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Dynamic Response Characteristics and Deformation Control of Soft–hard Interbedded Tunnel Surrounding Rock Under Excavation Disturbance

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Abstract

To investigate the influence of excavation disturbance on soft–hard interbedded surrounding rock, a numerical model of a tunnel excavated in soft–hard interbedded strata was established using 3DEC. The dynamic response characteristics and deformation control measures of the surrounding rock with different bedding dip angles were systematically analyzed. The results indicate that the bedding dip angle significantly governs the deformation pattern and stress transfer path of the surrounding rock. When the bedding dip angles are 0° and 90°, the distributions of vertical displacement and vertical stress are relatively regular. In contrast, under bedding dip angles of 30°, 45°, and 60°, the inclined bedding planes form unfavorable intersections with the tunnel contour, resulting in pronounced vertical displacement and vertical stress concentrations near the arch shoulder, sidewall, floor, and soft–hard rock interfaces. Consequently, the surrounding rock exhibits evident asymmetric responses. Among the investigated cases, the 45° bedding dip angle leads to more significant local deformation and stress concentration, and can therefore be regarded as a representative unfavorable condition for tunnel excavation in soft–hard interbedded rock masses. Reducing the excavation advance can decrease the disturbance intensity induced by a single excavation step, narrow the range of vertical displacement concentration, and alleviate local vertical stress concentration, thereby improving the stability of soft–hard interbedded surrounding rock during tunnel construction.

Keywords

Tunnel; Soft-hard interbedded rock masses; Excavation disturbance; Bedding dip angle; Prevention measures.

1. INTRODUCTION

Soft–hard interbedded surrounding rock is characterized by pronounced anisotropy and well-developed structural planes [1]. During tunnel excavation, such geological conditions can easily induce surrounding rock instability, overbreak or underbreak, and large deformation disasters [2-4], thereby seriously restricting construction safety and efficiency. With the continuous expansion of tunnel construction and the increasing number of tunnels in operation, deformation-induced damage has become increasingly prominent and poses a serious threat to train operation safety [5]. Once such problems occur during the operation stage, remediation is often difficult and costly [6,7]. Therefore, accurately identifying the dynamic response characteristics of soft–hard interbedded surrounding rock during construction and proposing

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reasonable deformation control measures are of great significance for ensuring the long-term stability of tunnels and reducing engineering risks.

Many scholars have investigated the deformation and failure mechanisms of soft–hard interbedded surrounding rock, the mechanical behavior of support structures, and deformation control technologies. Ren et al. [8] used the ANSYS finite element platform to systematically evaluate the stability of Grade V sandstone–mudstone interbedded surrounding rock in the Simian Mountain Tunnel, Chongqing, and optimized the primary support parameters accordingly. Ding et al. [9] carried out numerical simulations of the Yong'an Tunnel using the PFC2D discrete element platform and analyzed the differences in failure patterns and mechanisms of surrounding rock under different bedding dip angles. Yu et al. [10], based on a FLAC3D strain-softening model and field monitoring, revealed that a prestressed anchorage system can effectively control large deformation of squeezing soft rock in the Muzhailing Tunnel by increasing the lateral confinement of surrounding rock, improving soft rock mechanical parameters, and optimizing the prestress, length, and density of anchor cables. Lan et al. [11] investigated the TBM crossing of the F1 fault in the pilot tunnel of the Daliangshan No. 1 Tunnel through laboratory tests, numerical simulation, and field monitoring. They found that the deformation of surrounding rock in the fault fracture zone exhibited a "larger in the middle and smaller at both ends" pattern, and verified that comprehensive reinforcement measures could significantly reduce vault settlement and ground surface settlement. Li et al. [12] proposed a parameter optimization method for prestressed anchorage support in the soft rock section of the Muzhailing Highway Tunnel, in which allowable surrounding rock deformation was used as the control objective, and inverse analysis, numerical simulation, and a PSO-LSSVM model were combined; the rationality and feasibility of the method were verified through field application. Wu et al. [13] developed an active support parameter optimization method for prestressed anchor cables in soft rock tunnels based on an adaptive genetic algorithm, and comparative tests showed that the method could effectively improve anchoring force, control surrounding rock displacement, and enhance support quality and construction efficiency. Xiao and Zhou [14] investigated a deep-buried soft–hard interbedded tunnel and compared the deformation and stress evolution of surrounding rock under unsupported and supported conditions through numerical simulation, demonstrating that a composite lining support system can effectively control surrounding rock deformation and improve tunnel stability. Guo [15] studied the deformation mechanism of soft–hard interbedded tunnels under high geostress conditions based on the Jianshan Tunnel project and proposed targeted control measures. Yang et al. [16] combined physical tests with numerical simulation and pointed out that tunnel excavation and support design in soft–hard interbedded strata should pay particular attention to asymmetric deformation and failure in complex rock strata, especially the risk of large deformation in soft rock layers. Sun et al. [17] established a generalized Komamura–Huang rheological model and applied it to several tunnels, including the Wushaoling Tunnel. They demonstrated the limitations of conventional rigid support schemes and proposed yielding anchorage support measures, including the structural mechanism and key design and construction parameters of yielding anchors. Taking the Muzhailing Tunnel as an example, they further conducted two-dimensional numerical simulations and parameter analyses, and the method of "support while yielding and large-scale yielding anchors" has been successfully applied in several projects with favorable economic benefits. These studies indicate that bedding structure, lithological differences, and support methods are key factors affecting the stability of soft–hard interbedded tunnels. However, existing research mainly focuses on the static response of surrounding rock, single deformation indices, or support parameter optimization. Insufficient attention has been paid to the coupling relationship between the displacement field and stress field of soft–hard interbedded surrounding rock under excavation disturbance. In particular, the differences in

