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Preliminary study on determination of reasonable ratio of spacing to diameter of double tunnels under earthquake

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Abstract: For determining the reasonable ratio of spacing to diameter of double tunnels, the criterion is often only for the excavation, and does not take into account the earthquake situation. In order to ensure the stability of surrounding rock masses, safety and economic rationality during construction and operation of the adjacent tunnels, in this paper, the dynamic responses with different spacing under different earthquake actions and different constitutive relations are analyzed. Based on the plastic zone of the inter-tunnel rock mass connecting or not and the inflection point of the relative displacement curve of the key points of the surrounding rock mass of the tunnel, the reasonable ratio of spacing to diameter under earthquake action is preliminarily determined. The results show that the influence of the earthquake on single tunnel is smaller than that on double tunnels, regardless of the distance between the tunnels and the diameter of the tunnel. Under earthquake, the closer the double tunnels are, the relative displacement is larger. When the distance is smaller than the tunnel diameter, the relative deformation is much larger than other cases, when the distance is 2-3 times diameter, the relative deformation is basically maintained at a stable value. For different diameter of tunnels, the reasonable spacing is not the same under excavation, but its reasonable ratio of spacing to diameter is about 1.5, more than 1.5, the plastic zone of the surrounding rock between tunnels will not penetrate. The response trend of the surrounding rock is the same under excavation and earthquake, having nothing to do with the diameter, and its reasonable ratio of spacing to diameter is about between 2 and 3. Compared the reasonable ratio of spacing to diameter under excavation, the reasonable ratio of spacing to diameter under the action of the earthquake is larger, so it needs to determine the reasonable ratio of spacing to diameter in high seismic intensity areas, not only consider excavation, but also consider earthquake. It is hoped that the research can provide some technical reference for practical engineering.

With the national economic development and construction, a large number of railway tunnels, highway tunnels, mine tunnels, urban railways and hydraulic tunnels and other projects have been built. In the construction process, due to development needs, it often needs to form two, or even more parallel or cross underground tunnels group. In order to ensure the stability of the surrounding rock masses, safety and economic rationality during construction and operation of the adjacent tunnels, a reasonable spacing should be chosen for different sizes of tunnels. In other words, reasonable ratio of spacing to diameter of tunnels, has become an important and meaningful research topic.

For the determination of reasonable ratio of spacing to diameter, it generally uses engineering analogy, numerical method and model test and the corresponding design specifications.The engineering analogy method is the method that, through the statistics of the spacing of the underground caverns, puts forward the suggested value of the spacing of the caverns under the general conditions[1,2].The numerical method, based on the finite element, the discrete element, the

boundary element and other numerical software, and model test are used to calculate and analysis stress, displacement and the corresponding plastic zone of the adjacent caverns at different distances, and a reasonable spacing value with relatively stable influence is obtained [3-7].The design specification specifies different types of tunnels: for highway tunnels, "Code for Design of Road tunnels" (JTG_D70/2-2014)specifies the minimum spacing between different separate double tunnels corresponding to different grades of surrounding rock [8]; For the mine tunnel, although there is no corresponding specification, it has formed a reasonable spacing of the tunnel experience method[9]. "Code for Design of Railway tunnels" (TB-10003-2016) has also made the corresponding minimum spacing between adjacent single-track railway tunnels, and has also established a reasonable distance between adjacent single-track railway tunnels [10]. In order to ensure the stability of rock mass between adjacent tunnels, it is stipulated that the thickness of the tunnels should not be less than 2 times of the excavated tunnel diameter (or tunnel width)by"Specification for design of hydraulic tunnel"(SL279-2016)[11] .The research results and regulations for determining the minimum spacing or reasonable spacing of tunnels are for the tunnels in the excavation, construction process, operation and other conditions to maintain stability and not in the earthquake and other special circumstances. " Code for Design of Road tunnels " (JTG_D70-2004) [8] provides that "in areas where the peak ground motion acceleration is greater than 0.15, it is appropriate to conduct seismic strength and stability checking in the selection of small distance tunnels". Therefore, it is necessary to study the reasonable spacing of adjacent caverns for earthquake action.For the dynamic response of double tunnels under earthquake, Wang[12] discussed the influence of the variation of spacing on the dynamic stress concentration of tunnel surface by incident steady-state P、SV wave and SH-wave. Chen[13]studied the effect of the obliquely incident SV waveson double caverns in a layered half-space, and the ground displacement responses of the double caverns with different spacing. Zhao [14] used the damage plasticity model to analyze the seismic response of the underground caverns, and studied the effect of the distance between the chambers on the double-chamber and three-chamber models with soft, medium and hard rock. Although the above studies have analyzed the responses of underground tunnels with different spacing under earthquake action and the reasonable spacing range of different types of lithologic caverns has also been initially determined [14], but there is no reasonable spacing for the adjacent tunnels with different diameters. Therefore, the basic idea of this paper is to analyze the dynamic response of surrounding rock under earthquake and different constitutive relations for adjacent tunnels with different diameters, and to determine the reasonable ratio of tunnel diameter to diameter.

