# Vibration Response of Ground Surface Caused By Shallow Buried Tunnel Blasting

**Cui Guangqiang, Chung Ie-lung, Li Zhijian, Liu Yi, Zheng Jie, Huang Yuesen**

*Abstract*— **In order to study the influence of tunnel excavation by a drilling and blasting method on the ground surface, a method of predicting ground surface vibration waveforms suitable for actual drilling and blasting tunnelling engineering is established. First, based on the theoretical solution of surface vibration waves caused by spherical charge blasting, a more concise surface vibration wave function of spherical charge that is suitable for practical engineering is constructed. The correctness of the constructed waveform function is verified by the measured data. Second, the waveform function of surface vibration waves caused by cylindrical charge explosions perpendicular to the tunnel working face is obtained by superposition of the spherical charge. Then, the surface vibration response of the unexcavated section during tunnel blasting is calculated using the vibration wave superposition method. In the excavated section, the influence of the hollow effect of the tunnel on the vibration wave propagation was considered, and the surface vibration response of the tunnel was analysed using conformal transformation and vibration wave superposition. Finally, based on actual engineering, the correctness of this blasting vibration prediction method is verified using field test data.**

***Index Terms***— **vibration response; waveform prediction; conformal transformation; tunnelling blasting**

## I. INTRODUCTION

In recent years, traffic problems have become more and more prominent in cities. With the decreasing space available on the ground, people began to use underground space to solve urban traffic problems. The building of a large number of subway projects began in various cities. Drilling and blasting is one of the main construction methods in urban tunnel construction due to its strong adaptability to geological conditions and low excavation costs. However, the urban surface environment is relatively complicated, and the drilling and blasting method can easily influence the surface structure. Therefore, it is necessary to conduct research on the surface vibration caused by tunnel blasting.

Early studies on the surface vibration effect caused by explosions were conducted. De[1] studied the point source in the elastic half-space and obtained the vibration waveform function of the free surface particle caused by the point source. Е. И. Шемякин[2] used the incomplete separation of variables method to obtain the motion time history curve of the particle on the free surface under ball cavity pressure. The existing research on cylindrical dynamite[3-5] was carried out mostly by numerical simulation or superposition of short cylindrical dynamite. These studies were based on specific charges, and no research has been conducted on the problems that occurred in actual tunnelling.

In recent years, scholars have begun to study the problems that may arise during the blasting tunnelling process. Fu et al.[6] studied the vibration law in different parts of the tunnel near the tunnel blasting area by field testing, and they obtained the respective vibration velocity formulae of the near and far regions of the blasting area. Xiao[7] analysed the surface vibration velocity caused by subway tunnel construction using the drilling and blasting method based on field-measured data and numerical simulation. Guo et al.[8] used the Extreme Gradient Boosting (XGBoost) model to predict the peak particle velocity of blasting vibration to improve prediction accuracy. Luo[9] explored rock vibration frequency and its attenuation laws during tunnel blasting through theoretical calculations and verified the reliability of the theoretical calculations using the measured data and numerical simulations. Zhang et al.[10] analysed the surface vibration effects of shallow tunnel blasting by field testing. Xie et al.[11] used the measured single-hole blasting waveform to obtain the vibration waveform of the near field of slot hole blasting according to the Anderson superposition model. Most scholars[12-14] analysed the impact of tunnel blasting on the supporting structure or adjacent underground structures using the Sadowski formula or numerical simulation, based on field experiments of actual engineering. However, relatively few studies have been carried out on the vibration of the ground surface.

In summary, at present, the most relevant research on tunnel blasting vibration effects in domestic and foreign countries was tests based on the measured data. There has been no in-depth study on the basis of theory; the relevant waveform functions have not been obtained, and few studies with theoretical analysis have been conducted on the surface vibration response to blasting in the excavated section of the tunnel. Therefore, based on the basic theory, this paper obtains the vibration velocity waveform function to study the respective surface vibration responses of unexcavated and excavated sections during blasting in a shallow buried tunnel. The reliability of the method is then verified by the engineering measurement data.

## II. THEORETICAL SURFACE VIBRATION WAVEFORM FUNCTION OF SPHERICAL CHARGE BLASTING

In a uniform, isotropic elastic half-space, there is a spherical charge explosion at depth $h$ below the free surface.