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dynamic disturbance responses under different bedding dip angles and the corresponding prevention and control measures still require further systematic investigation.

Based on the above considerations, a three-dimensional discrete element numerical model of a soft–hard interbedded tunnel surrounding rock mass with different bedding dip angles was established using 3DEC. The evolution characteristics of the vertical displacement field and vertical stress field of the surrounding rock under excavation disturbance were analyzed. Furthermore, for a representative unfavorable bedding dip angle, the control effects of excavation advance optimization and shotcrete–bolt support were evaluated, aiming to provide a reference for stability control of soft–hard interbedded surrounding rock during tunnel construction.

2. NUMERICAL MODEL ESTABLISHMENT AND SIMULATION SCHEME DESIGN

To investigate the influence of different bedding dip angles on the dynamic response of soft–hard interbedded surrounding rock during tunnel excavation under high geostress conditions, a numerical model of a soft–hard interbedded tunnel was established using the three-dimensional discrete element platform 3DEC, as shown in Figure 1. The model has dimensions of 40 m in length, 10 m in width, and 40 m in height. Bedding planes with different dip angles, namely 0°, 30°, 45°, 60°, and 90°, were introduced to divide the surrounding rock into several interbedded strata. The thicknesses of the soft and hard layers were set to 0.5 m and 2.0 m, respectively. The tunnel cross-section was designed as a straight-wall arch, with a clear span of 5.0 m and a total height of 4.7 m. The arch crown consists of a standard circular arc with a radius of 2.5 m, while the straight-wall section has a height of 2.2 m. Non-reflecting boundaries were applied to the upper, lower, left, and right boundaries of the model to reduce the influence of boundary-reflected waves during dynamic calculation. Meanwhile, displacement constraints were imposed on the left, right, front, and rear boundaries. The mechanical parameters of the surrounding rock and structural planes are listed in Tables 1 and 2, respectively.