Numerical model

Calculation model

As shown in Fig. 1, a model of 600m long, 10m wide and 600m high is established. The tunnels are circular and the size of adjacent tunnels is the same. The distance between the tunnels with radius R is L and the depth is 300m. In order to reflect the influence of different spacing on the tunnels, it maintains the location of the right tunnel unchanged and change the location of the left one.The corresponding response of surrounding rock of the right tunnel is monitored. The numbers in the figureare the monitoring points of the surrounding rock of the right one. The whole calculation process includes the excavation of the tunnels and the influence of the seismic load on the tunnels. After the excavation, the viscous boundary is applied at the bottom of the model. The free boundary is imposed around the model and the free boundary is at the top. Before excavation, the geostress of

the model is composed of gravity. The parameters of surrounding rock are shown in Table 1.

Table 1 Physical and mechanical parameters of rock

Density (kg/m^3)	Elastic Modulus (GPa)	Poisson's ratio	Internal friction angle (^{0})	Cohesion (MPa)	P wave velocity (m/s)	S wave velocity (m/s)	tensile strength (MPa)
2720	5	0.27	38.66	1.4	1515.59	850.71	3

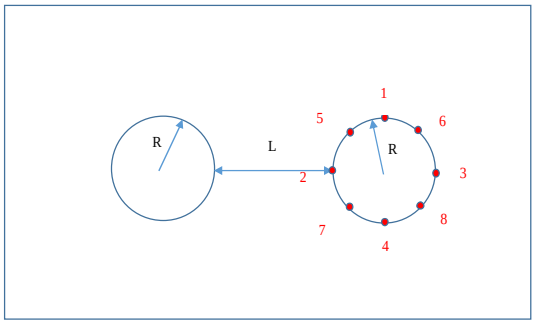


Fig.1 Schematic diagram of calculation model

Earthquake

Since the main purpose of this paper is to explore the general law, it can choose some typical time history of ground motion like Kobe wave. Since the effect of shear waves is often greater than that of compressional waves, ground motion is input at the bottom of the model as a horizontal shear wave.

Calculation scheme

The purpose of this paper is to analyze the dynamic responses of different spacing on surrounding rock of the tunnels under different earthquake actions and different constitutive laws (Mohr-Coulomb criterion referred to as M-C criterion) with different diameters, and to determine the reasonable ratio of tunnel spacing to diameter under the earthquake action, so the design of the conditions is shown in Table 2.

Table 2 Calculation scheme

Diameter2R(m) / SpacingL(m)	8.4	12	16
Elastic and M-C criterion	Single	Single	Single
	6.6	10	12
	8.6	18	
	11.6	24	22
	16.6	36	32
	21.6	48	48

Seismic Response Analysis of Double tunnels with Different Diameters

Fig. 2 shows the horizontal relative displacement time histories of two different tunnels with different diameters under the action of kobe wave. It has been pointed out that the relative displacement time of the monitoring points 1 and 4 and the monitoring points 2 and 3 are only given as the relative distance between the two monitoring points longer, the greater the relative displacement of the peak. It can be seen from the figure that, relative to a single tunnel, the peak value and the final value of the relative displacement of the monitoring points 1 and 4 of double

