The Calculation of Stability of Tunnel under Effects of Seismic Wave of Explosion

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Abstract

With a lot of experiments on explosion, the dynamic stability of grotto and sprayed anchor strutted grotto were studied under effects of seismic wave of explosion, and a formula was put out for calculating the stability. The results of calculation fitted results of testing well.

l. Introduction

It is usually needed to evaluated the stability of tunnels and galleries in structures of mines, railroads and hydro-electric engineerings under effects of dynamic loading, and the safety distance needed to be determined. The dynamic loads result mainly from explosion work and accidents. When the stability of tunnels and galleries are evaluated under effects of seismic wave of explosion, it should be considered the dynamic loads from explosion as well as static loads from rocky soil. The quantities of dynamic loads are related to amplitude and lasting period of seismic wave of explosion propagated among ground.

2. The dynamic strength of rocks

It is well known that under effects of dynamic loads, the limit range of rock strength increases with the increasing of loading rate. The increased value of strength relates to the nature of rocks and loading rate. The values of granite and marble are listed in table l.

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Table 1. The variations of compressive strength of rocks with loading rate

Rock	Loading rate V_1 kg/cm^2/sec	Com. strength σ_1 kg/cm^2	Loading rate V_2 kg/cm^2/sec	Com. strength σ_2 kg/cm^2	σ_2/σ_1
Granite	5	1220	20	2000	1.64
Marble	5	500	30000	980	1.98

Table l. The variations of compressive strength of rocks with loading rate

All of compressive strength of rocks increase with increasing of loading rate, but increased value is different for each rock. The compressive and flexural strength and elasticity modules of rock increase with a logarithmic function of loading rate.

3. The dynamic strength of rock mass

Because cracks and cleavages exist, the strength of rock mass is lower than that of rock. The discount factor is about 0.80~0.90. When the loading rate is l0^2~l0^{4}kg/cm^2/sec, the compressive strength of rock increases by l. l 6~1 .43 times and flexural strength increases by l .24~l .48 times. Because the damage of rock mass of tunnel is controlled by tensile strength, the dynamic strength of rock is taken as l.30~1.40 times of static strength. So, the formula for calculating the dynamic strength of rock mass is:

$$\sigma_D = K_D \sigma_P \tag{1}$$

Where: σ_D is dynamic tensile strength of rock mass (kg/cm^2); σ_P is ultimate static tensile strength of rock (kg/cm^2); K_D is increasing factor of dynamic strength of rock mass.

If the surface rocks of grotto are stable, the surface are usually sprayed with Scm thickness concrete and K is among l.04~1.26. If the surface rocks of grotto are unstable, the surface are usually strutted by rollbolts and then sprayed with Scm thickness concrete and K is among l.30~1.40.

4. The calcuiation of stability of tunnels under effect of seismic wave of explosion

4.1. Concentrated factors of dynamic and static stress of tunnel without lining

Under effect of plane wave of explosion, the concentrated factors of dynamic and static stress of tunnel without lining are listed in table 2.

Table 2. Concentrated factors of dynamic and static stress of tunnel without lining*

Pattern of tunnel	Position	Concentrated factor of dynamic stress		Concentrated factor of static stress
		Analytical $D/\lambda=0.12\sim0.15$	Numerical $D/\lambda=0.50$	
Straight wall	Arch	3.25~2.25	3.00	3.25
and round arch	Wall	2.00~1.65	1.80	1.50

*D is diameter of tunnel; λ is wave length

Table 2.
Concentrated factors of dynamic and static stress of tunnel without lining*

