Stability prediction and analysis for large underground cavern controlled by weak interlayer zone under high geostress

Shuqian Duan1,2,*, Guofeng Liu3, Po Gao1, Yuanda Sun1, Laibiao Xu1, Bei Cao4 and Quan Jiang2

1 School of Civil Engineering, Zhengzhou University, Zhengzhou, Henan 450001, China
2 State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, Hubei, 430071, China
3 School of Highway, Chang’an University, Xi’an 710064, China
4 Shaanxi Public Resources Trading Center, Xi’an, Shaanxi, 710000

Correspondence should be addressed to Shuqian Duan; shuqianduan@zzu.edu.cn

Abstract: Due to the special engineering geological characteristics of weak interlayer zone (WIZ) with the initial shear, the pre-consolidation, the water softening and clay generation, that occurs between different rock strata (e.g., tuff and basalt), it tends to represent potential threats to the overall stability of large underground cavern under high geostress, such as the large deformation of upper and lower rock masses, structural stress-induced collapse and the time-dependent plastic squeezing-out failure, which could never be neglected, and requires more widespread concern. Focusing on the prediction and analysis of such stability issues induced by WIZ, a novel constitutive model for WIZ, based on the unearthed macro-meso mechanical response of WIZ under complicated unloading stress paths, has been first established, and well embed into the effective numerical calculation platform, to realize the quantitative descriptions of the mechanical effects of stress path, the particle breakage as well as the mechanical parameter evolution of WIZ. Then the rock failure index for WIZ (RFD wiz) was derivated, to help determine the cracking scale, depth and degree of surrounding rock masses with WIZ. Based on the proposed model, the RFD wiz and the cracking-restraint design method, the prediction of the failure position and degree, as well as the dynamic optimization design of the reasonable supporting parameters of rock masses with WIZ in underground cavern, were ultimately realized. This study will provide theoretical basis for the analysis and prediction of the instability of deep underground projects controlled by rock masses with WIZ.

Keywords: Large underground cavern; Weak interlayer zone; Constitutive model; Rock failure index; High geostress

1 Introduction

A series of large and deep underground caverns, with large span and high sidewalls, are being constructed in complex and special tectonically active regions. The surrounding rock masses tend to lose integrity and continuity due to various geological structures, and to suffer from strong unloading disturbance due to the rapid underground excavations [1-4]. Especially, when the large cavern group encounters an interlayer namely weak interlayer zone (WIZ), with the initial shear, the pre-consolidation, the water softening and clay generation, that occurs between different rock strata (e.g., tuff and basalt), it tends to represent terrible excavation unloading destructions [5-10], such as the large deformation of upper and lower rock masses, structural stress-induced collapse and the time-dependent plastic squeezing-out failure, as shown in Figure. 1, which could never be neglected, and requires more widespread concern.
In the literature, some works have been reported on the mechanical model, stability prediction and analysis of WIZ. However, to the authors’ knowledge, the current establishment of related mechanical models mainly corresponds to the creep model relying on the long-term shear deformation and failure of WIZ, the Cauchy elastic model, and the Green superelastic model, etc. Hence, the models cannot directly reflect the nonlinear deformation, unloading volumetric expansion and the deterioration of mechanical parameters under the complex stress paths. That is, it can not meet the objective needs of the stability prediction and analysis of large underground caverns affected by WIZ. Moreover, there is still a lack of effective prevention and control method for the formation and development process of rock mass failure controlled by WIZ, furthermore, influencing the reasonable formulation of engineering disaster prevention strategies.

In view of this, on the basis of fully considering the unearthed macro-meso mechanical response and failure mechanism of WIZ under unloading stress paths under high geostress, a novel constitutive model for WIZ, has been first established, and well embed into the effective numerical calculation platform, to realize the quantitative descriptions of the mechanical effects of stress path, the particle breakage and the mechanical parameter evolution of WIZ. Then the rock failure index for WIZ (RFD_wiz) was derived, to help determine the cracking scale, depth and degree of surrounding rock masses with WIZ. Based on the proposed model, the RFD_wiz and the cracking-restraint design method, the prediction of the failure position and degree, as well as the dynamic optimization design of the reasonable supporting time of rock masses with WIZ in underground cavern, were ultimately realized.

