Optimization for Connected Steel Plates of Single-Layer Shaft Wall under Blasting Excavation by Numerical Simulation Method

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Abstract. In order to increase the cross-section utilization rate of the deep shaft, a new type single-layer wall with connected steel plates has been invented. The numerical simulation method is used to analyze the coupling interaction between the steel plate and the concrete. The results show that: there are four vibration strengthening regions in each formwork wall. The order from strength to weakness for the regions is as follows: the concrete outside of vertical steel plate > the concrete at the interface between shaft wall and rock wall > the concrete on the upper side of each formwork > the concrete on the lower side of each formwork. There are two potential leakage channels in the vicinity of the connected steel plate, and the channel under the inclined steel plate is a controlled channel. The thickness of steel plate has an important influence on the damage degree and range of concrete. The concrete damage is affected by vertical steel plate, inclined steel plate and thickness combination of themselves. When the project takes the inclined steel plate 10 mm and the vertical steel plate 6 mm, the phenomenon of crack and leakage of the concrete wall is greatly reduced, and the quality of the project is good.

Keywords: Single-layer shaft wall, Connected steel plate, Concrete damage, Blasting excavation, Steel plate-concrete

1. Introduction
With the depletion of shallow resources, the shaft with depth of more than 500m has gradually become the norm. The traditional double-layer shaft wall, the utilization rate of shaft section is below 40%, which is difficult to accept from the construction period to the cost of deep shaft [1], therefore, the new type single-layer shaft wall becomes the future development trend of deep shaft [2, 3]. The shaft wall structure is constructed in cycles by the formwork section element, and the connected steel plate is used to improve the concrete connection performance of the upper and lower formwork sections [4]. The drilling and blasting method is the only available construction method for the excavation of the bedrock section, and the blasting vibration will inevitably have a certain negative effect on the adjacent newly cast shaft wall structure [5]. In the single-layer shaft wall with connected steel plate, the concrete damage and destruction phenomenon in the vicinity to the connected steel plate appears. The direct manifestation is leakage at the connected steel plate. How to solve this problem has become an urgent work in the development of deep shaft [6, 7].
The impact damage of plain concrete shaft wall by blasting excavation has been studied, however, there is no steel plate inside [8]. The impact damage effect on concrete of adjacent region to connected steel plate by the thickness of vertical plate is studied, but by the thickness of inclined plate isn’t studied [9]. In references [10, 11], the propagation mechanism of shock wave in the soil with embedded plates is studied theoretically, and the optimal thickness of the plate is obtained. However, it is only limited to the single plate embedded in the soil, and the analytical solution cannot be derived for embedded multiple plates. In reference [12], a numerical simulation study was carried out on the propagation mechanism of the embedded slab in the soil under the ground explosion load action, but it was limited to the embedded single slab too. The experimental study on contact explosion of steel-concrete slabs was carried out in reference [13], moreover, SHPB experiment was carried out to study the propagation characteristics of stress wave in the three-layer medium composed of low-age concrete, steel plate and low-age concrete in reference [14]. In above two documents, it is found that the thickness of the intermediate plate has an important influence on the propagation of stress wave, and the concrete damage on both sides is affected by the thickness of steel plate. There is no report about the experimental research on the blasting stress wave propagating in the young concrete shaft wall with connected steel plate, and the impact damage of concrete in the vicinity of the connected steel plate.

Combined with the practical engineering of new type single-layer shaft wall with connected steel plate, the numerical model of equal scale itself is established. This paper studies the impact damage of concrete in the vicinity of connected steel plate affected by vertical steel plate, inclined steel plate and thickness combination of themselves. The optimum thickness combination between vertical steel plate and inclined steel plate is obtained, and the leakage problem of this kind of shaft wall structure has been preliminarily solved.

