Determination of safety factor for rock mass surrounding tunnel by sudden change of equivalent plastic strain in strength reduction method

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Abstract

A safety factor of rock mass surrounding the tunnel can be determined using the strength reduction method (SRM), however, it is the most important to solve the criterion of critical state. For the stability estimation of rock mass surrounding tunnel, there is need to discuss that it is preferable to use the same criteria for the slope, such as non-convergence of finite element calculation, penetration of plastic strain and sudden change of horizontal displacement. A safety factor can be determined by sudden change of equivalent plastic strain in relationship between a reduction coefficient of strength parameter and equivalent plastic strain. This method is based on the elasto-plastic FEM and the SRM by ABAQUS and Mohr-Coulomb yield criterion. Simulation results using this method show how a safety factor varies with geometries, friction angles and cohesions for circle and square tunnels. Simulation results also show a safety factor varying with quality change of rock mass, pore water pressure and tunnel depth.

1. Introduction

One of the important problems for structure calculation of a tunnel is how to estimate the stability of rock mass surrounding the tunnel. The stability of circular tunnels has been extensively studied at the Cambridge since the 1970s: see, for example, the work reported by Atkinson and Cairncross (1973), Davis et al. (1980), Mair (1979), and Seneviratne (1979). Before 1990s, most researches on the tunnel stability focused on the undrained stability of circular tunnels in clay. Davis et al. (1980) considered three different shapes of shallow underground opening relevant to tunneling and upper and lower bound stability solutions are derived for t

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To estimate the stability of rock mass surrounding the tunnel, recently, several researchers have conducted a few studies to apply the SRM. The SRM was first proposed by Zienkiewicz et al. (1975) and now it has been widely used in the estimation of the slope stability. The definition of the safety factor for a slope using the SRM is considered to be a ratio of actual shear strength to the lowest shear strength of soils or rocks material required to maintain the equilibrium of a slope (Dawson et al. 1999; Ugai 1989; Griffiths and Lane 1999; Liu et al. 2015).

Many researchers have compared the various criteria of the critical state of a slope, which is the most important in the estimation of slope stability using the SRM (Fu and Liao 2010; Khosravi and Khabbazzian 2012; Yuan et al. 2020; Zheng et al. 2009a; Zheng et al. 2009b). Various criteria were developed, however, there were mainly 3 methods by the penetration of equivalent plastic strain, non-convergence of numerical calculation and sudden change of horizontal displacement at a specific point, respectively.

Several researchers have sought for alternatives by establishing correlation between the estimation of the tunnel stability and the slope stability. Huang et al. (2012) determined the safety factor for a shallow tunnel in combination with the upper bound theorem of limit analysis and SRM. Jiang et al. (2009) judged critical failure state of tunnel by the penetration of equivalent plastic strain. Goh and Zhang (2012) and Yin et al. (2007) considered the non-convergence to be the criterion of the critical state, which produces the infinite plastic strain on the slide surface and the finite element calculation is not converged, when tunnel lost the stability and collapsed. The earthquake stability for rock or soil mass surrounding the tunnel was estimated by ANSYS program and SRM (Cheng et al. 2014). An et al. (2011) proposed that vault settlement or ground subsidence should be a major criterion for instability of tunnels. Zhang (2009) suggested that it was difficult to confirm the instability for rock mass surrounding the tunnel by the distribution of plastic zone or the non-convergence of the finite element calculation. And he proposed the sign of collapse in rock mass indicating that the slide move infinitely and the displacement of the slide surface change and develop infinitely. Liang (2019) analyzed the failure mechanism around deep excavations using rock failure process analysis (RFPA) with SRM.

There are several advantages for the application of the SRM in geotechnical stability analysis and the SRM is very attractive and commonly accepted approach among the geotechnical researchers and engineers (Huang et al. 2012; Shen and Karakus 2013). Presently, the safety factors used in the geotechnical stability analysis are mostly calculated by the FEM with shear strength reduction technique. However, the key for the estimation of tunnel stability using the SRM is how to judge the instability and how to determine the safety factor. Therefore, there is need to consider whether the criteria for slope can be also used in tunnel and need to develop a more suitable criterion determining the safety factor of rock mass surrounding the tunnel by the SRM.

In this paper, various criteria are compared and analyzed, such as the non-convergence of numerical calculation, sudden change of horizontal displacement and sudden change of plastic strain, respectively. And this paper presents a new criterion determining the safety factor of rock mass surrounding a tunnel by a sudden change of equivalent plastic strain on the relationship between the shear strength reduction

coefficient and the equivalent plastic strain value at a specific point. Simulation results using this method show how the safety factor varies with geometries, friction angles and cohesions for circle and square tunnels, respectively, and how the safety factor varies with quality change of rock mass, pore water pressure and tunnel depth, respectively.

