Abstract:** The process of constructing traffic tunnels through mountains, as well as metro tunnels, often involves using two parallel tunnels to enhance the operating capacity and improve convenience during operation of the tunnels. Currently, analyses of two-tunnel systems frequently assume circular tunnels embedded in an elastic, isotropic, and homogeneous soil mass, with a flat surface. However, in practice tunnels often feature cross-sections of various shapes depending on the intended use and the tunnelling technology employed. The geological conditions are typically complex and do not conform to the assumptions of elasticity or isotropic homogeneity. Tunnel cross-sections can be an arch, horseshoe arch, curved rectangle, ellipse, oval, and other shapes. Additionally, topographical surface conditions often vary and are not flat, as assumed in simplified theoretical problems. Relation to this problem requires in-depth research to ensure effective excavation, protection, and effective use of tunnels. This study investigated the mechanisms of rock mass alteration around tunnels with different cross-sections, considering changes in surface conditions, to determine the most suitable tunnel shapes for various scenarios. The results of the research showed that under both of the flat and changing surface conditions the suitable tunnel shapes are horse-shoe or sub-rectangular. In these cases, the displacement on the boundary of tunnels will be minimized.

**Keywords:** slopes; non-circular tunnels; numerical simulation; parallel tunnels; rock bolts; shotcrete

## 1 INTRODUCTION

The rapid and strong economic development in regions worldwide, including Vietnam, has brought about positive changes in infrastructure and transportation between mountainous areas, lowlands, fields, and urban cities. Traffic tunnels through mountains and subway systems have received increasing attention and are being constructed in many countries, including Vietnam [1-8]. The analysis and calculation of twin tunnels have attracted the interest of many scientists. They often assume the problem of twin tunneling in a semi-infinite plane with circular tunnel cross-sections in elastic media [3-10]. For non-circular tunnel cross-sections, these problems are typically conducted by using the method of complex variables and by converting to an equivalent section [11-13]. Such analyses usually focus on changes in internal forces and mechanical alterations, such as the plastic zone and the redistributed pressure zone around tunnels [4-7].

Recently, with the excavation of urban tunnels using widely adopted shield tunneling technology, issues related to surface subsidence caused by the construction of single and twin tunnels have garnered significant interest [3-7]. Nowadays, in modern technology and software development, numerical software is being increasingly utilized, offering high efficiency in tunnel design [4-6, 8, 11]. Currently, specialized software can be categorized into different analysis groups, such as Discontinuous Deformation Analysis (DDA), Finite Element Method (FEM), Discrete Element Method (DEM), and Boundary Element Method (BEM). The advantage of these methods is that the models closely represent actual conditions, simultaneously incorporating various influencing factors, including geological and hydrogeological conditions in the tunnel construction area. Additionally, the construction process, construction steps, and the installation of tunnel structures can also be simulated within the models. In this paper, the mechanical transformations and stability of twin tunnels with circular, arched, rectangular, sub-rectangular and horseshoe-shaped cross-sections will be analyzed to determine the most appropriate shape for tunnels.