tunnels are larger than those of the single tunnel, regardless of the spacing and the size of the tunnels. Points 2 and 3 are a bit different, for the peak and the final value of the relative displacement of a single tunnel being smaller than the case of close-up double tunnels, but larger than the case of long-distance double tunnels. This is because in the excavation, relative to a single tunnel, the right one of double tunnels will result in a deformation tendency to the left for the left one being too close, and the impact of monitoring points 3 is greater than that of the monitoring point 2. Therefore, the relative deformation of the monitoring points 2 and 3 is smaller than that of the single one. When the left tunnel is gradually away from the right one, the influence will gradually decrease and the deformation of the two tunnels will gradually become a single tunnel, as shown in Figure 2. For the double tunnels with diameter of 16m, due to the tunnel diameter increasing, when the spacing is too close, the left tunnel causes the monitoring point 2 of the right tunnel to develop to the right, and the monitoring point 3 is deformed to the left, which results in excavation deformation of single tunnel being smaller than that of close-up double tunnels and the same with that of long-distance double tunnels. However, the influence of the earthquake on the single tunnel is smaller than that on the double tunnels, which brings that the relative deformation of the monitoring points 2 and 3 in the middle and long-distance double tunnels, compared with the single tunnel, has no obvious rule. The closer the double tunnels spacing, the greater the relative displacement of the surrounding rock monitoring points. When the distance is smaller than the diameter, the relative deformation is much larger than the other cases, this is because the plasticity zone of the surrounding rock between the double tunnels has been penetrated. when the distance is 2-3 times diameter, the relative deformation is basically maintained at a stable value.

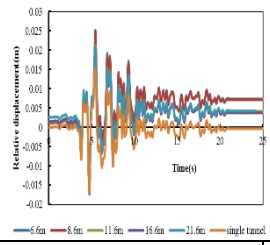
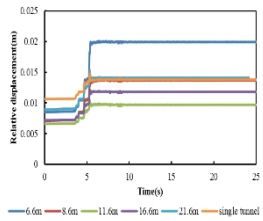
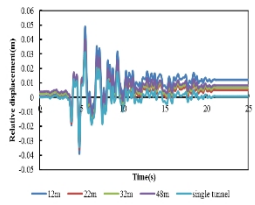
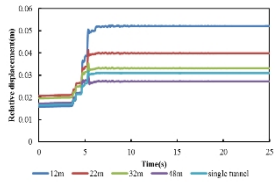
Diameter	Monitoring points 1 and 4	Monitoring points 2 and 3
8.4m		
16m		

Fig.2 Horizontal relative displacement time history of double tunnels with diameters

Determination of reasonable ratio of spacing to diameter

Study on reasonable ratio of spacing to diameter under excavation

Because of the stress redistribution caused by the excavation, the stress concentration or relaxation of the surrounding rock of the cavern make it produce shear yield or tensile yield. With the decrease of the distance between the caverns, the support of the surrounding rock will gradually decrease and the plastic zone will expand continuously. When the spacing is reduced to a certain extent, the plastic zone will break through, which will lead to the overall destruction of the tunnels.Therefore, the method of determining the reasonable spacing under excavation can be judged by analyzing the development of the plastic zone of surrounding rock. For the double tunnels

with diameter of 8.4m, When the distance between two tunnels is 11.6m, the plastic zone of the surrounding rock will begin to penetrate. The smaller the spacing is, the larger the penetration area will be; For the diameter of 12m double tunnels, although the spacing of 18m cannot make it through the surrounding rock, but the spacing of 10m, the surrounding rock has been penetrated, which indicates that the reasonable spacing should be between 10m-18m and trend to 18m. Similarly, the reasonable spacing of tunnels with diameter of 16m is between 12m-22m and trend to 22m. Therefore, for different diameter of the chamber, the reasonable spacing is not the same under the action of excavation, but its reasonable ratio of spacing to diameter is about 1.5. When it is less than 1.5, the caverns may be destroyed, which meets the requirements of the specification design [8-11].