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engineers (Huang et al. 2012; Shen and Karakus 2013). Presently, the safety factors used in the geotechnical stability analysis are mostly calculated by the FEM with shear strength reduction technique. However, the key for the estimation of tunnel stability using the SRM is how to judge the instability and how to determine the safety factor. Therefore, there is need to consider whether the criteria for slope can be also used in tunnel and need to develop a more suitable criterion determining the safety factor of rock mass surrounding the tunnel by the SRM. In this paper, various criteria are compared and analyzed, such as the non-convergence of numerical calculation, sudden change of horizontal displacement and sudden change of plastic strain, respectively. And this paper presents a new criterion determining the safety factor of rock mass surrounding a tunnel by a sudden change of equivalent plastic strain on the relationship between the shear strength reduction coefficient and the equivalent plastic strain value at a specific point. Simulation results using this method show how the safety factor varies with geometries, friction angles and cohesions for circle and square tunnels, respectively, and how the safety factor varies with quality change of rock mass, pore water pressure and tunnel depth, respectively.

2. Determination Of The Safety Factor

There are two well – accepted definition of the safety factor for rock or soil mass. One is the safety factor as strength reserve, i.e. when the strength of rock or soil mass is continuously reduced until it fails, a reduced ratio of the strength is just the safety factor, while the other is the safety factor as load reserve. This method increases continuously the gravity of rock or soil mass until it fails, i.e. an increased ratio of gravity is just the safety factor. For tunnel, a failure typically happens due to the reduction of rock mass strength caused by human blast excavation, therefore, the safety factor as strength reduction is more suitable for tunnel. For shear failure mode, failure mode of a tunnel is similar to that of a slope, and the the safety factor is a ratio of actual strength to yielding strength of rock or soil mass on shear failure surface. If shear strength parameters are continuously reduced using finite-difference or finite-element SRM until rock or soil mass arrive critical failure state, the reduction coefficient corresponding to critical state is just the whole safety factor of rock mass surrounding tunnel.

Stability estimation proposed in this section means a judgment of critical state and a determination of the safety factor, which is based on the Mohr-Coulomb strength criterion. The Mohr-Coulomb strength criterion is commonly used in a calculation of soil or rock mass. The safety factor of rock mass surrounding a tunnel can be defined as a ratio of actual shear strength parameters to critical failure shear strength parameters. And the stability estimation is performed with analysis results of elasto-plastic FEM and the SRM using ABAQUS.

2.1 Simulation of strength reduction process in ABAQUS

The shear strength reduction technique can be adopted to solve for a safety factor of tunnel stability. In this technique, a series of trial factors of safety are used to adjust the cohesion, c , and the friction angle, φ , of geomaterials, respectively, as equation (1). Surrounding rock mass can be idealized as an elastic, perfectly plastic material with cohesion and frictional angle. Shear strength parameters of rock mass

surrounding a tunnel are continuously reduced, and so the rock mass turns into critical state and the calculation stops. From the simulation results, plastic zone contribution and the factor of strength reserve can be obtained and the development process of the equivalent plastic strain can be monitored. In ABAQUS, the shear strength parameters of geomaterial can be reduced by using field variable F_v which equals to a strength reduction coefficient. The simulation of the strength reduction process in ABAQUS is as follows:

In the strength reduction calculation by ABAQUS, range of field variable F_v must be indicated so that the shear strength parameters can be reduced. Usually this range is equal to one of strength reduction coefficient. If the shear strength parameters of material are too small, non-convergence may occur. Therefore, a small value of F_v should be chosen to avoid non-convergence at the beginning of calculation, so that the strength parameters can be changed into the large value. According to our many calculation experiences, F_v may have the range of approximately 0.25 ~ 4.0 or 1.0 ~ 10.0, that is, the minimum value ($F_v^{\min}$) of the strength reduction coefficient may be chosen approximately as 0.25 ~ 1.0, the maximum value ($F_v^{\max}$) may be chosen approximately as 4.0 ~ 10.0. If a rock mass surrounding tunnel is soft, generally shear strength parameters are small. Thus at the beginning of the strength reduction, the rock mass can lose the stability and the calculation of elasto-plastic FEM for shear strength reduction can be also diverged. Therefore, it is more reasonable to choose the minimum value ($F_v^{\min}$) of the strength reduction coefficient as an enough small one than 1.0 and start on calculation. For the hard rock mass surrounding, the minimum value ($F_v^{\min}$) of 1.0 may be chosen, while the maximum value ($F_v^{\max}$) of large value (e.g., 4.0 ~ 10.0) may be chosen. Only under such condition, numerical calculation be sufficiently performed before divergence and total process of plastic strain development can be sufficiently monitored.

According to the field variable F_v (i.e., the strength reduction coefficient), change of the shear strength parameters of geomaterial can be defined, such as cohesion c , inner frictional angle φ , shear dilatation angle ψ , respectively. These parameters are related to the strength reduction coefficient F_v by following equation.

$$\begin{cases} c' = \frac{c}{F_v} \\ \varphi' = \arctan\left(\frac{\tan \varphi}{F_v}\right) \\ \psi' = \arctan\left(\frac{\tan \psi}{F_v}\right) \end{cases} \quad (1)$$

Where c' , φ' , ψ' is a reduced cohesion, a frictional angle and a shear dilatation angle, respectively.

