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Study on unloading cracking area of deep rock tunnel excavation

Abstract: The crack problem of deep rock tunnel under unloading is one of hot issue of rock mechanics at present. Elastic dynamics, Laplace transform and convolution theorem are used to solve transient stress field of blasting unloading around rock tunnel. The crack situation and crack area of blasting transient unloading of deep rock tunnel are given combining with Hopkinson dynamic rupture theory, and the result explains that the dynamic unloading disturbance brings about the rock burst disaster more easily. The example show that the theory and methods described here can correctly reflect the dynamic process caused by excavation and effectively estimate the destroy form of the rock mass induced by excavating unloading. The research achievements are in possession of direction value to stability analysis and supporting design of deep tunnel.

Key words: deep tunnel, crack, rock, blasting, transient stress field.

Introduction

For a long time, the stress-strain state of surrounding rock of underground engineering is researched, mainly using static elastic-plastic mechanics tools and continuum mechanics model. For deep engineering, the essence of deep excavation is rock unload and dynamic disturbance in high stress state under dynamic load, such as blasting vibration and the excavation unloading. The stability and destruction of deep rock engineering is a typical problem of deformation and damage of rock under static and dynamic loading. In this case, the nonlinear characteristics of rock and rock engineering system are more obvious than that of shallow mining rock. The quick release of surrounding rock stress will inevitably produce damage to underground tunnel surrounding rock under high stress during the process of drilling and blasting excavation, and cause the rock mechanical parameters decline sharply. This may form the unloading loose damage area of blasting excavation, Serious consequence would cause local buckling or cracking of rock retained, even supporting structural failure and damage, and induce rockburst and other serious consequences in underground engineering.

Deep tunnel blasting excavation is different from the manual and mechanized excavation method, shown in: on the one hand, explosion load that rock offered is large (greater than the original rock stress) under instantaneous blasting excavation of surrounding rock; on the other hand, rock blasting excavation unloading speed is quick, it belongs to the typical transient unloading process (non quasi static unloading). This needs to know the dynamic law on the kinetic level to make reliable prediction and effective control. Wang Yang et al [1]. put forward simulation method that made the plastic volume strain incremental correspond to the rock mass mechanics parameters of different unloading area, based on the unloading rock mechanics theory and used 3D finite difference software. Xiao Jianqing [2] solved the response law of surrounding rock stress and a dynamic and static explicit analytical solution during tunnel

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excavation for the underground circular tunnel excavation unloading effect, based on dynamics and rock elastic-plastic theory. Lv Wenbo [3] analyzed initial stress field dynamic unloading effect and failure mechanism on the boundary of circular tunnel during drilling and blasting excavation under the condition of high stress and hydrostatic pressure field, and calculated its damage range. Tao Ming [4] used LS-dyna software to simulate the rock unloading process in three-dimensional geostress, the results showed that the unloading process controlled by the rate of strain energy density, and rock burst was produced by rapid unloading of initial ground stress. Ozgur Yilmaz [5] discussed the rock damage range caused by blasting load under different explosives and site condition. Relatively speaking, the surrounding rock fracture under quasi-static unloading was more studied [6, 7], and the research on the transient unloading fracture was less. The dynamic unloading effect of deep circular tunnel excavation during drilling and blasting is analyzed by the theory of elastic dynamics and rock dynamics, and the rock damage range is calculated in this paper.