## 2 MODEL AND RESEARCH PROBLEM

### 2.1 Model Establishing

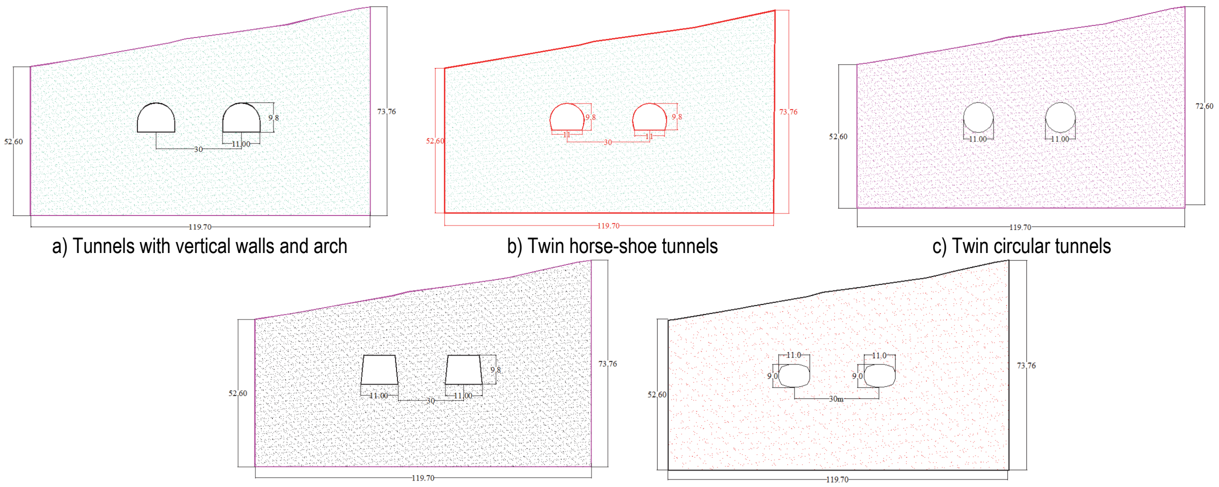
Consider a practical case involving twin tunnels to be constructed in a sloped area with changing topographic surface conditions (not flat). Due to the conditions of the construction site, the distance between the two tunnels is reduced to shorten the horizontal connections between them, facilitating construction and evacuation. The tunnels are designed to be relatively close to each other, with a span $B$ = 11.0 m and a height $H$ = 9.8 m, and are excavated in an area of relatively solid soil and rock. This study focuses on five different types of tunnel cross-sections to analyze the mechanical and displacement changes of the soil and rock around the tunnel boundaries when the twin tunnels are excavated simultaneously in parallel. Additional cases will be addressed in future research. The problem model is illustrated in Fig. 1. The tunnel span of 11.0 m is excavated in an area predominantly covered with soil, with soil and rock parameters calculated using RocLab 1.0 software, as described in Tab. 1.

**Table 1** Parameters of soil in studying

| Parameters | Symbol | Values | Units |
|---|---|---|---|
| Unit weight of rock | $\gamma$ | 0.018 | MN/m$^3$ |
| Tensile strength of rock mass | $\sigma_t$ | 0.020 | MPa |
| Cohesion of rock mass | $c$ | 0.050 | MPa |
| Friction angle | $\varphi$ | 19.00 | Degree |
| Young modulus | $E$ | 300.0 | MPa |
| Poisson ratio | $\mu$ | 0.300 | - |
| Total stress ratio (horizontal/vertical) | $\sigma_3/\sigma_1$ | 1,5 | - |

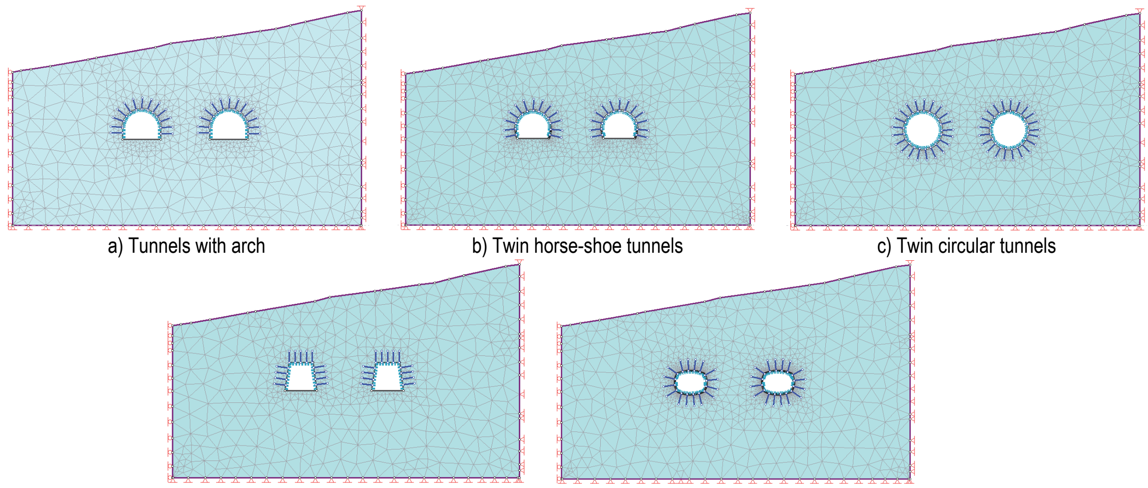
### 2.2 Numerical Modelling for Case Study

Using the numerical software Phase2, the problem can be simulated based on the input parameters provided in Tab. 1 and the theoretical model illustrated in Fig. 1, as shown in Fig. 2. The analysis results for the displacement distribution of soil and rock around the two tunnels are presented in Fig. 3.