The gravity (or volume load) must be applied and the equilibrium stress state must be created for the model. The field variable F_v should increase linearly till $F_v^{\max}$ in the later analysis. When the elastic-plasticity finite element calculation is ceased (i.e., the divergence in this calculation), results with total process of the calculation should be monitored so that a critical state can be judged and a safety factor can be determined.

2.2 Critical state and determination of safety factor

The stability estimation of rock mass surrounding tunnel is a process which judges a failure state of rock mass and at the same time, determines safety factor of strength reserve. From the observation of development process of equivalent plastic strain value, critical failure state can be judged. In other words, the moment when plastic strain starts to create is just the critical failure state. Next, it is also necessary to search for a sudden change point on the relative curve between the strength reduction coefficient (F_v) and the equivalent plastic strain value (PEEQ) so that the safety factor can be determined. This phenomenon of sudden change conforms to the appearance moment of the equivalent plastic strain in the excavation part of a tunnel. Finally, it is suggested that the reduction coefficient (F_v) corresponding to the sudden change point can be determined as the safety factor (Fig. 1). When the sudden change point on the curve is considered, attention is to confirm a relation between a reduction coefficient and an equivalent plastic strain corresponding to the sudden change point through numerical value. That is, it is necessary to make sure that the beginning point of plastic strain value occurring from zero coincide with the sudden change point. The above process is described in detail through numerical simulation for examples of Section 3.

3. Numerical Simulation For Examples

Examples of tunnel models using ABAQUS are simulated to calculate the safety factor based on the methodology described above. The tunnels are modeled to be on unlined circular tunnel and square tunnel, respectively, which have no internal pressure. The deformation is assumed to be the plane strain state. And the surrounding rock mass is modeled as a uniform Mohr-Coulomb material with a unit weight γ , cohesion c , inner friction angle φ , shear dilatation angle ψ , elastic modulus E , and Poisson's ratio μ , respectively (Fig. 2, Fig. 3). The surrounding rock mass is modeled using the Base Feature of 2D Planar shell. For without considering the pore water pressure, the element type of CPE6M (i.e., 6-node modified quadratic plane strain triangle) is used, while for considering the pore water pressure, the element type of CPE6M (i.e., 6-node modified quadratic plane strain triangle, pore pressure, hourglass control) is used. The range of field variable F_v (shear strength reduction coefficient) is defined as from 0.25 to 4.0.

3.1 Determination of the safety factor for the circle tunnel

Fig. 3 shows the finite element mesh along with the assumed boundary conditions. The geometric model is simulated as the vertical half considering vertical symmetry. The edge along the center axis line of tunnel is fixed in the horizontal direction, while the outside boundary part of circle arc is fixed both in the horizontal and vertical direction. And as for the load condition, it is assumed that the weight load of the ground is applied, while both outer and inner pore pressure are not applied. Physical and mechanical parameters of material for the circle tunnel geometries of $H/D = 2.0$ and $D = 5.0$ m are shown as Table 1.

Table 1. Physical and mechanical parameters of material.

Dry density	Elastic modulus	Poisson's ratio	Inner friction angle	Cohesion
$\rho/ \text{ t m}^{-3}$	$E/ \text{ GPa}$	ν	$\varphi/^\circ$	$c/ \text{ kPa}$
2.0	2.0	0.2	30	200

Analysis procedures are divided into 3 steps. Step 1, Step 2 and Step 3 are creation one of initial stress, removing one of excavation elements, and reduction one of the shear strength parameters, respectively. The calculation results in the visualization module is considered after finishing the finite element calculation.

This calculation example converged up to the increment step 100 of analysis step 3 (i.e., reduction one of the shear strength parameters) and finished computing the plastic strain increments. The equivalent plastic strain contours isn't shown at the increment step 0 to 43. However, the equivalent plastic strain begins to occur from the increment step 44. The equivalent plastic strain contours are shown at the increment step 54, the increment step 64 and the increment step 74, respectively. The distribution region of the equivalent plastic strain is gradually extended and it is shown that at the last increment step 100, the equivalent plastic strain is contoured as in Fig. 4. As a result, at the start, the equivalent plastic strain occurs from the side wall of excavation part while increases gradually with the increase of the reduction coefficient. Because the development state of equivalent plastic strain varies with the points of excavation of tunnel, the specific 5 points can be chosen at the top, the bottom and the sides of excavation part of tunnel, respectively, as shown in Fig. 5. For these 5 points, there are different relationships between the strength reduction coefficient (F_v) and the equivalent plastic strain (PEEQ) or between the strength reduction coefficient (F_v) and the horizontal displacement (U_1). These curves are plotted as shown in Fig. 6 (a) ~ Fig. 6 (e).

There are several remarkable results through the considering above calculation data of finite-element SRM for the circle tunnel.