The transient unloading mechanics model

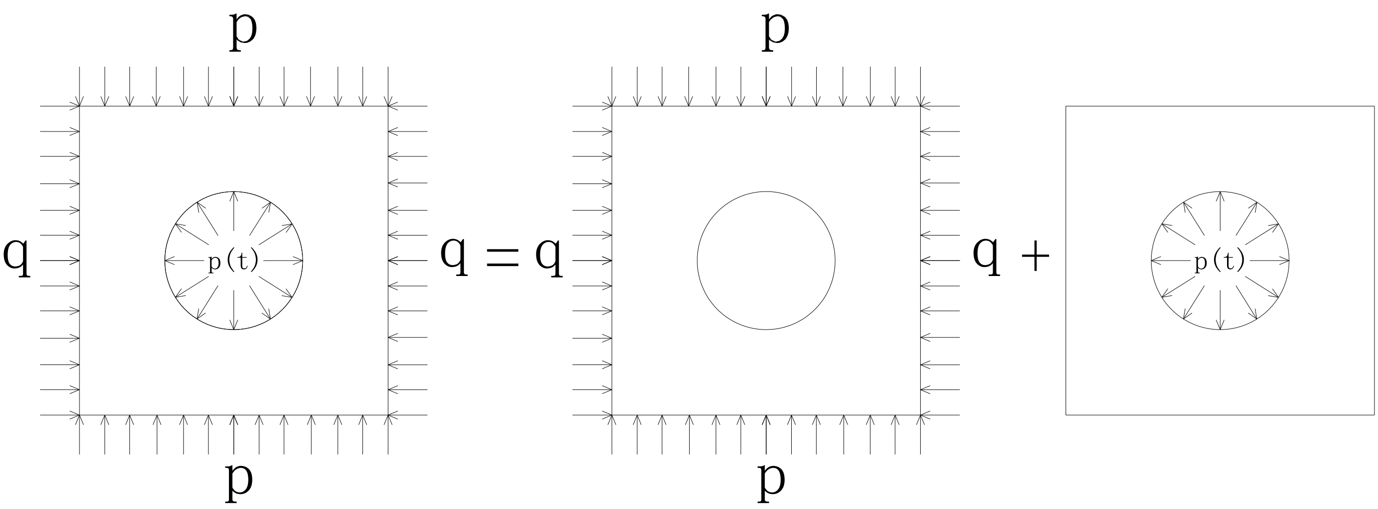

Fig. 1. Mechanical model of circular tunnel during excavation.

A long round-shaped tunnel in deep rock excavation is molded by a full face blasting, and elastic plane strain model is used. Assuming that rock is under hydrostatic pressure, and the excavation problem can be divided into two sub-problems superimposed [8, 9]: one is stress and displacement caused by the original rock stress p and q, the second is stress and displacement generated by the non-situ stress, but at excavation instant time t = 0, the interior walls of the cave suddenly have a uniform unloading pressure $p(t)$. The sum of both is the stress and displacement field of surrounding rock, as shown in Fig. 1.

The solution of the original rock stress field

Taking the origin of coordinates at the center of the tunnel cross-section, and solving in polar coordinates, according to the theory of elastic mechanics, the original rock stress field is:

$$\sigma_r' = \frac{p+q}{2}(1-\frac{a^2}{r^2}) + \frac{q-p}{2}\cos 2\varphi(1-\frac{a^2}{r^2})(1-3\frac{a^2}{r^2}), \tag{1}$$

$$\sigma_\varphi' = \frac{p+q}{2}(1+\frac{a^2}{r^2}) - \frac{q-p}{2}\cos 2\varphi(1+3\frac{a^4}{r^4}), \tag{2}$$

where a is the excavation tunnel radius; r is distance from tunnel center to investigation points; φ is circumferential direction coordinates.

The solution of the transient stress field

For a cylindrical cavity in the infinite elastic medium under non initial stress state, when t=0, a radial force $p(t)$ changing with time acts on the cavity wall. The phase that force unloads from the blast load pressure to the zero is called as dynamic unloading process (Fig. 2).

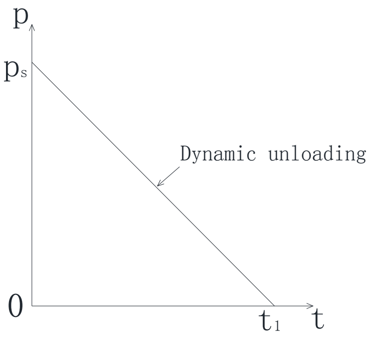

Fig. 2. CUrve of dynamic unloading process.

In the case of plane strain, the control equation of elastic wave is [10]:

$$\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} - \frac{u}{r^2} = \frac{1}{c_p^2}\frac{\partial^2 u}{\partial t^2}, \tag{3}$$

$$\sigma_r'' = (\lambda + 2\mu)\frac{\partial u}{\partial r} + \lambda\frac{u}{r}, \tag{4}$$

$$\sigma_\varphi'' = \lambda\frac{\partial u}{\partial r} + (\lambda + 2\mu)\frac{u}{r}. \tag{5}$$

Rock blasting excavation means the transient unloading of excavation load and the rapid release of elastic strain energy accumulated in rock. The initial and boundary conditions of this problem are:

$$u(r,t)=\frac{\partial u(r,t)}{\partial t}=0;(r\geq a,t<0)\,, \tag{6}$$

$$p(t)=[\sigma''(r,t)]_{r=a}=\begin{cases} 0;(t\leq 0) \\ p_s(1-\dfrac{t}{t_1});(0<t\leq t_1) \\ 0;(t>t_1) \end{cases}\,, \tag{7}$$

$$\lim_{r\to\infty}u(r,t)=0;(t>0)\,, \tag{8}$$

where $u(r,t)$ is medium particle radial displacement; $\sigma''_r,\sigma''_\varphi$ are radial stress and circumferential stress caused by the unloading cylindrical wave in the medium respectively; λ,μ are the lame constant; c_p is media elastic wave velocity; ρ is a medium density; t_1 is the transient unloading time; p_s is initial unloading pressure.

