

Numerical analysis of non-uniform segmental lining design effects on large-diameter tunnels in complex multi-layered strata

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Abstract. In recent tunneling projects, encounters with multi-layered strata have become more frequent as the desired scale of tunneling increases. Despite substantial practical experience, the design of large-diameter shield-driven tunnels often simplifies the surrounding ground as uniform, overlooking the complexities introduced by non-uniform geotechnical factors. This study comparatively analyzed the influence of design factors, particularly segment stiffness and joint parameters, on segmental lining behavior in layered ground conditions using numerical methods. A comprehensive parametric study revealed the significant impact of deformative interaction between the lining and the soft top soil layer on overall tunnel behavior. Permitting lining deformation in the soft soil layer effectively mitigated the induced internal forces but resulted in considerable tunnel lining convergence, adopting a peanut-shaped appearance. From a practical design perspective, application of a soft segment with lower stiffness near the stiff soil layer is an economically advantageous approach, alleviating internal forces within an acceptable convergence level. Notably, around the interfaces between soil layers with different stiffnesses, the induced internal forces in the lining were minimized based on joint rotational stiffness and location. This indicates the possibility of achieving an optimal design for segmental lining joints under layered ground conditions. Additionally, a preliminary design method was proposed, which sequentially optimizes parameters for joints located near soil layer interfaces. Subsequently, a specialized design based on the proposed method for complex multi-layered strata was compared with a conventional design. The results confirmed that the internal force was effectively relieved at an allowable lining deflection level.

Keywords: convergence; internal force; joint rotational stiffness; longitudinal joint design; numerical method

1. Introduction

Mechanized tunneling using tunnel boring machines (TBMs) is considered a pioneering method with numerous applications in underground construction. Shielded TBMs, which produce less noise and vibration during excavation, and can minimize surrounding ground deformation, are extensively employed in urban tunnel projects (An *et al.* 2022). Recently, significant advances in machinery technology have facilitated the construction of large-diameter shield-driven tunnels, even in soft soil strata (Bäppler 2016). With the increasing scale of tunnels, encounters with multi-layered strata have become more frequent, often necessitating passage through at least two distinct soil layers (Zhao *et al.* 2007). However, despite substantial practical experience, the design of large-diameter shield tunnels remains limited by the assumption of uniformly equivalent surrounding soil (ITA Working Group 2 2019). Tunnel behavior in multi-layered strata is complicated (Katebi *et al.* 2015, Alagha and Chapman

2019) due to various geotechnical factors, such as the properties of diverse soil layers, layer interface positioning (Do and Dias 2018), interlayer thickness, relative differences in stiffness between layers (Zhang *et al.* 2015), and inclination angle between the soil layers interface and the horizontal plane (Zhang *et al.* 2021). Non-uniform and non-linear internal forces are induced within the tunnel lining due to interactions between the ground pressure and surrounding ground (Do and Dias 2018, Zhang *et al.* 2021). Conventional structural solutions that overlook lining deformation characteristics in layered ground resort to increasing the strength and thickness of the segments, potentially resulting in overdesign and increasing direct construction costs (Mezger *et al.* 2018, Banihashemigargari and Rezaeifarei 2023). While prior studies on layered stratification typically considered the tunnel lining as a continuous ring with constant stiffness, there is limited research focusing on the influence of individual stiffness of segments or joint parameters on tunnel linings under layered ground conditions. Therefore, a specialized design methodology is necessary to consider the effects of significant factors in the segmental lining design on the mechanical responses of large tunnels in layered ground. To achieve a comprehensive understanding, it is necessary to analyze the influence of these factors on the internal forces and convergence induced in the tunnel lining.

The design of segments comprising the segmental lining must be thoroughly reviewed to ensure resilience across the

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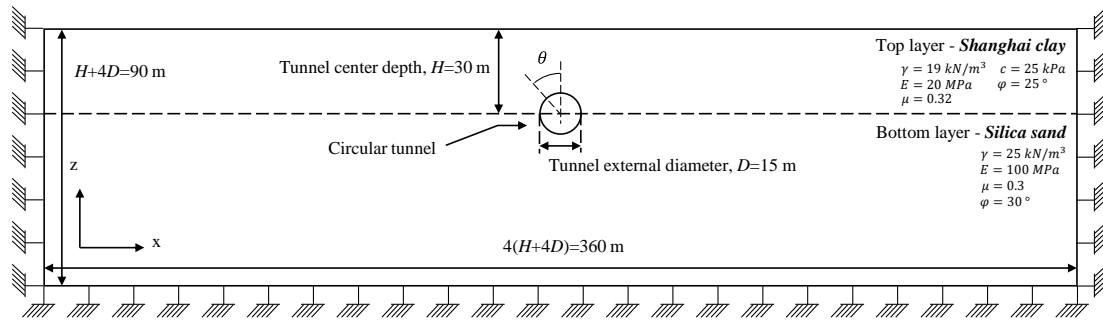


Fig. 1 Schematic of the circular tunnel through the layered ground in the numerical model

various stages (ITA Working Group 2 2019). In production and transportation stages, segments should be designed to ensure stability during storage and transportation, and in particular, the self-weight and dynamic load must be reviewed. During the construction phases, including TBM advancement and segment assembly, the design must ensure stability against the TBM jack thrust force and backfill grouting pressure. In these two stages, it is possible to sufficiently review various material properties and loading cases according to the design of the segment and TBM equipment. However, during the service stage, an in-depth review of long-term loads arising from the ground, groundwater, surcharges, and other relevant factors should be conducted. When evaluating the internal forces induced during the final service stage, it is imperative to calculate the ground pressure acting on the lining by considering the interaction between the ground and lining (Han *et al.* 2017). Two methods are commonly employed in numerical analyses.

The first is a simplified approach based on Winkler's theory (Schulze and Duddeck 1964) that considers the ground reaction force acting on the tunnel through discrete springs. The second involves directly assessing the entire ground model using the finite element method (FEM) or finite difference method (FDM). FEM, despite its high computational costs, is preferred for soft ground conditions due to its high accuracy (ÖVBB 2011). It can effectively capture non-uniform anisotropic stresses and diverse geological formations (ITA Working Group 2, 2019). Consequently, it has been widely adopted for modeling the ground surrounding linings, proving effective in studies involving interactions with multi-layered ground (Chu *et al.* 2007, Nunes and Meguid 2009, Katebi *et al.* 2015, Zhang *et al.* 2015, Do and Dias 2018, Zhang *et al.* 2021). The joint characteristics of segmental linings can be modeled indirectly or directly in numerical analysis. The simplified indirect method of considering a segmental lining as a rigid ring embedded in a continuous ground model cannot consider the joint parameters, rendering it unsuitable for layered ground conditions (Muir Wood 1975, Einstein and Schwartz 1979, Duddeck and Erdmann 1985, Takano 2000). Therefore, several studies have proposed the direct modeling of joints with rotational spring models to simulate realistic behaviors (Lee *et al.* 2001, Blom 2002, Ding *et al.* 2004, El Naggari and Hinchberger 2008, Teachavorasinskun and Chub-Uppakarn 2010, Do *et al.* 2013). Do *et al.* (2013) conducted a two-dimensional numerical simulation to

model links between the segments as spring joints with six degrees of freedom (DOF). They investigated the influence of the number of joints, joint distribution, and joint stiffness. However, their study was limited to uniform soil conditions and did not evaluate the impact of joint parameters by considering geotechnical factors in multi-layered strata. These limitations highlight the need to comprehensively investigate the effect of segmental lining design factors on the tunnel behavior around the interface of the soil layers.

Therefore, this study aimed to evaluate the mechanical response of segmental linings under layered ground conditions based on the design factors of segment stiffness and joint parameters. Accordingly, a comprehensive parametric analysis was conducted through numerical simulations. First, the deformation characteristics of the lining and its interaction with the layered ground were investigated, considering segment stiffness. Based on these findings, a method for designing the individual segment stiffness was developed, and the impact of each design method on the tunnel behavior was comparatively analyzed. The internal forces and convergence of the lining considering the joint rotational stiffness and distribution in the layered ground condition were then examined. Consequently, based on these investigations, an effective joint design method was formulated, focusing on the interfaces of distinct soil layers. The proposed method was applied to a complex multi-layered strata assumed by considering geotechnical factors that complicate the tunnel behavior through a literature review, and its effectiveness was evaluated from a practical perspective compared to the conventional design.

2. Numerical methodology

2.1 Description of the numerical model

2.1.1 General characteristics

A series of two-dimensional numerical simulations with a simplified model based on FEM were performed using a suitable commercial software, Abaqus 2022 (Dassault Systèmes Simulia Corp.). The numerical model comprised a multi-layered ground, segmental lining with longitudinal joints, and their interaction. Fig. 1 illustrates the general configuration of a numerical model of the plane-strain

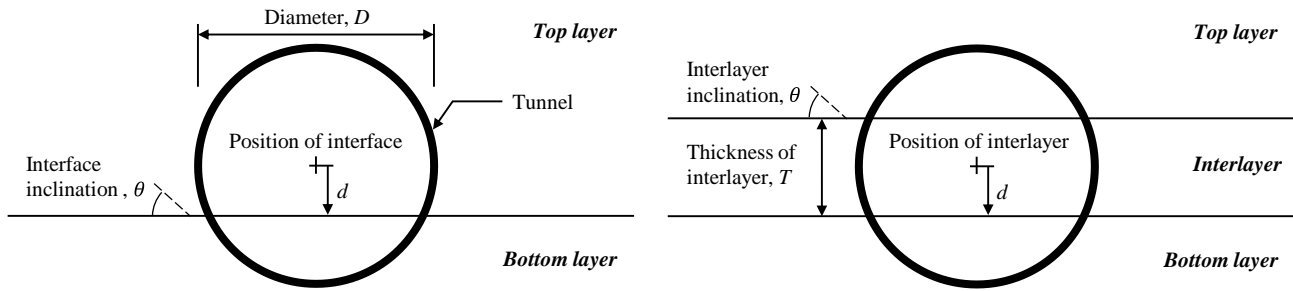


Fig. 2 Schematic of multi-layered ground conditions: (left) two-layered ground; (right) three-layered ground

conditions used to quantify the internal forces and convergence induced in the tunnel lining within layered ground. The centrifuge test performed by Zhang *et al.* (2021) to evaluate the behavior of a large-section tunnel under layered ground conditions was adopted to validate the numerical model. They prepared a ground model in a two-layered condition by forming the lower half with silica sand and the upper half with Shanghai clay in a soil box with a width of 900 mm and a height of 600 mm. They placed an aluminum tunnel model with a diameter of 150 mm, thickness of 4.6 mm, Young's modulus of 70 GPa, and Poisson's ratio of 0.2 in the center of the soil box and conducted tests under the condition of an acceleration of 100 g. Considering the scaling factor, the prototype used in their study has the dimensions of a 15-m-diameter tunnel located at a depth of 30 m, and the properties of the soils and tunnel lining are listed in Table 1. In this study, to minimize errors stemming from boundary effects, the height and width of the model were set to $(H+4D) = 90$ m and $4(H+4D) = 360$ m, respectively, as the optimal boundary for the tunnel external diameter D and tunnel center depth H (Zhao *et al.* 2012, Kavvas *et al.* 2017). Roller boundary conditions were applied to both sides and the base to restrict the horizontal and vertical displacements, respectively. Induced internal forces and convergence in the lining were deemed crucial during the design stage, focused investigation. Typically, in a two-dimensional model, a beam model of two rings that considers the transversal joints in the links between the rings can be used to consider changes in ground conditions or the influence of excavation on the longitudinal direction of the tunnel (Do *et al.* 2013). However, in this study, only one ring section and a longitudinal joint were considered to investigate the effect of the radial interaction between the tunnel and the ground.

