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Research and Application of Shaft Excavation by Deep Hole One-Time Blasting Technology

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Abstract: In the construction of subway, tunnel, mining and other underground projects, in order to speed up the construction progress, it is often necessary to excavate a shaft first and then dig at both ends of tunnel at the same time. The shaft excavation is a difficult problem in underground engineering. At present, the shaft excavation construction mainly adopts upward construction method and downward construction method, which are characterized by high labor intensity, high risk coefficient and slow construction speed. In order to realize the efficient excavation of vertical shafts, this paper presents a technology of deep hole one-time blasting into wells. Based on theoretical analysis and practical shaft engineering, the blasting parameters of the deep hole one-time blasting technology are given, such as hole diameter, spacing, layout, charge structure and blasting sequence of each hole, and the technical scheme is formed finally. The technology is applied in a shaft excavation construction in Changping District, Beijing of China and good results are obtained, which proves that the technique is feasible.

Keywords: Shaft Excavation, Deep Hole, One-Time Blasting, Millisecond Controlled Blasting

1. Introduction

Due to the limitation of construction conditions, most of the shaft excavation is constructed by drilling and blasting technology which has two main methods, namely, the downward construction method and the upward construction method [1-3]. The downward construction method is, from top to bottom, to drill, blast, smoke exhaust, risk exhaust, slag removal, support, measure, etc., and then to repeat above steps until the shaft excavation is dug well. This method has many disadvantages such as a narrow working face, difficulty in ventilation, frequent lifting, poor working conditions and low work efficiency that make it difficult to ensure the workers safety. By the means of a hanging tank or a working platform, the upward construction method's steps are similar to the down construction method except it is from bottom to top. This method has all disadvantages of the down construction method except for manual slagging.

For its' high labor intensity, high risk factor, slow construction speed and long construction period, the shaft excavation construction is a difficult point in underground engineering [4-7]. Therefore, domestic and foreign scholars have carried out a lot of research on it and proposed a new deep hole blasting technology, which has been applied in many practical engineering and achieved remarkable results [8-12]. Compared with the traditional drilling and blasting technology, the deep hole blasting technology is characterized by deeper blast-holes, larger amount of blasting cycles and significantly faster boring speed.

The deep hole blasting technology can be divided into two types that one is deep hole stratification (segment) blasting into wells and that the other is deep hole one-time blasting into wells. The deep hole stratification (segment) blasting technology is widely used in the practical engineering while the deep hole one-time blasting technology is adverse. The main reasons are that the theoretical research is still insufficient and the selection of the parameters of blasting lacks reasonable basis and means. Compared with the deep hole stratification (segment) blasting technology, the deep hole one-time blasting technology has more advantages, one of these is that all the blast-holes and the vertical whole section of the shaft excavation are completed once. Furthermore, the number of cycles in the construction process is only one cycle and there are faster construction speed, higher safety and lower labor intensity [13-14].

2. Project Overview

There is a shaft excavation in an underground tunnel project in Changping District, Beijing of China which connects two underground horizontal tunnels, one of whose elevation is -72.500m and the other is -97.560m as shown in Figure 1. Two elevators and a safety staircase are provided in the vertical shaft for personnel transportation. This shaft excavation whose diameter and depth are 8.400m and 25.06m respectively was excavated by drilling and blasting technology.

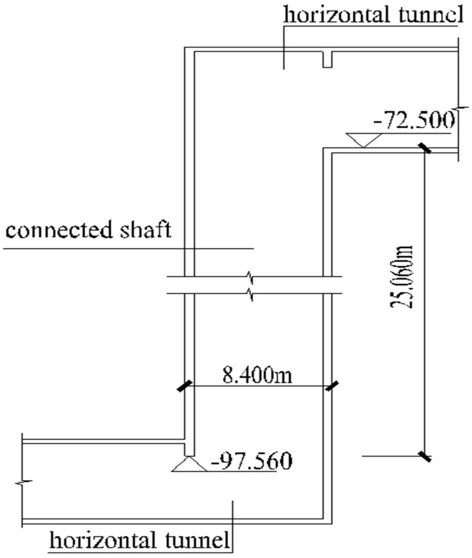

Figure 1. *The connected Shaft excavation.*

3. Blasting Scheme

3.1. Selection of Blasting Methods

The connecting shaft is located in the sandstone. The rock mass of sandstone is developed and the weathering of sandstone is serious. The sandstone's Platts coefficient F is 7-9. There are large construction safety hazards because of the poor geological conditions. In order to ensure the safety, reduce labor intensity and speed up construction progress, the deep hole one-time drilling and blasting method was adopted.

