Study on the influence of transient unloading on surrounding rock deformation in expanding excavation blasting

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\textbf{Abstract.} The tensile stress generated by the transient unloading of the in-situ stress may cause deformation, damage or even destruction of the surrounding rock. Based on the equivalent load method and the deleted element method, the influence of blast loading and transient unloading on the surrounding rock deformation is studied in the present study. The field blast vibration tests in the BaiHeTan hydropower station were carried to verify the numerical results. The results shown that the deformation simulated by the LS-DYNA agrees well with that measured in the field tests only if the coupling effect of blast loading and transient unloading are considered. In expansive excavation blasting, the convergent deformation caused by transient unloading is about 4 to 6 times greater than that caused by blast loading, and the deformed rock mass area caused by transient unloading is about 2 to 3 times larger than that caused by blast loading. However, plastic zone induced by the blast loading is much wider (about 2.1 times) than that induced by transient unloading. The results show that blast loading tends to cause more damage of surrounding rock, while transient unloading tends to cause larger deformation.

1. Introduction

With the strong demand for mineral resources, mining with buried depth of 500-2000m has gradually entered the scope of consideration. In deep excavation project, compared with the shallow rock mass, the geo-stress environment, deformation and failure characteristics of the rock mass has changed significantly. The high in-situ stress of the deep rock mass is the fundamental reason for the poor stability and support difficulty of deep excavation \cite{1,2}. When the blast loading acting on the retained rock mass decreases sharply and a new profile generated, the constraint effect on the retained rock mass is removed instantaneously, which is called transient unloading of in-situ stress \cite{3}. Relevant research and engineering practice show that during the blasting excavation process under high in-situ stress, the transient unloading will produce a strong dynamic effect, which seriously threatens the engineering safety \cite{4,5}. 
A lot of research has been carried out on the transient unloading of in-situ stress. Carter et al. [6] studied the excavation of long tunnels and found that the transient unloading of in-situ stress will produce strong tensile stress, the amplitude of which is related to the unloading rate. Mandal and Singh [7] discovered that the transient unloading of in-situ stress will greatly increase the over-excavated volume. Based on the concept of equivalent elastic action boundary, Lu, Wenbo et al. [8,9] proposed an equivalent numerical simulation method for the coupling effect of transient unloading and blast loading. Wang, Xuebin et al. [10] proposed a continuous-discontinuous medium method to numerically simulate the deformation-cracking-collapse process of the surrounding rock under transient unloading. And found that the shorter the unloading process, the more obvious the dynamic response of surrounding rock is, and the slower it reaches the stress equilibrium. Yan Peng et al. [11] used the dynamic calculation module of ANSYS to study the dynamic unloading process of the surrounding rock and found that the damage area in the surrounding rock caused by dynamic unloading is much larger than that caused by the quasi-static unloading. Most of the existing studies only involve the impact of explosive loading or transient unloading but ignore that deep rock mass excavation is under the coupled effect of them. Therefore, it is necessary to study the coupling effect of blast loading and transient unloading during excavation under high in-situ stress.

In the deep blasting excavation engineering, the surrounding rock is affected by the transient unloading of the initial stress and the blast loading at the same time. Blast loading will cause severe radial loading and radial cracks. While transient unloading is the opposite, causing radial unloading of the rock mass, leading to an increasing maximum dynamic shear stress and further aggravating the hoop cracks. The principle of the two effects is opposite, but both will lead to the cracking and destruction, which causes a very complicated response of rock. In this paper, based on the equivalent load method and the deleted element method, the coupling influence of blast loading and transient unloading on the surrounding rock deformation is studied. The field blast vibration tests in the BaiHeTan hydropower station were carried to verify the numerical results. The laws of displacement and plastic deformation of surrounding rock under the combined action of blast loading and transient unloading are studied respectively.

2. Engineering background
The research was carried out based on the expansion blasting excavation on the first floor of the main powerhouse on the right bank of the Baihetan Hydropower Station. The in-situ stress near the underground plant is dominated by tectonic stress. The field stress test suggests that the in-situ stress of the surrounding rock in the vertical direction is higher than in the horizontal and vertical direction. The direction of the first principal stress is between 22 ~ 26MPa, parallel to the excavation direction of the powerhouse; the second principal stress is between 14 ~ 18MPa; and the third principal stress is nearly vertical, is equivalent to the self-weight stress of overlying rock mass, generally 13 to 16MPa. The photo of the blasting result is shown in figure 1, and the blasting charge parameters are shown in table 1.
3. Field blasting vibration test

Since the upper middle pilot tunnel has been completed, the vibration measuring points are selected in the back direction of the blasting site, arranged along the tunnel axis on the side of pilot tunnel wall. See figure 2 for the specific layout location.