2.1.2 Layered ground

For layered ground, a two-layered condition was adopted to consider the influence of the interface between the two layers, and a three-layered condition was used to evaluate the impact of the interlayer. Fig. 2 illustrates the parameters defined for each condition. The inclination angle is the angle formed between the interface of soil layers and the horizontal axis. The layer between soil layers of similar properties is defined as an interlayer, and the angle between the interlayer and the horizontal axis is defined as the interlayer inclination angle. The inclination angle was assigned a positive value when the interface between layers rotated clockwise from the horizontal axis. The ground was

Table 1 Details of the reference case

Parameter	Symbol	Value	Unit
<i>Properties of Shanghai clay</i>			
Unit weight	γ_s	19	kN/m ³
Young's modulus	E_s	20	MPa
Poisson's ratio	μ	0.32	-
Internal friction angle	ϕ	25	°
Cohesion	c	25	kPa
Lateral earth pressure coefficient	K_0	0.5	-
<i>Properties of silica sand</i>			
Unit weight	γ_s	25	kN/m ³
Young's modulus	E_s	100	MPa
Poisson's ratio	μ	0.3	-
Internal friction angle	ϕ	30	°
Cohesion	c	0	kPa
Lateral earth pressure coefficient	K_0	0.5	-
<i>Properties of tunnel lining</i>			
External diameter	D	15	m
Thickness	δ	0.65	m
Unit weight	γ_s	24	kN/m ³
Young's modulus	E_s	25.2	GPa
Poisson's ratio	μ	0.2	-

*Data from a centrifuge experimental study conducted by Zhang *et al.* (2021)

modeled with a four-node plane-strain element (CPE4), and the linear elastic-perfectly plastic Mohr–Coulomb constitutive model (Khezri *et al.* 2016, Rezaei *et al.* 2019, An *et al.* 2022), was adopted, being a widely used model in the finite element analysis of tunnels. This study investigated a two-layered condition consisting of a soft top soil layer and a stiff bottom soil layer. The properties of Shanghai clay were assigned to the top layer, while silica sand properties were assigned to the bottom layer (Table 1). A three-layered condition was considered by placing a Shanghai clay interlayer between silica sand layers.

2.1.3 Tunnel lining

In this model, the segment was modeled as a two-node linear beam element (B21), and a linear elastic model with the input parameters listed in Table 1 was adopted. In the simulation, the internal forces induced in the segmental

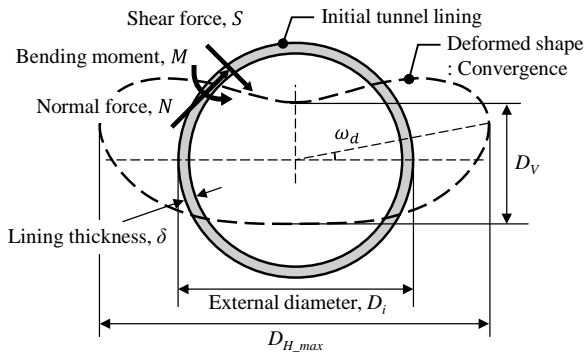


Fig. 3 Illustration of internal forces and convergence induced in the tunnel lining

lining were investigated, and the definitions and notations of the analyzed bending moment, shear force, and normal force are presented in Fig. 3. The convergence of the tunnel lining was evaluated, focusing on the vertical diameter change between the crown and invert ($D_V - D_i$), horizontal diameter change ($D_{H,max} - D_i$), and deflection angle (ω_d). The deflection angle is the angle between the point where maximum horizontal convergence occurs and the horizontal axis of the tunnel.

2.1.4 Longitudinal joint

The lining of a shield-driven tunnel is formed by connecting a ring in the longitudinal direction of the tunnel, comprising radial bonds between the segments. The connections between the segments and the rings include a high degree of jointing. Each ring comprises individual segments and longitudinal joints along the periphery of the tunnel, with transverse joints formed between the rings. In the numerical model, a longitudinal joint links two adjacent segment nodes and contains six DOF (three translational and three rotational components). In the two-dimensional model, the translational component in the longitudinal direction of the tunnel, and the rotational component about the axis parallel to the plane, were ignored. Therefore, a longitudinal joint can be modeled using two translational components (in the x - and z -directions) and one rotational component. The translational and rotational relative motions were modeled to exhibit spring-like behavior by adjusting the rotational, axial, and radial joint stiffnesses in connector elements (Fig. 4). For a comparative investigation of the influences of joint stiffness and arbitrary distribution under layered ground conditions using a simplified model, an elasticity model was adopted for the connector behavior. The results of a parametric study conducted by Do *et al.* (2013) for a broad range of joint stiffnesses under uniform ground conditions indicated negligible effects on the axial and radial stiffnesses. It was observed that rotational stiffness had a significant effect on the bending moment and convergence induced in the lining. Therefore, the influence of rotational stiffness was mainly evaluated; in the model, the translational components were fixed, and the stiffness of the rotational component was assigned through the ROTATION connector (Abaqus/CAE 2022). The longitudinal joint between the segments was assumed to follow Janssen's simplified model, which

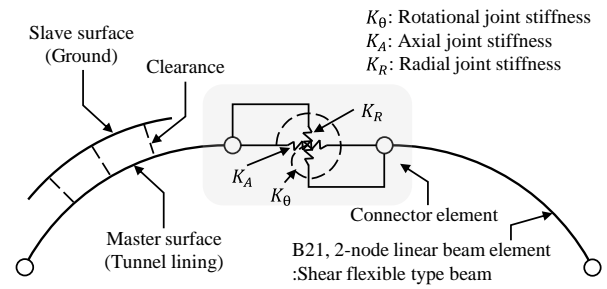


Fig. 4 Illustration of the connector element for longitudinal joints and the tunnel lining-ground interface

considers it as a contact between concrete surfaces with linear elastic behavior (Janssen 1983). The rotational stiffness of the joint, K_θ , calculated based on the maximum limit bending moment derived from the tunnel lining parameters listed in Table 1 was 500 MNm/rad/m.

2.1.5 Ground-tunnel lining interface

The interaction between the ground element and tunnel lining element was characterized using a surface-to-surface pressure-overclosure interface (Fig. 4). At the interface, the extrados of the tunnel lining, which was stiffer than the ground, was adopted as the master surface, and the excavated surface of the ground was designated as the slave surface. The normal behavior of the contact interface was simulated using the “hard contact” algorithm, which is commonly used in situations where support installation is performed simultaneously with excavation in a pressure-overclosure relationship (Abaqus/CAE 2022). The normal distance between the two surfaces was assumed to be 0 (excluding the annular gap and grouting). To consider the worst-case scenario, in which all loads from the layered ground are applied to the tunnel lining, the penalty effect was disregarded (Do and Dias 2018). To simulate a situation in which a shield-driven tunnel is integrated with the ground after grouting, a rough algorithm was adopted for the tangential behavior; furthermore, the full-bonding condition between the ground and tunnel lining was considered (Zhang *et al.* 2021).

2.2 Simulation procedure

The simulation comprised the geostatic, excavation, and tunnel lining installation steps. Fig. 5 demonstrates a simplified flowchart containing every step of the simulation procedure. To mitigate numerical instability within the layered ground, an appropriate geostatic stress field for each layer was predefined before the geostatic step. The tunnel excavation and tunnel lining installation were modeled using the “model change” method (Abaqus/CAE 2022). Once the ground elements were in equilibrium with respect to the gravitational force, the ground elements within the area to be excavated were deactivated. To simulate the support after excavation, the tunnel lining elements and the contact interface with the ground were activated simultaneously. Finally, after reexamining the balance of the gravitational force, the internal force and convergence induced in the tunnel lining were analyzed.

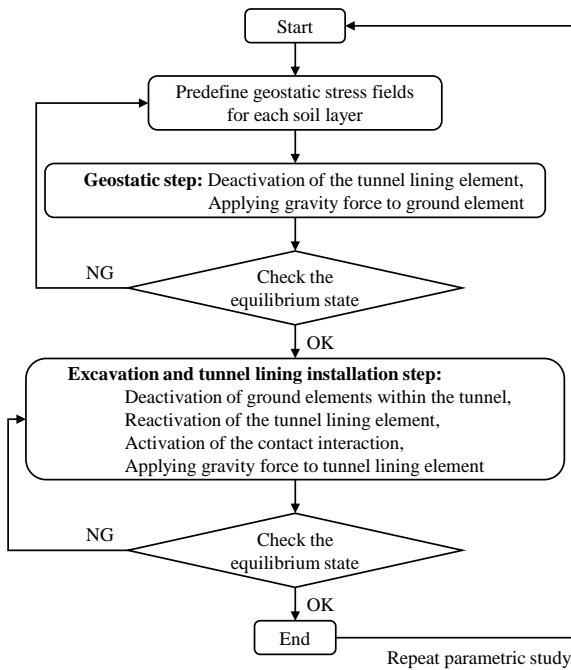


Fig. 5 Flowchart for the simulation procedure

2.3 Model validation

The validation of the established numerical model involved two distinct aspects: verification of internal forces induced in the tunnel lining due to the interaction with the layered ground, and validation of the joint model using connector elements adopted for segmental lining modeling. These validations were conducted independently. The validations focused on comparing the bending moments induced in the lining, the main mechanical considerations in the tunnel lining design.