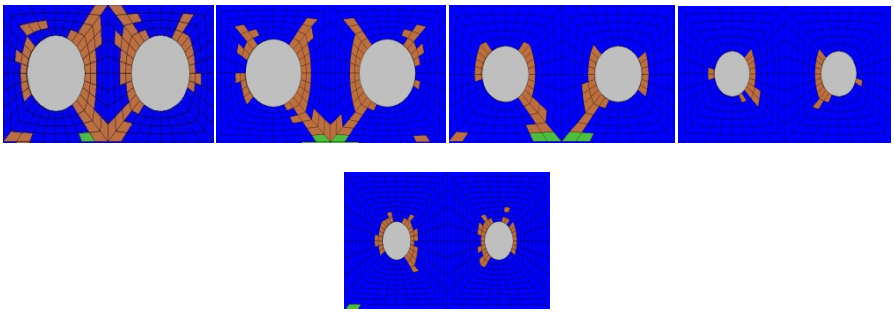
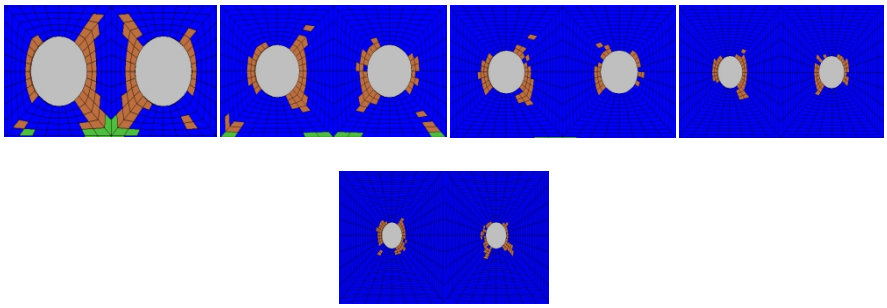
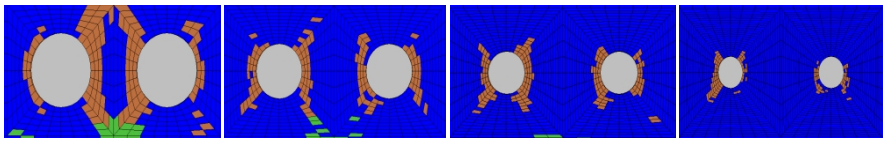
Diameter	Plastic zone of double tunnels with different spacing under excavation
8.4m(From 6.6m to 21.6m)	
12m(From 10m to 36m)	
16m(From 12m to 48m)	

Fig. 3 Plastic zone of double tunnels with different diameters under excavation

Study on reasonable ratio of spacing to diameter under earthquake

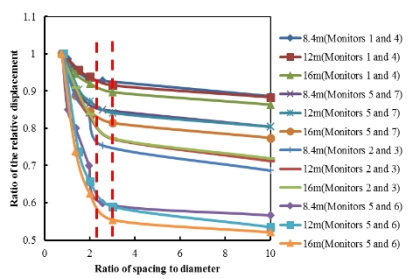
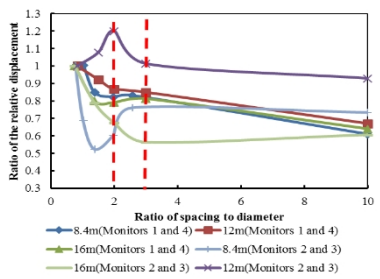
Usually, changes in internal or external factors often lead to expression changes of a part of the main project or the overall form. If such factors once reached a level, it may even make the main project damage.For the stability of tunnel, if the nature of the surrounding rock (internal factors) or the surrounding geological structure (external factors) have changed, this stage is often expressed in a certain characteristic curve of the tunnel surrounding rock by a linear change to the development of nonlinear acceleration changes, and the inflection point is the key to determine the stability of the tunnel.When the distance between two tunnels decreases, the surrounding rock as the key system to support the stability of the tunnels will cause the overall instability, and the relative deformation of the surrounding rock is often to determine the function of the tunnel structure. Therefore, in order to determine the reasonable hole spacing under specific diameter, the relationship between the relative deformation of the surrounding rock and the hole spacing is established to find the inflection point of the relationship curve. In the same way, the reasonable spacing under different diameters can be found out. Finally, according to the ratio of spacing to diameter,the reasonable ratio of spacing to

diameter under earthquake action is determined.