(1) It is difficult to determine the safety factor using non-convergence of finite element calculation. Because all the calculations finished at the reduction coefficient F_v of 4 and at this time all the safety

factors are determined to be 4 depending on the non-convergence of finite element calculation. But this can cause a very big error during the determination of the safety factor.

(2) It is difficult to determine the safety factor using the penetration of plastic strain. In other words, plastic strain value is very small and potential failure surface (i.e., plastic strain penetration zone) happens in soil slope but that doesn't happen in surrounding rock mass.

(3) It can't determine the safety factor using the sudden of horizontal displacement (U_1) because the sudden change point can't be found in all the relationships between the F_v and the U_1 for these 5 points. Therefore, the above 3 reasons indicate that it is difficult to determine using the preceding criteria for the slope such as non-convergence of finite element calculation, penetration of plastic strain and sudden change of horizontal displacement, respectively.

(4) The sudden change point can't be found in the relationships between the F_v and the PEEQ, therefore the safety factor can be determined by sudden change of equivalent plastic strain in relationship between a reduction coefficient of strength parameter and equivalent plastic strain.

However, the position of the sudden change point varied with the position of specific point as shown in Fig. 6, while there is the most obvious sudden change phenomenon in the equivalent plastic strain curve for the point 3 as shown in Fig. 6(c). During the reduction coefficient F_v increases more than 2.005 and the increment step increases more than 43, the value of the equivalent plastic strain keeps increasing almost linearly till the calculation stops and the distribution region of the equivalent plastic strain also expands. And the F_v in this case is 2.005 as the minimum among the reduction coefficients corresponding the sudden change points. Finally, the safety factor can be defined as about 2.0.

Then on the basis of the study above, a compact set of safety factor charts can be calculated and presented for the circle tunnels. Parameters considered in this section are for circle tunnels geometries of $H/D = 1.0 - 5.0$, $D=5.0$ m, friction angles of $\varphi = 5^\circ - 35^\circ$, and $\gamma D/c=0.5 - 3.0$. Table 2 shows the comparison of the safety factor solutions obtained using the sudden change of the equivalent plastic strain for the calculation arrange of the above. As shown in Table 2, the change of the safety factor can be obtained with geometries (H/D), friction angles (φ) and cohesions (c), respectively, for the circle tunnels. Table 2 shows that the larger H/D is, the smaller safety factor becomes while for the same H/D the smaller friction angle and cohesion are, the smaller the safety factors become.

Table 2. Comparison of safety factors obtained from the sudden change of equivalent plastic strain for circle tunnels ($H/D=1-5$, $\varphi=5-35^\circ$, $\gamma D/c=0.5-3.0$, $D=5$ m).

H/D	$\varphi(^{\circ})$	$\gamma D/c$					
		0.5	1.0	1.5	2.0	2.5	3.0
1	5	2.11	1.48	1.2	1.02	0.92	0.85
	10	2.18	1.55	1.27	1.13	1.02	0.95
	15	2.22	1.62	1.41	1.23	1.13	1.06
	20	2.29	1.73	1.48	1.34	1.23	1.16
	25	2.36	1.79	1.58	1.41	1.34	1.27
	30	2.42	1.86	1.65	1.51	1.44	1.37
	35	2.49	1.97	1.72	1.62	1.55	1.48
2	5	1.62	1.13	0.95	0.85	0.78	0.71
	10	1.69	1.2	1.02	0.92	0.85	0.81
	15	1.76	1.30	1.13	1.02	0.95	0.92
	20	1.83	1.41	1.23	1.13	1.06	1.02
	25	1.9	1.48	1.34	1.23	1.16	1.13
	30	2.00	1.58	1.44	1.34	1.30	1.23
	35	2.07	1.69	1.51	1.44	1.41	1.37
3	5	1.34	0.95	0.81	0.74	0.71	0.67
	10	1.44	1.06	0.92	0.81	0.74	0.71
	15	1.51	1.16	1.02	0.92	0.88	0.85
	20	1.58	1.27	1.13	1.06	0.99	0.95
	25	1.69	1.34	1.23	1.16	1.13	1.09
	30	1.76	1.44	1.34	1.27	1.23	1.20
	35	1.86	1.55	1.44	1.37	1.34	1.30
4	5	1.16	0.88	0.74	0.71	0.51	0.47
	10	1.27	0.95	0.81	0.74	0.62	0.62
	15	1.37	1.06	0.95	0.88	0.85	0.74
	20	1.44	1.16	1.06	0.99	0.95	0.85
	25	1.55	1.27	1.16	1.09	1.00	0.96
	30	1.62	1.37	1.27	1.20	1.11	1.07

	35	1.72	1.48	1.37	1.34	1.22	1.18
5	5	1.06	0.81	0.71	0.51	0.47	0.44
	10	1.16	0.88	0.78	0.62	0.59	0.58
	15	1.27	0.99	0.88	0.85	0.74	0.70
	20	1.37	1.09	0.99	0.95	0.85	0.81
	25	1.44	1.20	1.13	1.00	0.96	0.96
	30	1.55	1.30	1.23	1.11	1.07	1.07
	35	1.65	1.41	1.34	1.22	1.19	1.18