4.2. The calculation of stability of tunnel under effects of seismic wave of explosion

Under effects of seismic wave of explosion, the stable condition of rock mass of tunnel without lining is that the sum of static stress of mountain and dynamic stress of seismic wave of explosion is smaller than or equals to the dynamic strength of rock mass; that is:

$$\sigma = \sigma_{CT} + \sigma_{DT} < [\sigma_D] \quad (2)$$

Where: σ is the total stress among rock mass (kg/cm^2); $[\sigma_D]$ is allowable dynamic strength of dynamic strength of rock mass calculatted from equation (1) (kg/cm^2); σ_{DT} is dynamic stress of rock mass under effect of seismic wave of explosion, (kg/cm^2).

$$\sigma_{DT} = (l/K_0)(K_G\gamma/g)CeV \times 10^{-3} \quad (3)$$

Where: γ is unit weight of rock (kg/cm^2); V is vibrating velocity of rock particles in periphery of tunnel under effects of seismic wave of explosion (cm/sec); Ce is elastic velocity of longitudinal wave; g is acceleration of gravity g=9.81 m/sec^2; K_0 is reflection factor. Tested results showed that if the tunnel is acted by incident seismic wave of explosion, the factor is K_0 =2; if the tunnel is acted by reflected seismic wave of explosion, the factor is K_0 = 2.

4.3. The calculation of critical vibrating velocity of rock particles

From equation (2), the critical vibrating velocity of rock particle is:

$$Ve = K_0(K_D\sigma_P - \sigma_{CT})/(K_G\gamma Ce) \times l\,0^{-3} \quad (4)$$

Where: Ve is critical vibrating velocity of rock particle. When the critical vibrating velocity of rock particle is calculated to rock mass in elasticity zone, the elastic velocity of longitudinal wave Ce is taken; when the critical vibrating velocity of rock particle is calculated to rock mass with cracks, the elasto-plastic velocity of longitudinal wave Cp is taken, and it is taken Cp=Ce/2 if there is no tested data of Cp.

4.4. The calculation of critical vibrating velocity of rock particle for collapsed rock mass

The tested results showed that when the properties of tunnel structure change to plasticity, cracks appear in arch and in boundaries between arch bottom and side wall. With the continuous effect of explosion wave, the deformations of arch and side wall increase, but the stress in rocks doesn't increase and the tunnel appears a unloading effect. Under effect of a normal big explosion, the self-vibrating frequency of rock is 10~15 Hz and the seismic wave of explosion lasts 0.4~0.6 sec. If the tunnel is taken as a structure, the unloading factor of tunnel in plasticity zone is solved from theory calculation, thus the critical vibrating velocity of rock particles in collapsed rock mass is:

$$Vp = K_O(KD\sigma_{P+}\sigma_{CT})g/(K_G\gamma C_P) \bullet (1/K_z) \times l0^{-3} \quad (5)$$

With tested data of deformation of tunnel caused by effect of seismic wave of explosion, the unloading factor Kz is solved theoretically. If unloading factories Kz=0.80~0.65, rock mass appears partial collapsing and the collapsed volume is usually smaller than Im^3. If unloading factor is Kz = 0.50~0.35, the rock mass appears large area collapsing.

4.5. Comparison between results of calculation and practical tests

Known a round arch and straight wall tunnel without lining, rollbolt and sprayed concrete. The span is L=3m, height is H=3m. The rock is granite with macro crystalline (weathering). The properties of rock are tested as: Pope's factor f=4~6; unit weight γ -2.64t/m ; elastic velocity of longitudinal wave Ce=2060m/sec; dynamic elastic modules E=0.928xl0^{5}kg/cm^2; Poisson ratio μ = 0.30; internal friction angle ϕ = 41°06'; static ultimate tensile strength σp = 23.60kg/cm^2.

Chosen f=5, Ce=2060m/sec, Cp=l030ni/sec, Kp=1.15, K_O=2, Kz=0.65 for partial collapsing and Kz=0.35 for large area collapsinng, the results of calculation is listed in table 3.