2. Project Overview
The auxiliary shaft of Menkeqing mine in Inner Mongolia is constructed by freezing drilling and blasting method, and the shaft wall structure is a new type of single-layer shaft wall with connected steel plate, which is one of the earlier projects of this kind of shaft wall. The design depth of the shaft is 785 m, the raw diameter of the shaft is 10.9 m, and the thickness of the shaft wall is 1.3 m. The blasthole has a depth of 4.5 m and a diameter of 55 mm. Five stages millisecond delay electric detonators of 0 ms, 25 ms, 50 ms, 75 ms and 100 ms are selected. T220 rock water gel explosive with diameter of 45 mm and charge length of 400 mm is adopted. The blasting parameters are shown in table 1, and the blasthole layout is shown in figure 1.

| Circle | Number of blastholes / individual | Circle diameter / m | Angle / ° | Dosage per circle / kg | Blastholes spacing / mm | Section | Dosage per section / kg |
|--------|----------------------------------|--------------------|----------|------------------------|------------------------|---------|------------------------|
| 1      | 8                                | 1.7                | 90       | 41.0                   | 651                    | I       | 41.0                   |
| 2      | 14                               | 3.4                | 90       | 71.7                   | 757                    | II      | 161.3                  |
| 3      | 20                               | 5.2                | 90       | 89.6                   | 813                    | III     | 268.8                  |
| 4      | 27                               | 6.9                | 90       | 121.0                  | 801                    | IV      | 153.6                  |
| 5      | 33                               | 8.6                | 90       | 147.8                  | 817                    | V       | 208.0                  |
| 6      | 40                               | 10.4               | 90       | 153.6                  | 816                    |         |                        |
| 7      | 65                               | 12.3               | 89       | 208.0                  | 594                    |         |                        |

The entity and cross-section of the connected steel plate and the construction process of the shaft wall are shown in figure 2, the geometric dimensions of connected steel plates are shown in table 2. The shaft is constructed from top to bottom in cycles by the formwork section element. The footage of each formwork is 4m, which takes 2.5 days. The shaft wall is made of C65 concrete, and the bottom of the newly poured concrete is 4m away from the tunnel face. The blade foot support stands on the rock
of the face, and the connected steel plate is placed on the blade foot support. The inner side is the overall downward steel template, which moves down to the blade foot support, and the outer side is the rock wall. The shaft wall concrete is poured into the above-mentioned enclosure structure, and the construction process is shown in figure 2.

| Upper vertical plate / mm | Lower vertical plate / mm | Inclined plate / mm | Angle / ° | Vertical plate thickness / mm | Inclined plate thickness / mm |
|--------------------------|--------------------------|---------------------|----------|--------------------------|--------------------------|
| H₁                       | H₂                       | L₁                  | α        | T₁                       | T₂                       |
| 200                      | 200                      | 1650                | 45       | 6 | 10 | 12 | 6 | 8 | 10 | 12 |

Table 2. Geometric parameters of connected steel plate.

Figure 1. Blastholes arrangement (units:mm).

Figure 2. The entity and cross-section of the connected steel plate and the construction process of the shaft wall.

3. Numerical Model and Material Parameters

3.1. Numerical Model

According to the symmetry of the shaft structure, the model takes 1/4 structure. Considering that the range of blasthole crush circle and fracture circle is 10 ~ 30 times of the blasthole diameter, about 1.5 m; the numerical simulation calculation range is about 100 times of the blasthole diameter, about 5 m. In addition, the diameter of the outermost hole is 6.15 m, which is 11.15 m in total. Therefore, the outer boundary radius of the model is taken as 12.0 m. The height below the face is 9.0 m, and the height above the face is 17.0 m. There are three shaft formworks in the model.

The blasting scheme of the construction site is 7 circles and 5 stages, as shown in table 1. If modeling according to the actual situation, there will be a large number of deformed elements, and the calculation process will have a negative volume phenomenon, which will not converge and the calculation cannot be completed. Therefore, it is difficult for the blastholes in the numerical model to correspond to the field blastholes. Considering the equivalent charge and Saint Venant's principle, in order to make the numerical model as similar as possible to the engineering site, there are five stages explosives in the finite element model. According to the amount of explosives and the number of blastholes in each stage, the diameter of blastholes of each circle in the numerical model is determined, as shown in figure 3. A multi-material algorithm is used for explosive and air, lagrange algorithm is used for shaft wall and surrounding rock, and fluid-solid coupling is used between surrounding rock,
shaft wall and air. In order to eliminate the influence of stress wave reflection on the model boundary, symmetrical constraints are imposed on the two radial surfaces of the model. The inner surface of the shaft wall is a free boundary, and the other surfaces are non-reflective boundaries.