![Figure 2. Layout of measuring points for on-site vibration testing](image)

The data of field test are shown in Table 2. When the distance from blasting site is close (such as MP-1), the vibration velocity perpendicular to the tunnel axis is the largest, which also has the fastest attenuation along the distance. The vibration velocity parallel to the tunnel axis is generally larger than other directions. In terms of dominant frequency, due to some various uncontrollable random factors on site, the regularity is relatively poor. But it still shows a certain degree of upward and downward trend with the increase of distance from blasting site.

![Figure 1. photo of blasting result](image)

### Table 1. Blasting charge parameters

| Parameter                                      | Value                  |
|-----------------------------------------------|------------------------|
| Diameter of explosive charge:                 | 25.0mm                 |
| Explosive type:                                | emulsion explosive     |
| Single hole charge:                           | 650g for peripheral holes, 2300g for auxiliary holes, 2500g for blasting holes |
| Unit consumption:                             | 80kg/m³                |
| Total charge:                                 | 186.4kg                |
| Charge linear density:                        | 160~200g/m            |
| Maximum single-shot charge:                   | 36.8kg                 |
| Detonation method:                            | electric detonator     |

### Table 2. Field test results data of blasting vibration

| Point No. | Distance from blasting site /m | Perpendicular to tunnel PPV cm/s | F /Hz | Parallel to tunnel PPV cm/s | F Hz | Vertical PPV cm/s | F Hz |
|-----------|-------------------------------|---------------------------------|-------|----------------------------|------|-------------------|------|
| MP-1      | 35.28                         | 5.73                            | 120.2 | 5.03                       | 131.1| 1.47              | 115.6|
| MP-2      | 54.59                         | 2.24                            | 144.2 | 4.11                       | 143.7| 0.64              | 133.3|
| MP-3      | 72.85                         | 0.81                            | 149.2 | 0.83                       | 149.1| 0.44              | 138.9|
| MP-4      | 103.72                        | 0.54                            | 133.7 | 0.95                       | 141.2| 0.51              | 137.1|
| MP-5      | 122.39                        | 0.49                            | 139.3 | 0.67                       | 132.4| 0.49              | 109.4|

4. Model of numerical simulation

4.1. Model parameters
Based on the equivalent load method and the deleted element method, the influence of blast loading and transient unloading on the surrounding rock deformation is studied. The in-situ stress of the surrounding rock is taken as $\sigma_1 = 26\text{MPa}, \sigma_2 = \sigma_3 = 13\text{MPa}$. The direction of the first principal stress is consistent with the of tunnel axis, the second and third principal stress are perpendicular to the tunnel axis. Due to the large size of the model, the kg-m-s unit system is selected. The external dimensions of the model are 100*100*150m. Non-reflective boundary condition is applied to the surface boundary of the model. And the in-situ-stress is applied to the back boundary, upper boundary and right boundary, corresponding to the first, second and third principal stresses respectively. Displacement constraints are imposed on the front boundary, lower boundary and left boundary. The schematic diagram of the specific model and the elements meshing diagram are shown in figures 3 and 4.

![Figure 3. Schematic diagram of model size](image)

**Figure 3.** Schematic diagram of model size

**4.2 Material parameters**

Because the rock material has a high dynamic yield strength, which far exceeds the static strength that can be measured in a laboratory test. When the rock mass is subjected to a severe impact load in a very short time, it tends to show plasticity rather than elastic brittleness. Therefore, the kinematic hardening plasticity material type is selected for the rock material, and the specific physical and mechanical properties are based on laboratory testing and field mapping data, see table 3.

| Density g/cm³ | Tensile strength MPa | Compressive strength MPa | Elastic Modulus GPa | Poisson's ratio | Shear strength MPa |
|---------------|----------------------|--------------------------|---------------------|----------------|-------------------|
| 2.71          | 12                   | 135                      | 45                  | 0.22           | 8.56              |

**4.3 Loads parameters**

For models that focus on the borehole group effect, since the minimum time step size during the calculation depends on the time the stress wave passes through the minimum element, establishing boreholes and meshing dynamite elements will inevitably lead to an enormous file size and low computational efficiency. Therefore, for the sake of calculation efficiency, the blasting load of a single borehole is usually converted into the equivalent blasting load on the contour surface by a conversion formula to analyse the dynamic responses of the surrounding rock under the borehole group effect. The specific conversion process is as follows.