Table 3. A comparison of critical vibrating velocity of rock particles from calculation and from practical tests cm/sec

	No damage [V1]	Slight cracking [V2]	Partial collapsing [V3]	Large area collapsing [V4]
Tested	30	30~50	50~100	100~200
Calculated	30.36	30.36~60.73	60.73~93.42	93.42~173.48

Table 3. A comparison of critical vibrating velocity of rock particles from calculation and from practical tests cm/sec

The calculated results fit the tested results well and the maxiinum error is smaller than 20%.

5. Applications in engineering

5.1. Land form

If the thickness of rock mass at minimum resistant line of grotto is smaller than 50 times of explosive diameter, the rock mass is called gentle slop; if the thickness of rock mass is bigger than 50 times of explosive diameter, the rock mass is called steep slop.

When a explosive in grotto explosion, a projection of rock over the grotto takes place if the grotto is in a gentle slop and projection doesn't take place if the grotto in a steep slop.

5.2. Geology

The classification of rock is made according to features of structure and is listed in table 4.

Table 4. Classification of structure of rock mass

Classification	Sturcture features	Comp. strength of rock kg/cm	Elastic velocity of longitudinal wave m/sec	n
Concordant structure	Rock mass is a whole or a giant layer, extramly undeveloped joints, no dominate strructure plane Bo*=1~2, M<0.5	>300	>4000	>0.85
Massive structure	Rock mass is a massive or thick layer structure, undeveloped joints most of structure planes are joint plane and closed (such as psephyte) Bo=2~3, M=0.5~2	>200	3000~4000	0.85~0.6
Fragment structure	Rock mass is a less thick layer or massive structure, developed joint, most of structure planes are jiont planes. Bo=3~4. M=2~5	>100	2000~3500	0.6~0.3

*Bo is joint data; M is number of joints in one meter; $n=(Cv/Ce)^2$; Cv is longitudinal wave velocity of rock mass m/sec. Ce is longitudinal wave velocity of rock m/sec.

Table 4. Classification of structure of rock mass

5.3. The critical vibrating velocity of wall rock with different degree of damage

The velocity are listed in table 5.

Table 5. Critical vibrating velocity of wall rock of grotto [V1], [V2], [V3], [V4]

Rocks	Unit weight (t/m^3)	Comp. strength (kg/cm^2)	Tens. strength (kg/cm^2)	No damage (cm/sec)	Slight damage (cm/sec)	Intermediate damage (cm/sec)	Serious damage (cm/sec)
Hard	2.60~2.70	750~1100	21~34	27	54	82	153
rock	2.70~2.90	1100~1800	34~51	31	62	96	178
	2.70~2.90	1800~2000	51~57	36	72	111	209
Soft	2.00~2.50	400~1000	11~31	29	58	90	167
rock	2.00~2.50	1000~1600	34~45	35	70	107	199

Note: 1. The data in this table are applicable for grottoes in gentle slop; if grottoes in steep slop, the data needed to be multiplied by 2.

2. If the hole of explosives is parallel or oblique or perpendicular to a grotto, the critical vibrating velocity of wall rock [V1], [V2], [V3] and [V4] need to be multiplied by 1.0, 1.2 and 1.4, respectively.

3. The data in the table are applicable for rocks with concordant structure and the data need to be multiplied by 0.9 or 0.8 for rocks with massive structure and fragment structure, respectively.

Table 5. Critical vibrating velocity of wall rock of grotto [VI], [V2], [V3], [V4]

5.4. The determination of support pattern of wall rock

According to the relation between perpendicular vibrating velocity of seismic wave of explosion and critical vibrating velocities of wall rock of no damage[V1], slight damage[V2], intermediate damage[V3] and serious damage[V4], the support pattern of wall rock is determined:

A. if Vv<[V1], sprayed with #200 plain concrete of thickness 50 cm;

B. if [VI]<Vv<[V2], sprayed with #200 plain concrete of thickness 80 cm;

C. if [V2]<Vv<[V3], net and concrete; a 250x250 mm net made of 8mm steel is placed on the surface of wall rock and then sprayed with #200 plain concrete of thickness 80~100mm;

D. if [V3]<Vv<[V4], net, concrete and roltbolt; a 250x250 mm net is placed on surface and sprayed with ~200 plain concrete of thickness 80~I00 mm, and ~16x2000 mm rollbolts are installed. The rollbolts are made of mortar and arranged with a distance of 2000x2000 mm to each other.