2 Constitutive model establishment based on the unloading mechanical response of WIZ

The macro-meso triaxial loading and unloading test results reveal that the WIZ has significant nonlinearity, expansion dilatancy, parameter degradation, and deformation stress anisotropy under different loading and unloading stress paths and high initial stress states[7-8], which is a key issue that should be considered in establishing a reasonable constitutive model of WIZ. Herein, a simple constitutive model, considering the non-linear dilatation and deterioration of WIZ, namely UDDM model, is built, based on the theory of incremental elastic-plasticity.

2.1 Unloading elastic modelling formulation

The loading and unloading constitutive model of WIZ obeys the following two basic assumptions:(1) The WIZ can be regarded as an isotropic linear elastic material from the initial hydrostatic pressure confining to the unloading point. (2) During the unloading and shearing process of different stress paths, the anisotropy of the deformation parameters (elastic modulus, shear modulus, etc.) could be reflected in the certain difference of the deformation parameters degradation in the direction parallel to the maximum principal stress and perpendicular to the maximum principal stress. And there is a certain functional correspondence between the two-direction parameter degradation.
Figure 2. Two-stage loading and unloading constitutive model of WIZ.

The two-stage loading and unloading constitutive model of WIZ is shown in Figure 2.

(1) Elastic loading stage

The WIZ can be regarded as the isotropic linear elastic medium in the hydrostatic pressure state before unloading, and the matrix form of incremental stress-strain relationship in this stage could be expressed as

$$\begin{bmatrix} \Delta \varepsilon \\ \Delta \sigma \end{bmatrix} = [D] \begin{bmatrix} \Delta \sigma \\ \Delta \varepsilon \end{bmatrix}$$

where $[\Delta \varepsilon]$ and $[\Delta \sigma]$ are respectively the strain increment and stress increment of WIZ; $[D]$ is the corresponding flexibility matrix, which can be seen as follows:

$$[D] = \begin{bmatrix}
\frac{1}{E} & -\frac{\nu}{E} & -\frac{\nu}{E} & 0 & 0 & 0 \\
-\frac{\nu}{E} & \frac{1}{E} & -\frac{\nu}{E} & 0 & 0 & 0 \\
-\frac{\nu}{E} & -\frac{\nu}{E} & \frac{1}{E} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{E}{G} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{E}{G} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{E}{G}
\end{bmatrix}$$

(2)

where $E$, $G$ and $\nu$ are tangent Young’s modulus, shear modulus and the Poisson’s ratio.

When Equation (2) is changed in the principal stress space, it could be formatted as

$$\begin{bmatrix} \Delta \varepsilon_x \\ \Delta \varepsilon_y \\ \Delta \varepsilon_z \\ \Delta \sigma_x \\ \Delta \sigma_y \\ \Delta \sigma_z \end{bmatrix} = \begin{bmatrix}
\frac{1}{E} & \frac{1}{E} & \frac{1}{E} & \frac{1}{E} & \frac{1}{E} & \frac{1}{E} \\
\frac{1}{E-2G} & \frac{1}{E-2G} & \frac{1}{E-2G} & \frac{1}{E-2G} & \frac{1}{E-2G} & \frac{1}{E-2G} \\
\frac{1}{E} & \frac{1}{E} & \frac{1}{E} & \frac{1}{E} & \frac{1}{E} & \frac{1}{E} \\
\frac{1}{E} & \frac{1}{E} & \frac{1}{E} & \frac{1}{E} & \frac{1}{E} & \frac{1}{E} \\
\frac{1}{E} & \frac{1}{E} & \frac{1}{E} & \frac{1}{E} & \frac{1}{E} & \frac{1}{E} \\
\frac{1}{E} & \frac{1}{E} & \frac{1}{E} & \frac{1}{E} & \frac{1}{E} & \frac{1}{E}
\end{bmatrix} \begin{bmatrix} \Delta \sigma_x \\ \Delta \sigma_y \\ \Delta \sigma_z \\ \Delta \sigma_x \\ \Delta \sigma_y \\ \Delta \sigma_z \end{bmatrix}$$

(3)

where $\Delta \varepsilon_x$, $\Delta \varepsilon_y$, $\Delta \varepsilon_z$, $\Delta \sigma_x$, $\Delta \sigma_y$, $\Delta \sigma_z$ are respectively the strain increment and stress increment corresponding to the three principal stress directions in WIZ.