The peak load on the blast hole wall can be calculated according to the theory of Chapman-Jouguet [12]. The formula is as follows:
\[ P_{b_0} = \frac{\rho_0 D^2}{2(\gamma + 1)} \left( \frac{a}{b} \right)^{2\mu} \]  

(1)

Where \( \rho_0 \) is the explosive density; \( D \) is the detonation velocity; \( \gamma \) is the isentropic index; \( a \) is the diameter of the charge roll; \( b \) is the diameter of the blast hole. The diameter of the charge rolls \( a \) is 25cm. The diameter of the blast hole \( b \) is 42cm. The density of the explosive \( \rho_0 \) is 1000kg/m\(^3\). The explosive velocity is between 3000-5000m/s, so the intermediate value \( D=4000m/s \) is taken in this model. The isentropic index \( \gamma \) is 3. According to (1), the equivalent load on the blast hole wall is calculated to 139MPa. Since the attenuation of the stress wave around a single blast hole follows the law of power function with distance. When considering the group holes effect, the relationship between the blast loading \( P_{be} \) on the equivalent boundary and the blast loading \( P_{b0} \) on the blast hole wall satisfies the following formula \(^{[13]}\)

\[ P_{be} = kP_{b0} \left( \frac{R_0}{R_1} \right)^{2\frac{\mu}{1-\mu}} \left( \frac{R_1}{R_2} \right)^{2\frac{\mu}{1-\mu}} \]  

(2)

Where \( k \) is the load influence coefficient of group holes related to the number and distribution of blast holes; \( R_0 \) is the blast hole radius; \( R_1 \) is the radius of the crushing zone; \( R_2 \) is the radius of the fracture zone; \( \mu \) is the Poisson's ratio of the surrounding rock.

Take the radius of crushing zone and fracture zone to be 3 times and 10 times the radius of blast hole respectively, and the load influence coefficient of group holes \( k \) is 50. According to (2), the peak value of the explosion load on the excavation boundary is 71.6MPa. To consider the effect of blast loading and transient unloading, four test conditions (blast loading, transient unloading, coupling of them, and Quasi-static unloading) were selected for numerical simulation. The specific conditions load forms are shown in table 4. For condition 1\#, the triangular load is used for equivalent simulation. Because the load ascending time is extremely short, it is assumed that the load ascending time is equal to the propagation time of the detonation wave, which should be set to \( t_1=10ms \), while the descending time should be set to \( t_2=25ms \) \(^{[11]}\). The transient unloading is controlled by the *LOAD_REMOVE_PART command to delete the excavated rock elements. Assuming the interaction between the excavated rock and the retained rock ends when the blasting crack penetrates, the crack development time \( t_3=2.7ms \) is taken as the time required to completely delete the excavation rock elements \(^{[14]}\). As a control group, Quasi-static unloading time is set to 1000ms. Figure 5 represents the stress-time curves on the excavation surface under four test conditions.

**Table 4. Numerical simulation load forms**

| No. | Load form        |
|-----|------------------|
| 1   | Blast loading    |
| 2   | Transient unloading |
| 3   | Coupling of 1&2  |

(a) Blast loading  
(b) Transient unloading
Quasi-static unloading
(Unloading time set to 1000ms)

Figure 5. Stress time history curve of excavation surface

5. Result verification and analysis

5.1 Result verification

5.1.1. Comparison with vibration monitoring data. Export the numerical simulation vibration data and compare it with the field test data (table 2). It can be seen from Figure 6 that in the numerical simulation, regardless of whether transient unloading is considered, the tendency of the peak vibration velocity to attenuate with increasing distance is roughly similar. However, when transient unloading is not considered, the peak vibration velocity is obviously lower than the field test data. Only when the coupling effects of blast loading and transient unloading are considered at the same time, it is more consistent with the field test result.