6. The calculation of perpendicular vibrating velocity of seismic wave of explosion

Based on analysis of tested data from explosion on ground, mine explosion including standing shot, long hole volley fning, long hole short-delay blasting, directional explosion and internal explosion of tunnel, empirical formulae for calculating the perpendicular vibrating velocity of rocks in various geological conditions are listed in table 6 and drawn in fig. l and 2.

Table 6. Empirical formulae of perpendicular vibrating velocity of rock particles under effects of seismic wave of explosion

No	Pattern of explosion	Explosion conditions and explosive quantity	Grological condition	$Vv=k(Q^{1/3}/R)^{\alpha}$ k	α
1	ground explosion	Central charged Q=1, 3, 5, 10, 15, 14,100t	Granite	98.76	1.37
2	Unshelted big explosion	A. once delayed blasting Q=9320t	Diabase	804	2.24
			Disbase	630	2.80
	①Standing shot	B. Vollery blasting Q=1000t	Diabase	206	1.81
		Q=534t	Metamorphic rock	180	1.47
		Q=111~178t	Metamorphic rock	79	1.39
			Phyllite	82.5	1.32
		Q=20t	Mica-quartz schist	152	1.56
			Phyllite	156	1.93
		Q=305t	Diabase	718	2.40
			Granite and marble	150	2.00
	②Long-hole vollery blasting	Q=200t	Marble	77.6	2.33
		Q=103t	Quartz	624	2.41
		Q=8~14t	Limestone	125.7	1.63
			Limestone	130	1.80
			Limestone	140	1.80
			Limestone	200	1.80
			Limestone	340	1.80
	③Long-hole shoet ddelay blasting	A. 6 pieces Q=45.9	Gneiss	180	1.83
			Gneiss	116.2	1.73
		B. 10 pieces Q=4.23t	Marble	378	1.60
			Marble	107	1.50
		C. 10 pieces Q=4.74t	Primary	130	1.70
		D. 10 pieces	Quartz	142	1.61
			Quartz	153	1.60
	④Directional blasting	A. Total Q=13394t	Sandstone	240	2.00
		B. Total Q=503t	Diabase	115	2.00
3	Internal explosion of tunnel	Linear charge Q=8~15t	Granite	99.6	1.72
			Granite	111.2	1.92
			Granite	591.4	2.30
			Granite	90.8	1.82

Note: Vv is perpendicular vibratting velocity of seismic wave of explosion (cm/sec); Q is total quantity of explosion; R is distance between centre of explosion and testing point (m).

Table 6. Empirical formulae of perpendicular vibrating velocity of rock particles under effects of seismic wave of explosion

Fig. l.
Distribution of perpendicular vibrating velocity of seismic wave of explosion