3.2. Arrangement of the Blast Hole

The blast-hole layout of the deep hole one-time drilling and blasting method are illustrated in Figure 2.

3.2.1. The Cut Hole Arrangement

The 7 cut holes in total who form a regular hexagon are arranged in the center of the connected shaft and every 3 cut holes form an equilateral triangle as shown in Figure 1. The function of the cut hole is to crush the rock in the triangular area and form a crushing zone in the center of the shaft. Under the action of the explosive force and gravity, the rock in the crushing zone is thrown out to provide the blasting free surface and the blasting space for the subsequent blast hole.

3.2.2. The Empty Hole Arrangement

The empty holes, a total of six, are arranged in the center of each equilateral triangle composed of the cut holes to provide a compensation space for the pulverization of the rock in the triangular region to avoid secondary diagenesis.

3.2.3. The Caving Hole Arrangement

The caving holes are arranged on the three concentric circles between the shaft excavation contour and the regular hexagon contour composed of the cut holes. The caving hole is to collapse and break the rock to form a fracture zone in that the rock slides down to the bottom of the shaft by gravity.

3.2.4. The Pre-split Hole Arrangement

The pre-split holes are arranged on the contour line of the shaft excavation. After the pre-split hole is detonated, precast cracks are formed which separate the rock in the excavation area from the rock outside the excavation area. Accordingly, the disturbance to the surrounding rock of the shaft by the main blasting is weakened and the stability of surrounding rocks is maintained. Then stable blasting profile is formed.

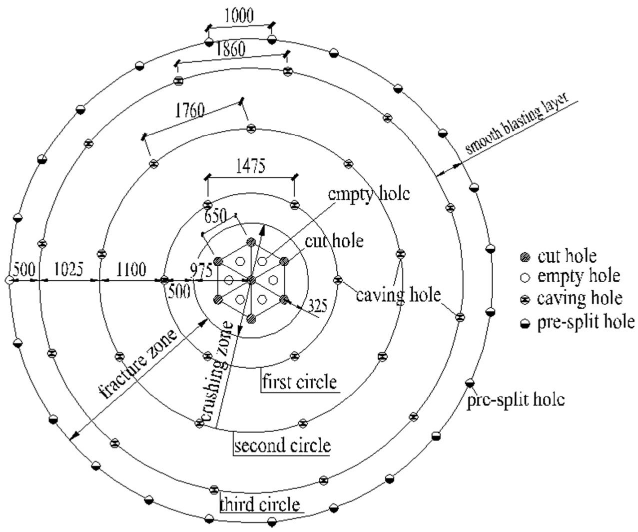

Figure 2. *Blast hole layout of the connected Shaft.*

3.3. Construction Steps

Firstly, dig out respectively two chambers at the top and bottom of the connected shaft to prepare conditions for construction and reserve space for the slag pile. Secondly, drill all the blast holes that are completed at one time by the deep hole drilling rig. Finally, all hole charge is completed and connected to the detonation network at one time.

3.4. The Detonation Network and Blasting Sequence

Compound network and millisecond controlled blasting are adopted to the detonation network. The pre-split holes are detonated first and then the cut holes and finally the caving holes.

4. Blasting Design of Deep Hole One-Time Blasting into Wells

4.1. The Parameter of the Cut Hole

As mentioned above, the function of the cut hole is to crush the rock in the triangular area and form a crushing zone in the center of the shaft. So the charge of cut hole is large and the hole diameter is small.

4.1.1. Size of the Crushing Zone

It is necessary to ensure that the size of the crushing zone meets certain requirements. Because if the size is too large, the cut hole and the empty hole will be so many and if the size is too small, the blasting effect of the fracture zone will be not good and the slag will be not easy to slip. The practice shows that the diameter of the crushing zone is suitable for 3/20 to 5/20 of the diameter of the shaft excavation. In this paper, the diameter of the crushing zone is about 1.950m.