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**Cui Guangqiang,** Institute of Engineering, Fujian Jiangxia University, Fujian 350108, China
**Chung Ie-lung,** Institute of Engineering, Fujian Jiangxia University, Fujian 350108, China
**Li Zhijian,** Fuzhou Industrial Park Development Group Co., Ltd · Fujian 350007, China
**Liu Yi,** Huaqiao University, Fujian 362000, China
**Zheng Jie,** China Construction Science and Engineering Group Co., Ltd., Guangdong 518000, China
**Huang Yuesen,** Fujian Second Construction Group Co., Ltd., Fujian 350000, China

According to the equivalent cavity theory, the explosion of the spherical charge can be equivalent to a ball cavity pressure source with a radius $a$ and an internal pressure $p(t)$, as shown in Fig.1. The half-space medium has a density $\rho$, a Young's modulus $E$, and a Poisson's ratio $v$. The free surface is on the z = 0 plane, the spherical charge is on the z-axis, the distance from the point $B(x,y,0)$ on the free surface to the coordinate origin is $r$, the distance to the pressure source is $R$, and the pressure source $p(t)=p_0e^{-\alpha_0 t}$.

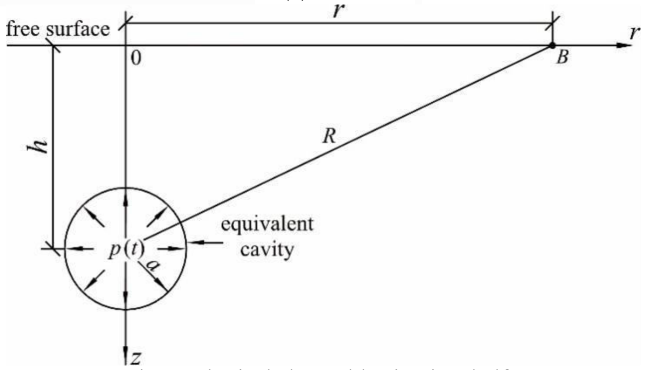

Fig.1 Spherical charge blasting in a half-space

The vibration velocity function of the surface particle under the action of the spherical cavity pressure source with radius $a$ and internal pressure is deduced based on the free surface particle derived from De[1] under the point source action. This function is shown in the following equation:

$$\begin{cases} v_r(t)=f''(0)g_r(t)+\int_{(R-a)/v_p}^{t} f'''(t-\tau)g_r(\tau)d\tau \\ v_z(t)=f''(0)g_z(t)+\int_{(R-a)/v_p}^{t} f'''(t-\tau)g_z(\tau)d\tau \end{cases} \quad (1)$$

Where $f(t)$ is source strength function, the expression is as follows:

$$\begin{cases} f(t)=-4\pi Ae^{-\xi\omega_0 t}\left[\begin{matrix}(\frac{\alpha_0}{c_p^2}+\frac{1}{R})\cos(\omega_d t) \\ +\left(\frac{\omega_d^2+\xi\omega_0-\alpha_0}{c_p^2\omega_d}+\frac{\xi\omega_0-\alpha_0}{R\omega_d}\right)\sin(\omega_d t)\end{matrix}\right]+4\pi A\left(\frac{\alpha_0}{c_p^2}+\frac{1}{R}\right)e^{-\alpha_0 t} \\ A=\frac{ap_0}{\left(\omega_0^2-2\xi\omega_0\alpha_0+\alpha_0{}^2\right)\rho} \end{cases} \quad (2)$$

in which $\omega_0=2c_s/a$, $\omega_d=\omega_0\sqrt{1-(\xi)^2}$; $\xi=c_s/c_p$, $c_p$, and $c_s$ are the propagation velocity of $p$ and $s$ waves, respectively; and $c_p=\sqrt{(\lambda+2\mu)/\rho}$ and $c_s=\sqrt{\mu/\rho}$.

