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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF BLASTING-INDUCED GROUND VIBRATION FROM TUNNEL UNDERCROSSING A VILLAGE

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ABSTRACT

To study the effect of blasting-induced vibration on ground buildings when tunnel undercrossing a village, a blasting vibration trial was carried out in Beizhuang tunnel in Henan Province, China. The safety blasting distance and reasonable explosive charge were pre-estimated according to empirical formula. The attenuation of ground vibration velocity was simulated using a 3D numerical model. Less explosive charge and longer distance to blasting source would result in lower ground vibration. When designed explosive charge was 54 kg, the safe distance was 42.26 m. While the distance between building and blasting source was about 37 m, the maximum explosive charge was 36.24 kg. The numerical results showed that the significantly horizontal affect region of blasting vibration was within 50 m to blasting source. Accordingly, effective vibration control is necessary to avoid disturbing human daily life during tunneling.

KEYWORDS

Tunnel undercrossing a village, In-situ test, FEM, blasting vibration, safe distance, reasonable explosive charge

1. INTRODUCTION

Various highway tunnels were constructed in China in last two decades to meet economy development and transportation function. For the purpose of economy and security, drilling and blasting are widely used in the construction of tunnel. Consequently, part of the explosive energy converts into seismic waves, which may cause somewhat damage to ground buildings [1, 2]. Gong et al. [3] suggested that a field blasting trial and vibration monitoring was necessary before tunnelling under buildings in a railway tunnel case study. Xia et al [4] and Li et al [5] studied the effects of tunnel blasting on surrounding rock and the lining systems of adjacent existing tunnels, respectively, and proposed some possible schemes of vibration control to ensure the safety of the existing tunnels. Singh [6] conducted filed investigations for several coal mines in India to analyse the effect of blasting on adjacent coal mines. Umit [7] investigated the ground vibration induced by blasting during the construction of the Istanbul Kadıköy–Kartal metro tunnel, and the particle velocities and frequency values of all blast events were evaluated according to Turkish Environmental Regulation [8]. In order to comprehensively understand the dynamic responses of tunnel and building to blasting vibration, numerical model was introduced to precisely analysis of in-situ data.

Jiang et al. [9], Zhu et al. [10] and Xu et al. [11] established a 3D nonlinear constitutive model to investigate the variation of internal force and settlement during the tunnel excavation, respectively. Tian and Li [12] introduced a numerical simulation in a different model to analyse the dynamic responses of building to ground shock induced by an explosion in tunnel. Numerous experiments have established to study response of building to blasting waves induced by the explosion in tunnel [13-15]. The optimal scheme of blasting explosive in new tunnel construction was argued by Wang et al [16] and Shao et al. [17, 18] in a numerical model using ANSYS/LS-DYNA program. However, little research has been carried out to discuss the blasting-induced ground vibration in tunnelling under cross a village. In this work, the blasting-induced ground vibration when tunnelling under cross a village was in-situ tested and numerical studied in Beizhuang tunnel in Henan province, China. The safety distance of blasting construction was evaluated by using the empirical formula [20-23]. The designed explosive charge of the shallow area was also optimized according to the safety distance. Significantly affect region of blasting vibration was obtained through the numerical experimental. The research results have provided guidance for the blasting excavation of Beizhuang tunnel, also guaranteed the safety of ground buildings.

2. TEST SITE DESCRIPTIONS

The Beizhuang tunnel undercrossed Beizhuang village, in Gongyi, China (Figures 1 and 2). The length of the left line is about 2505 m, and its range is ZK20+130-ZK22+635. While the length of the right line is 2530 m, and its range is YK20+085-YK22+615. The width and the height of the tunnel are 10.75 m and 7.10 m, respectively. The surrounding rock of the tunnel is mainly weathered limestone. The range of undercrossing section is K20+400-K20+900, and the depth of the tunnel is 37-55 m. The Beizhuang village was densely built, and most of the buildings were masonry structure and fragile to vibration.

The tunnel was constructed by bench method, and its surrounding rock belongs to grade IV. Given the cost of construction, especially in terms of time and security, the drilling and controlled blasting method was adopted when tunnelling, and the tunnelling footage is from 1.0 m to 1.2 m.