2.3.1 Induced internal forces of tunnel lining in layered ground

The results of the centrifuge test performed by Zhang *et al.* (2021) were used to validate the numerical model simulating the interaction between the layered ground and the tunnel. Table 1 lists the parameters used herein. Consequently, the behavior near the interface was adequately captured, and the size and distribution of the bending moment concurred in two different methodologies (Fig. 6). This confirmed that the interaction between the layered ground and the tunnel lining accurately reflects the effect on the internal forces.

2.3.2 Changes in internal forces of tunnel lining by joint stiffness

The results of an FDM-based study conducted by Do *et al.* (2013) were compared to validate the joint connector model; Table 2 lists the parameters used therein. The rotational stiffness ratio, $\lambda = K_R / EI$, a dimensionless factor proposed by Lee *et al.* (2001), was adopted to compare the bending moment induced in the lining. The bending moment ratio, the ratio of the maximum absolute value of the bending moment induced in the segmental lining to the corresponding value developed in the continuous lining,

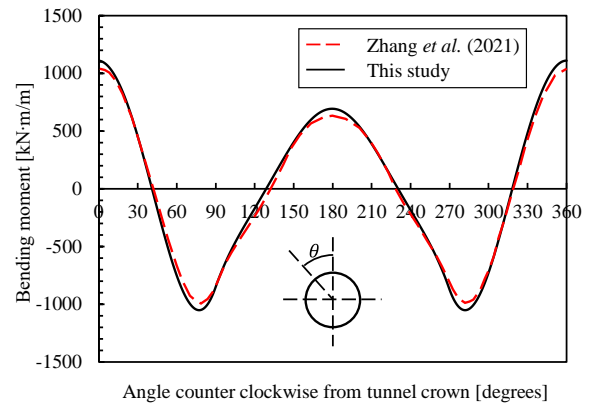


Fig. 6 Comparison of bending moment induced in layered ground tunnel lining for validating numerical model

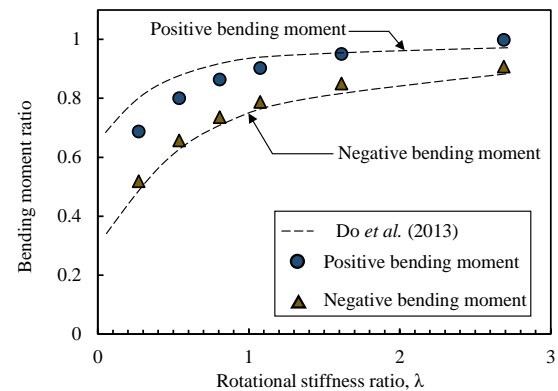


Fig. 7 Comparison of the bending moment ratio with the rotational stiffness ratio for validating joint elements

Table 2 Joint element validation parameters

Parameter	Symbol	Value	Unit
<i>Properties of clayey sand</i>			
Unit weight	γ_s	17	kN/m ³
Young's modulus	E_s	150	MPa
Poisson's ratio	μ	0.3	-
Internal friction angle	φ	37	°
Cohesion	c	500	kPa
Overburden	H	20	m
Lateral earth pressure coefficient	K_0	0.5	-
<i>Properties of tunnel lining</i>			
External diameter	D	9.1	m
Thickness	δ	0.4	m
Unit weight	γ_s	24	kN/m ³
Young's modulus	E_s	35	GPa
Poisson's ratio	μ	0.15	-

*Data from an FDM numerical study conducted by Do *et al.* (2013)

was compared with λ . The results of the joint connector established in the FEM-based model are similar to the results of the FDM-based model reported in the literature (Fig. 7).

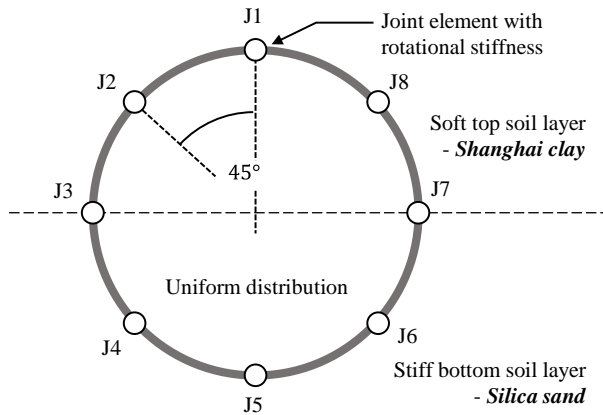


Fig. 8 Schematic of an eight-segment ring configuration with the joint element as reference case

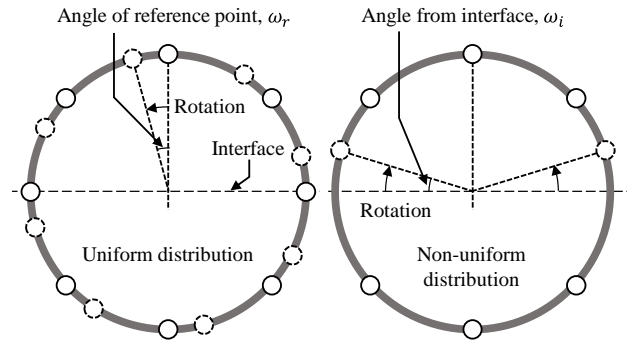


Fig. 10 Joint distributions for the uniform type (left) and the non-uniform type (right) orientations

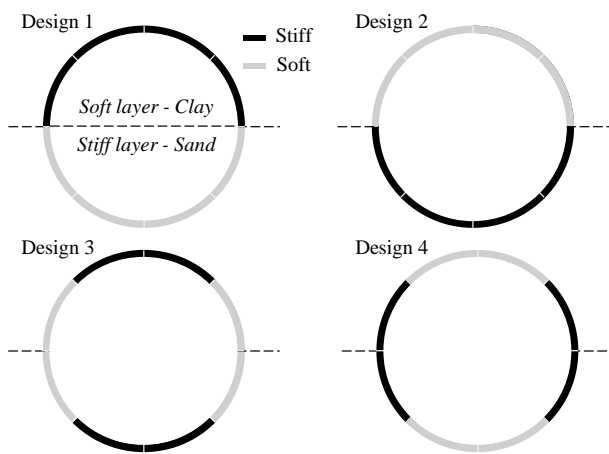


Fig. 9 Schematic of the individual segment stiffness design method

3. Parametric study

This study aimed to evaluate the behavior of segmental linings under layered ground conditions by investigating the influence of design factors. Accordingly, a comprehensive parametric study was conducted using a series of numerical simulations based on the validated model. This section describes the factors primarily considered in this study, which significantly influence the behavior of large-diameter tunnels. Subsequently, a comparative analysis was conducted on the impact of each factor on the tunnel behavior, specifically focusing on changes in the internal forces and convergence induced in the lining owing to interactions with the layered ground. Based on the main findings, an enhanced design for a large-diameter shield-driven tunnel in multi-layered strata was proposed.

3.1 Influencing factors and case configuration

The most crucial factor in segmental lining design is the ring configuration, which is determined by the number of segments. An increase in the number of segments reduces the rigidity of the segmental ring. However, in practical engineering considerations, optimizing the design for efficient transportation and erection processes favors an increased number of segments as the tunnel diameter increases. A specialized approach is necessary for designing tunnels with diameters exceeding 11 m, such as dividing the tunnel into eight segments, each covering 45°, and dividing one segment into key and counter-key segments (ITA Working Group 2 2019). The load applied to each segment decreases as the number of segments (i.e., the number of joints) increases, resulting in reduced bending moments and a diminished orientation influence (Do *et al.* 2013). Therefore, in this study, the minimum recommended number of segments for the tunnel diameter was adopted to investigate the influence of the joint distribution. A large-diameter tunnel with a diameter of 15 m consisting of eight segments, each covering 45° without a key segment, was used as a reference case (Fig. 8).

The primary factors influencing segmental lining design include segment stiffness and joint parameters. A thorough parametric study was conducted to assess the behavior of segmental linings under layered ground conditions, focusing on the impact of these two factors. Table 3 lists the

Table 3 Numerical simulation cases for the parametric study

Segment stiffness				
Case No.	Segment stiffness [GPa]	Segment stiffness of soft section [GPa]	Segment design method [-]	
1	2.5, 5, 7.5, 12.5, 18.75, 25	-	reference	
2	25	12.5	1, 2, 3, 4	
Joint parameters				
Case No.	Angle of reference point [°]	Angle from interface [°]	Rotational stiffness [MN·m/rad/m]	Joint design method [-]
3	0, 22.5	-	10, 50, 100, 200, 500, 1500	Uniform, Equal stiffness
4	0	-	10, 50, 100, 200, 300	Uniform, Non-equal stiffness
5	2.5 intervals from 0 to 22.5	-	500	Non-uniform, Equal stiffness
6	-	2.5 intervals from -45 to 45	10, 50, 100, 200, 300	Non-uniform, Non-equal stiffness

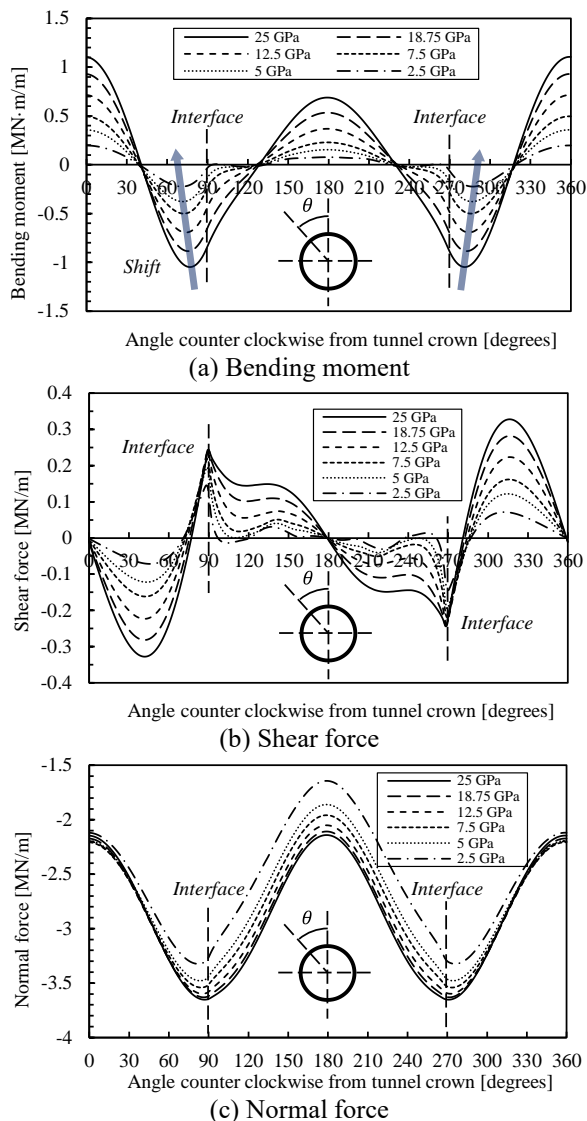


Fig. 11 Internal forces induced in the lining depending on the segment stiffness under two-layered ground conditions

numerical simulation cases for the parametric studies. A clear understanding of the interaction between the lining and the layered ground is imperative for the design of a segmental lining under layered ground conditions characterized by complex tunnel behavior distinct from uniform ground conditions. Case 1 involves the evaluation of lining deformation with variations in the segment stiffness, examining its interaction with the surrounding ground. To explore an economical design approach of segment stiffness, four individual segment stiffness design methods were considered (in contrast to employing segments with high strength to resist deformation (Fig. 9)), which accounted for the relative stiffness and interfaces of the soil layers. The impact of each design method on the tunnel behavior in layered ground was comprehensively evaluated in Case 2, with the results analyzed from a practical perspective.