4.1.2. Diameter of the Cut Hole

To determine the diameter of the cut hole, we need consider, not only the size of the crushing zone but also the charge of the hole and the amount of crushed rock. In addition, it is necessary to consider the workload of the drilling. As everyone knows, if the diameter of the cut hole is large, the charge of the hole and the amount of crushed rock and the distance between two holes will be also large while the number of the holes will be correspondingly small and if the diameter of the cut hole is small, the above will be just the opposite. In generally, when the cross section of the shaft is large, the crushing zone is also large and the diameter of the cut hole is large accordingly. When the cross section of the shaft is small, the crushing zone is also small and the diameter of the cut hole is small accordingly. Furthermore, it couldn't be better that all the drilling operations are completed by one drilling machine. In this connected shaft, the diameter of the cut hole is 120mm.

4.1.3. Distance Between the Cut Holes

The impact load exerted around the blast hole after the explosion of the cartridge under the condition of columnar uncoupled charge is shown in Equation (1) and Equation (2) [15]. The radical stress and the tangential stress at any point in the rock are as shown in Equation (3) and Equation (4) respectively [15].

$$\mathrm{P} = \frac{1}{2}\mathrm{P}_0\mathrm{K}^{-2\gamma}l_e n \tag{1}$$

$$\mathrm{P}_0 = \frac{1}{1+\gamma}\rho_0\mathrm{D}^2 \tag{2}$$

$$\sigma_r = PR_0^{-\alpha} \tag{3}$$

$$\sigma_\theta = -b\sigma_r \tag{4}$$

where: P_0 is the pressure of the explosive; K is the radical non-coupling coefficient of the charge, $K = \frac{r_b}{r_c}$, where r_b is the diameter of the blast hole and r_c is the diameter of the cartridge; γ is the expansion thermal insulation index of the detonation product, generally takes 3; l_e is charge axial coefficient; n is the pressure increase factor when the explosives collide with the wall of the hole, generally takes 10; ρ_0 is the density of the explosive (kg/m^3); D is the explosive speed (m/s); σ_r is the radical stress and σ_θ is the tangential stress; R_0 is distance ratio, $R_0 = \frac{r}{r_b}$ where r is the distance from the calculation point to the center of the charge (mm); α is the attenuation index of load propagation, $\alpha = 2 \pm \frac{\mu_d}{1-\mu_d}$ where the positive sign is used for the shock wave zone and the negative sign is used for the stress wave zone; μ_d is the dynamic Poisson's ratio, $\mu_d = 0.8\mu$; μ is the Poisson's ratio of the rock; $b = \frac{\mu_d}{1-\mu_d}$.

If the rock is broken, it must satisfy in the following Equation (5).

$$\sigma_r = R_0^{-\alpha}P \geq [\sigma_{cd}] = K_d[\sigma_c] \tag{5}$$

Where: $[\sigma_{cd}]$ is dynamic ultimate compressive strength of rock (MPa); $[\sigma_c]$ is the ultimate compressive strength of rock (MPa); K_d is dynamic stress intensity enhancement factor, generally takes 8.

It can be obtained from the formula 5 that the radius of the crushing ring formed by the explosion of the cylindrical charge is as shown in Equation (6).

$$\mathrm{r} = \left(\frac{P}{[\sigma_{cd}]}\right)^{\frac{1}{\alpha}}\mathrm{r}_b \tag{6}$$

The distance between the blast holes at crushing zone is shown in following Equation (7).

$$E = 2\mathrm{r} = 2\left(\frac{P}{[\sigma_{cd}]}\right)^{\frac{1}{\alpha}}\mathrm{r}_b = \left(\frac{P}{K_d[\sigma_c]}\right)^{\frac{1}{\alpha}}2\mathrm{r}_b = \left(\frac{P}{K_d[\sigma_c]}\right)^{\frac{1}{\alpha}}\mathrm{D}_b \tag{7}$$

Where: D_b is the diameter of the blast hole, $D_b = 2r_b$.

Considering the original cracks in the rock and the fact that the rock in the crushing zone does not need to be completely crushed to be thrown out, the distance between the cut holes in the crushing zone can be amplified by 1.5 times according to the actual engineering experience. So E is shown in Equation (8).

$$E = 1.5\left(\frac{P}{K_d[\sigma_c]}\right)^{\frac{1}{\alpha}}\mathrm{D}_b \tag{8}$$

As known from section 3.1.2, the diameter of the cut hole is 120mm.