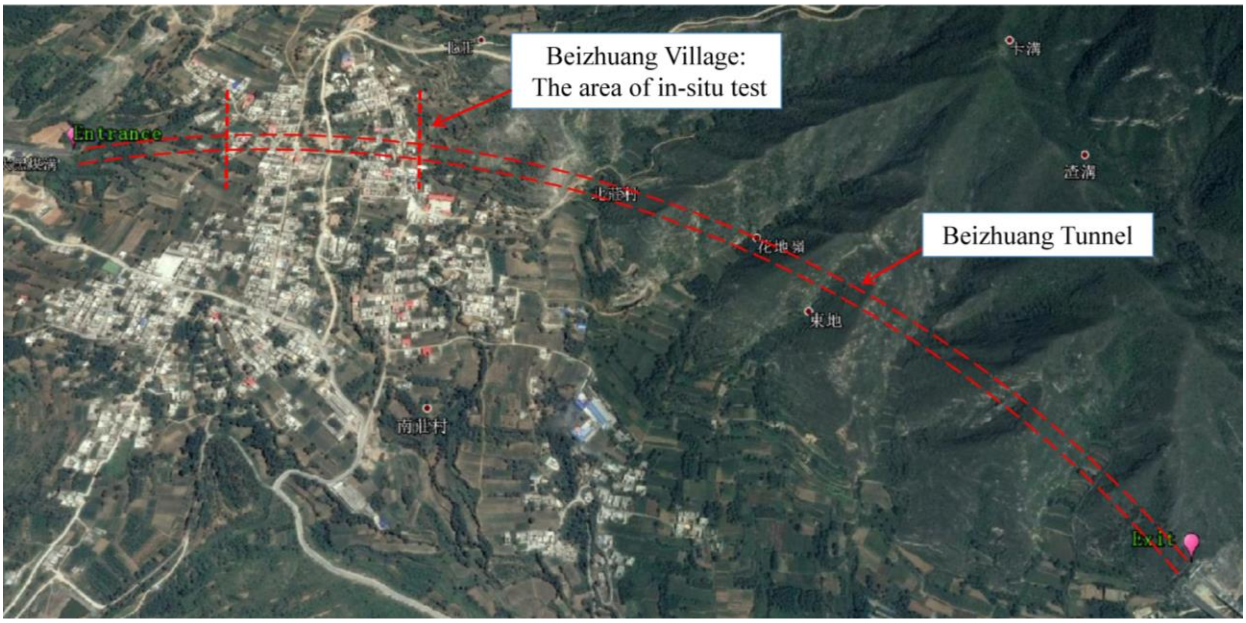

Fig. 1 - The Beizhuang tunnel

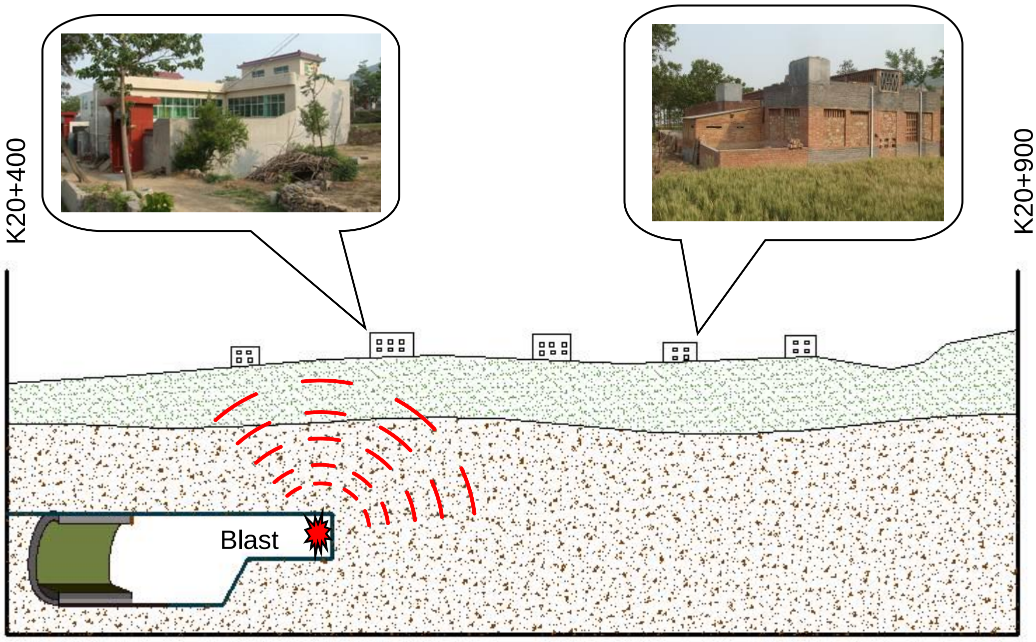

Fig. 2 - The profile diagram of tunnel undercross Beizhuang village

3. IN-SITU TEST

3.1. Test scheme

The section of the tunnel beneath Beizhuang village was subjected to short footage and weak blasting. Vibration data was acquired by REFTEK130B seismograph (US), the sensor was GURALP (UK). Sensor was installed to test point by gypsum, if the test point is on the hard rock, just fixed it on rock surface, in case of weathered rock, the weathered layer should be removed and then build concrete pier for fixing.

To obtain the ground vibration velocity, 5 testing points were placed along centre lines of the tunnel. The layout diagram of test points was shown in Figure 3.

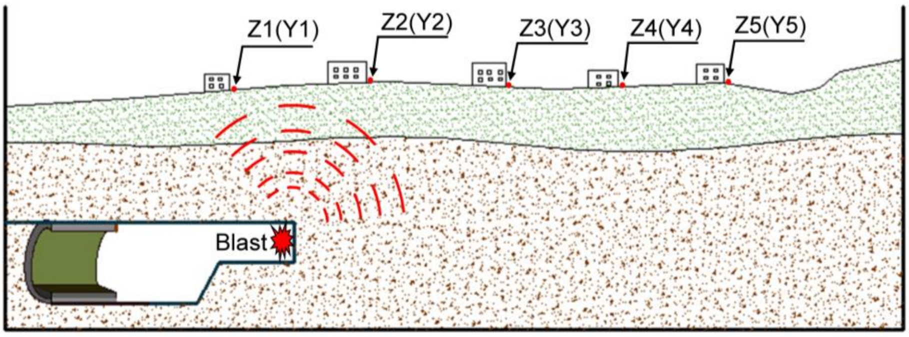

Fig. 3 - The layout diagram of test points for blasting vibration

To study the influence of tunnel blasting on buildings, the blasting test was carried out at ZK20+470 and YK20+510 in main tunnel and ZK20+400 and YK20+415 in pedestrian cross hole, respectively. Test points were placed from section ZK20+472 to YK20+510, with space of 25-55 m. The explosive charge for blasting was 54 kg for main tunnel and 9 kg for pedestrian cross hole. The distance between test the point and the blasting point along left line and right line of tunnel was shown in Tables 1 and 2, respectively.