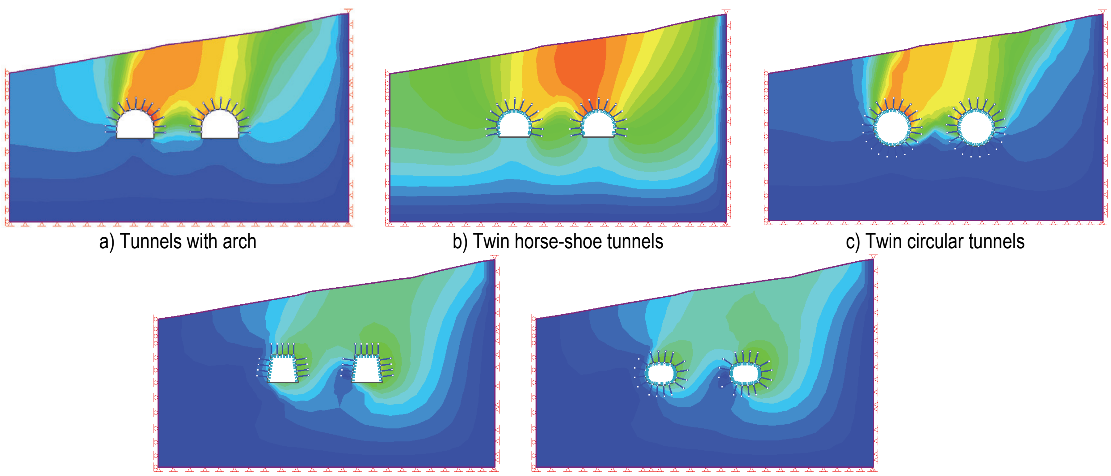
a) Tunnels with vertical walls and arch
b) Twin horse-shoe tunnels
c) Twin circular tunnels
d) Twin trapezoidal tunnels
e) Twin sub-rectangular tunnels

**Figure 1** The theoretical model for analytical problems



a) Tunnels with arch
b) Twin horse-shoe tunnels
c) Twin circular tunnels
d) Twin trapezoidal tunnels
e) Twin sub-rectangular tunnels

**Figure 2** Numerical models for analytical problems



a) Tunnels with arch
b) Twin horse-shoe tunnels
c) Twin circular tunnels
d) Twin trapezoidal tunnels
e) Twin sub-rectangular tunnels

**Figure 3** Displacement distribution around two tunnels

The tunnels are supported by rock bolts combined with steel mesh shotcrete. Based on numerical methods, the models can be used to select appropriate parameters for the rock bolts and steel mesh shotcrete. The characteristics of the rock bolts and the steel mesh shotcrete are described in Tabs. 2 and 3.

**Table 2** Characteristic of rock bolts

| Parameters | Symbol | Values | Units |
|---|---|---|---|
| Diameter of rebar of rock bolts | $d$ | 20 | mm |
| Modulus of steel bar of rock bolts | $E_t$ | 200000 | MPa |
| Tensile capacity of rock bolts | $P_c$ | 0.1 | MN |
| Residual tensile capacity of rock bolts | $P_{re}$ | 0.01 | MN |
| Rock bolt pattern $a \times b$ | $a \times b$ | 2 × 1.5 | m |
| The length of rock bolts | $L$ | 4.0 | m |
| Normal to boundary of tunnels | - | - | - |

**Table 3** Parameters of steel mesh and shotcrete

| | |
|---|---|
| Wire mesh with diameter B40 × 40, mm | 4.0 |
| The thickness of shotcrete, mm | 30 |
| Young's Modulus, MPa | 36000 |
| Poisson ratio | 0.15 |
| Compressive strength $\sigma_c$, MPa | 41 |
| Tensile strength $\sigma_{ts}$, MPa | 5.0 |

Observing the displacement distribution results in Fig. 3, it is evident that the circular tunnel has the smallest influence area, followed by the horseshoe-shaped tunnel, and finally the straight-walled arch tunnel such as distribution colors of total displacements. To analyze the stress-deformation changes around the tunnels, a graph of stress and displacement values at different positions along the tunnel boundary is established. The purpose of this analysis is to evaluate the role of tunnel shape in the variation of stress and rock displacement values at the tunnel boundary, thereby determining the most effective cross-sectional type for the tunnels.

By the above analysis, the relationship can be obtained.