The $g(t)$ in Formula (1) is Green's function, and the expression is as follows:

$$\begin{cases} g_r(x,y,0,\tau)=\frac{1}{\pi^2 R}\int_0^{\frac{\pi}{2}}\mathrm{Re}\{w_r\gamma_p\}d\Psi \\ g_z(x,y,0,\tau)=\frac{1}{\pi^2 R}\int_0^{\frac{\pi}{2}}\mathrm{Re}\{w_z\gamma_p\}d\Psi \end{cases} \quad (3)$$

where

$$\begin{cases} w_r=\frac{p\gamma_s}{2v_s^2\eta} \\ w_z=0.5v_s^{-2}\eta^{-1}\left(p^2-\left(q^2+1/\left(2v_s^2\right)\right)\right) \\ \eta=\left(q^2+1/\left(2v_s^2\right)-p^2\right)^2+\left(p^2-q^2\right)\gamma_p\gamma_s \\ \gamma_{p,s}=\left(q^2+1/v_{p,s}^2-p^2\right)^{0.5} \quad (\mathrm{Re}\,\gamma_{p,s}\ge 0) \\ q(\Psi)=R^{-1}\left(\tau^2-v_p^{-2}(R-a)^2\right)^{0.5}\sin\Psi \quad (0\le\Psi\le 0.5\pi) \\ p(\Psi)=\left(r/R^2\right)\tau+i\left(h/R^2\right)\left(\tau^2-(R-a)^2/v_p^2\right)^{0.5}\cos\Psi \end{cases}$$

## III. CONSTRUCTED VIBRATION WAVEFORM FUNCTION OF SPHERICAL CHARGE BLASTING

Because the elastic medium and the actual medium are very different from each other and the obtained vibration function is complex in form, this function derived from elastic media is not suitable for application in practical engineering. Therefore, it is necessary to construct a vibration waveform function which is more concise and can be applied to the actual medium according to the theoretical solution of the vibration function.

According to the form of the source intensity function (2), the surface vibration waveform can be fitted using the following formula:

$$v(t)=a_1e^{-b_1 t}\left[\cos(c_1 t)+d_1\sin(c_1 t)\right] \quad (4)$$

where, $a_1$, $b_1$, $c_1$ and $d_1$ are the coefficients that need to be fitted. In this formula, $a_1$ is related to the peak velocity of the particle vibration, $b_1$ is related to the decay rate of the particle velocity, $c_1$ is related to the particle vibration frequency and $d_1$ is a constant.

Because the actual medium contains many cracks and joints, the vibration velocity peak, the vibration velocity decay rate and the particle vibration frequency on the surface of the actual medium are different from those obtained in the elastic medium. Therefore, the $a_1$, $b_1$ and $c_1$ fitted and obtained by the theoretical solution will differ from their values in the actual medium, so $a_1$, $b_1$ and $c_1$ are constructed from the actual medium and $d_1$ is obtained by fitting.

Fitting a plurality of velocity waveforms in the vertical direction and the horizontal direction when r is equal to 5 m, 10 m, 15 m and 20 m, the respective d values obtained are very close to 1. Thus, $d_1=1$, and the constructed waveform function can be obtained as follows:

$$v(t)=a_1e^{-b_1 t}\left[\cos(c_1 t)+\sin(c_1 t)\right]=\sqrt{2}a_1e^{-b_1 t}\sin(c_1 t+\pi/4) \quad (5)$$

Because the starting point of the waveform obtained by the above formula is not at the origin, which is inconsistent with the actual situation, it is appropriately modified to shift the waveform forward by $\pi/4$ units to obtain the constructed form:

$$v(t)=\sqrt{2}a_1e^{-b_1 t}\sin(c_1 t) \quad (6)$$

The currently accepted peak velocity formula is the Sadowski formula, and $\sqrt{2}a_1$ in equation (12) is related to the peak velocity. So, taking $\sqrt{2}a_1=k\left(\sqrt[3]{Q}/R\right)^{\alpha}$, $b_1$ is related to the decay rate of the particle velocity, and the main factor affecting the decay rate of the vibration velocity is the comprehensive nature of the rock, so the classification score of the rock is linked with $b_1$; $c_1$ is related to the particle vibration frequency, and $c_1=2\pi f$. According to the vibration frequency calculation formula given by two scholars, Jiao[15] and Tang[16], a frequency calculation formula $f=2k\left(\sqrt[3]{Q}/\lg R\right)^{\alpha-1}$ related to rock characteristics and charge and blasting distance is constructed.