![Connected steel plate](image1)
![Concrete of each formwork shaft wall](image2)
![Five stage explosive](image3)
![Overall model](image4)

**Figure 3.** Shaft model with connected steel plate.

### 3.2. Material Parameters

The test blocks are made according to the mix proportion of shaft wall concrete on-site, and the material parameters are measured according to the age of shaft wall concrete. Explosive uses MAT_HIGH_EXPLOSIVE_BURN material, the rock and steel plate adopt the dynamic hardening elasto-plastic constitutive model, the keyword is MAT_PLASTIC_KINEMATIC, concrete uses RHT material model. For the details of the constitutive selection and the value of key parameters of explosives, rocks, steel plates and concrete materials, please refer to the author's literature [14].

### 4. Impacting Damage and Leakage of Single-Layer Shaft Wall with Connected Steel Plate

The thickness of vertical steel plate and inclined steel plate used in practical engineering are 6 mm, 8 mm, 10 mm and 12 mm respectively. A total of 16 connected steel plate cases based on permutation and combination. For the sake of simplicity, the thickness of inclined plate is marked with H and the thickness of vertical plate is marked with V in the following part of this article.

Whether the single-layer shaft wall with the connected steel plate leaks depends on the damage degree of the concrete in the vicinity of the connected steel plate. According to the structural characteristics of the shaft wall and the actual leakage situation of the engineering, there are only two water passages, as shown in figure 4. The two water passages are composed of concrete in the following three regions: concrete outside of vertical steel plate (region one), concrete on the upper side of each formwork (region four, located under the inclined steel plate), concrete on the lower side of each formwork (region three, located on the upper side of the inclined steel plate). The damage of concrete in region one and region four determines the penetration of "water passage one", and the damage of concrete in region one and region three determines the penetration of "water passage two".

Taking steel plate thickness combination H6V12 case as an example to carry out damage contour analysis: figure 5 (a) shows the overall damage degree of the shaft wall vertical section, region one > region four > region three. Figure 5(b) shows the damage of the concrete (region one) outside of vertical steel plate, the damage value is 1.0, and the water has completely passed through. The lower part of the inclined steel plate (region four), front of impacting surface, is seriously damaged, and most
of the region is damaged close to 1, as shown in figure 5(c). The upper part of the inclined steel plate (region three), back of impacting surface, the damage is light, the damage value is less than 0.1, see figure 5(d), (e), therefore, the passage two is not through and does not leak water. The damage of passage one is much greater than that of passage two, and whether the shaft wall structure leaks depends on passage one. Whether the passage one leaks is determined by vertical steel plate, inclined steel plate and thickness combination of themselves.

Figure 4. Water passage channel at the connected steel plate.

Figure 5. Shaft wall damage contour.

The concrete outside of the vertical steel plate is completely damaged, which will not be discussed again below. The length of the inclined steel plate is 1650 mm. It is divided into five units along the length from the intersection of the vertical steel plate and the inclined steel plate. The corresponding positions of the center of each unit are 0.115 m, 0.445 m, 0.775 m, 1.105 m and 1.435 m. The concrete damages on the upper side of the first formwork (region 4, front of impacting surface), the lower side
of the first formwork (region 3, back of impacting surface), and the lower side of the second formwork (region 3, back of impacting surface) are listed in Table 3. The results show that the damage on the front of impacting surface is strengthened, and the damage range is larger, and the damage value is close to 1; and that the damage on the back of impacting surface is weakened, the damage range is small, and the damage value is less than 0.1.