The joint parameters influencing the tunnel behavior are the joint rotational stiffness and distribution. For Cases 3–6,

each element was distinctly investigated to delineate the impact of the joint parameters on the tunnel behavior under layered ground conditions (Table 3). Cavalaro and Aguado (2010) conducted experimental research on various packers used to prevent excessive stress concentration between segments. They found that the stiffness of longitudinal joints was affected by the properties of the packer materials and the load combination. To investigate the effect of the rotational stiffness of a joint in practical terms, a comprehensive range should be considered based on the stiffness derived from the contact between the concrete segment surfaces. Do *et al.* (2013) found that when the rotational stiffness ratio was approximately 2.5, the effect of the joint was negligible. Considering the parameters of the tunnel lining listed in Table 1, when λ is 2.5, the rotational stiffness may be backwards-calculated as 1441.75 MNm/rad/m. Therefore, the influence of the joint rotational stiffness was investigated over a range from small stiffnesses that behave like a hinge to values where the joint influence is negligible (i.e., ranging from 10 to 1500 MNm/rad/m).

The joint configurations were classified depending on two main parameters: spacing and rotational stiffness. The configuration with a constant joint spacing was categorized under the uniform type, and the one with a varying joint spacing under the non-uniform type. Additionally, rotational stiffness was considered, with uniformity across all joints indicating the equal stiffness type and variations among joints indicating the non-equal stiffness type. Fig. 10 illustrates the definitions of the reference point and interface angles for uniform and non-uniform type configurations, respectively. In the context of tunnel behavior under uniform ground conditions, an eight-joint lining with a reference point angle of 0° is considered favorable, whereas an angle of 22.5° indicates a critical-type configuration (Do *et al.* 2013).

3.2 Segment stiffness

3.2.1 Continuous lining stiffness

To investigate the resulting internal forces and convergence induced in the lining under layered ground conditions, the segment stiffness was varied from 25 to 2.5 GPa. The internal forces induced in the lining, including the bending moment, shear force, and normal force, decreased as the stiffness of the lining decreased (Fig. 11). Notably, the point with the maximum negative bending moment shifted to the soft layer (Fig. 11(a)). This can be explained by the interaction between the tunnel lining and the layered ground. The lining deforms when subjected to ground pressure and then causes a reaction force on the surrounding ground. Consequently, among soil layers, the soft soil layer with a low stiffness predominantly undergoes deformation. This leads to a redistribution of the ground pressure acting on the lining and changes in the internal forces induced in the lining. These results show that the lining deformation in the soft soil layer alleviates internal forces in the lining, thereby influencing the overall tunnel behavior. The internal force relaxation induced in the lining is more pronounced when the deformation in the soft soil layer increases as the

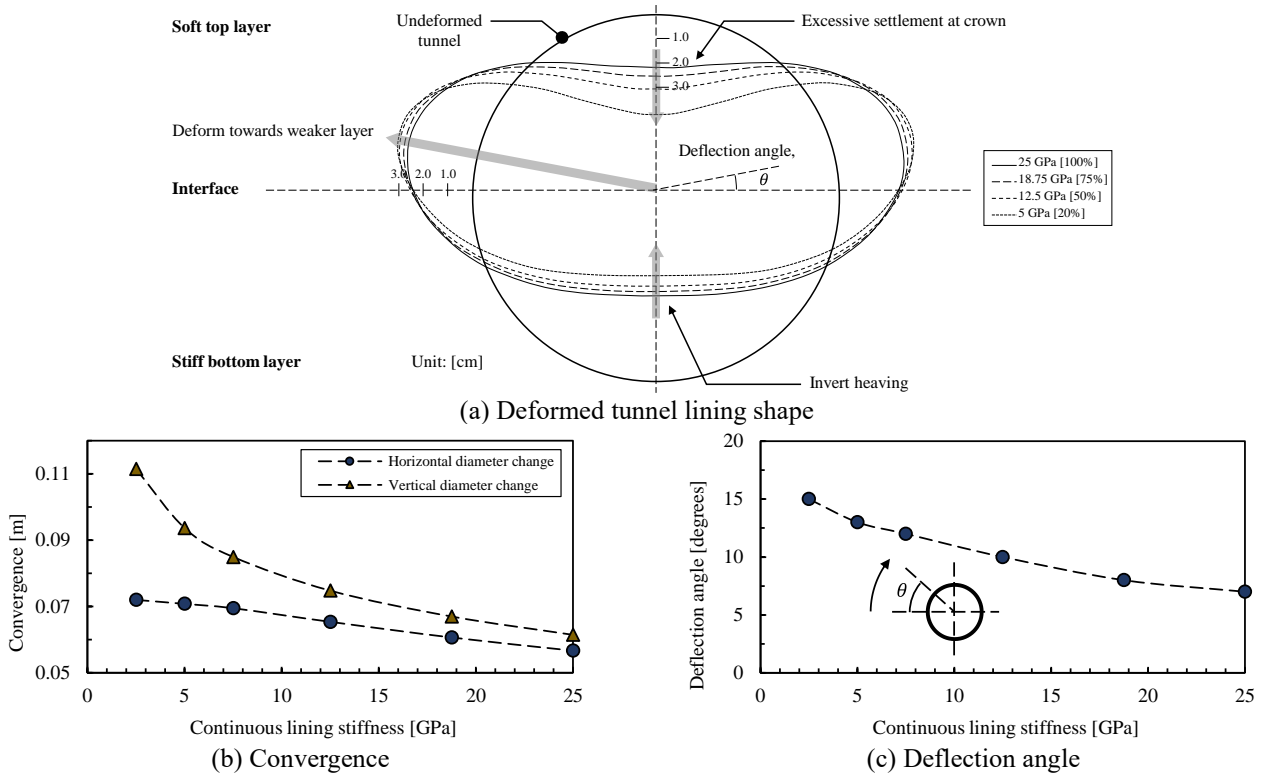


Fig. 12 Tunnel convergence depending on segment stiffness under two-layered ground conditions

lining stiffness decreases. Similarly, the shear forces are generally reduced with decreased lining stiffness. Around the soil layer interfaces, the dissipation of shear forces due to the decrease in lining stiffness was more effective in a stiff soil layer (Fig. 11(b)). A minimal change was observed in the normal forces within the practical range of the segment stiffness (Fig. 11(c)). This can be explained by the fact that the change in confining pressure on the lining is insignificant, even though the deformation of the soft soil layer redistributes the ground pressure. Thus, the impact of layered ground conditions on the normal force is negligible.

Fig. 12 depicts the convergence of the tunnel in layered ground with respect to the lining stiffness variation. Due to the lateral earth pressure coefficient being less than 1 ($K_0 = 0.5$), resulting in a vertical load on the lining greater than the horizontal load, the internal diameter at the crown narrowed, and the springline underwent expansion, leading to a prevalent convergence in the transverse ellipse mode (Xie *et al.* 2021). Convergence is increased due to increased lining deformation resulting from decreased lining stiffness. It is notable that lining deformation occurs predominantly in the soft soil layer, and as the lining stiffness decreases, the point with maximum horizontal convergence shifts to the soft soil layer (Fig. 12(a)). As the lining stiffness decreases, in contrast to the increase in the horizontal diameter, the vertical diameter decreases, causing the lining to develop progressively into a “peanut shape” (Fig. 12(b)). The deflection angle between the point of maximum horizontal convergence and the horizontal axis of the tunnel increased as the lining stiffness decreased (Fig. 12(c)). This indicates that as the lining stiffness decreases, the lining deflects

toward the soft soil layer. These findings have important implications for economic design considerations. It is recommended that segments with relatively low stiffness be used in the section adjacent to the soft soil layer to efficiently mitigate the internal forces induced in the lining. This approach facilitates a reduction in the section forces, potentially reducing the thickness and strength of the segments. However, the utilization of segments with low stiffness may cause the lining to deflect toward the soft soil layer or cause excessive convergence. Therefore, in practical terms, segment stiffness should be designed to satisfy the allowable deformation level criteria for tunnel lining.