The No. 2 Rock explosive, the diameter of which is 100mm, is adopted and it is charged by continuous and nun-coupling columnar charge with a decoupling coefficient 1.2. The attenuation index of load propagation α is 1.67 ($\alpha = 2 - \frac{\mu_d}{1-\mu_d} = 1.67$). The parameters of dynamite and rock are shown in Table 1. Then it can be calculated by above date that the distance between the cut holes at crushing zone is 650mm.

Table 1. *Parameters of dynamite and rock.*

The No. 2 Rock explosive		The rock (mainly sandstone)		
ρ_0(kg/m^3)	D(m/s)	[σ_c]/(MPa)	[σ_t]/(MPa)	M
1000	3600	79.8	4.3	0.31

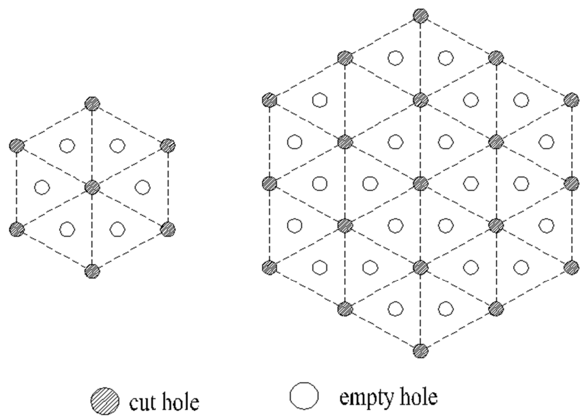

Figure 3. *Arrangement of the cut holes and the empty holes.*

4.1.4. Arrangement of the Cut Holes and the Empty Holes

The arrangement of the cut holes and the empty holes of the shaft is very important and a reasonable arrangement can achieve the ideal blasting effect in the crushing zone. According to years of practical experience, the blasting effect of the cut hole adopting the arrangement of the equilateral triangular mesh is best and the empty holes are arranged in the center of the equilateral triangle composed of the cut holes as shown in Figure 3. In actual use, the arrangement of six triangles or 24 triangles may be chosen according to the size of the crushing zone and the distance between the cut holes.

The arrangement of the cut holes and empty holes in the crushing zone of the connected shaft excavation in this paper is shown in Figure 2.

4.1.5. Charge Form of the Cut Holes

The charge weight of the cut holes should be large and the form can be continuous and decoupled columnar charge or continuous and coupled columnar charge. When choosing the continuous and decoupled columnar charge, the non-coupling coefficient should be no more than 1.5 and the higher the rock strength value, the lower the non-coupling coefficient should be. The length of the blockage at both ends of the hole is 20 to 25 times the diameter of the cut hole.

The shaft uses the No. 2 Rock explosive, whose diameter is 100mm and charge form is continuous and decoupled columnar. The non-coupling coefficient is 1.2. There are 2 delay nonel detonators arranged in every cut hole. The charge form of the cut holes is as shown in Figure 4.

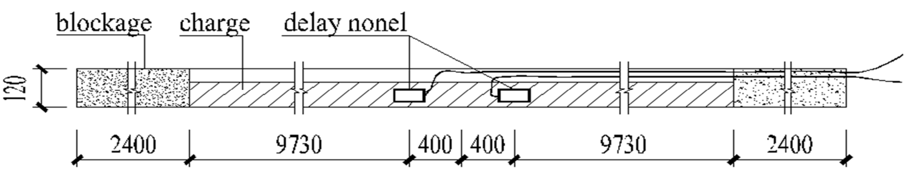

Figure 4. *Charge form of the cut hole.*

4.2. The Parameter of the Empty Hole

There are two purposes of the empty holes, one is to provide compensation space for the pulverization of the rock and to avoid the secondary diagenesis of the pulverized rock. The other is to provide a vacant surface for the blasting of the blasthole. The diameter, number and arrangement of the empty hole have an important influence on the efficiency of rock's pulverization in the crushing zone. The practice has shown that the secondary diagenesis can be effectively avoided when the ratio of the area of the cut and empty holes to the area of the pulverized rock in the crushing zone is greater than 10%.

In this connected shaft, the empty holes whose diameter is 120mm are arranged in the center of the equilateral triangle composed of the cut holes as shown in figure 2. The ratio of the area of the cut and empty holes to the area of the pulverized rock is 9.3% close to 10%.