Fig.4shows the relative displacement of surrounding rock monitoring points with different spacing for different diameter. The ordinate is the ratio of the relative displacement of the two tunnels with larger spacing to the relative displacement of the two tunnels with the smallest tunnel spacing for different diameters, and abscissa is the ratio of spacing to diameter, assuming ratio of spacing to diameter of a single tunnel of 10. It can be seen from the figure that under the action of earthquake, the relationship between relative displacement and ratio of spacing to diameter of the same monitoring point under different diameters is relatively similar on the condition of elastic model, which shows that for tunnels with different diameters, the response trend of the surrounding rock under combined action of excavation and earthquake is the same, and has nothing to do with the diameter.For elastic model, more than ratio of 3, the curve is constant velocity change and relatively flat, and less than ratio of 2.3,the curve is basically accelerated change, and steep, so the inflection point is between 2.3 and 3; for MC criteria, the curve has not obvious changes like the case under elastic constitutive, but generally the inflection point in the between 2 and 3 position. The results show that the reasonable ratio of spacing to diameter of two tunnels is about 2 and 3 under the combination action of excavation and earthquake, and the result of literature [14] is also validated.

Excluding the effects of excavation, the relative displacements of the monitoring points of the surrounding rock masses with different diameters under seismic action are shown in Fig.3. Compared with the double action of excavation and earthquake, the relative displacement with the ratio of spacing to diameter with only consideration of earthquake action is more smooth and more obvious and the relationship between relative displacement and ratio of spacing to diameter of the same monitoring point under different diameters is more similar. It is shown that the response of surrounding rock of the tunnels under earthquake is the same, which is independent of the size of the tunnels. The inflection point is also between 2 and 3, which indicates that the reasonable ratio of spacing to diameter of double tunnels is between 2 and 3.

Compared with the reasonable ratio of spacing to diameter under excavation, the reasonable ratio under earthquake action is larger, because the earthquake action will aggravate the damage of surrounding rock. Therefore, when it is necessary to determine the reasonable spacing, it should be analyzed for different diameters, not only considering the excavation, but also considering the seismic action, rather than simply according to the standard design to determine the reasonable spacing of the tunnels.

Load Case	Elastic model	M-C criteria
Excavation and earthquake		

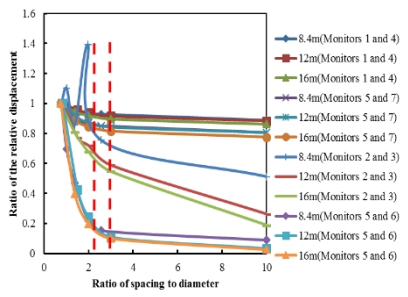
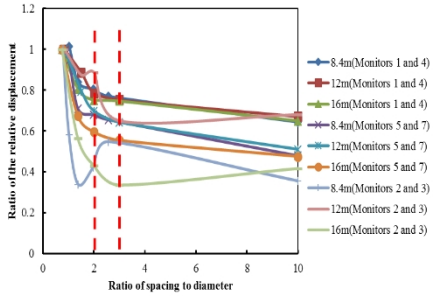
Earthquake		

Fig.4 Relative displacement response under different spacing and diameters

Conclusion

In this paper, the dynamic response of surrounding rock under earthquake and different constitutive relation is analyzed for two tunnels with different diameters and the reasonable ratio of tunnel diameter to diameter is preliminary determined. The following conclusions are obtained:

(1) Under earthquake, the closer the double tunnels spacing, the greater the relative displacement of the surrounding rock monitoring points. When the distance is smaller than the diameter, the relative deformation is much larger than the other cases, this is because the plasticity zone of the surrounding rock between the double tunnels has been penetrated. when the distance is 2-3 times diameter, the relative deformation is basically maintained at a stable value.

(2) For different diameter of the chamber, the reasonable spacing is not the same under the action of excavation, but its reasonable ratio of spacing to diameter is about 1.5. When it is less than 1.5, the caverns may be destroyed, which meets the requirements of the specification design.

(3) For tunnels with different diameters, the response trend of the surrounding rock under combined action of excavation and earthquake is the same, and has nothing to do with the diameter, which indicates that the reasonable ratio of spacing to diameter of double tunnels is between 2 and 3. Compared with the double action of excavation and earthquake, the relative displacement with the ratio of spacing to diameter with only consideration of earthquake action is more smooth and more obvious and the relationship between relative displacement and ratio of spacing to diameter of the same monitoring point under different diameters is more similar. The reasonable ratio of spacing to diameter is also between 2 and 3.

(4) Compared with the reasonable ratio of spacing to diameter under excavation, the reasonable ratio under earthquake action is larger. Therefore, when it is necessary to determine the reasonable spacing, it should be analyzed for different diameters, not only considering the excavation, but also considering the seismic action, rather than simply according to the standard design to determine the reasonable spacing of the tunnels.

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