3.2.2 Individual segment stiffness design

To investigate the effect of the non-uniform segment stiffness design considering the layered strata on the mechanical response of the tunnel lining, four design methods were considered (Fig. 9). To account for the relative stiffness differences between segments, the stiffness of the stiff segment was set to be the same with the reference case at 25 GPa, while the stiffness of the soft segment was assumed at 12.5 GPa. Common to all design methods, the bending moment and shear force in the area near soft segments decreased (Fig. 13). This can be explained by the soft segment inducing large deformation in the surrounding ground, thereby relieving the internal forces induced in the segment. A key finding is that the soft segment affects not only its surrounding area but also the overall mechanical response of the lining by influencing the internal force distribution. Notably, the behavior of the

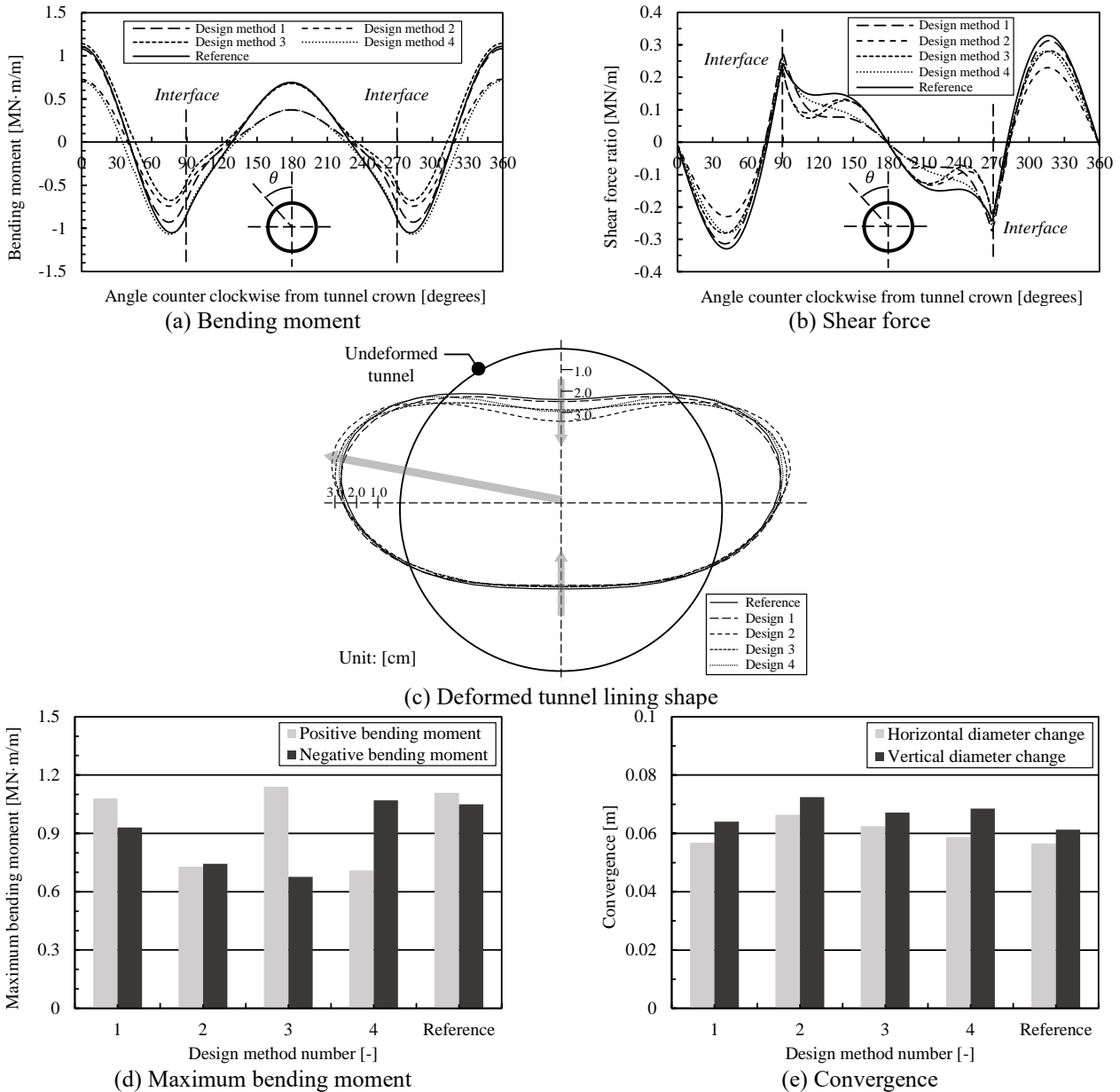


Fig. 13 Internal forces and convergence of the lining according to the individual segment stiffness design method

tunnel differed significantly depending on the placement of the soft segments. Design 1, involving a stiff segment in the upper half of the tunnel, partially mitigated the negative bending moments, despite the convergence levels being comparable to the reference case. This outcome arises from permitting some deformation in the stiff bottom soil layer while constraining excessive deformation in the soft top soil layer through the use of the stiff segment. Design 2, which applied a soft segment in the upper half of the tunnel, effectively alleviated the internal forces of the lining by inducing deformation of the soft top soil layer. However, significant convergence issues were observed. Design 3, which employed soft segments in the springline, induced deformation in the soft soil layer around the interface, significantly reducing the negative bending moment, but increasing horizontal convergence in the soft layer. In Design 4, which features a stiff segment in the springline

and a soft segment in the crown, a substantial vertical convergence problem was observed due to significant deformation of the soft layer near the crown. Nevertheless, it was confirmed that the positive bending moment was effectively alleviated. These findings highlight the feasibility of economically designing large-diameter tunnels in the layered ground by mitigating internal forces by utilizing soft segments partially. However, the importance of determining suitable segment stiffness and arrangement considering practical considerations such as lining deflection verification is also emphasized (ÖVBB 2011).

3.3 Joint parameters

3.3.1 Joint rotational stiffness

To comparatively investigate the effect of the rotational stiffness of the joint on the mechanical response of a large-

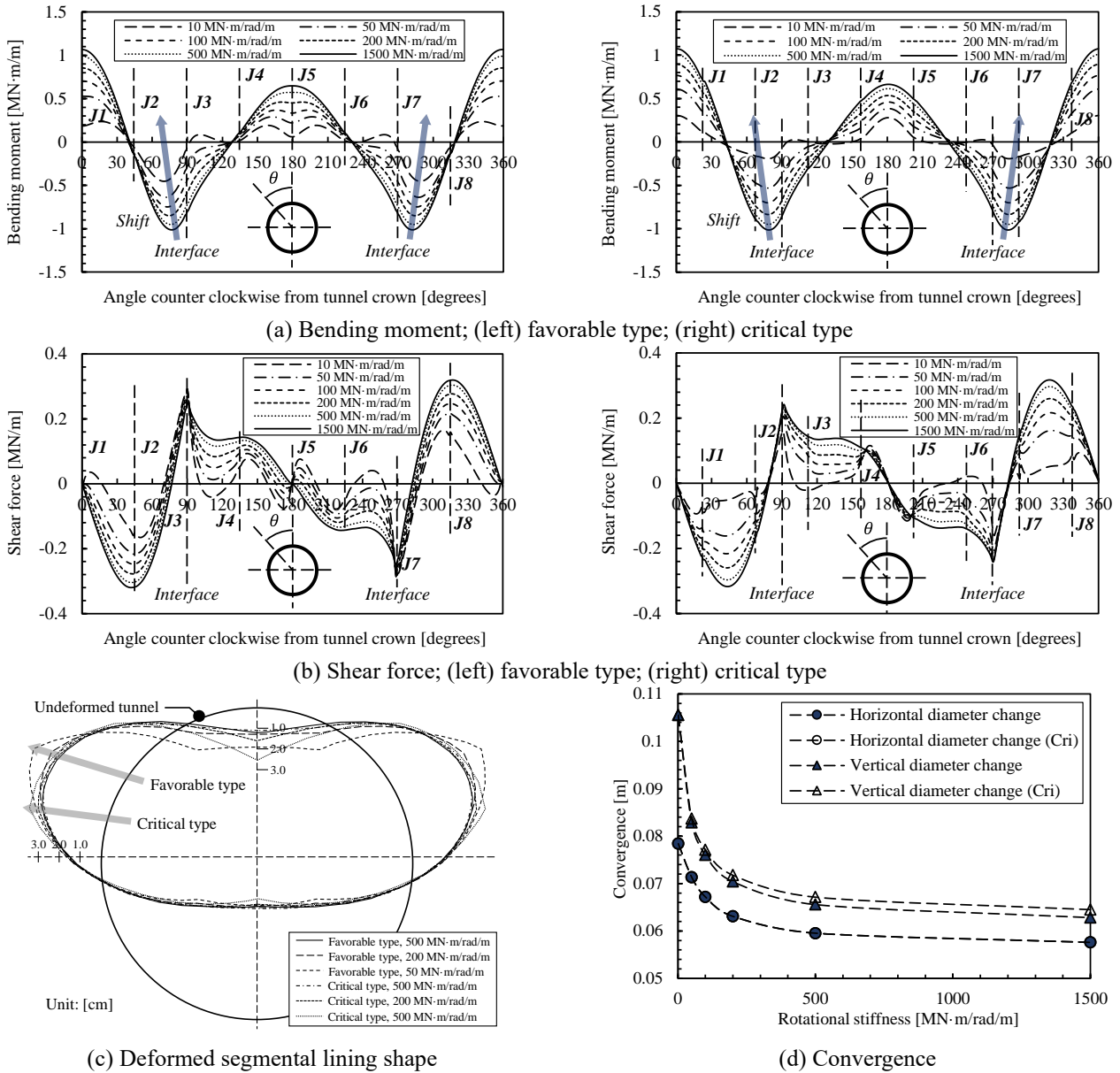


Fig. 14 Internal forces and convergence of segmental linings according to the rotational stiffness

diameter tunnel under layered ground conditions, the rotational stiffness was varied from 1,500 to 10 MNm/rad/m. Fig. 14 presents the internal forces and convergence of the lining for the favorable and critical orientation types according to rotational stiffness. The bending moments induced in the lining, which are independent of joint distribution, were alleviated as the rotational stiffness decreased. This resulted from the increase in the deformation of the lining as the rotation of the segments at the joint progressively increased, signifying a transition in the joint behavior from spring-like to hinge-like (Rashiddel *et al.* 2022). It is important to note that with a decrease in the rotational stiffness of joint, the point with the maximum negative bending moment shifted to the soft layer (Fig. 14(a)). This can be explained by the fact that the deformation of the surrounding ground due to the rotation of the segments at the joint is dominant in the soft top soil

layer, and it becomes more significant as the joint rotational stiffness decreases. This can be confirmed by the shift in the point of maximum horizontal convergence to a soft layer and deformation of the lining into a peanut shape as the rotational stiffness decreased. The critical-type configuration demonstrated a more significant vertical diameter change (Fig. 14(c)). Regardless of the distribution, it was observed that convergence increased as the rotational stiffness of joint decreased (Fig. 14(d)). These findings highlight that the application of soft joints characterized by relatively low rotational stiffness in practical ranges will enable economical large-diameter tunnel design in layered ground.