Tab. 1 - The distance between testing point and blasting point along left line of tunnel

Test points	Z1	Z2	Z3	Z4	Z5
Location	ZK20+472	ZK20+507	ZK20+532	ZK20+562	ZK20+617
Horizontal distance away from the blasting point(main tunnel ZK20+470)/m	2	37	62	92	147
Spatial distance away from the blasting point (main tunnel ZK20+470)/m	44.9	60.2	80.5	107.0	157.6
Spatial distance away from the blasting point (pedestrian cross hole ZK20+400)/m	85.5	117.2	141.0	170.8	224.1

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Tab. 2: The distance between test point and blasting point along right line of tunnel

Test points	Y1	Y2	Y3	Y4	Y5
Location	YK20+510	YK20+535	YK20+565	YK20+595	YK20+645
Horizontal distance away from the blasting point(main tunnel YK20+510)/m	0	25	55	85	135
Spatial distance away from the blasting point (main tunnelYK20+510)/m	44.9	51.6	72.6	98.2	144.3
Spatial distance away from the blasting point (pedestrian cross holeYK20+415)/m	102.2	129.4	157.9	187.1	236.3

3.2. Analysis of blasting vibration velocity

The high frequency part of the blasting seismic wave was wholly absorbed by the soil, while the low frequency part could propagate for a long distance [24-27]. The maximum ground vibration velocity was calculated according to the maximum amplitude of horizontal wave. The peak particle velocity (PPV) at each test point in main tunnel was shown in Table 3, and the PPV at each test point in pedestrian cross hole was shown in Table 4. The attenuation of vibration velocity on ground surface due to blasting in main tunnel and pedestrian cross hole were shown in Figures 4 and 5.

Tab. 3 - The PPV at each test point in main tunnel

Testing point	Explosive charge (kg)	Horizontal distance (m)	Spatial distance (m)	V_{max} (cm/s)	Testing point	Explosive charge (kg)	Horizontal distance (m)	Spatial distance (m)	V_{max} (cm/s)
Z1	54	2	44.9	1.366	Y1	54	0	44.9	1.313
Z2	54	37	60.2	1.021	Y2	54	25	51.6	1.174
Z3	54	62	80.5	0.852	Y3	54	55	72.6	0.64
Z4	54	92	107.0	0.426	Y4	54	85	98.2	0.388
Z5	54	147	157.6	0.142	Y5	54	135	144.3	0.088

Tab. 4 - The PPV at each test point in pedestrian cross hole

Testing point	Explosive charge (kg)	Horizontal distance (m)	Spatial distance (m)	V_{max} (cm/s)	Testing point	Explosive charge (kg)	Horizontal distance (m)	Spatial distance (m)	V_{max} (cm/s)
Z1	9	72	85.5	0.508	Y1	9	90	102.2	0.561
Z2	9	107	117.2	0.388	Y2	9	120	129.4	0.459
Z3	9	132	141.0	0.412	Y3	9	150	157.9	0.388
Z4	9	162	170.8	0.223	Y4	9	180	187.1	0.132
Z5	9	217	224.1	0.034	Y5	9	230	236.3	0.028

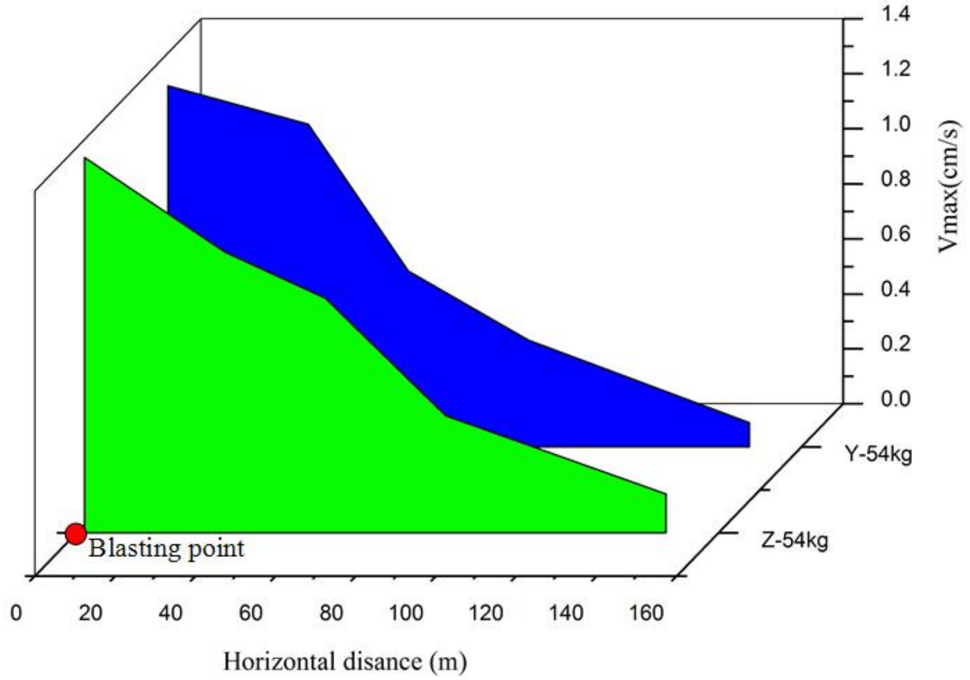

Fig. 4 - Attenuation of vibration velocity on ground surface due to blasting in pedestrian in main tunnel