4.3. The Parameter of the Pre-split Hole

4.3.1. Diameter of the Pre-split Hole

The diameter of the pre-split hole is mainly determined by the size of the excavation section, equipment conditions and blasting quality and it is preferably 80-250 mm generally. In recent years, there are some instances with larger diameter of the pre-split holes such as 310 mm achieving a good pre-cracking effect.

Generally speaking, when the excavation section is large and the blast hole is deep, a larger aperture should be selected and when the excavation section is small and the blast hole is shallow, a smaller aperture is should be selected. If the blasting surface is required to be a high flatness, the diameter of the hole can be 32 to 100 mm.

The diameter of the pre-split hole in the connected shaft is 100mm.

4.3.2. Distance Between the Pre-split Hole

The distance between the pre-split hole is determined by the diameter of the holes and the charge weight. When the diameter of the pre-split hole and charge weight are large, the distance is large and the number of holes is small; otherwise, the distance is small and the number of holes is large. Both the research results and the practice suggest that the crack zones are formed around the two blast holes when the adjacent holes are simultaneously detonated. When the distance between the pre-split hole is large, the cracks are not penetrated, but when the distance is less than a certain distance, there will be a through crack between the holes.

According to the stress interference principle, when the stress superposed by the tangential stress generated by the explosion in the direction of the connection between two blast holes is larger than the tensile strength of the rock, the through crack between the holes is formed.

It can be obtained by Equation (3) and Equation (4) that the largest superposed tangential stress is shown in Equation (9).

$$\sigma_{\theta m} = 2b\sigma_r = \frac{2bP}{R_0^{\alpha}} \tag{9}$$

When $\sigma_{\theta m}$ is greater than or equal to the dynamic ultimate tensile strength of rock as shown in Equation (10), it will be formed the through crack in the rock.

$$\sigma_{\theta m} = \frac{2bP}{R_0^{\alpha}} \geq [\sigma_{td}] \tag{10}$$

Where: σ_{td} is the dynamic ultimate tensile strength of rock. Under the dynamic stress, the dynamic ultimate tensile strength of rock is almost same with the static ultimate tensile strength of rock. So σ_{td} is equal to σ_t.

Bring $R_0 = \frac{r}{r_b}$ into formula 10 and the distance between the pre-split hole is obtained as shown in Equation (11).

$$E = 2r = \left(\frac{2bP}{[\sigma_{td}]}\right)^{\frac{1}{\alpha}} D_b \tag{11}$$

Considering the original cracks in the rock, the distance between the pre-split holes in the crack zone can be amplified by 1.2 times according to the actual engineering experience. So E is shown in Equation (12).

$$E = 1.2\left(\frac{2bP}{[\sigma_{td}]}\right)^{\frac{1}{\alpha}} D_b \tag{12}$$

To ensure controllable explosive and no form a crushing zone around the pre-split holes, the initial stress acting on the blast hole's wall is less than or equal to the dynamic ultimate compressive strength of rock as shown in Equation (13).

$$P \leq [\sigma_{cd}] = K_d[\sigma_c] \tag{13}$$

In this connected shaft, the diameter of the pre-split hole is 100mm. The No. 2 Rock explosive, the diameter of which is 50mm, is adopted and it is charged by discontinuous and nun-coupling columnar charge with a nun-coupling coefficient 2.0. The axial coefficient of charge is 0.8 and the attenuation index of load propagation α is 2.33 ($\alpha = 2 + \frac{\mu_d}{1-\mu_d} = 2.33$). The parameters of dynamite and rock are shown in Table 1. Then it can be calculated by above date that the distance between the pre-split holes is 1048mm, actually takes 1000mm. The arrangement of the pre-split hole is as shown in figure 2.

4.3.3. Charge Form of the Pre-split Hole

The charge form can be discontinuous and decoupled columnar charge or continuous and decoupled columnar charge. The non-coupling coefficient should be between 1.5 and 4. In order to make the blasting surface more regular and form a better quality excavation surface, it is necessary to control the charge weight of the pre-split hole to ensure that no crushing zone is formed around the holes. The length of the blockage at both ends of the pre-split hole, which is 15 to 20 times the diameter of the pre-split hole, is slightly shorter than that of the cut hole.