To solving equations (3) using the Laplace transforms method, and take Laplace transform on t for control equation, the follow equation is gotten:

$$\frac{\partial^2 u^*}{\partial r^2}+\frac{1}{r}\frac{\partial u^*}{\partial r}-\frac{u^*}{r^2}=\frac{P^2}{c_p^2}u^*\,, \tag{9}$$

where P is the complex parameter of Laplace transform; u^* is the Laplace transform of u.

Supposing $s=\mathrm{Pr}/c_p$, then the equation is transformed into:

$$\frac{\partial^2 u^*}{\partial s^2}+\frac{1}{s}\frac{\partial u^*}{\partial s}-(1+\frac{1}{s^2})u^*=0\,. \tag{10}$$

The general solution of equation is:

$$u^*=A(p)I_1(s)+B(p)K_1(s)\,, \tag{11}$$

where $I_1(s)$ and $K_1(s)$ are the first class and second class modified Bessel function of modified Bessel equation respectively.

The Laplace transform of boundary conditions (8) is:

$$\lim_{r\to\infty}u^*(r,s)=0\,. \tag{12}$$

The general solution of the differential equation is: $u^*=B(p)e^{-s}\sqrt{\pi/2s}$. (13)

Taking the Laplace transform on the boundary conditions (7), it can be obtained:

$$p^*(p)=p_s(\frac{1}{p}-\frac{1}{t_1p^2})\,.$$

By the stress boundary conditions and formula (4), it is obtained:

$$[(\lambda+2\mu)\frac{du}{dr}+\lambda\frac{u}{r}]_{r=a}=p(t).$$

Taking Laplace transform, it can be gotten:

$$[(\lambda+2\mu)\frac{du^*}{dr}+\lambda\frac{u^*}{r}]_{r=a}=p^*(p). \tag{14}$$

Resulting integration constant $B(p)$: $B(p)=\dfrac{e^{p\frac{a}{c_p}}p_s c_p\sqrt{2pac_p}}{(\lambda+2\mu)(k-p)\sqrt{\pi}}(\dfrac{1}{p}-\dfrac{1}{t_1p^2})$.

Then $$u^*=\frac{e^{p\frac{a-r}{c}}p_s c_p\sqrt{a}}{(\lambda+2\mu)(p-k)\sqrt{r}}(\frac{1}{t_1p^2}-\frac{1}{p}), \tag{15}$$

in which, $k=\dfrac{c_p(\lambda-2\mu)}{2a(\lambda+2\mu)}$.

According to the relationship between displacement and stress, radial stress can be obtained:

$$\sigma_r''=\frac{p_s\sqrt{a}}{\sqrt{r}}\{(1-\frac{a}{r}+\frac{a}{krt_1}-\frac{1}{kt_1})e^{k(t-\frac{r-a}{c_p})}+[\frac{a}{r}+\frac{1}{kt_1}-\frac{a}{krt_1}-\frac{a}{rt_1}(t-\frac{r-a}{c_p})]\};(\frac{r-a}{c_p}<t\le\frac{r-a}{c_p}+t_1). \tag{16}$$

The total stress fields are: $\sigma_r=\sigma_r'+\sigma_r''$, $\sigma_\varphi=\sigma_\varphi'+\sigma_\varphi''$.

A numerical example of surrounding rock damage caused by transient unloading

Transient unloading damage around tunnel surrounding rock is similar to the dynamic fracture (Hopkinson cracking), called flaking or spalling, caused by the reflection of compressive stress waves on the free surface. During the spallation, the first layers of crack appeared, the new free surface is formed at the same time. The incident pressure waves will continue to reflect on the new free surface, which will make it possible to cause the second layer crack, and so on. Under certain conditions, it may form a multi-layer cracking and produce a series of slivers.

Assuming that the radius of a deep circular rock tunnel is 2.5 m, the rock is the medium hard sandstone rock, and its density is 2300 kg/m^3, elastic modulus is 36 GPa, rock static tensile strength is 12 MPa, rock dynamic strength and static strength ratio is 2. The original rock stress is 30 MPa.

Taking different blast loading pressures and total unloading time, the calculation results are shown in Table 1.