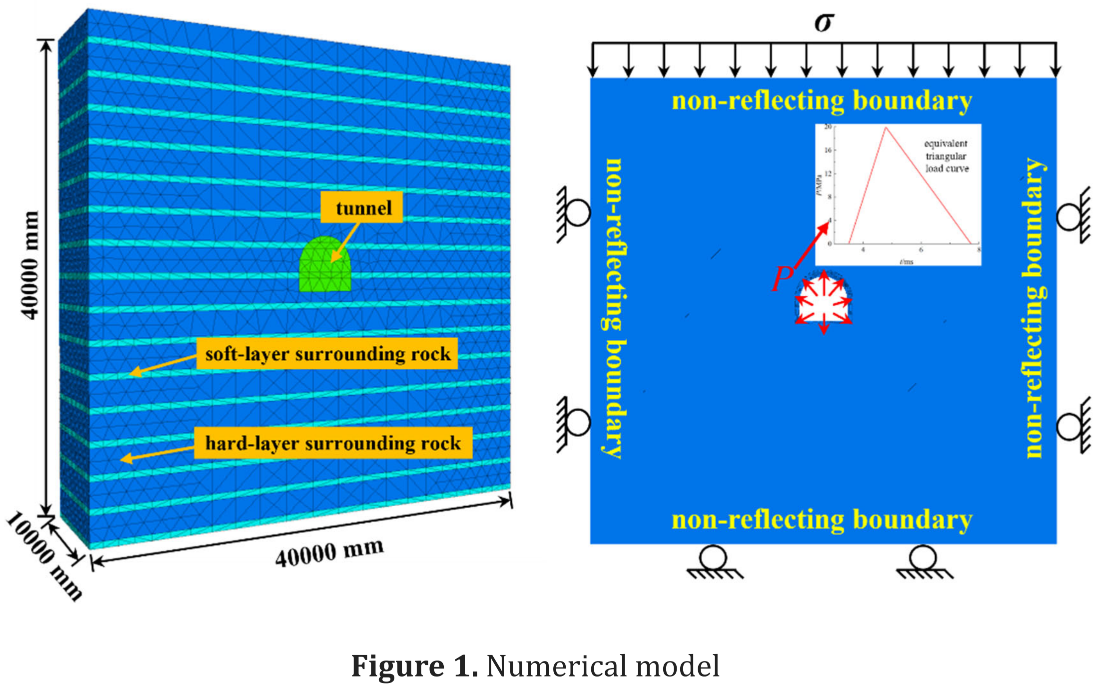

Figure 1. Numerical model

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Table 1. Physico-mechanical parameters of surrounding rock blocks

Rock layer	Elastic modulus (GPa)	Cohesion (MPa)	Internal friction angle (°)	Tensile strength (MPa)	Poisson's ratio	Density (g/cm3)
Hard layer	25	2.40	35	2	0.3	2.65
Soft layer	10	1.10	20	1.20	0.36	2.80

Table 2. Mechanical parameters of bedding structural planes

Normal stiffness (GPa/m)	Shear stiffness (GPa/m)	Internal friction angle (°)	Cohesion (MPa)	Tensile strength (MPa)
5.8	2.9	18	1	1

In this study, the excavation process of a tunnel in soft–hard interbedded surrounding rock was simulated using the 3DEC numerical platform to investigate its dynamic response. The built-in monitoring function of the software was employed to continuously record the evolution of the displacement and stress fields in the surrounding rock around the tunnel section. Five comparative cases were established according to different bedding dip angles, namely θ = 0°, 30°, 45°, 60°, and 90°. During the numerical calculation, the initial geostress equilibrium state was first generated, followed by tunnel excavation along the prescribed excavation path. A disturbance load with a peak value of 20 MPa was then applied to the excavation zone to reproduce the excavation-induced disturbance during actual construction. The vertical displacement and vertical stress distributions around the tunnel opening and near the bedding planes were mainly extracted to analyze the deformation behavior and stress redistribution characteristics of the surrounding rock with different bedding dip angles, thereby providing a basis for the subsequent design of deformation control measures.

3. DYNAMIC RESPONSE CHARACTERISTICS OF SOFT-HARD INTERBEDDED TUNNEL SURROUNDING ROCK WITH DIFFERENT DEDDING DIP ANGLES

3.1. Dynamic response characteristics of the vertical displacement field

The vertical displacement contours of the soft–hard interbedded surrounding rock with different bedding dip angles during dynamic excavation disturbance are shown in Figure 2. As indicated in Figure 2, the vertical displacement in all cases is mainly concentrated in the vault settlement zone and the floor heave zone, suggesting that the near-field rock mass around the tunnel first exhibits a pronounced vertical deformation response under the combined effects of excavation unloading and disturbance loading. Owing to the differences in stiffness and strength between the soft and hard rock layers, the deformation of the surrounding rock does not develop uniformly, but is strongly controlled by the spatial orientation of the bedding planes.