3.2 Determination of the safety factor for the square tunnel

Then the determination of safety factor for square tunnels can be simulated. Fig. 7 and Fig. 8 show the finite element mesh along with the assumed boundary conditions for square tunnel. The geometric model is simulated as the vertical half considering vertical symmetry. The edge along the center axis line of tunnel is fixed in the horizontal direction, while the outside boundary part is fixed both in the horizontal and vertical direction. And as for the load condition, it is assumed that the weight load of the ground is applied, while both outer and inner pore pressure are not applied. Physical and mechanical parameters of material for the square tunnel of $H/B = 2.0$, $B = 5.0$ m are equaled to that in Table 1 for the circle tunnel.

Analysis procedures are divided into 3 steps. Step 1, Step 2 and Step 3 are creation one of initial stress, removing one of excavation elements, and reduction one of the shear strength parameters. The calculation results in the visualization module is considered after finishing the finite element calculation.

This calculation example converged up to the increment step 45 of analysis step 3 (i.e., reduction step of the shear strength parameters) and finished computing the plastic strain increments. The equivalent plastic strain contours isn't shown at the increment step 0 - 25. However, the equivalent plastic strain begins to occur from the increment step 26. The equivalent plastic strain contours are shown at the increment step 36, the increment step 40 and the increment step 43, respectively. The distribution region of the equivalent plastic strain is gradually extended and it is shown that at the last increment step 45, the equivalent plastic strain is contoured as in Fig. 9. As a result, at the start, the equivalent plastic strain occurs from the corners of top and bottom of excavation part while increases gradually with the increase of the reduction coefficient. Because the development state of equivalent plastic strain varies with the points of excavation of tunnel, the specific 5 points can be chosen at the top, the bottom and the sides of excavation part of tunnel, respectively, as shown in Fig. 10. For these 5 points, there are different relationships between the strength reduction coefficient (F_v) and the equivalent plastic strain (PEEQ) or between the strength reduction coefficient (F_v) and the horizontal displacement (U_1). These curves are plotted as shown in Fig. 11 (a) - Fig. 11 (e).

There are several remarkable results through the considering above calculation data of finite-element SRM for a square tunnel as for a circle tunnel. (1) It is difficult to determine the safety factor using non-convergence of finite element calculation. The calculations for point 1 and point 5 finished at the reduction coefficient F_v of 4 and at this time the safety factors are determined to be 4 depending on the non-convergence of finite element calculation, while the calculations for point 2, point 3 and point 4 finished at the reduction coefficient F_v of 1.80 and at this time the safety factors are determined to be 1.80 depending on the non-convergence of finite element calculation. But this can cause a very big error during the determination of the safety factor. (2) It is difficult to determine the safety factor using the penetration of plastic strain. In other words, plastic strain value is very small and potential failure surface (i.e., plastic strain penetration zone) happens in soil slope but that doesn't happen in surrounding rock mass. (3) It can't determine the safety factor using the sudden of horizontal displacement (U_1) because the sudden change point can't be found in all the relationships between the F_v and the U_1 for these 5 points. Therefore, the above 3 reasons indicate that it is difficult to determine using the preceding criteria for the slope such as non-convergence of finite element calculation, penetration of plastic strain and sudden change of horizontal displacement, respectively. (4) The sudden change point can't be found in the relationships between the F_v and the PEEQ, therefore the safety factor can be determined by sudden change of equivalent plastic strain in relationship between a reduction coefficient of strength parameter and equivalent plastic strain. However, the position of the sudden change point varied with the position of specific point as shown in Fig. 11, while there is the obvious sudden change phenomenon in the equivalent plastic strain curve for the point 2, point 3 and point 4, respectively, as shown in Fig. 11(b) - Fig. 11(d). And the F_v of the sudden change point for point 2 is the minimum as 1.1875 among the reduction coefficients corresponding the sudden change points for points 2, 3 and 4, respectively, and the increment step of this F_v is 25. During the reduction coefficient F_v increases more than 1.1875 and the increment step increases more than 25, the value of the equivalent plastic strain keeps increasing almost linearly continuously till the calculation stops, and the distribution region of the equivalent plastic strain also expands. Finally, the safety factor can be defined as about 1.19.

Then on the basis of the study above, a compact set of safety factor charts can be calculated and presented for the square tunnels. Parameters considered in this section are for square tunnels geometries of $H/B = 1.0 - 5.0$, $B=5.0$ m, friction angles of $\varphi = 5^\circ - 35^\circ$, and $\gamma B/c = 0.5 - 3.0$, respectively. Table 3 shows the comparison of the safety factor solutions obtained using the sudden change of the equivalent plastic strain within the range of the above. As shown in table 3, the change of the safety factor can be obtained with geometries (H/B), friction angles (φ) and cohesions (c), respectively, for the square tunnels. Table 3 shows that the larger H/B is, the smaller safety factor becomes while for the same H/B , the smaller friction angle and cohesion are, the smaller the safety factors become.