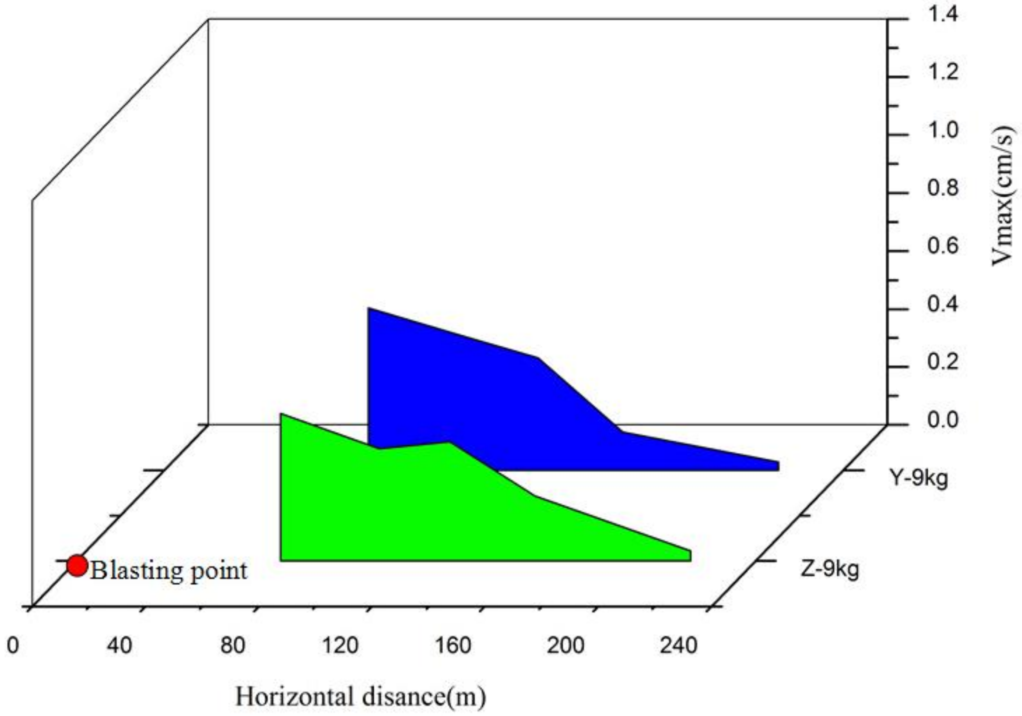

Fig. 5 - Attenuation of vibration velocity on ground surface due to blasting in pedestrian cross hole

It is obvious that less explosive charge and longer distance to blasting source could greatly slower vibration velocity on ground (Tables 3 and 4). When explosive charge is 54 kg, the maximum ground vibration velocity of left tunnel attenuated from V_{max} = 1.366 cm/s (Z1) to V_{max}= 0.142 cm/s (Z5), and that of the right tunnel attenuated from V_{max} = 1.313 cm/s (Y1) to V_{max} = 0.088cm/s (Y5). When explosive charge was 9 kg, the maximum ground vibration velocity of left tunnel attenuated from V_{max} = 0.508cm/s (Z1) to V_{max} = 0.034cm/s (Z5), and that of the right tunnel attenuated from V_{max} = 0.561cm/s (Y1) to V_{max} = 0.028cm/s (Y5).

As the Figure 4 shows that the vibration velocity on ground surface due to blasting construction attenuates faster within the horizontal range of 50m. It is observed from Figures 4 and 5 that the vibration velocity due to blasting construction in pedestrian cross hole is far less than that in main tunnel, which is mainly associated with the decrease of explosive charge and increase in distance to blasting point.

The buildings above Beizhuang tunnel were defined to sustain blasting vibration velocity of 2.0 -2.5 cm/s, within the range of 10 Hz of frequency [28]. The maximum ground vibration velocity was 1.366 cm/s, so the ground buildings were safe when the designed explosive charge was approximate 54 kg.

3.3. Prediction of safe distance and reasonable explosive charge

Except for explosive charge and distance to blasting source, propagation of seismic wave was also influenced by charge measures, detonation mode and stratum characteristic. However, only the empirical formula (1) was commonly applied in engineering field [20-23]:

$$v = K(Q^{1/3} / R)^{\alpha} \tag{1}$$

Where v is the PPV; Q is maximum explosive charge of each blasting; R is the distance of test point to blasting source; K and α are the factors to reflect the influence of non-primary factors, which could be determined by regression analysis of in-situ test data.