| Steel plate cases | The lower part of the inclined steel plate (one formwork) | The upper part of the inclined steel plate (one formwork) | The upper part of the inclined steel plate (two formwork) |
|-------------------|----------------------------------------------------------|----------------------------------------------------------|----------------------------------------------------------|
|                   | P01 | P02 | P03 | P04 | P05 | P01 | P02 | P03 | P04 | P05 | P01 | P02 | P03 | P04 | P05 |
| H12V12 1          | 1   | 1   | 0.98 | 0.78 | 0.78 | 0.02 | 0.018 | 0.012 | 0.08 | 0.003 | 0.021 | 0.017 | 0.012 | 0.008 | 0.002 |
| H10V12 0.88       | 0.83 | 0.76 | 0.695 | 0.66 | 0.05 | 0.038 | 0.022 | 0.011 | 0.002 | 0.019 | 0.015 | 0.013 | 0.008 | 0.002 |
| H8V12 1           | 1   | 1   | 1   | 0.977 | 0.024 | 0.02 | 0.016 | 0.01 | 0.003 | 0.017 | 0.013 | 0.009 | 0.006 | 0.003 |
| H6V12 1           | 1   | 1   | 1   | 1   | 1   | 0.029 | 0.025 | 0.018 | 0.012 | 0.006 | 0.039 | 0.027 | 0.016 | 0.008 | 0.002 |
| H12V10 1          | 1   | 1   | 1   | 1   | 0.913 | 0.025 | 0.02 | 0.017 | 0.013 | 0.003 | 0.034 | 0.028 | 0.012 | 0.006 | 0.001 |
| H10V10 0.98       | 0.91 | 0.9 | 0.886 | 0.8 | 0.022 | 0.015 | 0.013 | 0.009 | 0.005 | 0.025 | 0.012 | 0.003 | 0.008 | 0.001 |
| H8V10 1           | 1   | 1   | 1   | 0.82 | 0.028 | 0.025 | 0.019 | 0.012 | 0.006 | 0.003 | 0.022 | 0.012 | 0.006 | 0.001 |
| H6V10 1           | 1   | 1   | 1   | 1   | 0.932 | 0.031 | 0.025 | 0.022 | 0.012 | 0.006 | 0.043 | 0.027 | 0.016 | 0.008 | 0.002 |
| H12V8 1           | 1   | 1   | 1   | 1   | 0.942 | 0.028 | 0.024 | 0.016 | 0.011 | 0.006 | 0.053 | 0.036 | 0.022 | 0.011 | 0.001 |
| H10V8 1           | 1   | 1   | 1   | 1   | 0.98 | 0.019 | 0.016 | 0.012 | 0.01 | 0.005 | 0.022 | 0.012 | 0.008 | 0.002 |
| H8V8 0.945        | 0.85 | 0.79 | 0.777 | 0.7 | 0.044 | 0.027 | 0.002 | 0.012 | 0.005 | 0.035 | 0.025 | 0.018 | 0.001 | 0.004 |
| H6V8 0.953        | 0.86 | 0.78 | 0.78 | 0.763 | 0.041 | 0.036 | 0.024 | 0.002 | 0.006 | 0.042 | 0.027 | 0.021 | 0.015 | 0.006 |
| H12V6 0.968       | 0.91 | 0.79 | 0.732 | 0.678 | 0.017 | 0.016 | 0.012 | 0.001 | 0.007 | 0.035 | 0.026 | 0.013 | 0.009 | 0.003 |
| H10V6 0.884       | 0.768 | 0.661 | 0.63 | 0.568 | 0.022 | 0.02 | 0.018 | 0.012 | 0.01 | 0.041 | 0.029 | 0.018 | 0.008 | 0.001 |
| H8V6 0.91         | 0.807 | 0.72 | 0.682 | 0.534 | 0.02 | 0.016 | 0.014 | 0.012 | 0.009 | 0.018 | 0.012 | 0.009 | 0.005 | 0.002 |
| H6V6 0.929        | 0.805 | 0.778 | 0.68 | 0.531 | 0.028 | 0.026 | 0.017 | 0.012 | 0.005 | 0.015 | 0.01 | 0.008 | 0.007 | 0.002 |
| Sum               | 15.449 | 14.759 | 14.194 | 13.842 | 12.582 | 4.488 | 0.367 | 0.272 | 0.186 | 0.087 | 0.499 | 0.351 | 0.222 | 0.131 | 0.038 |
| Max               | 0.88 | 0.768 | 0.661 | 0.63 | 0.531 | 0.017 | 0.015 | 0.012 | 0.008 | 0.002 | 0.015 | 0.01 | 0.008 | 0.005 | 0.001 |
| Ave               | 0.966 | 0.922 | 0.887 | 0.865 | 0.786 | 0.028 | 0.023 | 0.017 | 0.012 | 0.005 | 0.031 | 0.022 | 0.014 | 0.008 | 0.002 |