Based on the above analysis, the relationship between vertical stress and displacement at the tunnel boundaries for the two tunnels (left and right) in the model can be determined for five different tunnel shapes under sloped topographical surface conditions (sloping from right to left, as shown in Fig. 2). The results are presented in Figs. 4 to 7.

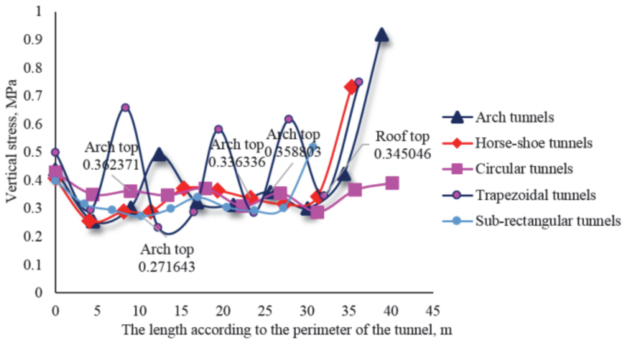



**Figure 4** Vertical stress on the boundary of the left tunnel

The results from Figs. 4 to 7 show that for each different tunnel cross-section tunnels (left or right), the stress and displacement values (seeing in Tab. 4 of this article) at the top of the arch (the position at risk of destabilizing the tunnel) vary. However, the minimum stress on the roof in the case of a horseshoe-shaped tunnel is the smallest, corresponding to the most stable shape.

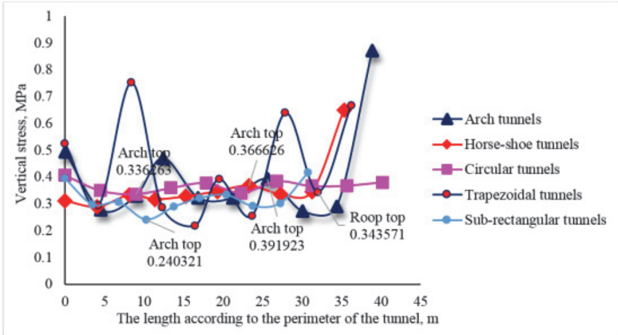



**Figure 5** Vertical stress on the boundary of the right tunnel

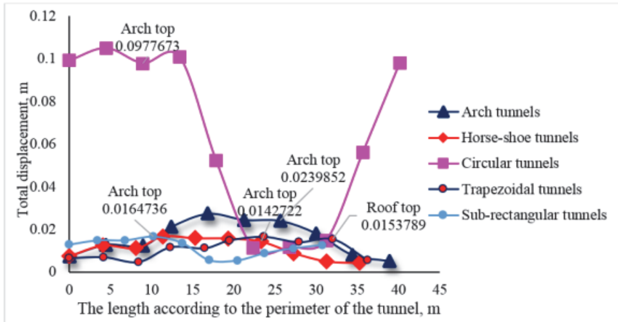



**Figure 6** Displacement distribution on the boundary of the left tunnel

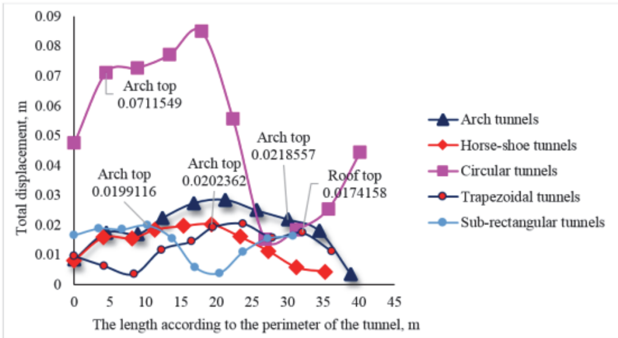
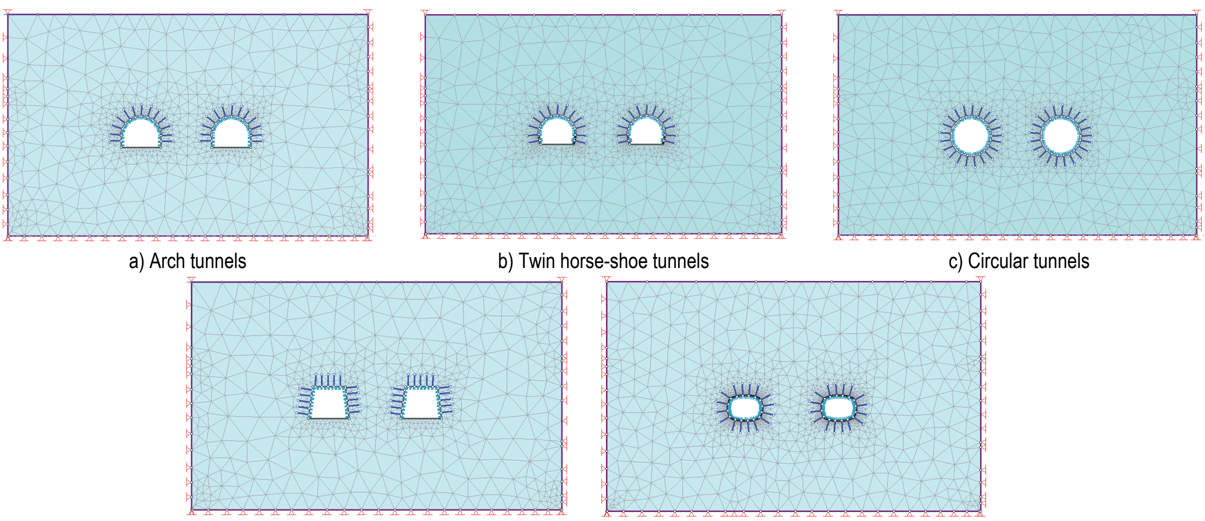