Millisecond detonation was adopted in the blasting of Beizhuang tunnel, the explosive charge Q=54 kg. Formula (2) was obtained when substitute vibration velocity at each test point and the distance to blasting source into formula (1):

$$\begin{aligned} v_1 &= K(Q^{1/3} / R_1)^{\alpha} \\ v_2 &= K(Q^{1/3} / R_2)^{\alpha} \\ &\ldots\ldots \\ v_n &= K(Q^{m} / R_n)^{\alpha} \end{aligned} \tag{2}$$

Then K = 250, α=2.0 were got from formula (2).

Then, the safety distance for blasting and reasonable explosive charge for Beizhuang tunnel could be got by formula (1) and the maximum tolerant vibration velocity.

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a. *Prediction of safety distance for blasting in Beizhuang Tunnel*

When the designed explosive charge $Q_{\max}$ and maximum tolerant vibration velocity $v_{\max}$ are given, the safety distance is:

$$R_{\min} = Q_{\max}^{1/3} \left(K / v_{\max} \right)^{1/\alpha} \tag{3}$$

The designed explosive charge of Beizhuang Tunnel is 54 kg and the maximum tolerant vibration velocity defined in literature [28] is 2.0 cm/s, so the safe distance could be obtained from the formula (3):

$$R_{\min} = 42.26 \text{ m}$$

b. *Prediction of reasonable explosive charge for Beizhuang Tunnel*

When the allowable designed vibration velocity $v_{\max}$ and the distance between ground surface and blasting source *R* are given, the allowable maximum explosive charge is:

$$Q_{\max} = R^3 \left(v / K \right)^{3/\alpha} \tag{4}$$

If the designed explosive charge $Q_{\max}$ = 54 kg is adopted, the safety distance for blasting is 42.26 m according to the above discussion. While the depth of the section of Beizhuang tunnel is 37-50 m, and the distance between some of buildings and blasting point is shorter than the defined safe distance, so the designed explosive charge should be cut down in shallow part. The calculation was carried out according to the minimum depth (*R* = 37 m) of the tunnel, so the explosive charge Q_{opt} could be gained from formula (4):

$$Q_{opt} = 36.24 \text{ kg}$$

4. NUMERICAL INVESTIGATION

It was very difficult to obtain complete field data due to various limitations in-situ, in that case, a 3D numerical model was set up in MIDAS/GTS [29] to comprehensively analysis the ground vibration velocity induced by blasting in the right tunnel of Beizhuang tunnel.

4.1. Numerical model

The model was built according to in-situ engineering conditions. The tunnel was one centred circle section with net width of 10.75 m and net height of 7.10 m, the building size was 10×10×6 m (L×W×H), and bottom size of the model was 40×180 m (L×W). The model height referred to the depth of the section from YK20+500 to YK20+680 of the Tunnel, was 44-53 m. The surrounding rock was subject to Mohr-Coulomb yield criteria, with surface spring built on its surrounding. The simulated explosive charge was about 54 kg. Parameters of the model were shown in Table 5.

Tab. 5: Parameters of the model

Materials Category	Modulus of elasticity E（MPa）	Poisson's ratio μ	Bulk density γ（kN/m^3）	Cohesive force C（kPa）	Friction angle φ（°）
Weathered limestone	19	0.29	24	1500	40
Building	25	0.18	28	0	0

4.2. Analysis of ground vibration velocity

Since section YK20+510 was right above the blasting point in the tunnel, the influence of blasting vibration on ground was significant. The testing point on this section was selected as the typical section to obtain the waveform chart of three-component blasting vibration velocity (Figure 6). In order to facilitate analysis, it is defined that X was the direction normal to axial line of tunnel, namely, transverse direction; Y was the direction along axial line of tunnel, namely longitudinal direction; Z was the direction normal to ground surface, namely vertical direction.