Whether the shaft wall structure leaks depends on passage one. The damage degree and range corresponding to various cases are different, and the steel plate thickness combination needs to be optimized. Figure 6 shows the damage contour of shaft wall vertical section under 16 cases, and reveals the coupling effect between vertical steel plate and inclined steel plate.

According to Table 3, the maximum damage envelope, the minimum damage envelope, the maximum damage case H6V12, and the minimum damage case H10V6 of the 16 cases of the concrete on the upper side of the formwork are drawn in Figure 7(a). In H6V12 case, the concrete is completely damaged, passage one is through, and the shaft wall leaks. In H10V6 case, the concrete has the least damage and no water leakage. The closer to the surrounding rock, the greater the damage, and the closer to the shaft axis, the smaller is the damage. In the same way, the damage of the concrete on the lower side of the formwork of 16 cases is shown in Figure 7(b), and the damage of the concrete on the lower side of two formwork of 16 cases is shown in Figure 7(c). The damage of concrete on the front of impacting surface (region 4) is much greater than the damage of concrete on the back of impacting surface (region 3), that is, “passage one” becomes the control channel, and the H10V6 case is the optimal steel plate thickness combination.
Figure 6. Summary of shaft wall damage contour (16 cases).

Figure 7. Damage characteristic curve of concrete.

5. Conclusion
(1) There are two potential water passages in the single layer shaft wall with connected steel plate. The passage on the lower side of the inclined steel plate is the control passage. There is an optimized thickness combination of connected steel plate, and the H10V6 case is the best. With the above-mentioned case, the concrete damage degree on the lower side of the inclined steel plate is the lightest and the damage range is the smallest.

(2) Under the action of blasting seismic wave, there are four vibration strengthening regions in each formwork shaft wall. They are the concrete outside of vertical steel plate (region one), the concrete at the interface between shaft wall and rock wall (region two), the concrete on the lower side of each
formwork (region three, located on the upper side of the inclined steel plate), the concrete on the upper side of each formwork (region four, located under the inclined steel plate).

3) According to the order from strength to weakness, the concrete outside of vertical steel plate (region one) > the concrete at the interface between shaft wall and rock wall (region two) > the concrete on the upper side of each formwork (region four, located under the inclined steel plate) > the concrete on the lower side of each formwork (region three, located on the upper side of the inclined steel plate). This conclusion is applicable to the same type of shaft wall with various geometrical dimensions.

4) When the thickness of vertical steel plate is changed, the concrete damage in the vicinity of the inclined steel plate changes significantly; when the thickness of the inclined steel plate changes, the concrete damage in the vicinity of the vertical steel plate also changes significantly, which shows that the vertical steel plate and the inclined steel plate are coupled. It is impossible to derive analytical solutions for such engineering problems, and it is reasonable to use numerical simulation method to solve such engineering problems.

Acknowledgments
This study was supported by the national 13th five-year key R&D plan of China (2016YFC0600904), the key cultivation project of Xuzhou institute of technology (XKY2011106), the science and technology project of Jiangsu construction system (2012ZD36), the Xuzhou science and technology project (XM12B080).

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