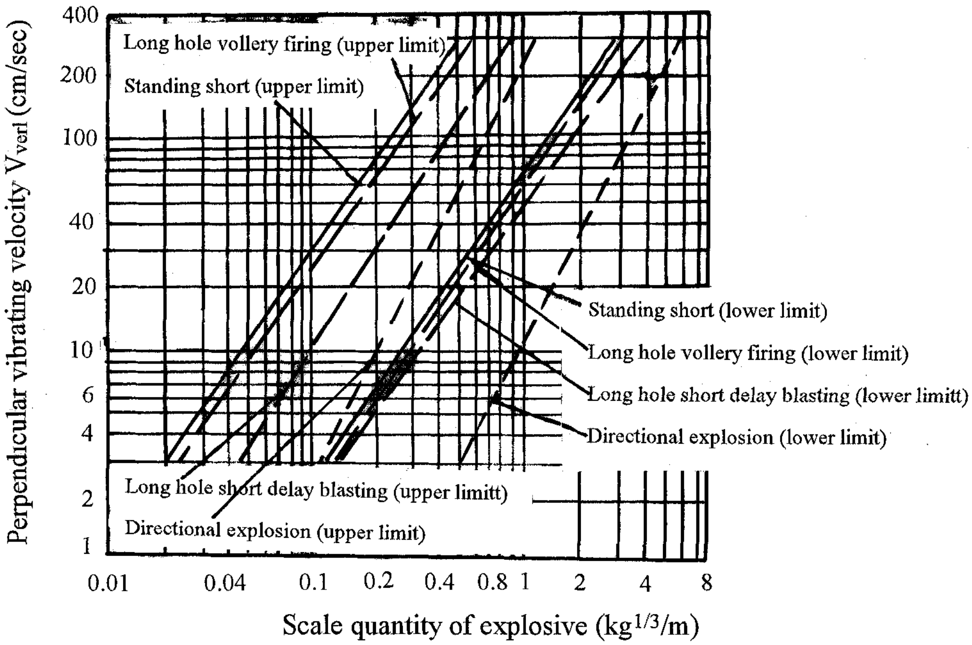

Fig.1. Distribution of perpendicular vibrating velocity of seismic wave of explosion

Fig.2. Distribution of velocity of seismic wave of internal explosion of tunnel

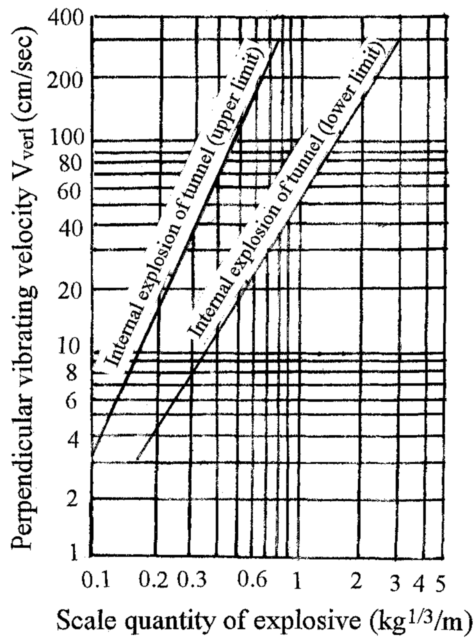

Fig.2. Distribution of velocity of seismic wave of internal explosion of tunnel

Fig. 1 and fig.2 show relations between perpendicular velocity of rocks and scale quantity of explosive$Q^{1/3}/R$ under various conditions of explosion.

7. Safety distance of tunnel without lining under effect of seismic wave of explosion

With the empirical formulae and tested data in table 6, the calculating formula of safety distance is derived:

$$R = 1/([V]/k)^{(1/\alpha)} Q^{1/3} \qquad (6)$$

Where: R is safety distance (m) of tunnel without lining under effects of seismic wave of explosion; α, K are factors determined from tested data in table 6 or in fig. 1~2.; Q is calculated explosive quantities: total quantities of standing shot, the maximum quantity among each delay explosion and the maximum quantity in each period of short-delay blasting; [V] is critical vibrating velocity of rock particles (cm/sec) and calculated with equation (4), (5) or with formulae in table 5.

8. Conclusions

l. On basis of balance between dynamic strength of rock and the sum of dynamic and static stress acted on tunnel, the formulae for calculating critical vibrating velocity of rocks are derived when tunnel without lining un elastic state appears cracking, partial collapsing and large area collapsing under effect of seismic wave of explosion. The results of calculating fit the tested results well.

2. With the critical vibrating velocity, the support pattern of rollbolt and sprayed concrete, and safety distance of stability of grotto are determined.