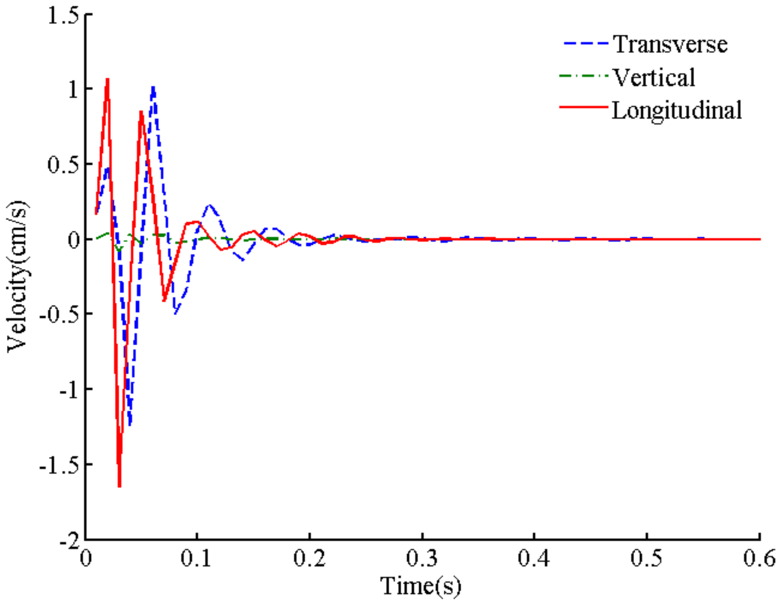
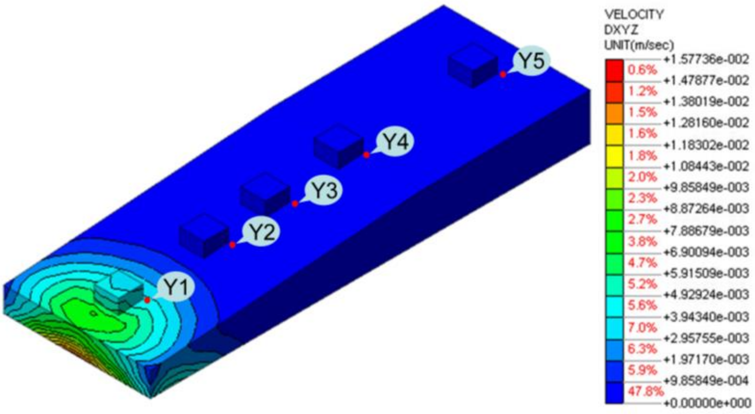
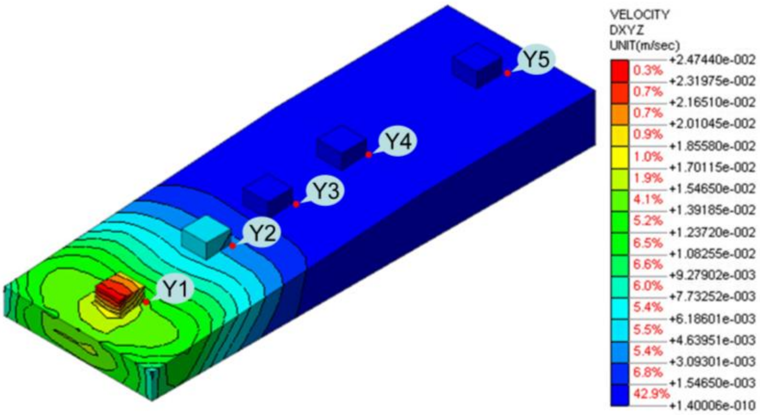


Fig. 6 - The typical waveform (Y=0m)

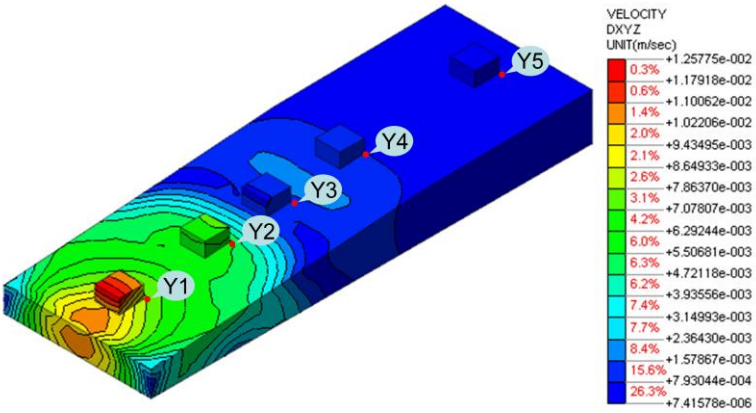
As shown in Figure 6, the vibration velocities along X direction and Y direction were much higher than that of Z direction, and the maximum vibration velocity at Y=0 m is 1.67 cm/s. The vibration velocity attenuated faster within the first 100 ms after blasting. The velocity nephograms of ground with time were shown in Figure 7.



(a) t=10 ms

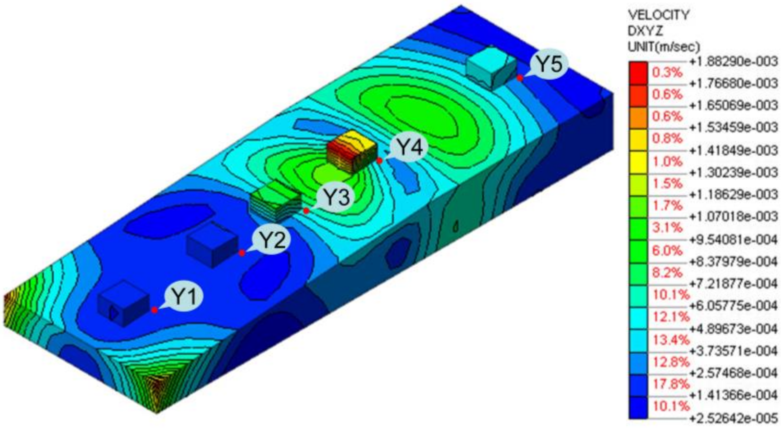


(b) t=20 ms



(c) t=40 ms

Fig. 7 - Velocity nephograms of ground with time



(d) t=80 ms

Fig. 7 - Velocity nephograms of ground with time

Figure 7 clearly displays the distribution of ground vibration velocity within 10 ms, 20 ms, 40 ms and 80 ms after blasting. When t =10 ms, vibration is only generated around blasting source. The maximum vibration velocity takes place at the point of Y=0 m and the PPV on the ground is less than that of the top of building. The seismic wave propagates in strata and attenuated gradually with the increase of time. When t=80 ms, the seismic wave propagates to the point of Y=135 m, and the corresponding PPV of this point is 0.068 cm/s, however, the PPV of the point Y=0 m attenuates to 0 cm/s at the same time.