In summary, the constructed waveform function is:

$$v(t)=k\left(\sqrt[3]{Q}/R\right)^{\alpha}e^{-2\beta t}\sin(\omega t) \quad (7)$$

where $Q$ is charge quantity, kg; $\beta = 100 - RMR$ is the relationship between the $\beta$ value and the surrounding rock classification; $R$ is the blasting distance from explosive source to measured point; $\omega = 2\pi f$ and $f = 2k\left(\sqrt[3]{Q}/\lg R\right)^{\alpha-1}$ ; $k$ and $\alpha$ are the coefficient and attenuation index related to the topography and geological conditions of the blasting point, respectively.

In the rock, $k$ = 30~70; in the soil, $k$ = 150~250; and $\alpha$ = 1~2, in which the harder the rock mass, the smaller the value of $k$ and $\alpha$.

Taking the excavation blasting of Taishan Sightseeing Avenue as a project case, the above-mentioned constructed function is verified by an on-site blasting test in micro-weathered granite.

A spherical charge with a radius d = 0.045 m explodes in weathered granite at a depth of 2 m. The blasting distance is 10.2 m. The granite is hard rock, so taking $k = 35$ , then $\alpha = 1.3$ . $\beta$ of the rock is 25. The value of the parameter is substituted into formula (13) to obtain the surface vibration velocity waveform function (14) of the actual medium. The calculated vibration waveform and the measured waveform are shown in Fig.2.

$$v(t) = 1.15e^{-50t}\sin(400t) \tag{8}$$

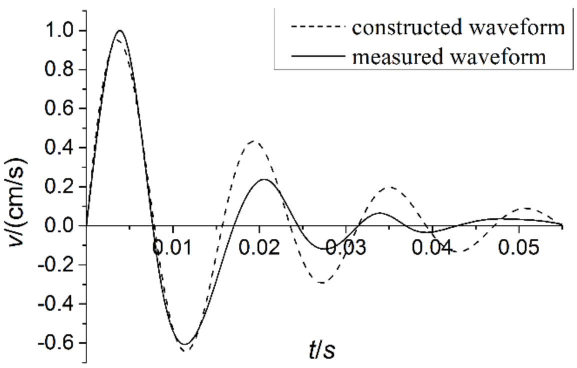


Fig.2 Velocity waveform comparison chart

As shown in Fig.2, the shape, peak value and duration of the constructed waveform are in good agreement with the measured waveform, so the constructed vibration velocity waveform function in the actual medium is reasonable.

## IV. SURFACE VIBRATION RESPONSE OF THE UNEXCAVATED SECTION

Most of the existing literature has studied the cylindrical charge perpendicular to the surface as a plane problem. In the case of tunnelling by the drilling and blasting method, the cylindrical charge is horizontally parallel to the free surface and is a three-dimensional problem.

Starfield and Pugliese[3] analysed the strain field caused by the explosion of vertical cylindrical dynamite by dividing the cylindrical dynamite into a number of short cylindrical dynamites. In this paper, the superposition theory is used to divide the cylindrical dynamite into several short cylindrical dynamites; thus, the short cylindrical dynamite is equivalent to a spherical charge. Finally, by superimposing the spherical charge, the surface vibration waveform caused by the explosion of the horizontally placed cylindrical dynamite is analysed.

When studying the surface vibration response caused by cylindrical dynamite blasting in tunnelling, the vibration of the surface particle can be divided into two cases. The first case is the vibration of the surface point above the nexcavated segment in front of the face, and the second case is the vibration of the surface point above the excavated segment of the tunnel, as shown in Fig.3.

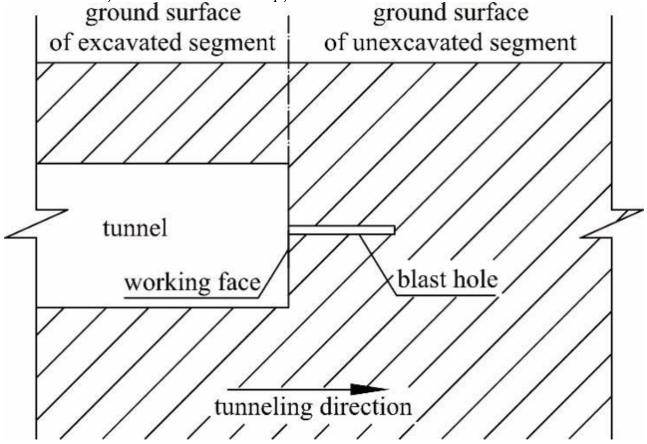


Fig.3 Tunnelling state diagram

The existence of a tunnel cavity in the excavated section affects wave propagation and is not in accordance with the Sadowski empirical formula. The constructed vibration waveform function of spherical charge blasting comes from the Sadowski formula. Therefore, this paper studies only the vibration waveform function of the surface point of the unexcavated section.