Figure 6. peak vibration velocity distribution diagram (cm/s)

In terms of dominant frequency, it can be seen from Figure 7 that the dominant frequency obtained by numerical simulation has a clear law with the increase of distance. However, due to the influence of various uncontrollable factors on site, the regularity of the field test result is relatively poor. It can still be found that if the effect of transient unloading is not considered, the calculated dominant frequency is obviously too high from the field test result. When the coupling effect is considered, due to the low-frequency vibration effect induced by transient unloading [5], the calculated dominant frequency is relatively lower and closer to the field test results.

Figure 7. Dominant frequency distribution diagram (Hz)
5.1.2. Comparison with displacement monitoring data. Export the rock surface displacement data obtained in the numerical simulation and calculate the corresponding horizontal convergence and crown settlement data. Compare them with the field test results, See table 5 for details. In condition 1#, the excavated rock mass is not removed, almost no convergent deformation occurs, thus the displacement result cannot represent the real situation. In condition 2# or condition 4#, since the loosening effect of surrounding rock caused by blasting is not considered, the convergence displacement data are both lower than the measured value. Only when blast loading and transient unloading are considered at the same (condition 3#), the horizontal convergence and crown settlement data are relatively consistent with the field test. The convergent deformation caused by transient unloading is about 4 to 6 times that caused by blast loading.

| No. | Convergence /mm | Crown settlement /mm |
|-----|-----------------|----------------------|
| 1#  | -0.70           | 0.53                 |
| 2#  | 2.02            | 2.51                 |
| 3#  | 2.51            | 3.82                 |
| 4#  | 0.91            | 1.29                 |
| Field test data | 2.9         | 4.3                  |

Therefore, it can be concluded that the numerical simulation method can truly and effectively simulate the action process of blasting excavation. And the deformation simulated agrees well with that measured in the field tests only if the coupling effect of blast loading and transient unloading are considered.

5.2 Result analysis

5.2.1. Effect on displacement. Three typical sections are selected, namely the front side of the blasting site (the side to be excavated), the rear side of the blasting site (the side that has been excavated), and the right wall of the pilot tunnel, to analyse the displacement of the surrounding rock.

As shown in the surrounding rock displacement vector figure 8, when only considering blast loading (condition 1#), the deformation of surrounding rock in front of blasting site mainly occurs in the projection plane of the blasting area, toward the pilot tunnel. While the deformation caused by other areas is not obvious. The effect of transient unloading on the surrounding rock is mainly to cause the surrounding rock to shrink strongly towards the excavated rock, resulting in a larger range of deformation than the blast loading does. In the case of quasi-static unloading (condition 4#), the surrounding rock also has a similar tendency to shrink, but its displacement value is obviously smaller than that of transient unloading, which is only about half of the latter. When considering the coupling of blast loading and transient unloading (condition 3#), the displacement towards the pilot tunnel wall caused by the dynamic loading and the shrinkage displacement towards the excavated rock caused by the transient unloading superimposed on each other. The range of influenced rock under the coupling effects is wider than under any single factor.

From the maximum displacement statistics table 6, regardless of whether transient unloading is considered, the maximum resultant displacement is almost equal. However, the main contribution of blast loading to the deformation is in the horizontal direction towards the pilot tunnel. The displacement in the vertical direction is relatively small. The effect of transient unloading is the opposite, the vertical displacement is greater than the horizontal displacement. Under the coupling effect, displacement in any direction is greater than under one single factor.
Figure 8. Displacement vector distribution in front of blasting site

Table 6. Table of maximum displacement in front of blasting site

| No. | Max horizontal displacement/mm | Max vertical displacement/mm | Max resultant displacement/mm |
|-----|-------------------------------|-----------------------------|----------------------------|
| 1   | 0.16                          | -0.23                       | 0.25                       |
| 2   | 0.40                          | -0.93                       | 1.01                       |
| 3   | 0.49                          | -1.03                       | 1.05                       |
| 4   | 0.24                          | -0.67                       | 0.77                       |

Compared with the front side of blasting site, the rear side has less deformation, especially for the blast loading effect. The comparison between figure 9(b) and figure 9(c) shows that the influence of blast loading is merely negligible. Therefore, on the rear side of the blasting site, the rock deformation is dominated by the unloading effect. The stress redistribution effect caused by quasi-static unloading accounts for a large proportion of the rock deformation, while transient unloading further aggravates the shrinkage deformation. This is because the additional dynamic stress generated by transient unloading aggravated the damage in the rock mass, resulting in the increase of the surrounding rock displacement and the influence range.