(2) Non-linear unloading degradation stage

In various stress relief paths of confining pressure, higher deviator stress will increase new damage and increase anisotropy. It has also been pointed out that the change of the increment of shear modulus can better reflect the development process of anisotropic damage caused by the deformation of rock and soil materials.[11] Through various unloading tests of WIZ, it can be found that the shearing process is accompanied by the deterioration of the deformation modulus and the generation of anisotropy in the nonlinear loading of WIZ.[7-8]. In this nonlinear unloading stage, the deteriorating shear modulus $G_{pl}$ consistent with the direction of the maximum principal stress and the shear modulus at the starting point of this stage $G_s$ basically satisfy the following equation:
where \( G_{p1} \) is the deteriorating shear modulus consistent with the direction of the maximum principal stress; \( q \) is the generalized shear stress of WIZ at different moments in the process of deterioration at this stage; \( q_f \) is the generalized deviatoric stress corresponding to the unloading ultimate bearing strength; \( q_u \) is considered to be the generalized shear stress of the initial unloading point; \( a \) is the correction factor of stress strain curve ranging from 0 to 1.

Similarly, the relationship between the shear modulus \( G_{p2} \) perpendicular to the direction of the maximum principal stress and the shear modulus corresponding to the starting point of unloading \( G_s \) can be expressed as follows:

\[
G_{p2} = \left[ 1 - a \left( \frac{q - q_u}{q_f - q_u} \right)^2 \right] G_s
\]

(5)

where \( G_{p2} \) is the deteriorating shear modulus perpendicular to the direction of the maximum principal stress; \( b \) is the correction factor of stress strain curve ranging from 0 to 1. When \( G_{p1} \leq G_{p2} \), it reflects the dilatancy anisotropy, otherwise, it can represent the shear shrinkage property of WIZ.

Hence, the matrix of the stress–strain relation in the principal stress coordinate could be seen as

\[
\left[ \Delta \varepsilon_1 \right. \left. \Delta \varepsilon_2 \right] = \begin{bmatrix} \frac{1}{E} & \frac{1}{E} & \frac{1}{E} \\ \frac{1}{E} & \frac{1}{E} & \frac{1}{E} \\ \frac{1}{E} & \frac{1}{E} & \frac{1}{E} \end{bmatrix} \begin{bmatrix} \frac{1}{2G_{p1}} & \frac{1}{2G_{p1}} & \frac{1}{2G_{p1}} \\ \frac{1}{2G_{p1}} & \frac{1}{2G_{p2}} & \frac{1}{2G_{p2}} \\ \frac{1}{2G_{p1}} & \frac{1}{2G_{p2}} & \frac{1}{2G_{p2}} \end{bmatrix} \begin{bmatrix} \Delta \sigma_1 \\ \Delta \sigma_2 \\ \Delta \sigma_3 \end{bmatrix}
\]

(6)

where \( \Delta \varepsilon_1 \), \( \Delta \varepsilon_2 \), \( \Delta \varepsilon_3 \), \( \Delta \sigma_1 \), \( \Delta \sigma_2 \), and \( \Delta \sigma_3 \) are respectively the maximum, intermediate, and minimum principal stress or strain increments during the nonlinear unloading stages. Then the volumetric strain increment could be obtained as Equation (9)

\[
\Delta \varepsilon_v = (\Delta \varepsilon_v)_p + (\Delta \varepsilon_v)_q = \Delta \varepsilon_v / K_p + \Delta \varepsilon_v / K_s
\]

(7)

\[
K_p = \frac{E}{3(1 - 2\nu)} \quad K_s = \frac{3G}{3G - 2\nu}
\]

(8)

where \( (\Delta \varepsilon_v)_p \) and \( (\Delta \varepsilon_v)_q \) are the volumetric strain caused by hydrostatic stress and the volumetric strain due to shear stress in the unloading stage; \( K_p \) and \( K_s \) are the equivalent elastoplastic volume modulus and the equivalent compression modulus.