The relative position of the tunnel to the vibration predicted point $B$ and the details of the cylindrical dynamite are shown in Fig.4. The variables in Fig.4 are expressed as follows: $h$ is the buried depth of the cylindrical dynamite; $y$ is the horizontal distance from the vibration predicted point $A$ to the line directly above the cylindrical dynamite; $R_i$ is the distance from the centre of the $i$th spherical charge to the predicted point $A$; $x$ is the distance from the predicted point $A$ to the tunnel face; $x_i$ is the distance from the centre of the $i$th charge to tunnel working surface; $\delta$ is the length of each charge; $l_1$ is the stemming length; $d$ is the cylindrical dynamite diameter, and $r$ is the tunnel radius.

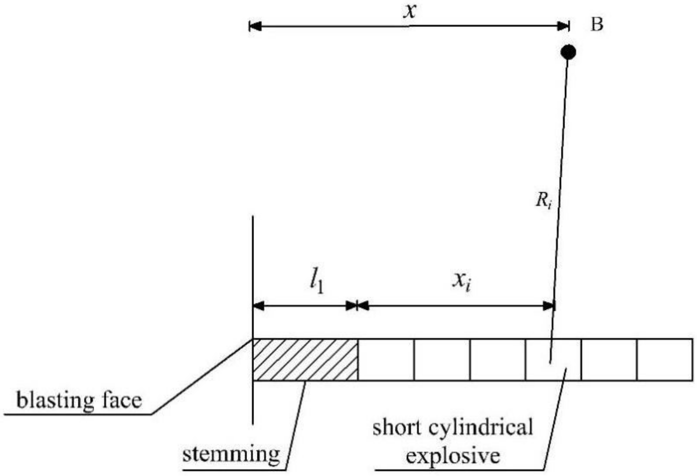


Fig.4 Cylindrical dynamite segmentation diagram

As can be seen from Fig.4, the distance from the centre point of the $i$th charge to surface point $B$ is as follows:

$$R_i = \left(y^2 + \left(x - l_1 - x_i\right)^2 + \left(h + r\right)^2\right)^{0.5} \tag{9}$$

The time from the detonation to the explosion of the $i$th charge is $x_i/c_D$ , and $c_D$ represents the explosive detonation velocity (VOD). The time at which the stress wave generated by the $i$th segment charge reaches the predicted point B is $R_i/c_p$, and $c_p$ is the propagation velocity of the $p$-wave in the medium. Therefore, the total time from detonation to the time at which the stress wave generated by the $i$th segment travels to surface point $B$ is as follows:

$$t_i = \frac{x_i}{c_D} + \frac{R_i}{c_p} \tag{10}$$

If the detonating charge at $t = 0$, then the formula related to the vibration velocity caused by the $i$th segment of the cylindrical dynamite is a function of $(t - t_i)$.

As demonstrated in the previous section, the surface vibration waveform function caused by the explosion of spherical charges in the actual medium is expressed by Formula (7).Therefore, the surface particle velocity waveform function caused by the $i$th charge blasting is as follows:

$$v_i(t) = k\left(\sqrt[3]{Q_i}/R_i\right)^{\alpha} e^{-2\beta(t-t_i)} \sin\left[2k(\sqrt[3]{Q_i}/\lg R_i)^{\alpha-1}(t-t_i)\right] \tag{11}$$

in which $Q_i$ indicates the weight of explosives, $\rho$ is the explosive density and the remaining variables are as previously defined.

Finally, by superimposing the velocity of each segment of $N$ divided by the cylindrical dynamite, the surface particle vibration velocity function caused by the explosion of a single cylindrical dynamite perpendicular to the tunnel's working face at any time is obtained:

$$v = \sum_{i=1}^{N} v_i(t) \tag{12}$$

## V. Surface Vibration Response of the Excavated Section

In the excavated rock section, the vibration velocity of A on the ground surface cannot be obtained directly by the above method because a tunnel with radius $r$ is hollow. Therefore, in this paper, the vibration velocity of point $A'$ on the top surface of the excavated tunnel is obtained first, and then the vibration velocity of point $A$ on the ground surface of the excavated rock section is finally obtained according to the vibration velocity of point $A'$.