When θ = 0°, the bedding planes are nearly horizontal, and the high-value zones of vertical displacement are mainly concentrated near the vault and floor, showing a relatively regular distribution. When θ = 90°, the bedding planes are nearly vertical, and the vertical deformation of the surrounding rock also exhibits a certain degree of symmetry. In contrast, when θ = 30°, 45°, and 60°, the inclined bedding planes intersect the tunnel opening, causing obvious deflection and local concentration of the displacement field near the vault, arch shoulder, and floor. The high-value vertical displacement zones extend along the bedding planes, and the deformation of the surrounding rock presents pronounced asymmetric characteristics. Among these cases, under the 45° bedding dip angle, the bedding planes obliquely pass through the tunnel boundary, and displacement concentration near the arch shoulder and floor is more

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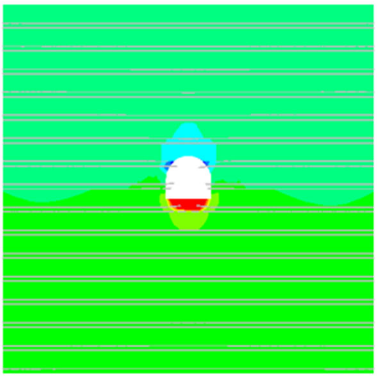
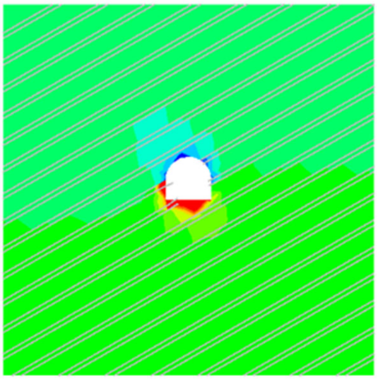
evident, indicating that interlayer sliding and local deformation concentration are more likely to occur under this bedding condition.

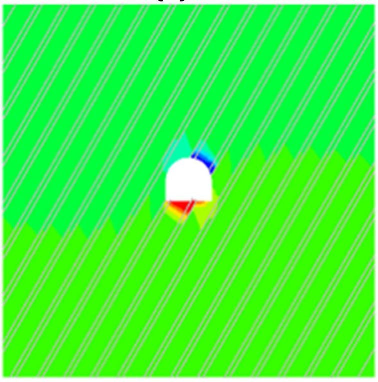
Based on the analysis of vertical displacement, the deformation of soft–hard interbedded surrounding rock under excavation disturbance is jointly controlled by excavation unloading, dynamic disturbance, and weak bedding planes. When the inclined bedding planes intersect unfavorably with the tunnel contour, the asymmetric deformation of the surrounding rock becomes more pronounced. In this case, the sidewalls, arch shoulders, wall feet, and floor are more likely to become deformation-sensitive zones.



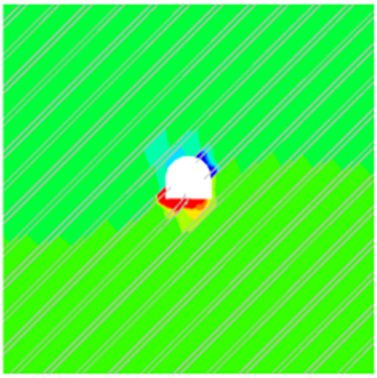
(a) 0°



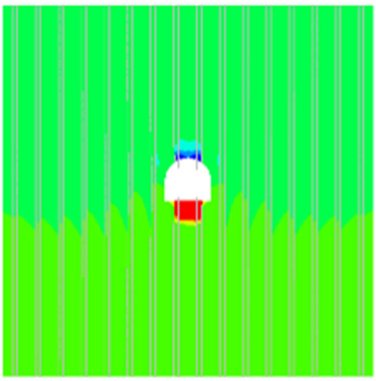
(b) 30°



(c) 45°



(d) 60°



(e) 90°

Figure 2. Evolution characteristics of vertical displacement in soft–hard interbedded surrounding rock (unit: m)

3.2. Dynamic response characteristics of the vertical stress field

Figure 3 shows the vertical stress contour distributions of the soft–hard interbedded surrounding rock with different bedding dip angles during dynamic excavation disturbance. The results indicate that: (1) after excavation, the vertical stress around the tunnel is