2.2 Failure criterion and plastic potential function

Based on the undrained triaxial unloading test results, the Mogi strength criterion could describe the mechanical characteristics of WIZ under loading and unloading. In order to facilitate the selection of plastic potential function and the calculation of partial differentiation, the Mogi-Coulomb strength criterion will be expressed in the form of \( p-q \) stress space, shown as

\[
f^* = q_p p + \beta_p q - k_p = 0
\]

(9)
\[
q_v = \frac{\sqrt{3} \sin \varphi}{\cos \theta_v}
\]
(10)

\[
k_v = \frac{\sqrt{3} \cos \varphi (\frac{\sqrt{3}}{2} - \frac{\sin \theta_v}{3} - \frac{\sqrt{3} \sin \varphi}{\sqrt{3} \cos \theta_v})}{\cos \theta_v - \frac{1}{\sqrt{3}} \sin \theta_v \sin \varphi}
\]
(11)

\[
\beta_v = \frac{\sqrt{3}}{3} q_v
\]
(12)

where \(p, q, c\) and \(\varphi\) are the mean stress, the deviatoric stress, cohesion and internal friction angle; \(\theta_v\) is the stress Lode angle.

For the tensile strength criterion of WIZ, it could be modified as

\[
f' = p - \frac{\sin \theta_v}{3} q - \sigma' = 0
\]
(13)

The tension-shear composite strength criterion of WIZ in \((p, q)\) space is shown in Figure 3.

The final equation of angular bisector is as follows:

\[
\left(\frac{\sqrt{3}}{3} q - (k_v - q_v \sigma') - (k_v - q_v \sigma') p - \frac{\sin \theta_v}{3} q - \sigma'\right) = 0
\]
(14)

The plastic potential function of shear failure of WIZ is selected according to the non-associated flow law, and the plastic potential function of tensile failure is based on the associated flow law. The specific expressions of the two are as follows:

\[
g' = q_v \left\{ p + \left(\frac{\sqrt{3}}{3} - \frac{\sin \theta_v}{3} q_v\right) q \right\}
\]
(15)

The plastic modification of shear stress increment after the partial differential solution is shown as

\[
\Delta p = -\lambda' K q_v
\]
\[
\Delta q = -\lambda' G \left(\frac{\sqrt{3}}{3} - \frac{\sin \theta_v}{3} q_v\right)
\]
(16)

\[
\lambda' = \frac{q_v p' + \left(\frac{\sqrt{3}}{3} - \frac{\sin \theta_v}{3} q_v\right) q'}{G \left(\frac{\sqrt{3}}{3} - \frac{\sin \theta_v}{3} q_v\right) + K q_v}
\]
(17)

where \(p'\) and \(q'\) are the current mean stress and deviatoric stress; \(q_v = \frac{\sqrt{3} \sin \varphi}{\sqrt{3} \cos \theta_v}\).

Similarly, the plastic modification of tensile stress increment is shown as
\[ \Delta \rho = - \lambda' K \]
\[ \Delta q = - \lambda' G \left( \frac{\sin \theta}{3} \right) \]
\[ \lambda' = \frac{p' - \sin \theta q' - \sigma'}{K} \]

where \( p' \) and \( q' \) are the current mean stress and deviatoric stress.

3 Derivation and determination of rock failure index of WIZ

Based on Equations (9) ~ (14), the damage degree index \( R_{FD_{WIZ}} \) before and after failure can be deduced as follows [16]:

\[
\begin{align*}
R_{FD_{WIZ}} &= \begin{cases} 
1 - YD_{wiz} & \text{before failure} \\
1 + \epsilon_{v}^{ \prime \prime } & \text{after failure}
\end{cases} \\
yD_{wiz} &= \begin{cases} 
- \beta g \frac{\sigma_{2} + \sigma_{3}}{2} & \sigma_{2} - \sigma_{3} \leq \sigma_{p_{2}} \\
\frac{\sigma_{1} - \sigma_{3}}{2} & \sigma_{1} - \sigma_{3} > \sigma_{p_{2}}
\end{cases} \\
\sigma_{p_{2}} &= \frac{3 k_{v} \cos \phi \sqrt{q + 2 q_{p} \sin \theta_{p}}}{1 - \sin \phi}
\end{align*}
\]

where \( YD_{wiz} \) is the geometric distance between the stress state of a point on the \( \pi \) plane before failure and its spatial strength envelope surface and hydrostatic pressure line; \( \sigma_{p_{2}} \) is the coordinates of the intersection point of angle bisector between two strength envelops and \( p \) coordinate axis; \( \epsilon_{v}^{ \prime \prime } \), \( \overline{\sigma} \), \( \overline{\epsilon_{v}} \) \( \text{limit} \) and \( \overline{\sigma} \) \( \text{limit} \) are current and limit values of plastic volumetric and shear strain.