Table 3. Comparison of safety factors obtained from the sudden change of equivalent plastic strain for square tunnels ($H/B=1-5$, $\varphi=5-35^\circ$, $\gamma B/c=0.5-3.0$, $B=5$ m).

H/B	$\varphi(^{\circ})$	$\gamma B/c$					
		0.5	1.0	1.5	2.0	2.5	3.0
1	5	1.53	1.11	0.93	0.81	0.74	0.70
	10	1.60	1.19	1.00	0.93	0.81	0.78
	15	1.68	1.23	1.08	0.96	0.89	0.85
	20	1.71	1.30	1.15	1.04	0.96	0.93
	25	1.79	1.38	1.23	1.11	1.04	1.00
	30	1.86	1.45	1.30	1.19	1.15	1.11
	35	1.94	1.56	1.38	1.30	1.23	1.19
2	5	1.26	0.93	0.78	0.70	0.63	0.59
	10	1.38	1.00	0.85	0.78	0.70	0.70
	15	1.45	1.11	0.96	0.89	0.81	0.78
	20	1.53	1.19	1.04	0.96	0.93	0.89
	25	1.60	1.26	1.15	1.08	1.04	1.00
	30	1.68	1.38	1.23	1.19	1.11	1.11
	35	1.75	1.45	1.34	1.26	1.23	1.19
3	5	1.19	0.89	0.74	0.66	0.59	0.51
	10	1.30	0.96	0.85	0.74	0.70	0.66
	15	1.41	1.08	0.96	0.85	0.81	0.78
	20	1.49	1.19	1.04	0.96	0.93	0.89
	25	1.60	1.26	1.11	1.04	1.00	0.96
	30	1.68	1.38	1.23	1.15	1.11	1.08
	35	1.75	1.45	1.34	1.26	1.23	1.19
4	5	1.10	0.82	0.71	0.51	0.48	0.44
	10	1.20	0.92	0.82	0.66	0.63	0.59
	15	1.27	1.03	0.92	0.78	0.74	0.70
	20	1.38	1.13	0.96	0.89	0.89	0.85
	25	1.48	1.24	1.08	1.00	0.96	0.96
	30	1.55	1.34	1.19	1.15	1.11	1.08

	35	1.66	1.38	1.30	1.26	1.23	1.23
5	5	0.99	0.75	0.67	0.48	0.44	0.44
	10	1.09	0.85	0.74	0.63	0.59	0.59
	15	1.20	0.96	0.88	0.74	0.74	0.71
	20	1.30	1.10	0.94	0.89	0.89	0.84
	25	1.40	1.20	1.05	1.00	0.96	0.98
	30	1.51	1.31	1.17	1.11	1.11	1.09
	35	1.62	1.34	1.28	1.26	1.23	1.23

4. Change Of The Safety Factor With Various Conditions Of Rock Mass

There are many factors affecting stability of surrounding rock mass. However, the most important factors are geostructure, structure and property within a rock mass, groundwater and stress in the earth's crust, respectively. The safety factor of surrounding rock mass is the changeable indices depending on the above conditions of surrounding rock mass. If the safety factor is obtained, it will be simple to define excavation limit and liner thickness of a tunnel. The larger safety factor is, the larger excavation space will be and the thinner liner thickness will be. That is because the safety factor relates to geological conditions, tunnel depth and seepage action and so on. Namely this means that the safety factor of surrounding rock mass is an important index reflecting the condition of surrounding rock mass. Therefore, in this section, it is useful to simulate how the safety factor varies with the quality class of the surrounding rock mass, pore water pressure and tunnel depth, respectively. The quality of surrounding rock mass is divided into degree I to degree V and the calculation cases are divided into nine. The surrounding rock mass for the circle tunnel of diameter $D = 6.6\text{m}$ is modeled as homogeneous Mohr-Coulomb material. The property parameters of surrounding rock mass are shown in Table 4 and action mode of load is shown in Fig. 12. As shown in Fig. 12, p_0 increases linearly depending on the water depth (H_w) as pore water pressure activating surrounding rock mass, while σ_H increases linearly depending on the ground depth (H) as natural stress of surrounding rock mass.

Table 4. Calculation cases and physical and mechanical parameters with rock mass quality.

Case	Quality Class of rock mass	$\rho/t \cdot m^{-3}$	ν	$E/G \text{ Pa}$	$\varphi/^\circ$	$c/M \text{ Pa}$
1	Ⅰ-1	2.7	0.17	35.0	60	5.0
2	Ⅰ-1	2.5	0.17	25.0	60	4.0
3	Ⅰ-2	2.5	0.17	10.0~35.0	57.2	3.5
4	Ⅰ-1	2.3	0.2	15.0	55.1	3.2
5	Ⅰ-2	2.3	0.2	10.0	50.2	2.0
6	Ⅰ-1	2.0	0.25	4.0~5.5	40.1	1.2
7	Ⅰ-2	2.0	0.25	4.0	40.1	1.0
8	Ⅰ-1	1.7	0.3	2.5	30.1	0.8
9	Ⅰ-2	1.5	0.35	1.0	26.6	0.2

First of all, it is useful to simulate how the safety factors vary with the quality class of surrounding rock mass for the tunnel with depth of $H = 30 \text{ m}$, $H = 65 \text{ m}$, $H = 100 \text{ m}$, $H = 200 \text{ m}$, $H = 300 \text{ m}$ and $H = 400 \text{ m}$, respectively. The values of the safety factor in each case are shown in Fig. 13, respectively.