To obtain the equivalent linear propagation distance from the equivalent spherical explosive $i$ to point $A'$ on the top surface of the tunnel, the model is first simplified, and then the vibration effect at point $A'$ is analysed. The influence of the ground surface and the bottom of the tunnel cavity is temporarily disregarded in this process. The model and coordinate system are shown in Fig.5.

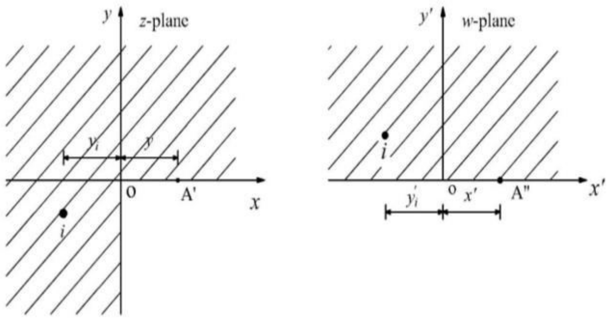


Fig.5 Simplified model of a tunnel

The conformal transformation is used to transform the vibration problem at point $A'$ caused by the blast of the equivalent spherical explosive $i$ in Fig.5 into the problem of the surface vibration effect caused by the blast of the equivalent spherical explosive $i$ in the half space, and the $z$-plane with complex boundaries in the plane coordinate system of the complex field is transformed into the $w$-plane with simple boundaries, as shown in Fig.5.

Therefore, the exponential form of the equivalent spherical explosive $i$ in the $w$-plane is Formula (14), which is obtained from the conformal transformation of boundary transformations $w = z^{2/3}$.

$$w = \sqrt[3]{y_i^2 + r^2} \exp[i\frac{2}{3}(\arctan\frac{r}{y_i} + \pi)] \tag{13}$$

The relationship of vibration prediction point $A''$ is as follows:

$$\begin{cases} y_i'' = \sqrt[3]{y_i^2 + r^2} \cos\left(\frac{\pi}{3} - \frac{2}{3}\arctan\frac{r}{y_i}\right) \\ r'' = \sqrt[3]{y_i^2 + r^2} \sin\left(\frac{\pi}{3} - \frac{2}{3}\arctan\frac{r}{y_i}\right) \\ y' = y^{2/3} \end{cases} \tag{14}$$

Therefore, the distance from the equivalent spherical explosive $i$ in the $w$-plane to the vibration prediction point $A''$ is the equivalent linear distance from the equivalent spherical explosive $i$ to the top surface mass $A'$ on the tunnel.

$$R_i' = \sqrt{\left[y^{2/3} + \sqrt[3]{y_i^2 + r^2}\cos\left(\frac{\pi}{3} - \frac{2}{3}\arctan\frac{r}{y_i}\right)\right]^2 + \left[\sqrt[3]{y_i^2 + r^2}\sin\left(\frac{\pi}{3} - \frac{2}{3}\arctan\frac{r}{y_i}\right)\right]^2} \tag{15}$$

Although the vibration wave from $A'$ to $A$ will continue to reflect after its transmission between the two points, but due to the depth of the tunnel and the reflection of the vibration wave propagation attenuation, the superposition of the reflected vibration wave on the surface has little effect on the vibration velocity, and the attenuation of the vibration wave in the free surface reflection process is more complex. It is difficult to express this with a specific formula, so this paper does not consider the superposition effect of the wave on the surface and the top surface of the tunnel reflection.

The equivalent propagation distance $R_i$ from the equivalent spherical explosive $i$ to ground surface $A$ of the excavated section is calculated as follows:

$$R_i = R_i' + h \tag{16}$$

Finally, the equivalent linear propagation distance $R_i$ and blasting parameters are substituted into equation (16) and (12) to obtain the vibration velocity of ground surface $A$ in the excavated section caused by the simplified cylindrical explosive.

## VI. Engineering Case

The peak ground surface vibration velocity on the tunnel axis is calculated based on the drilling and blasting method of tunnelling engineering for the approach ventilation-cum-safety cavern of the Xiamen Pumped Storage Power Station.