4.3. Comparative analysis of test results and simulation results

In order to analyse the distance-dependent attenuation of the ground vibration velocity, a comparative study between simulation results and test results was conducted using the ground PPV along the axial direction (Y direction) of tunnel. The attenuation of the ground vibration velocity vs. horizontal distance was shown in Figure 8.

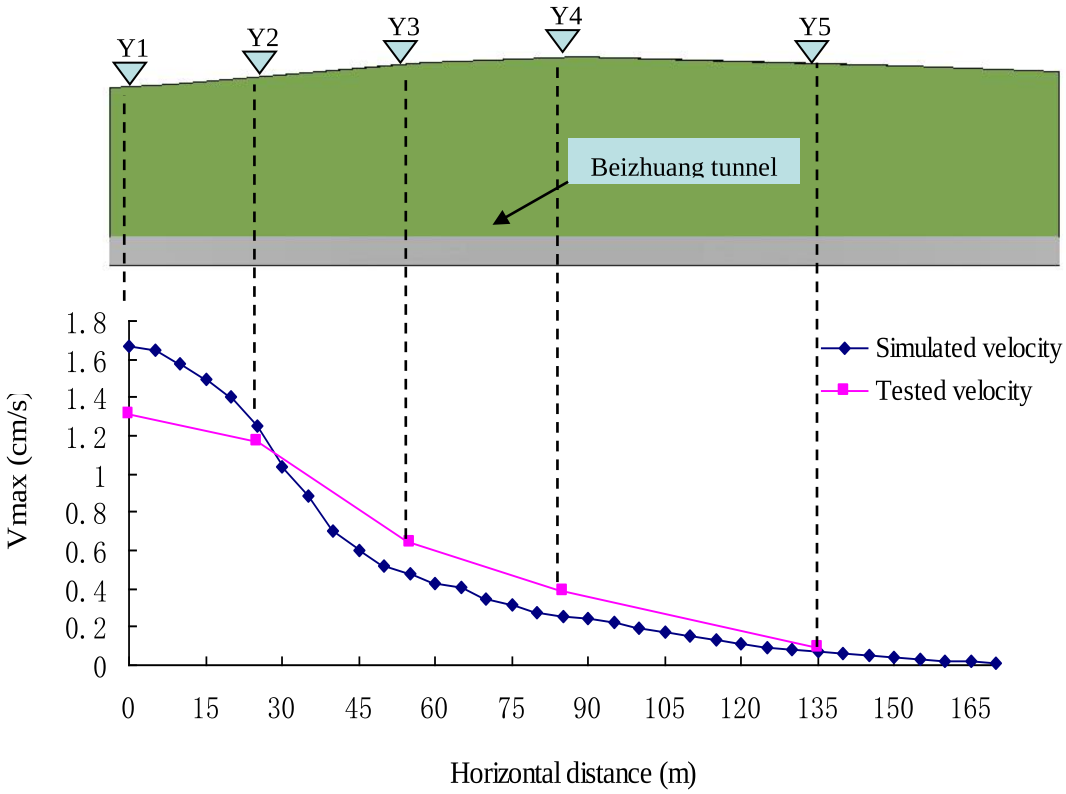


Fig. 8 - Attenuation of the ground vibration velocity vs. horizontal distance

The simulation curve indicates that the farther the distance to blasting source, the smaller the ground vibration velocity. When horizontal distance is Y=50 m, the maximum ground vibration velocity is 0.52 cm/s, which is only one third of that of Y=0 m. After the point of Y=50 m, the attenuation of ground vibration velocity is slowed. Since the soil was supposed to be uniform and continuous in numerical calculations, the simulation results were fairly ideal. Therefore, the ground vibration velocity in numerical calculations is slightly higher than that of in-situ test within 30 m horizontally, and it attenuates quickly. The main attenuation area of ground vibration velocity is within 50 m (Figures 7 and 8), so buildings within this area should be protected during blasting construction.

5. CONCLUSIONS

For the purpose of safety and economy, it is quite essential to determine the safe distance and design a reasonable explosive charge in tunnelling under cross a village. Experimental and numerical results about Beizhuang tunnel are as following:

(1) The blasting induced ground vibration velocity is closely associated with explosive charge and distance to blasting source. Less explosive charge and longer distance to blasting source lead to lower ground vibration velocity and less damage to ground building.

(2) When the explosive charge is around 54 kg, the maximum PPV is 1.366 cm/s, which is lower than the maximum vibration velocity allowed for building in masonry structure.

(3) When the distance between building and blasting source is more than 42.26 m, the explosive charge of 54 kg is relatively safe. While the blasting point is 37 m to building, the maximum explosive charge is 36.24 kg.

(4) With the increase of horizontal distance to blasting source, the ground vibration velocity attenuates rapidly. The main attenuation area for ground vibration velocity is within 50 m horizontal to the blasting source, which is also the significant affect region of blasting vibration.

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REFERENCES

[1] Kuzu C., 2008. The mitigation of the vibration effects caused by tunnel blasts in urban areas: a case study in Istanbul. Environmental Geology, 54, 1075-1080.

[2] Zhu J.H., 2007. The safety evaluation of the close building under the tunnel blasting vibration. Chinese Journal of Explosives ＆ Propellants, 30, 78-79.

[3] Gong L., Qiu W.G., Gao X.Q., 2006. Controlled blasting experimental research of railway tunnel under through buildings closely. Rock and Soil Mechanics, 27, 1089-1092.