4 Stability prediction of rock masses controlled by WIZ during underground excavation

The evolution of fracture depth and failure degree of rock masses with WIZ \( (R_{FD_{WIZ}}) \) with the layer-by-layer excavation of a large underground cavern, based on the aforementioned constitutive model UDDM and the numerical model, as illustrated in Figure. 4a, b and c.

It could be shown that with the layered excavation of the workshop, especially during the excavation of the I-III layers, the fracture range of in WIZ at the top arch increases rapidly, and it is completely broken through after the excavation of the third layer III, showing that the fracture degree and failure depth of the top arch increase rapidly. During the excavation of the second layer, the increase rate of rock failure degree in WIZ is much higher than the increase rate of rock failure depth, which indicates that although the deformation of WIZ does not increase obviously, the rock failure is developing continuously. The control of the deformation and failure of WIZ should consider both the deformation and the failure of the dislocation zone.

Therefore, rock masses with WIZ in the top arch should be supported in time after the completion of excavation of the central pilot tunnel, and the reinforcement and support of the arch and high side wall should not be later than the end of excavation of layer III.
Figure 4. Evolution of fracture depth and failure degree of rock masses with WIZ (RFDwiz) with the layer-by-layer excavation of large underground cavern: (a) The adopted numerical model; (b) Evolution of fracture depth and failure degree of rock masses with WIZ (RFDwiz); (c) Evolution Contour of RFDwiz.
5 Supporting time optimizing of rock masses with WIZ based on the cracking-restraint design method

Figure 5 gives the failure depth evolution of rock massed controlled by WIZ in the top arch of the large underground cavern with the layer-by-layer excavation, to help optimizing the supporting time of rock masses controlled by WIZ, based on the numerical model (Figure 4a) as well as cracking-restraint design method [12]. The main understandings are under follows.

(1) In the actual underground excavation of rock masses with WIZ in the top arch, the supporting lagged over 12 m, which exacerbated the instability of rock massed with WIZ, leading to the local strong relaxation, slipping and fracture of the rock masses with WIZ. Hence, it is evident that the supporting time of the rock mass with WIZ in the actual excavation was too late, requiring the dynamic optimization and control.

(2) Hence, it could be obtained that only when the supporting time is reasonable, can the subsequent development of fracture and deformation of rock mass with WIZ be effectively controlled, and the performance of the supporting structure can be reasonably played, reducing the catastrophic damage and construction cost finally.

(3) The reduction ratio of fracture depth and fracture range of rock mass in WIZ could reach 20%-35% if the idea of the cracking-restraint design method is adopted to rationally optimize the supporting time. Therefore, the supporting time for rock mass in WIZ in the top arch should not be later than the deformation of surrounding rock, the sudden increase of stress and the rapid development of cracks, and it is more appropriate to support the lagging face within 4~6m.

6 Conclusion

(1) The novel proposed constructive model could reflect the nonlinear characteristics of various deformations of WIZ under different loading and unloading paths, the anisotropic characteristics caused by unloading, the obvious volumetric expansion during unloading and the deterioration of deformation parameters. There are relatively few parameters in the mechanical model, and the parameters are easy to obtain. Therefore, the prediction and feedback analysis of the mechanical response of the surrounding rock could be given quickly.

(2) The rock failure index for WIZ (RFD/wiz) is derivated, based on the proposed model, to help determine the cracking scale, depth and degree of surrounding rock masses with WIZ. It has been successfully
adopted in the prediction of the failure position and degree, as well as the dynamic optimization design of the reasonable supporting parameters of rock masses with WIZ in underground cavern, combined with the cracking-restraint design method.

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