Figure 9. Displacement vector distribution of rear side of blasting site

Table 7. Table of maximum displacement of rear side of blasting site

| No. | Max horizontal displacement/mm | Max vertical displacement/mm | Max resultant displacement/mm |
|-----|-------------------------------|-----------------------------|----------------------------|
| 1   | -0.99                         | 0.44                        | 1.06                       |
| 2   | 0.32                          | -1.14                       | 1.15                       |
| 3   | -1.12                         | -1.32                       | 1.48                       |
| 4   | -0.11                         | -0.52                       | 0.57                       |

As shown in figure 11, the blast loading mainly causes the retained rock directly behind the blasting site to move towards the depths along the tunnel axis. The effect of transient unloading is mainly the shrinkage displacement towards the excavated rock. Especially at the top and bottom, there is a considerable vertical inwards displacement trend. The displacement caused by transient unloading in the horizontal direction is opposite to that caused by blast loading, and the influence
range is very limited. Under the coupling effect, as shown in Figure 10(c), In the horizontal direction, the displacement toward the depth of the rock mass caused by blast loading dominates, but the superposition of the transient unloading in the near blasting area makes the horizontal displacement slightly smaller than that of the distant area. While in the vertical direction, since the displacement directions of blast loading and transient unloading are similar, the rock mass is still dominated by inward shrinkage.

![Figure 10](image)

(a) Blast loading  (b) Transient unloading  (c) Coupling effect  (d) Quasi-static unloading

**Figure 10.** Displacement vector distribution in tunnel axial direction

**Table 8.** Table of maximum displacement in tunnel axial direction

| No. | Max horizontal displacement/mm | Max vertical displacement/mm | Max resultant displacement/mm |
|-----|--------------------------------|-----------------------------|-----------------------------|
| 1   | -1.02                          | 0.76                        | 1.05                        |
| 2   | 1.19                           | 2.20                        | 2.25                        |
| 3   | -1.10                          | 2.10                        | 2.27                        |
| 4   | 0.54                           | 1.34                        | 1.10                        |

5.2.2. Effect on plastic deformation. Figure 11(b). shows that when only considering transient unloading, plastic deformation mainly occurs at the corners of the pilot tunnel immediately behind the excavation area, the stress concentration. The maximum strain reaches $1.04 \times 10^{-3}$. The plastic deformation in other places is relatively small. In figure 11(a), the impact of blast loading on plastic strain is large and deep. Plastic strain occurred on the three rock surfaces directly in contact with the excavated rock, and the maximum plastic strain reached $1.1 \times 10^{-3}$. In figure 11(c), the overall plastic deformation zone of condition 3# is like the working condition 1#. And the superposition effect of transient unloading further increases the range and extent of its plastic deformation, so that the maximum plastic strain reaches $1.7 \times 10^{-3}$, which increases by 54% compared to the condition where transient unloading is not considered. And the plastic zone induced by the blast loading is much wider (about 2.1 times) than that induced by transient unloading.

![Figure 11](image)

(a) Blast loading  (b) Transient unloading  (c) Coupling effect  (d) Quasi-static unloading

**Figure 11.** Plastic strain cloud diagram

**Table 9.** Statistical table of plastic zone

| No. | Max plastic | Plastic strain |
|-----|-------------|----------------|
Strain $\times 10^{-4}$ & Total Volume / m$^3$ \\
--- & --- \\
1 & -10.2 & 0.76 \\
2 & 11.9 & 2.20 \\
3 & -11.0 & 2.10 \\
4 & 5.40 & 1.34

6. Conclusion

(1) Regardless of whether transient unloading is considered in the numerical simulation, the tendency of the peak vibration velocity to attenuate with increasing distance is roughly similar. However, if transient unloading is not considered in the numerical simulation, the simulated peak vibration velocity and dominant frequency differ from the field data. When the coupling effect of blast loading and transient unloading is considered, the simulation results are more consistent with the field data. Therefore, the influence of transient unloading cannot be ignored in the numerical simulation calculation of deep underground blasting excavation.

(2) In underground blasting excavation, the convergent deformation caused by transient unloading is about 4 to 6 times that caused by blast loading. The volume of deformed rock mass caused by transient unloading is about 2 to 6 times larger than that caused by blast loading 3 times.

(3) In terms of plastic strain, plastic zone induced by the blast loading is much wider (about 2.1 times) than that induced by transient unloading. The results show that blast loading tends to cause more damage of surrounding rock, while transient unloading tends to cause larger deformation.

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