[4] Xia X., Li H.B., Li J.C., Liu B., Yu C., 2013. A case study on rock damage prediction and control method for underground tunnels subjected to adjacent excavation blasting. Tunnelling and Underground Space Technology, 35, 1-7.

[5] Li X.H., Long Y., Ji C., Zhong M.S., Zhao H.B., 2013. Study on the vibration effect on operation subway induced by blasting of an adjacent cross tunnel and the reducing vibration techniques. Journal of Vibroengineering, 15, 1454-1462.

[6] Singh P.K., 2002. Blast vibration damage to underground coal mines from adjacent open-pit blasting. International Journal of Rock Mechanics and Mining Sciences, 39, 959-973.

[7] Umit Ozer., 2008. Environmental impacts of ground vibration induced by blasting at different rock units on the Kadikoy–Kartal metro tunnel. Engineering Geology, 100, 82-90.

[8] Khandelwal M., Singh T.N., 2007. Evaluation of blast-induced ground vibration predictors. Soil Dynamics and Earthquake Engineering, 27, 116-125.

[9] Jiang X.L., Jia Y., Zhao B.J., Wang T., 2008. Analysis of influence of metro tunnel construction on adjacent buildings. Rock and Soil Mechanics, 29, 3047-3052.

[10] Zhu G.Q., Lin Z., Zhu Y.C., Yang C., 2012. Research on influences of in-situ tunnel extension project on adjacent buildings. Rock and Soil Mechanics, 33, 251-256.

[11] Xu J., Gu Y.L., Kang J.M., 2005. Study on interaction of tunnel and upper structure. Rock and Soil Mechanics, 26, 889-892.

[12] Tian L., Li Z.X., 2008. Dynamic response analysis of a building structure subjected to ground shock from a tunnel explosion. International Journal of Impact Engineering, 35, 1164-1178.

[13] Tian L., Li Z.X., 2004. Dynamic responses of sliding base isolated buildings subjected to shock wave of underground explosion. Explos Shock Waves, 24, 16-23.

[14] Mostaghel N., Davis T., 1997. Representations of Coulomb friction for dynamic analysis. Earthquake Engineering and Structural Dynamics, 26, 541-548.

[15] Fan J., Tang J.X., 2001. Dynamic characteristics and earthquake response analysis of structures supported on slide-limited friction base isolation system. Jianzhu Jiegou Xuebao & Journal of Building Structures, 22, 20.

[16] Wang X.Y., Shao Z.S., Qiao R.J., 2013. Study on the dynamic responses of blasting vibration on undercrossing railway tunnel with small distance. Chinese Journal of Applied Mechanics, 30, 527-532.

[17] Shao Z.S., Li P.P., Wang X.Y., 2014. Study on the blasting vibration control of tunnel with small distance. Chinese Journal of Applied Mechanics, 31, 230-235.

[18] Shao Z.S., Qiao R.J., Wang X.Y., 2012. Numerical Investigation into Effect of Free Surface on the Response of Blasting Induced Vibration. Chinese Journal of Underground Space and Engineering. 8, 1052-1058.

[19] Yao Q., Yang X.G., Li H.T., 2014. Residential comfort assessment due to blasting vibration. Journal of Vibroengineering, 16, 674-684.

[20] GB6722-86., 1986 Chinese Code for Blasting Safety Standards. China Standard Publishing Company, Beijing.

[21] Xie Q.M., Xia Y.Y., Li X.P., 2003. Study on blasting vibration control of creep mass slope of longtan hydropdwer station. Chinese Journal of Rock Mechanics and Engineering, 22, 1929-1932.

[22] LÜ T., Shi Y.Q., Huang C., Li H.B., Xia X., Zhou Q.C., Li J.R., 2007. Study on attenuation parameters of blasting vibration by nonlinear regression analysis. Rock and Soil Mechanics, 28, 1871-1878.

[23] Wu T., Peng L.M., Zhai X.D., 2009. Monitoring and Safety Evaluation of Construction Blasting for Metro Tunnels Underpassing Densely Populated Areas. Modern Tunnelling Technology, 46, 48-52.

[24] Xue W.J., Wang L.B., Druta C., 2014. Monitoring the Speed, Configurations, and Weight of Vehicles Using An In-Situ Wireless Sensing Nework. IEEE Transactions on Intelligent Transportation Systems 2014. doi: 10.1109/TITS.2014.2364186.

[25] Yao Y., He C., 2009. Analysis of Blasting Vibration Response of Parallel Set Small Clear-distance Tunnels and Blasting Control Measures. Rock and Soil Mechanics, 30, 2815-2822.

[26] Nateghi R., 2011. Prediction of Gound Vibration Level Induced by Blasting at Different Rock Units. International Journal of Rock Mechanics and Mining Sciences, 48, 899-908.

[27] Xue Y.G., Li S.C., Zhang D.F., 2014. Vibration characteristics in subway operation and environmental responses of ancient buildings. Polish Journal of Environmental Studies, 23, 231-241.

[28] GB6722-2003., 1999. Chinese Code for Blasting Safety Standards. China Standard Publishing Company, Beijing.

[29] MIDAS GTS. 2009. User supports web page. < http://gts.midasit.co.kr/Tech_default/default.asp>.