Furthermore, to explore the impact of a non-equal rotational stiffness design, the mechanical response of the tunnel was assessed by adjusting the rotational stiffness around the area where a significant bending moment was

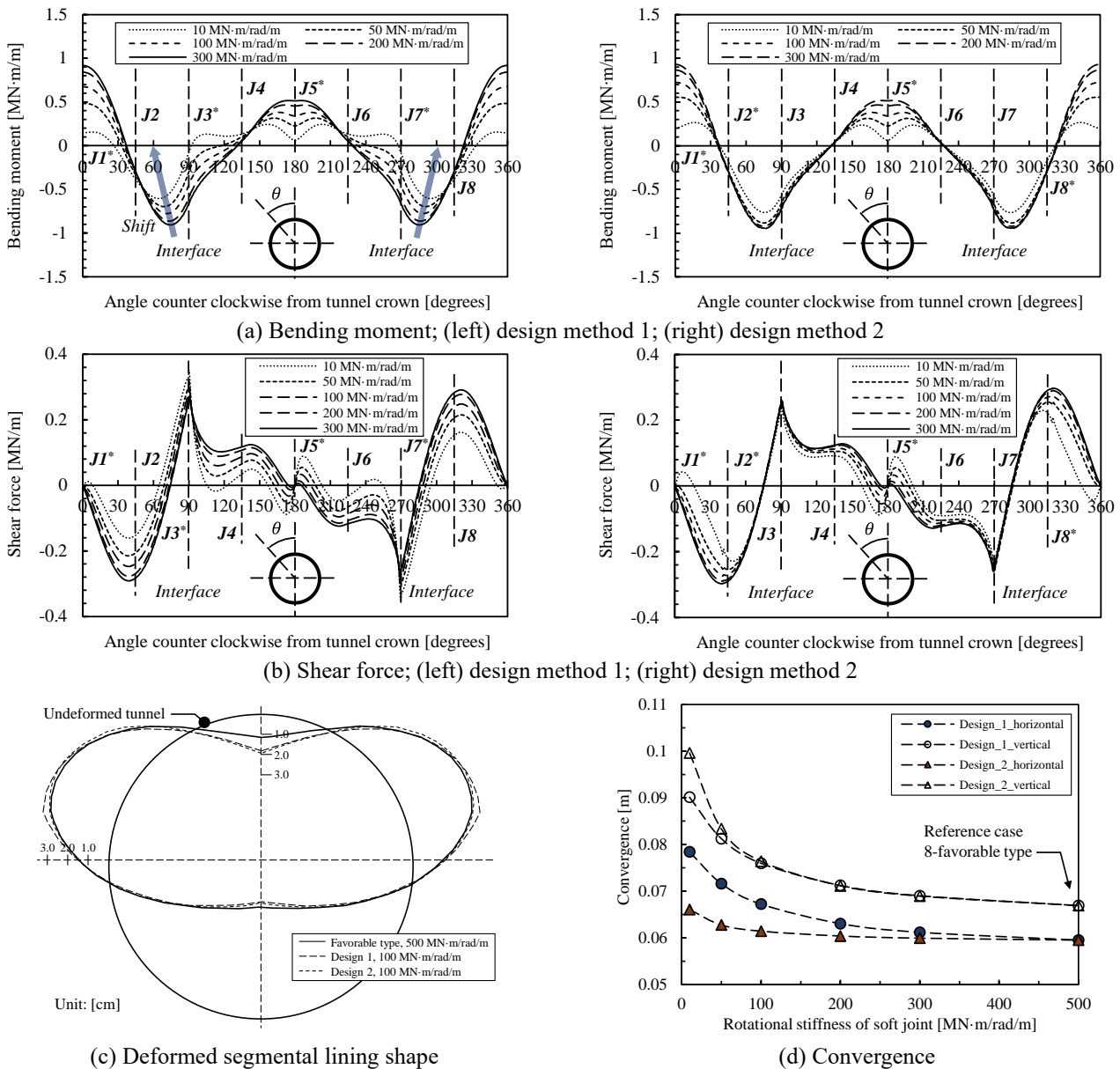


Fig. 15 Internal forces and convergence of lining with the rotational stiffness of soft joint based on the joint design method

induced to a relatively low level. For comprehensive investigation in a practical range, the rotational stiffness of the soft joint was varied from 300 to 10 MNm/rad/m. Method 1 involved the application of soft stiffness to joints 1, 3, 5, and 7, whereas Method 2 employed soft stiffness at joints 1, 2, 5, and 8. The internal forces and convergence changes induced in the lining by the two methods are illustrated in Fig. 15, which depend on the rotational stiffness of the soft joint. The results highlight that the non-equal stiffness design of joints significantly impacts the behavior of tunnels in the layered ground. It was confirmed that applying a soft joint affects internal forces not only in the segment around the soft joint but also in the whole tunnel. Regardless of the design method, as the stiffness of the soft joint decreased, the bending moment induced in the lining decreased significantly (Fig. 15(a)). As the rotational stiffness of the soft joint decreased, the shear force

generally decreased, but the relaxation effect at the soil layer interfaces was insignificant (Fig. 15(b)). Notably, the relief of internal forces induced in the lining was significantly affected by the placement of the soft joint around the point of the maximum negative bending moment. It was found that compared to Method 2, the soft joint in Method 1 was located closer to the point of the maximum negative bending moment, thereby relieving internal forces more effectively. However, this caused the deformation of soft soil layer around the interface, resulting in greater horizontal convergence (Fig. 15(c)). These results indicate that the non-equal stiffness design that partially utilizes soft joints with relatively low rotational stiffness effectively alleviates internal forces induced in the lining under layered ground conditions. Additionally, from a practical perspective, the importance of the strategic placement of soft joints and a stiffness design to control convergence and alleviate internal forces is emphasized.

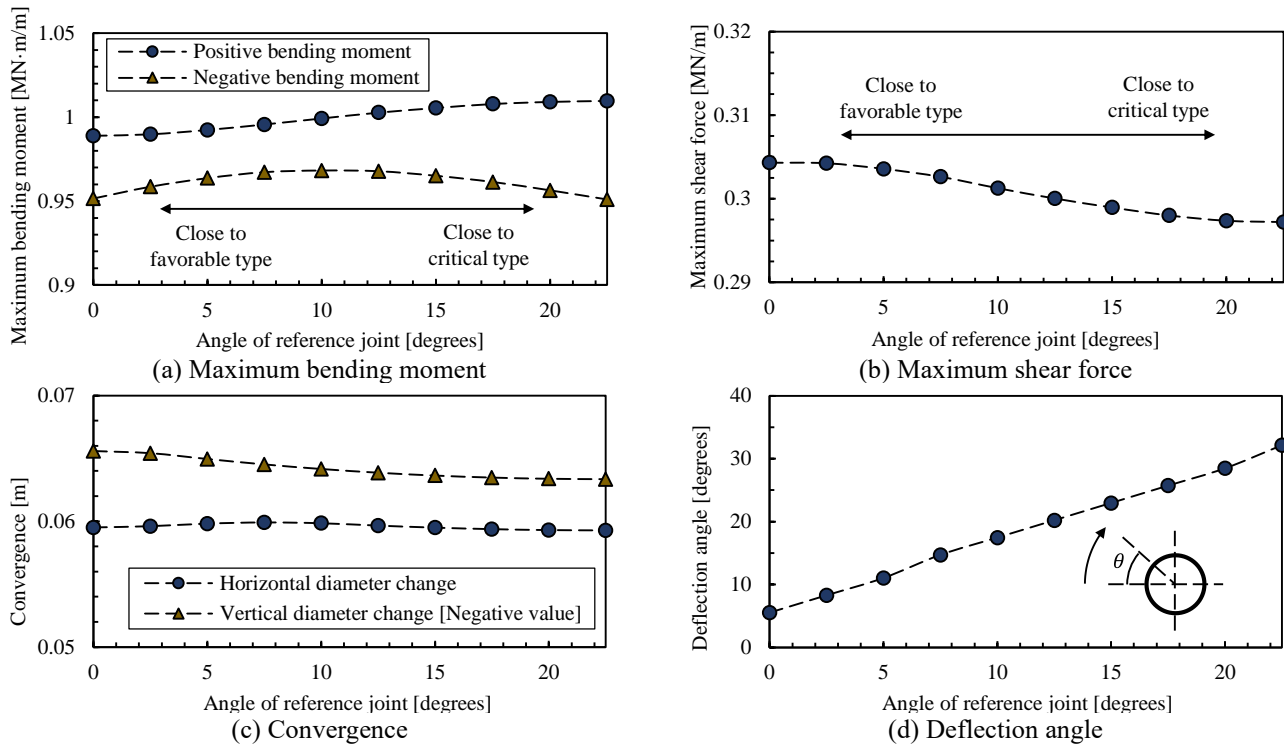


Fig. 16 Internal forces and convergence induced in linings according to the angle of a uniform type reference joint

3.3.2 Joint distribution

To investigate the effect of a uniform-type joint orientation on the behavior of a large-diameter tunnel within layered ground, the angle of the reference joint was varied from 0° to 22.5° in 2.5° intervals (Fig. 10). Fig. 16 illustrates the variation in the maximum internal forces and induced convergence within the segmental lining based on this angle. The results indicated that, as the angle decreases to a favorable orientation of joints, both the positive and negative bending moments decrease. The positive bending moment exhibited an upward trend as the angle increased. In contrast, the negative bending moment initially increased, then peaked, and subsequently declined (Fig. 16(a)). As the angle increased and approached the critical orientation of joints, a slight decrease in the shear force was observed (Fig. 16(b)). This can be explained by the consideration that in uniform distribution design, where all joints rotate simultaneously, one joint near the interface is located in the stiff bottom layer and the remaining joints are located in the soft top layer, causing non-uniform internal forces in the lining. The observation revealed an increase in the deflection angle with changing orientation. However, a minimal change in convergence was observed, and its impact on the deformation of the lining was found to be negligible (Figs. 16(c) and 16(d)). These findings underscore that the uniform distribution joint design is ineffective in alleviating internal forces in the segmental lining design of large-diameter tunnels in layered ground. Nonetheless, the findings have confirmed that this can efficiently manage tunnel convergence from a serviceability perspective.