As shown in Fig. 13, the safety factor has close relation with the quality class of surrounding rock mass and the tunnel depth. The lower the quality class of rock mass is and of the higher the tunnel depth is, it becomes smaller. That is, the softer rock mass and the deeper tunnel depth is, the smaller the safety factor becomes. As shown in Fig. 13, the safety factor is reduced from above 1.0 to below 1.0 with the decrease of the quality class of rock mass. If the tunnel is shallow, the safety factor is rapidly reduced, however, if the tunnel is deep, the safety factor is slowly reduced. To put it concretely, if the tunnel depth is 30 m, the safety factor is rapidly reduced from 7.07 to 0.77, while if the tunnel depth is 65 m, the safety factor is rapidly reduced from 4.01 to 0.51. If the tunnel depth is 100 m, the safety factor is reduced from 2.97 to 0.4, while if the tunnel depth is 200 m, the safety factor is reduced from 1.98 to 0.31. If the tunnel depth is 300 m, the safety factor is reduced from 1.62 to 0.25, while if the tunnel depth is 400 m, the safety factor is reduced from 1.40 to 0.25.

With the increase of the tunnel depth, the safety factor becomes smaller and smaller. If the quality class of rock mass is high (i.e. hard rock mass), the safety factor is rapidly reduced, however, if the quality class of rock mass is low (i.e. soft rock mass), the safety factor is slowly reduced. To put it concretely, when the tunnel depth is increased from 30 m to 400 m in the calculation case 1 (i.e. very hard rock mass), the safety factor is rapidly reduced from 7.07 to 1.4, and in the calculation case 2 (i.e. hard rock mass), the safety factor is rapidly reduced from 6.29 to 1.31. Also in the calculation case 3, the safety factor is rapidly reduced from 5.57 to 1.19, while in the calculation case 4, the safety factor is rapidly reduced from 5.45 to 1.12. However, in

the calculation case 7, all the safety factors are below 3.0 and the safety factor is slowly reduced from 2.21 to 0.54, while in the calculation case 8, all the safety factors are below 2.0 and the safety factor is slowly reduced from 1.91 to 0.42. And in the calculation case 9 (i.e., very soft rock mass), all the safety factors are smaller than 1.0 and the safety factor is slowly reduced from 0.77 to 0.25. In all the calculation cases, when the tunnel depth is smaller than 100 m, the safety factors show a marked trend toward reduction.

Then, it is useful to simulate how the safety factors vary with the outside pore water pressure and the class of quality of surrounding rock mass for the tunnel of depth with $H = 30$ m, $H = 65$ m, $H = 100$ m, respectively. For action heads of $H_w = 0$ m, $H_w = 60$ m, $H_w = 80$ m and $H_w = 100$ m, respectively, the pore water pressure of 0 kPa, 588 kPa, 784 kPa and 980 kPa are activated on the bottom of model, respectively. Action head is the value by which pore water pressure activated on the bottom is converted into water head. At that time, the pore water pressure activities as triangle distribution load. Fig. 14 shows how the safety factors vary with the action head of $H_w = 0$ m, $H_w = 60$ m, $H_w = 80$ m and $H_w = 100$ m, respectively, for the calculation case of 1 - 9 and the tunnel depth of $H = 30$ m. Fig. 15 shows how the safety factors vary with the action head of $H_w = 0$ m, $H_w = 60$ m, $H_w = 80$ m and $H_w = 100$ m, respectively, for the calculation case of 1 - 9 and the tunnel depth of $H = 65$ m. As in Fig. 14 and Fig. 15, Fig. 16 illustrates the curves by which the safety factors are changed for the tunnel depth with $H = 100$ m and in general the safety factors are smaller than the cases of $H = 30$ m and $H = 65$ m, respectively.

As shown in Figs 14 - 16, the safety factors relate not only to the quality class of rock mass and tunnel depth but also to the pore water pressure. And the higher pore water pressure is, the smaller safety factor becomes. When the pore water pressure increases, the safety factor reduces, while the higher the quality class of rock mass is and the shallower tunnel depth is, the more obvious this trend is. For example, as shown in Fig 14, when the tunnel depth is 30 m, the higher quality class of rock mass is, the trend of the safety factor being reduced is obvious with the increase of pore water pressure, however, the lower quality class of rock mass is, this trend is vague. On the other hand, as shown in Fig. 15 and Fig. 16, respectively, the higher pore water pressure is, the vaguer the reducing trend of safety factor with the increase of the tunnel depth is.