Table 1

The cracking areas at different blast loading pressures and total unloading time

No.	Blast loading pressure (MPa)	Total un-loading time (μs)	The number of layers	The first layer thickness (m)	The second layer thickness (m)	The third layer thickness (m)	The 4th layer thickness (m)	The cracking area (m)
1	70	200	2	0.3170	0.3572	–	–	0.6742
2	70	400	2	0.5610	0.6889	–	–	1.2499
3	90	200	3	0.2434	0.2666	0.2936	–	0.8036
4	90	400	3	0.4267	0.4984	0.5909	–	1.5160
5	110	200	4	0.1975	0.2127	0.2297	0.2489	0.8888
6	110	400	4	0.3443	0.3901	0.4464	0.5160	1.6968

The type of rock can be changed. For granite, its density is 2650 kg/m^3, elastic modulus is 42 GPa， poisson’s ratio is 0.25, rock static tensile strength is 15 MPa. For shale, its density is 2200 kg/m^3, elastic modulus is 20 GPa， poisson’s ratio is 0.3, rock static tensile strength is 6 MPa. Rock dynamic strength and static strength ratio is 2. Results are shown in Table 2.

Table 2

The cracking areas for different rocks

No.	The type of rock	Blast loading pressure (MPa)	Total unloading time (μs)	The number of layers	The first layer thickness (m)	The second layer thickness (m)	The third layer thickness (m)	The 4th layer thickness (m)	The 5th layer thickness (m)	The 6th layer thickness (m)	The 7th layer thickness (m)	The cracking area (m)
1	andston	90	200	3	0.2434	0.2666	0.294	–	–	–	–	0.804
2	granite	90	200	2	0.3256	0.3685	–	–	–	–	–	0.694
3	shale	90	200	7	0.1092	0.1141	0.119	0.125	0.130	0.136	0.143	0.876

When using mechanical excavation, it is equivalent to the original rock stress unloading, and stress unloading rate is slower. The rock breaking strength is static strength. Results are shown in Table 3.

Table 3

The cracking areas for using mechanical excavation in sandstone

No.	Original rock stress（MPa）	Total unloading time（s）	The number of layers	The first layer thickness（m）	The second layer thickness（m）	The cracking area（m）
1	30	0. 1	2	2.8501	8.4881	11.3382
2	30	10	2	2.8866	8.7416	11.6282
3	30	20	2	2.8868	8.7429	11.6297

It can be seen from Table1~3:

1. The number of damage layers caused by transient unloading is only related to the unloading pressure peak, regardless of the total unloading time. Under the same conditions, the greater the pressure, the more fracture layers.

2. Thickness of fracture layers is determined by the unloading pressure and total unloading time. Under the same conditions, the greater the pressure, the smaller rupture thickness, the greater the range of cracking areas; the shorter the total unloading time, the smaller rupture thickness, the smaller range of cracking areas.

3. The larger the rock tensile strength is, the smaller the rupture layers and cracking areas.

4. When the pressure unloading time is long enough, such as mechanical excavation, cracking layer thickness varies smaller, and cracking area tends to a constant value.

Conclusion

Deep tunnel crack phenomenon is the result of stress redistribution in surrounding due to rock tunnel excavation unloading. So, during deep tunnel full-face excavation, transient dynamic unloading effect must be considered. The dynamic theoretical solution of radial stress field in surrounding rock during excavation, derived by integral transform, can be used to calculate the response induced by the surrounding rock excavation. But it should be noted that the general solution of Bessel's equation was progressively treated, the results should be a difference between actual, can not reflect the wave effect of transient stress field, and depict the zonal disintegration phenomenon of deep tunnel. This will be the issue for further research.

Acknowledgements

This research is supported by the Specialized Research Fund for the Doctoral Program of Higher Education of China (Grant No.20113718110002), the Fund of the State key Laboratory of Disaster Prevention & Mitigation of Explosion & Impact (PLA University and Technology) (No.DPMEIKF201307), Huaqiao University Research Foundation（13BS402).

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The report was delivered at the 5th *Russian-Chinese Scientific Technical Forum Deep Level Rock Mechanics and Engineering*, August, 5-7th, 2015, Weihai, CPR. On its basis, the author has written an article especially for *FEFU: School of Engineering Bulletin*.

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УДК 539.3

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Исследование трещинообразования при разгрузке массива горных пород, вызванного строительством глубокого тоннеля

Аннотация: Проведенное исследование трещинообразования при разгрузке массива горных пород при строительстве глубокого тоннеля показало, что теория и методы, описанные в статье, могут правильно отображать динамические процессы, возникающие при выемке грунта, и эффективно оценивать формы разрушения горных пород при разгрузке.

Ключевые слова: глубокий тоннель, трещина, горные породы, взрывные работы, поле переходных напряжений.

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