**Figure 7** Displacement distribution on the boundary of the right tunnel



a) Arch tunnels b) Twin horse-shoe tunnels c) Circular tunnels

d) Trapezoidal tunnels e) Two sub-rectangular tunnels

**Figure 8** Models for analytical problems under flat surface conditions

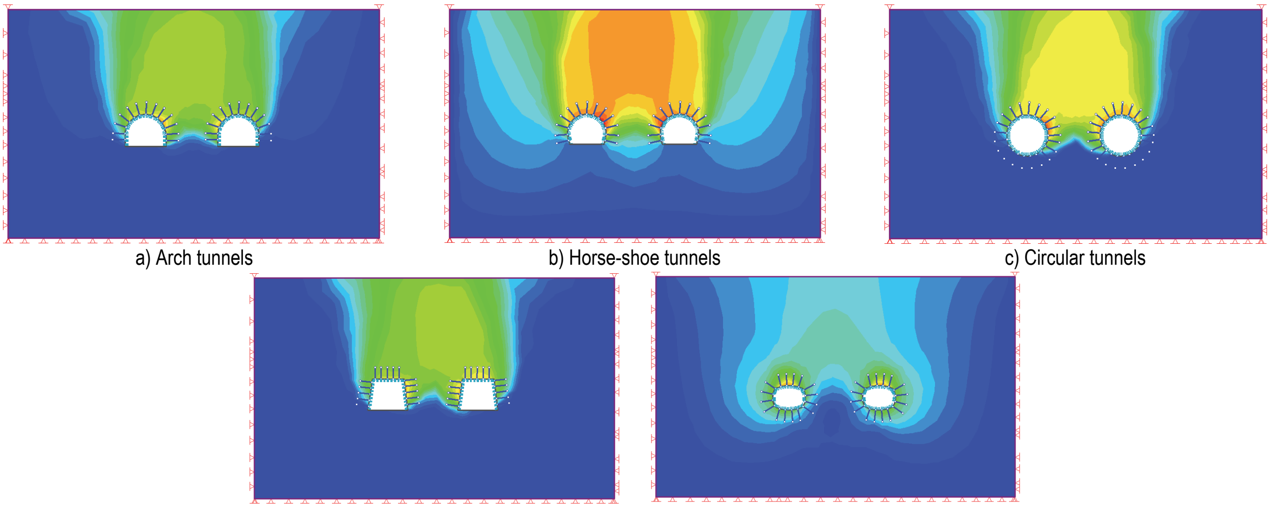



**Figure 9** Displacement distribution of rock mass around tunnels

To clearly observe the difference between the two tunnels under changing surface conditions, a comparative analysis was conducted with the case of two tunnels under horizontal surface conditions, using a similar numerical analysis model. The models for this case are shown in Fig. 8. The numerical model results for the displacement distribution around these tunnels are presented in Fig. 9.

Since the ground surface is flat and the problem model is symmetric, the determination of stress and displacement on the tunnel boundary can be defined for either tunnel (left or right). After the analysis, the relationship between the variation of stress and displacement at the tunnel boundary can be obtained, as shown in Figs. 10 and 11.