The tunnel section adopts the city gate cave type with a round arch and straight walls. The excavation section size is 7.2 m × 7 m, and the distance from the top surface of the tunnel to the ground surface is 50 m. Half of the blasting detonators are type 2, the type of explosive for the No.2 rock emulsion explosive; the density and detonation velocity of this explosive are 1100 kg/m$^3$ and 3500 m/s, respectively. The rock grade surrounding the tunnel is III, its Poisson's ratio is 0.24, its modulus of elasticity is 62 GPa and its density is 2700 kg/m$^3$. The drilling depth is 2.5 m, the explosive length is 1.5 m, the length of the blast-hole stemming is 1 m and the maximum explosive weight is 20 kg. In the process of tunnel blasting excavation, several blasting vibration tests are conducted with the TC-4850 blast vibration signal collectors produced by Chengdu Zhongke Measurement and Control Co., and five to eight measurement points are arranged each time. All vibration signal collectors are arranged on the ground above the tunnel axis, with one above the tunnel blasting excavation and two to four above the excavated and unexcavated sections of the tunnel symmetrically. The layout of the measurement points is shown in Fig.6.

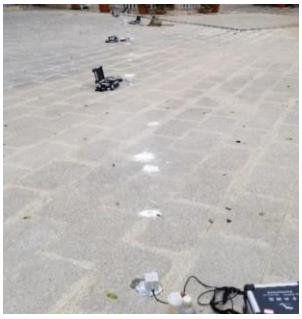

Fig.6 Partial measurement point of the vibration measuring instrument layout

The explosive hole in this tunnelling engineering is a cylindrical explosive with a radius of 0.062 m and a length of 1.5 m. The cylindrical explosive is simplified into 10 equivalent spherical explosives with a radius of 0.076 m. The mass of a single equivalent spherical explosive is 2 kg. $k$, $\alpha$ and $\beta$ are taken as 120, 1.6 and 50 respectively according to the rock parameters of the engineering.

The surface vibration velocity in the excavated and unexcavated areas can be calculated according to the above formula. The theoretical peak vibration velocity and the measured peak vibration velocity are plotted, as shown in Fig.7. The horizontal coordinates of Fig.7 are 0 for the point on the surface above the centre of the pillar-shaped package. The negative coordinates correspond to the surface of the unexcavated section of the tunnel, and the positive coordinates correspond to the surface of the excavated section of the tunnel.

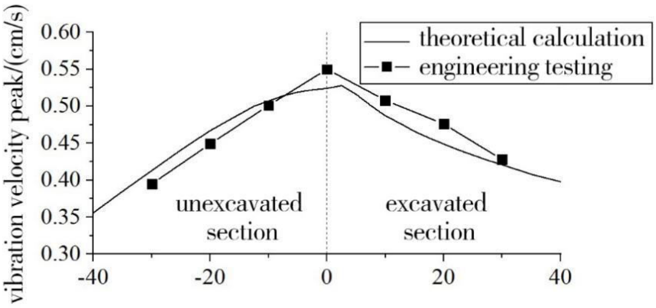


Fig.7 Comparison diagram of peak distribution of velocity

Fig.7 shows that the peak vibration velocities obtained from the theoretical calculations are in ood agreement with the measured peak vibration velocities, which verifies the correctness of the calculation method. The peak vibration velocities of both the theoretical and measured excavated sections shown in Fig.7 are slightly larger than those of the unexcavated section, which is aligned with the conclusions reached in other papers related to excavated tunnel sections.

## VII. Conclusions

1. Based on the point source theory solution, the surface particle vibration waveform function caused by spherical charge blasting is derived. Then, according to the Sadowski formula, the surrounding rock grading score Rock Mass Rating and the empirical formula of the frequency, a vibration waveform function of the spherical charge blasting that is suitable for practical engineering and concise is constructed.

2.Using superposition theory, in consideration of the detonation time and the wave propagation time, the cylindrical dynamite is divided into a plurality of spherical charges, and the vibration waveform function of the cylindrical dynamite blasting is obtained.

3. By simplifying the total charge into the amount of charge in a blast hole and using the conformal transformation and vibration wave superposition, the vibration response of the ground surface in the excavated and unexcavated sections caused by tunnel cut blasting is studied.

4. The method of predicting the surface vibration waveform caused by tunnelling blasting is verified by the data measured in actual engineering. The predicted waveform is in good agreement with the measured waveform.

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