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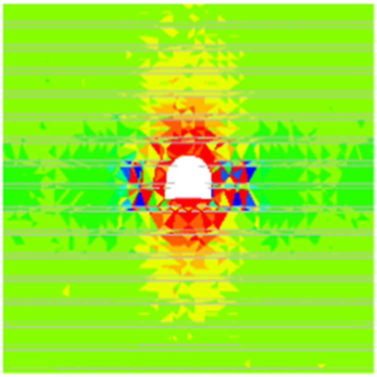
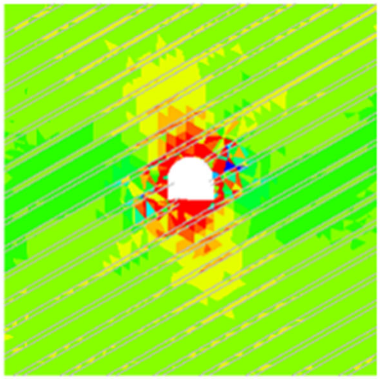
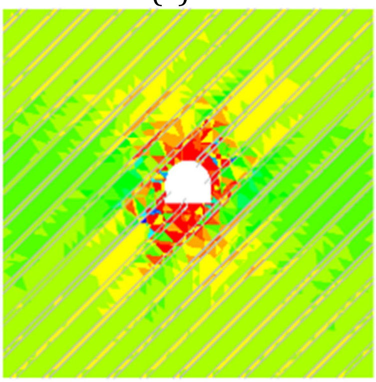
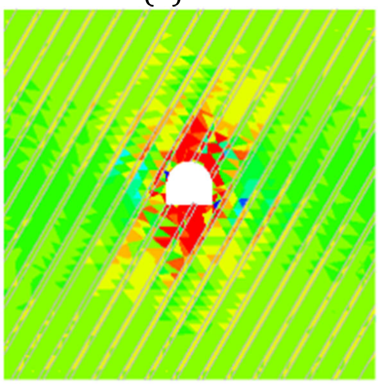
significantly redistributed, with high-stress zones mainly concentrated at the vault, floor, and local areas where the bedding planes intersect the tunnel boundary. This suggests that dynamic disturbance intensifies stress adjustment and local stress concentration near the excavation boundary. (2) The bedding dip angle has a pronounced influence on the vertical stress distribution. Under horizontal and vertical bedding conditions, the stress distribution is relatively regular, and the high-stress zones are mainly controlled by the tunnel geometry. In contrast, under inclined bedding conditions, the stress field exhibits obvious asymmetry, and the high-stress zones shift and extend along the bedding planes. (3) Owing to the significant differences in mechanical properties between the soft and hard rock layers, stress concentration is likely to occur at the soft–hard rock interfaces and around the tunnel corners during disturbance load propagation. Therefore, targeted reinforcement should be applied to the arch shoulders, sidewalls, and floor to reduce the risks of local failure and progressive instability.


(a) 0°


(b) 30°


(c) 45°


(d) 60°

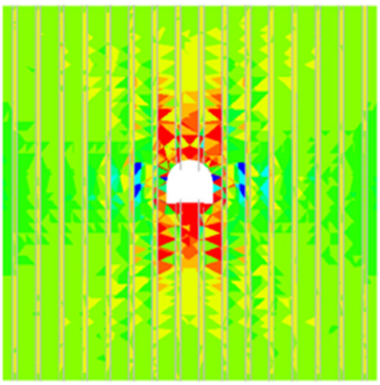

(e) 90°

Figure 3. Evolution characteristics of vertical stress in soft–hard interbedded surrounding rock (unit: MPa)

4. PREVENTION AND CONTROL MRASURES FOR FAILURE OF SOFT-HARD INTERBEDDED SURROUNDING ROCK

4.1. Design of prevention and control schemes

During tunnel construction, the deformation and failure behavior of soft–hard interbedded surrounding rock directly affects engineering safety and stability [18,19]. Variations in bedding dip angle can result in significant differences in stress mechanisms, deformation patterns, and failure modes [20-22], which may induce engineering problems such as vault instability, excessive sidewall deformation, interlayer sliding, and damage to support structures [23]. For tunnels excavated under such unfavorable geological conditions, control schemes should be developed by comprehensively considering the surrounding rock properties, in situ stress environment, and construction method [24,25]. Based on the dynamic excavation model established in Section 2, the constitutive relationship, boundary conditions, and physico-mechanical parameters were kept unchanged. The soft–hard interbedded surrounding rock with a bedding dip angle of 45° was selected as a representative unfavorable case. Three excavation advances of 2.0 m, 1.5 m, and 1.0 m were adopted to analyze the evolution characteristics of vertical displacement and vertical stress under different excavation advances, thereby revealing the control effect of excavation advance optimization on large deformation of the surrounding rock.