To explore methods for optimizing joint parameters in

large-diameter tunnels under layered ground conditions, the impact of non-uniform and non-equal stiffness joint designs around the interface on tunnel behavior was evaluated. To consider only the influence of joints around soil layer interfaces, the positions of joints 3 and 7 were varied from -40° to 40° in 2.5° intervals from the interface, while the positions and rotational stiffness of the remaining six joints were kept fixed (Fig. 10). The rotational stiffnesses of soft joints 3 and 7 were varied from 300 to 10 MNm/rad/m. Fig. 17 illustrates the maximum internal forces and convergence according to angles from the interface. The results revealed that the positive bending moment exhibited a minimum value when the joint is placed near the interface, increased to a maximum at approximately $30^\circ - 35^\circ$, and then decreased (Fig. 17(a)). Conversely, the negative bending moment exhibited a decreasing trend, with a minimum value when the joint was located approximately $10^\circ - 15^\circ$ from the interface, and then increased (Fig. 17(b)). This can be explained by the fact that, when the joint is placed at the point with maximum negative bending moment, the deformation of the soft soil layer is increased, and, accordingly, the internal force of the lining is alleviated. These results suggest that optimizing the placement of joints near the soil layer interfaces by shifting them toward a soft layer can significantly alleviate the negative bending moment induced in the lining. Similar trends were observed for the shear forces, where the location of the joint on the soft layer side led to a decrease in shear force (Fig. 17(c)). In contrast, the placement on the stiff layer side resulted in a slight increase in the maximum shear force. These findings imply that optimizing the location of soft joints at the interface of soil layers with different stiffnesses can

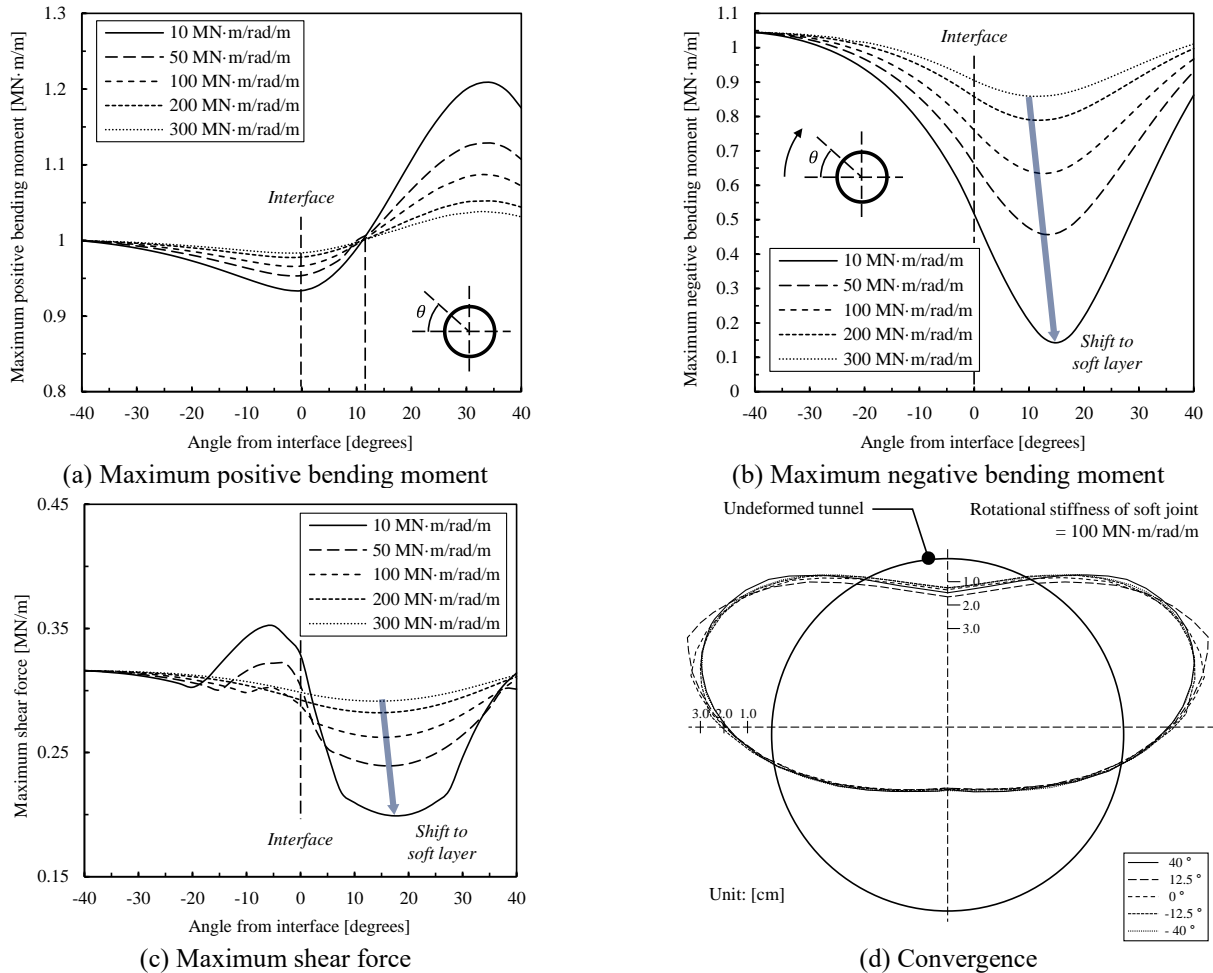


Fig. 17 Internal forces and convergence of lining according to the joint position and rotational stiffness around the interface

effectively mitigate the internal forces including the bending moment and shear force induced in the lining.

An important observation is that the optimal distribution of the joint is also affected by the stiffness of the soft joint. In both the case of maximum negative bending moment and maximum shear force, the shift of the optimal point to the soft soil layer as the stiffness of the soft joint decreases was confirmed (Figs. 17(b) and 17(c)). This can be explained by the fact that a decrease in the stiffness of the soft joint causes greater deformation of the soft soil layer and shifts the point with the maximum negative bending moment. This means that, when simultaneously considering the difference in stiffness of soil layers and the rotational stiffness of the soft joint, the optimal distribution of the joint that can maximize the relief of internal forces can be obtained. Fig. 17(d) illustrates convergence when a soft joint with a rotational stiffness of 100 MNm/rad/m is placed at five different points around the interface. Horizontal convergence was the most pronounced when the soft joint was located at 12.5°, coinciding with the point at which the maximum negative bending moment was minimized. Furthermore, horizontal convergence decreased when the joint was positioned on the stiff soil layer compared with its placement at the interface. These results confirm the effective alleviation of internal forces at an acceptable level

of convergence from a serviceability perspective. These findings suggest a methodology for determining joint parameters to balance the conflicting aspects of internal force relief and convergence management when designing the segmental lining of a large tunnel in layered ground.

4. Design for segmental linings through complex multi-layered strata

4.1 Discussion of robust design method

To explore the mechanical responses of tunnels considering soil stratification, numerous numerical (Chu *et al.* 2007, Nunes and Meguid 2009, Katebi *et al.* 2015, Zhang *et al.* 2015, Do and Dias 2018, Zhang *et al.* 2021) and experimental (Hagiwara *et al.* 1999, Nunes and Meguid 2009, Li *et al.* 2013, Zhang *et al.* 2015, Zhang *et al.* 2021) studies have been conducted. In the two-layered conditions, the key factors considered included the interface location, relative stiffness between the layers, and inclination of the interface. Positioning the interface lower within the tunnel resulted in an increased bending moment, particularly when situated below the springline, leading to increased shear forces. Furthermore, as the interface approaches the invert,

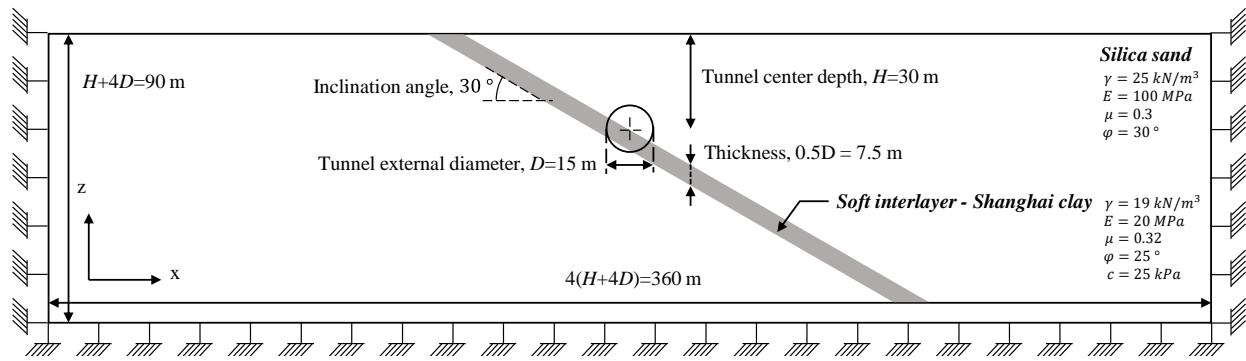


Fig. 18 Schematic of a circular tunnel through complex multi-layered ground in a numerical model

convergence becomes significant. An increase in the relative stiffness difference between the two layers was associated with elevated bending moments, shear forces, and convergence, with a pronounced impact near the interface. The influences of the interface location and relative stiffness disparity on the normal force were found to be negligible. The inclination of the interface introduced an asymmetrical distribution of internal forces within the lining, with larger internal forces and convergence as the inclination angle increased, particularly in sections exposed to wider soft layers. In the three-layered conditions, the significant factors include interlayer location, interlayer thickness, and relative stiffness between the layers. A lower placement of a relatively soft interlayer within the tunnel resulted in higher bending moments. When situated below the springline, it leads to substantial convergence. The bending moment and convergence increased with the increase in the thickness of the interlayer. Variations in relative stiffness affected the bending moments, shear forces, and convergence, with more significant differences yielding more pronounced effects. These factors had negligible impacts on the normal force.

Based on a comprehensive literature review, the most complex multi-layered ground condition arises when a soft interlayer, characterized by a significant discrepancy in relative stiffness, assumes an inclined disposition beneath the springline. Findings from the parametric studies in the previous chapter indicate that the design of joint parameters around soil layer interfaces has a substantial impact on the mechanical response of large-diameter tunnels. This demonstrates that internal forces in segmental linings can be effectively mitigated by optimizing the rotational stiffness and distribution of joints around soil layer interfaces. Placing soft joints, characterized by relatively low rotational stiffness, on the side of the soft soil layer at interfaces can significantly reduce the negative bending moments and shear forces induced in the linings. However, this design can induce excessive deformation of the soft layer, resulting in significant convergence problems characterized by large horizontal convergence and peanut-shaped deflections. Therefore, from a practical perspective, the robust design of large-diameter tunnels in layered strata necessarily requires meeting acceptable convergence criteria through strict deflection verification. Design guidelines involving the optimization of joint parameters derived from layered

ground conditions can be applied in a similar way to interlayer interfaces in multi-layered ground conditions. Therefore, in the following section, the mechanical responses of large-diameter tunnels in complex multi-layered strata according to a special design based on the proposed method and conventional design of 8-joint favorable type were comparatively analyzed.