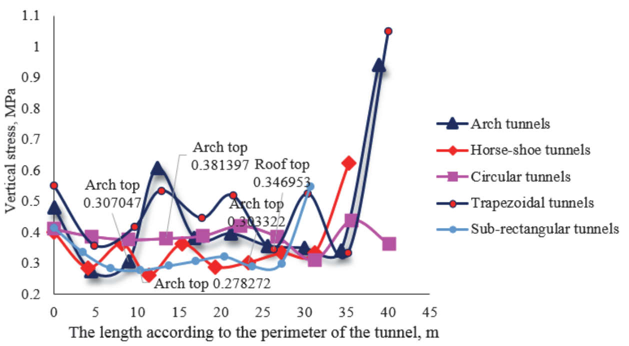



**Figure 10** Vertical stress on the boundary of left tunnel under flat surface conditions

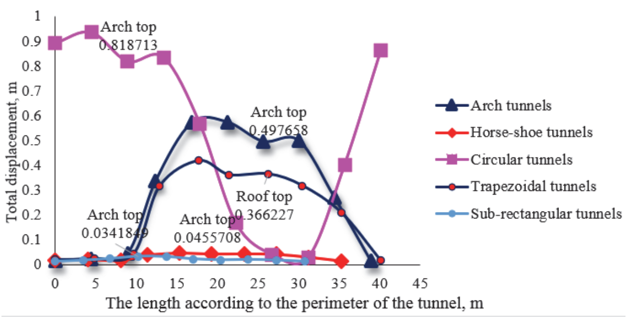



**Figure 11** Displacement on the boundary of left tunnel under flat surface condition

Through the analysis, the displacement values at the roof of the tunnels can be obtained for both cases: when the ground surface is flat and when it is changed, as shown in Tab. 4. The graphs for these cases are presented in Fig. 12.

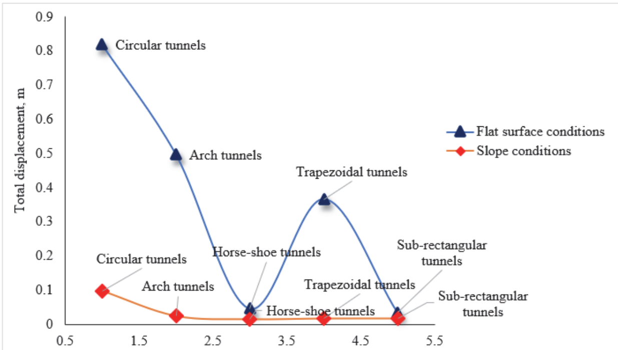



**Figure 12** Comparisons of displacement values in two cases of soil flat and slope surface conditions

**Table 4** Displacement values on the top of tunnels, m

| Circular tunnels | Arch tunnels | Horse-shoe tunnels | Trapezoidal tunnels | Sub-rectangular tunnels | Surface conditions |
|---|---|---|---|---|---|
| 0.818713 | 0.497658 | 0.045571 | 0.366227 | 0.0341849 | Flat |
| 0.097767 | 0.023985 | 0.014272 | 0.016379 | 0.0164736 | Slope |

## 3 CONCLUSIONS AND DISCUSSIONS

Based on the above theoretical analysis and the results from the numerical analysis model, it is found that the model boundary soil surface condition has a certain influence on the distribution of stress and displacement in the rock mass, as well as on the boundaries of the tunnels in various cases.

In the case of flat ground surface conditions, the stress and displacement values are symmetric around the tunnels. However, when the soil surface is sloped, as in the research problem, the stress and displacement values tend to shift to the left because the soil surface has a slope from right to left. As a result, the tunnels experience larger stress and displacement values on the left side. This can be explained by the difference in topographic elevation: in a homogenized problem, the greater the depth into the mountain, the higher the stress and displacement.

For both cases, where the ground surface is flat or sloped, the suitable cross-section for the two tunnels should be a horseshoe arch or sub-rectangular shape. In these cases, the stress and displacement values at the top of the tunnel are smaller than in other cases, making the tunnel the most stable in terms of the pressure acting on the tunnel linings.

The numerical analysis model and numerical methods should be applied in the analysis and design process, including the early prediction of rock pressure and the preliminary selection of the initial support structure for tunnels. However, it is necessary to maintain flexibility and adaptability when updating geological conditions in each section and other tunnel areas in practice.

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