The shaft uses the No. 2 Rock explosive, whose diameter is 50mm and length is 400mm at intervals of about 100mm. It is charged by discontinuous and decoupled columnar charge with a decoupling coefficient 2 and an axial coefficient 0.8. There are 2 delay nonel detonators arranged in every pre-split hole. The charge form of the pre-split holes is as shown in Figure 5.

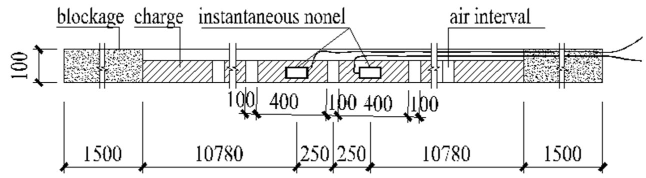

Figure 5. *Charge form of pre-split hole.*

4.4. The Parameter of the Caving Hole

4.4.1. Circle Size of the Caving Hole

As described in section 2.2.3, the caving holes are arranged in the form of concentric circles between the crushing zone and the contour composed of the pre-split holes. The distance between adjacent concentric circles is called the circle size. In theory, the circle size is equal to the minimum resistance line, w for short, which is related to the charge weight of the caving hole. The Equation (14) and Equation (15) show the relationship between the w and the charge weight under standard throwing condition. If the charge weight is determined, the line w, that is the circle size, is determined too.

$$Q = k_b V = k_b \cdot \frac{1}{2} \cdot 2r_z w l = k_b w^2 l \tag{14}$$

$$Q_l = \frac{Q}{l} = k_b w^2 \tag{15}$$

Where: Q is the charge weight of the caving hole; k_b is unit dosage coefficient under standard throwing condition (kg/m^3), k_b is 1.4 kg/m^3 for sandstone (f=7~8); r_z is bottom radius of blasting funnel (m), under standard throwing condition, $r_z = w$; w is the minimum resistance line (m); l is the depth of the caving hole; Q_l is linear density of charge.

In this paper, the diameter of the caving hole is 100mm. The No. 2 Rock explosive diameter of which is 50mm is adopted and it is charged by continuous and nun-coupling columnar charge with a nun-coupling coefficient 2.0. The w is 1.184m after calculation. In the connected shaft, the actual circle size is as shown in figure 1. The size between the crushing zone and the first circle is 0.5m and that between first circle and the second circle is 1.1m and that between third circle and the second circle is 1.025m.

4.4.2. Distance Between the Caving Hole

It is good for rock crushing that the arrangement of the caving hole adopts the form of small circle size and large hole distance as the practice shown. The density factor (the ratio of the distance of the caving hole to the minimum resistance line) is generally between 1.0 and 2.0. The blasting with a density factor greater than 2.0 is called wide hole space blasting.

The actual distance between the caving hole in this project is: 1.475m for the first circle and 1.76m for the second circle and 1.86m for the third circle as shown in figure 2.

4.4.3. Thickness of Smooth Blasting Layer

The smooth blasting layer is a layer of rock between the pre-split holes and the outermost caving holes, the thickness of which is also called the thickness of smooth blasting layer. For shaft pre-split blasting, the thickness is generally about 0.5 times of the minimum resistance line of the caving hole and it takes 500mm in this shaft.

4.4.4. Charge Form of the Caving Hole

What can evenly crush the rock is the uncoupling charge of the caving holes. The millisecond delay detonator is detonated in the caving hole and the length of the blockage at both ends of the holes is equal to the minimum resistance line w.

The shaft uses the No. 2 Rock explosive, whose diameter is 50mm and adopts the continuous and decoupled columnar charge with a non-coupling coefficient is 2. There are 2 delay nonel detonators arranged in every caving hole and the length of the blockage at both ends of the holes is 1.0m. The charge form of the caving hole is similar to that of the cut hole as shown in Figure 4.

4.5. Design of the Blasting Network

Millisecond controlled blasting is particularly important to the success of deep hole one-time blasting technology. It can reduce the energy released by the blasting and the disturbance to surrounding rock. In addition, by controlling the initiation sequence and the delay time of the blast hole, the slag can be accurately thrown out to ensure the shaft not be blocked and the slag be broken evenly.