5. Discussion And Conclusion

The focus of this paper is on a new method of solving the safety factor of rock mass surrounding a tunnel.

First, Various criteria are compared and analyzed, such as the non-convergence of finite element calculation, penetration of plastic strain and sudden change of horizontal displacement, respectively, estimating method of slope stability. Thus, it was found that the same estimating method of slope stability can't be used in tunnel stability.

Second, the sudden change of equivalent plastic strain in the SRM is used to estimate the stability of rock mass surrounding a tunnel. For the circle tunnel, the sudden change phenomenon of the equivalent plastic strain was very obvious on side wall of excavation part for any circle tunnels and the reduction coefficient corresponding the sudden change point was the minimum. Namely, the best solutions to the safety factor is obtained from the plastic strain curve for the specific point on side wall of a circle tunnel. While for the square tunnel, the sudden change phenomenon of the equivalent plastic strain was quite obvious on the corners of top and bottom of excavation part for any square tunnels and the reduction coefficient for the sudden change point was the minimum. This method is relatively effective and simple for the judgment of the critical state and for the determination of the safety factor of the rock mass surrounding tunnel and can overcome the weakness of previous criteria.

Third, on the basis of this method, compact sets of the safety factors charts are proposed for circle and square tunnels. Table 2 and 3 show that the safety factors is varied with geometries (H/D or H/B), friction angles (φ) and cohesions (c) for the circle and square tunnels. In the other word, table 2 and table 3, respectively, show that the larger H/D or H/B is, the smaller safety factor becomes while for the same H/D or H/B the smaller friction angle and cohesion are, the smaller the safety factors become.

Fourth, it is important to understand the implication of the safety factors shown in Figs. 14 - 16. These Figs imply that the safety factor has close relativity with the quality class of surrounding rock mass, the tunnel depth and pore pressure. And as shown in these Figs, the deeper the tunnel, the softer the surrounding rock mass and the higher pore pressure is, the smaller safety factors become. The safety factors under every calculation condition can be classified smaller than 1.0, 1.5 or larger than 2.0 using the above calculation results. It is interesting to note that the safety factors can be obtained depending on the class of quality of surrounding rock mass, the pore water pressure and tunnel depth, respectively.

This study will be exploited in any rock mass surrounding tunnel where the stability estimation is needed, and it seems that this is a new prospecting standard for the judgment of critical failure state. It is important to carefully monitor plastic strain behavior of the surrounding rock mass in different parts of the tunnel. On the based this, it needs to estimate not only the local instability but the total instability induced by the local instability. It appears that this is the whole stability estimation of rock mass surrounding tunnels.

However, since compared calculation models are not sufficient, these results were not examined for all cases and may be influenced by some external factors. Our research may have a limitation. The stability estimation is limited for only surrounding rock mass of homogeneous material. Further studies are needed in order to judge more rationally critical failure state for the stability estimation of tunnel or surrounding rock mass with any structure type and any rock mass condition. The research for the stability estimation of tunnel has direct influence on the investment of tunnel construction and is of great significance in protecting environment or decreasing environmental pollution.

Declarations

Declaration of interest statement

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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Figures

Figure 1

Sudden change point on the relative curve between the strength reduction coefficient (F_v) and the equivalent plastic strain value (PEEQ)

Figure 2

Plane strain circle tunnel

Figure 3

Finite element mesh of a circle tunnel

(a)

(b)

Figure 4

SRM analysis for a circle tunnel: (a) Equivalent plastic strain; (b) Deformed mesh

Figure 5

Selection of specific 5 points in excavation part of circle tunnel

(a) Curve for point 1

(b) Curve for point 2

(c) Curve for point 3

(d) Curve for point 4

(e) Curve for point 5

Figure 6

Relation curves between the strength reduction coefficient (F_v) and the equivalent plastic strain (PEEQ), between the strength reduction coefficient (F_v) and the horizontal displacement (U_1) on the specific 5 points of a circle tunnel

Figure 7

Plane strain square tunnel

Figure 8

Finite element mesh of square tunnel

(a)

(b)

Figure 9

SRM analysis for a square tunnel: (a) Equivalent plastic strain; (b) Deformed mesh

Figure 10

Selection of specific 5 points in excavation part of circle tunnel

(a) Curve for point 1

(b) Curve for point 2

(c) Curve for point 3

(d) Curve for point 4

(e) Curve for point 5

Figure 11

Relation curves between the strength reduction coefficient (F_v) and the equivalent plastic strain (PEEQ), between the strength reduction coefficient (F_v) and the horizontal displacement (U_1) on the specific 5

points of a square tunnel

Figure 12

Calculation model

Figure 13

Safety factor with quality class of surrounding rock mass and tunnel depth

Figure 14

Safety factor with quality class of surrounding rock mass for H = 30 m

Figure 15

Safety factor with quality class of surrounding rock mass for H = 65 m

Figure 16

Safety factor with quality class of surrounding rock mass for H = 100 m