4.2 Special joint design

To investigate the effectiveness of the proposed method, ground conditions that complicated the tunnel behavior derived through a comprehensive literature review in Section 4.1 were assumed (Fig. 18). In the assumed complex multi-layered ground condition, a three-layered condition with a Shanghai clay interlayer between silica sand layers crossing the lower half of the tunnel at an inclination angle of 30° was considered as a geological factor ($E_{\text{clay}}/E_{\text{sand}} = 0.2$). The interlayer was assumed to be located below the springline, and the bottom of the interlayer was located at the invert of the tunnel. To limit the occurrence of excessive convergence and alleviate the internal forces induced in linings, the rotational stiffness of the joints around the interfaces was assumed to be 100 MNm/rad/m, and the remainder were set to 500 MNm/rad/m.

Given the formation of two interfaces owing to the inclined interlayer across the tunnel, the parameters of the four adjacent joints need to be determined. Concurrent consideration of the parameters of the four joints mutually influencing one another is necessary for accurate optimization. However, this approach requires substantial computational resources considering the number of involved parameters. For efficient optimization during the preliminary design stage, a sequential optimization strategy that focuses on the joints closest to the interface based on the distribution of the favorable joint type can be effective. Therefore, optimization was prioritized on the interface located at the bottom of the interlayer and at the intersection of the invert. Next, the positions of the remaining joints were sequentially determined to derive a joint design with optimal distribution. As this sequential optimization is repeated, the obtained results gradually converge towards those achieved through the simultaneous consideration of multiple parameters. However, this iterative approach may

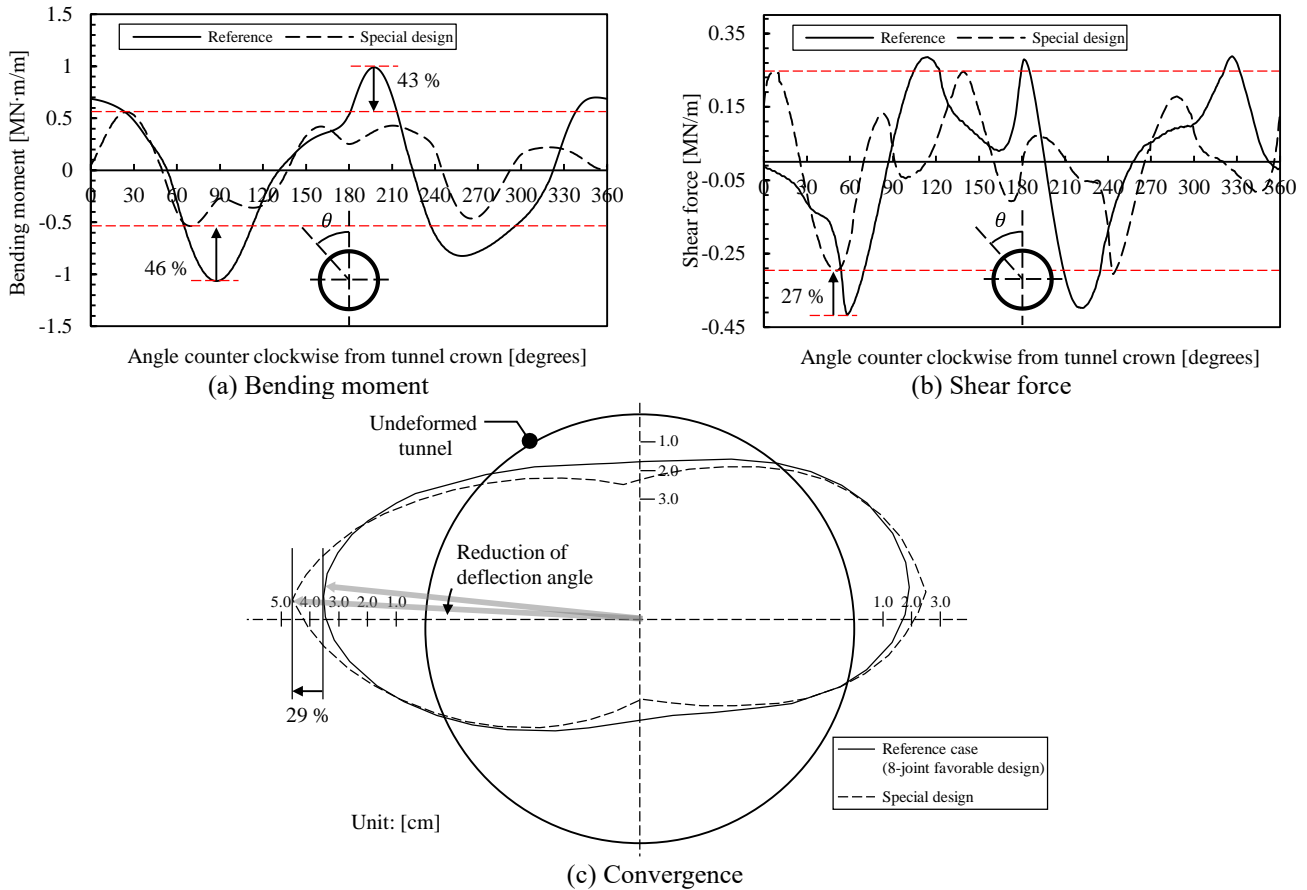


Fig. 19 Comparison of uniform favorable and special designs for segmental linings through complex multi-layered ground

eventually decrease efficiency, rendering it unsuitable for simple reviews in the preliminary design phase. Therefore, in this study, only one cycle was considered without considering the iterative approach. Fig. 19 shows the mechanical response of the linings for each design in terms of the induced internal forces and convergence. Compared to the conventional design with a uniform favorable orientation, the non-uniform design based on soft joint distribution optimization effectively mitigated the bending moments and shear forces induced in the linings. The maximum bending moment was effectively reduced, in particular, the reduction in the negative bending moment was greater (Fig. 19(a)). The shear forces showed similar results (Fig. 19(b)). It was observed that soft joint distribution optimization not only alleviates the induced internal forces but also affects their distribution. This may result from the distribution of the ground pressure applied to the lining changing due to the deformation of the soft interlayer. It was confirmed that horizontal convergence slightly increased due to the deformation of the soft interlayer (Fig. 19(c)). Previously, the Austrian Society for Concrete and Construction Technology (ÖVBB 2011) presented a serviceability limit for deformation verification of segmental lining with diameters up to 8m. They recommended a vertical displacement of 15 mm for the crown and invert and 35 mm for the horizontal displacement of the sidewall as allowable deformation limits in a segmental lining with a diameter of 8 m.

Assuming that the allowable deformation increases linearly with increasing diameter, the allowable horizontal deformation of the large-diameter tunnel considered in this study with a diameter of 15 m is approximately 65 mm. Therefore, the convergence of the lining resulting from the special design through the proposed method satisfies the serviceability limit criteria for deformation. In addition, it was confirmed that the lining that had been deflected by non-uniform ground pressure was partially relieved.

These results highlight that a design method based on a soft joint distribution optimization strategy considering soil interlayer interfaces can be effectively utilized in the preliminary design stage of segmental linings of large-diameter tunnels under multi-layered strata. The proposed method was derived by focusing on segmental lining deformation according to joint parameters and changes in internal forces induced in the lining under layered ground conditions. In practical terms, the segmental lining is also affected by groundwater pressure and ground settlement. In shield tunnels under undrained conditions, the groundwater level affects the magnitude of the groundwater pressure applied to the lining and also significantly impacts the deformation of the lining by changing the unit weight and elastic modulus of the soil layer. Changes in the lining deformation affect the ground settlement again, which changes the earth pressure. These variations complicate the ground and lining interactions; however, the proposed method does not consider these factors. Additionally, in

tunnel engineering practice, the joint location of the shield tunnel continuously changes along the longitudinal direction of the tunnel to ensure structural stability by resisting deformation. Segments are manufactured and transported in advance to improve constructability, and therefore adjusting the joint position and segment size is challenging. The results of this study suggest that the proposed method can be applied by maintaining the location of the joints that they are not staggered in the longitudinal direction of the tunnel through straight jointing between segmental tunnel rings in a layered ground section of the same longitudinal profile. However, this design may reduce the stability of the overall tunnel structure, and therefore an in-depth review of the longitudinal behavior of tunnels is recommended. To improve the proposed specialized design method of the large-diameter segmental lining in layered ground, further research involving three dimensional numerical simulations and centrifuges considering tunnel longitudinal design, groundwater pressure, ground settlement, and earth pressure is required.

5. Conclusions

This study conducted a comprehensive parametric investigation using numerical methods to analyze the impact of segment stiffness and joint parameters on the behavior of large-diameter shield-driven tunnels through layered strata. Based on the numerical simulations, key findings and relevant design suggestions are provided as follows:

- In layered ground conditions, deformation of the tunnel lining is predominantly observed in the soil layer with relatively low stiffness. These interaction characteristics between the lining and layered ground significantly influence the overall tunnel behavior
- Application of segments with low stiffness effectively mitigates the induced internal forces within the lining. However, convergence to a peanut shape is observed as the lining deflects toward the soft soil layer.
- Utilization of segments with low stiffness to sections adjacent to the stiffer soil layer effectively alleviated internal forces at acceptable deformation levels.
- As the rotational stiffness of the joint decreases, internal forces induced in the lining decrease, but deformation and of the lining increase within the soft layer.
- Non-equal rotational stiffness design of joints in layered strata significantly influences tunnel behavior, emphasizing the effectiveness of using soft joints to alleviate bending moments at the soil layers interface.
- A uniform distribution design with the same spacing between joints is effective in managing deformation of the lining from a serviceability perspective, but has limitations in relieving internal forces induced in the lining.
- Around the soil layer interfaces, joint placement can be optimized to reduce internal forces induced in the lining. It can be highlighted as a potential solution for improving the

design of segmental linings in layered strata.

- The optimal distribution of joints in a layered ground is affected by the rotational stiffness of the joints. As the rotational stiffness decreases, the optimum joint location shifts toward the soft soil layer.
- The special design based on the proposed method effectively alleviated the internal forces induced in the lining at the allowable lining deformation level in complex multi-layered strata compared to the conventional design.
- The proposed method is limited as it can only be applied by straight jointing between rings on layered ground of the same profile in the longitudinal direction of the tunnel.
- This study focused on analyzing the relationship between lining deformation and the internal forces induced in the lining, but it did not consider the effects of groundwater pressure and ground settlement on changes in the earth pressure that is applied to the lining.

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