4.2. Optimization of Excavation Advance

Figure 4 presents the dynamic response characteristics of vertical displacement and vertical stress in the soft–hard interbedded surrounding rock under three different excavation advances, with the total excavation length kept constant at 10 m. The results indicate that varying the excavation advance does not alter the fundamental deformation pattern or stress distribution mode around the tunnel in soft–hard interbedded strata. However, it has a significant influence on the magnitude of surrounding rock deformation and the degree of stress concentration.

From the perspective of the vertical displacement field, the area with relatively large displacement gradually decreases as the excavation advance is reduced. Meanwhile, displacement concentration near the arch shoulder, sidewall, and floor is alleviated to some extent. This indicates that controlling the excavation advance can effectively reduce the disturbance intensity induced by unloading in a single excavation step, allowing the deformation of the surrounding rock to be released progressively and thereby suppressing the occurrence of overall instability and failure of the rock mass. A reasonable reduction in excavation advance can lower the risk of surrounding rock instability, reduce construction interruptions and rework caused by collapse, local rockfall, or sudden large deformation, and is therefore beneficial for improving the continuity of the construction process.

From the perspective of the vertical stress field, variations in excavation advance have a limited influence on the overall distribution range of high-stress zones around the tunnel. However, the degree of stress concentration generally decreases as the excavation advance is reduced. A larger excavation advance causes the surrounding rock to undergo more intense stress release and redistribution within a short period, which can easily induce local stress concentration at the arch shoulder, sidewall, and floor. By optimizing the excavation step length and reasonably controlling the advance of each excavation cycle, the instantaneous unloading rate of the surrounding rock can be effectively reduced. This enables a more gradual stress adjustment process and consequently lowers the risk of local failure and progressive instability.

Therefore, under complex soft–hard interbedded surrounding rock conditions, optimizing the excavation advance plays an important role in controlling surrounding rock deformation and regulating stress distribution. Short-advance staged excavation can reduce the disturbance range induced by a single excavation step, decrease the degree of deformation and stress

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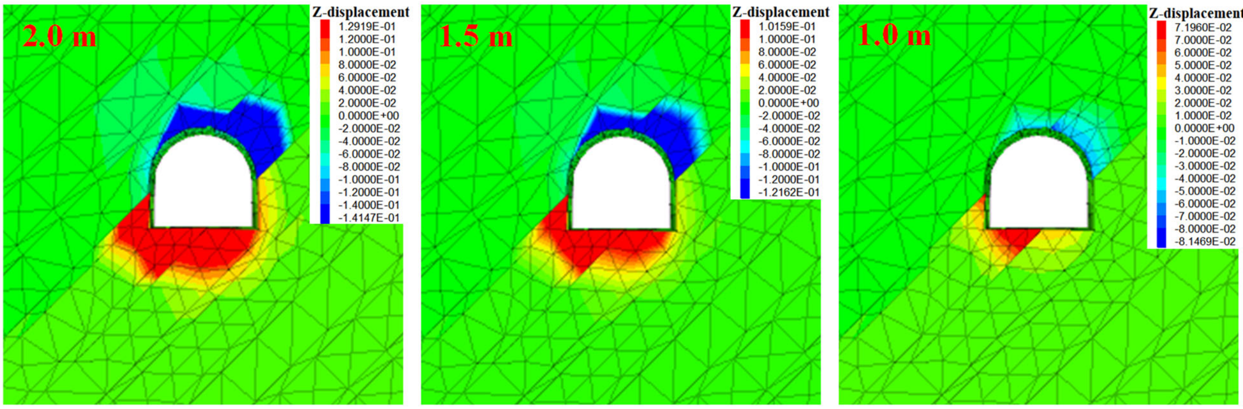
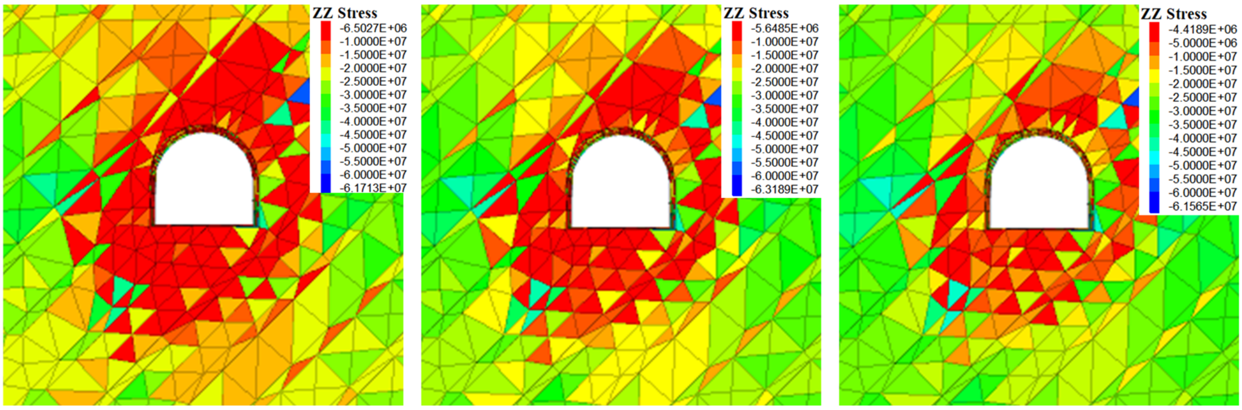
concentration in the surrounding rock, and create favorable conditions for the timely installation of subsequent support. It is therefore an effective active control measure for tunnel construction in soft–hard interbedded surrounding rock.