Firstly, the pre-split hole is detonated to generate the through crack along the shaft sideline that reduces the impact on the surrounding rock for the energy released by subsequent detonation blasting to maintain the stability of the surrounding rock and forms a relatively regular excavation surface to slide down the slag smoothly. Detonating the pre-split hole after 100ms can ensure that the blasting network has been arrived to each blast hole to avoid damage to itself by the first blasting. Secondly, it is time to detonate the cut hole after the pre-split hole is detonated for 50ms that can avoid superimposing the two explosions energy and causing large disturbance to surrounding rock. Finally, the caving hole is detonated. About 50ms after the explosion of the cut hole, the first circle of the caving hole is detonated to ensure that the dross in the crushing zone is thrown and slipped out of the crushing zone, providing free surface and explosion space for the subsequent blasting of caving hole. Then the second circle, the third circle, etc. are detonated in turn and the caving holes in each circle are deferred for 25ms on the basis of the previous circle.

In this shaft excavation, the millisecond controlled blasting technology combined with delayed blasting in hole and delayed blasting outside hole was adopted. The blasting system and network are a plastic nonel tube blasting system and a multi blasting network respectively. Firstly, the pre-split hole is detonated with the 5 nonel tubes outside the hole detonated for 100ms delay and the nonel tubes in the hole detonated instantaneously. Then the cut hole is detonated with 5 nonel tubes outside the hole detonated for 100ms delay and 3 nonel tubes in the hole detonated for 50ms delay. Finally, the 3 circles caving hole is detonated. The first circle caving hole is detonated with the nonel tubes outside the hole detonated instantaneously and 9 nonel tubes in the hole detonated for 200ms delay. The second circle caving hole is detonated with the nonel tubes outside the hole detonated instantaneously and 10 nonel tubes in the hole detonated for 225ms delay. The third circle caving hole is detonated with the nonel tubes outside the hole detonated instantaneously and 11 nonel tubes in the hole detonated for 250ms delay. The blasting network of the shaft excavation is shown in figure 6.

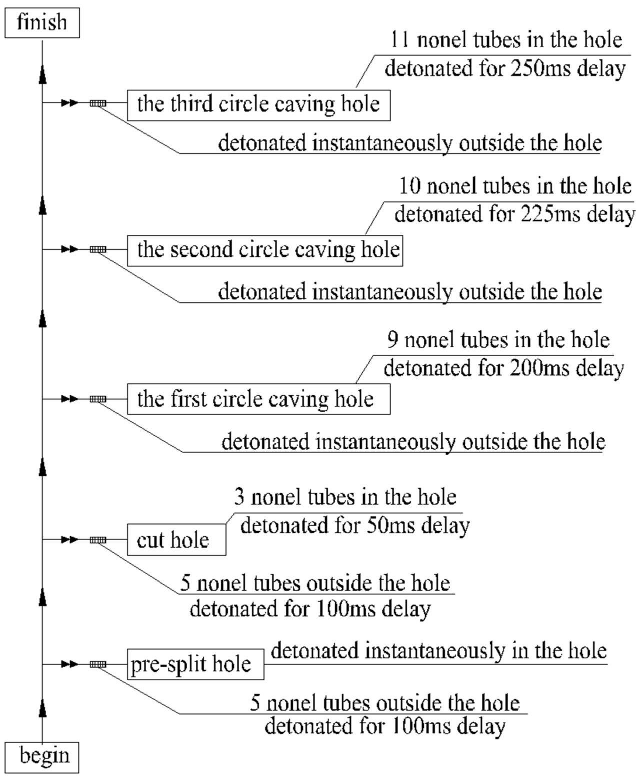

Figure 6. *Schematic diagram of initiation network.*

5. Conclusion

This paper presents a new construction method for shaft excavation, namely, the technology of deep hole one-time blasting into wells and gives the parameters of the blasting holes including pre-split hole, cut hole, empty hole and caving hole.

The theoretical analysis and practical vertical shaft which located in Changping District, Beijing of China show that this technology has great advantages of high construction speed, high safety and low labor intensity in the shaft excavation construction and is worth promoting.

The technical step of the method is to presplit the rock around the shaft firstly and then to throw out the slag crushed in the crushing zone and finally to slip the slag broken in the fracture zone. It has been proven that reasonable parameters of blasting and application of millisecond controlled blasting are the keys to the success of the shaft excavation.

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