In summary, during tunnel excavation in soft–hard interbedded strata, reducing the excavation advance and adopting staged excavation can effectively decrease the degree of surrounding rock deformation and stress concentration, thus suppressing excavation-induced instability and failure. Short-advance excavation limits the disturbance range of each excavation cycle, mitigates deformation accumulation and local stress concentration, and facilitates the timely application of subsequent control measures. Therefore, it provides an effective active control approach for tunnels constructed in soft–hard interbedded surrounding rock.



(a) Vertical displacement



(b) Vertical stress

Figure 4. Evolution characteristics of vertical displacement and vertical stress of surrounding rock under different excavation advances

5. CONCLUSIONS

Based on the three-dimensional discrete element numerical analysis method implemented in 3DEC, this study investigated the dynamic response characteristics of vertical displacement and vertical stress, as well as failure prevention and control measures, for tunnels excavated in soft–hard interbedded surrounding rock. The main conclusions are as follows:

(1) The stability of tunnels in soft–hard interbedded surrounding rock is significantly affected by the bedding dip angle. When θ = 0° and 90°, the vertical displacement of the surrounding rock exhibits a relatively symmetrical distribution. In contrast, when θ = 30°, 45°, and 60°, the inclined bedding planes form unfavorable intersections with the tunnel contour, causing the high-value zones of vertical displacement to shift and extend along the bedding planes. As a result, the deformation of the surrounding rock shows pronounced asymmetric characteristics.

(2) Under excavation disturbance, the vertical stress field of the soft–hard interbedded surrounding rock undergoes significant redistribution. The high-value zones of vertical stress are mainly concentrated at the tunnel crown, floor, and the intersections between bedding planes and the tunnel opening. Inclined bedding planes alter the internal stress transfer path of the surrounding rock, causing the stress concentration zones to extend along the bedding direction. This increases the risk of shear slip, tensile cracking, and local failure near the arch shoulder, sidewall, floor, and soft–hard rock interfaces.

(3) Reasonably reducing the excavation advance can effectively improve the stability of soft–hard interbedded surrounding rock. Short-advance staged excavation can decrease the disturbance intensity induced by each excavation step, reduce the extent of vertical displacement concentration and the degree of vertical stress concentration, and promote a more gradual deformation release and stress adjustment process in the surrounding rock. In practical tunnel construction, an integrated control strategy involving “short advance, timely closure, and necessary advance reinforcement” should be adopted according to the surrounding rock conditions, so as to reduce the risk of surrounding rock instability induced by excavation disturbance.

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