Tunnelling and Underground Space Technology 71 (2018) 292–297

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

A case study on the cavity effect of a water tunnel on the ground vibrations induced by excavating blasts

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ARTICLE INFO

Keywords:
Cavity effect
Tunnel
Blast vibration
PPV

ABSTRACT

The cavity effect means the amplifications of blast vibrations when propagating through a cavity inside the rock mass. It has been investigated by a series of blast tests in an underground water tunnel. Monitoring points were set up in pairs on the ground surface and symmetrically about the tunnel face. The amplifying coefficient of blast vibrations was defined as the PPV (peak particle velocity) ratio of the two symmetry points. It is found that the amplifying coefficient first rises to a maximum of 3.5, and then falls down with the distance in the tunnel axial direction. Meanwhile, tunnel radius and its buried depth are two other influencing factors. The coefficient linearly increases with tunnel radius, while decreases with the depth in a power function. These results suggest that the cavity effect only works within a limited scope on the ground, and mainly occurs in shallow tunnel excavations. By introducing a ratio of the tunnel depth to its radius, an empirical formula was proposed to calculate the amplifying coefficient. It can be used to predict the PPV amplifications and therefore define a vibration control area for the safety of ground structures and facilities. It could also be applied to more site conditions by choosing appropriate parameter values in the formula.

1. Introduction

Until now, the blast technique has still been the most common method in tunnel excavations due to its low cost, high efficiency and easy operation. Equally remarkable are its side effects, such as the blast-induced damage and vibrations. Generally, damage only occurs in a limited range around the explosive source, while vibrations have a much wider range of influence. They will propagate not only along the tunnel axis, around its periphery, but also upward far to the ground. The ground vibrations may have an adverse impact on the property safety and people's health in the neighborhood, arising civilian complaints (Lee et al., 2016; Ozer, 2008). Their influences on the ground structures and sensitive devices are also a significant consideration in the excavation site (Nateghi, 2011). Therefore, severe restrictions on blast vibrations have been implemented and the limits are becoming increasingly strict in recent years (Arora and Dey, 2010; Kim and Song, 2015).

To exercise control over the blast vibrations, the prerequisite is to investigate their propagations in rock mass and thereby make accurate predictions of PPV (peak particle velocity) at varied locations. Many PPV predictors have been proposed for level ground and undulate terrain conditions (Alvarez-Vigil et al., 2012; Khandelwal and Singh, 2007; Kumar et al., 2016; Lu et al., 2010; Nateghi, 2011; Xia et al., 2014; Zhang et al., 2000), respectively. However, few of them can deal with the problems of underground tunnel blasts. In this case the excavated section of the tunnel turns into a void space, which will change the structural integrity of rock mass and thereby leads to more complicated transmissions and reflections of blast waves (Zhang et al., 2005). Singh et al. (2015) monitored the blast vibrations at an open-pit mining and found that the PPVs recorded on the ground surface are much higher than those inside the underground opening at the same scaled distance. Same conclusions have been drawn by Blair (2014) and Feldgun et al. (2014). Such a phenomenon may be attributed to the following reasons. First, in comparison with external free-air explosions, tunnel blasts are performed in interior and confined conditions, which will generate higher intensity of shock waves and in turn cause more damage to nearby residential and industrial structures (Wu et al., 2004b). Second, as stated above, the underground void space created by the tunnel excavation plays an important role in the propagation of blast waves.

Moreover, there also exist interesting and important differences among rock behaviors on the ground (Basarir et al., 2010; Tao et al., 2013). For example, Zhang et al. (2005) have conducted blast tests inside a railway tunnel and measured the ground vibrations at several points. These points were arranged symmetrically on both sides of the tunnel face. It is found that there is a discrepancy between the PPVs of

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http://dx.doi.org/10.1016/j.tust.2017.08.026
Received 14 October 2016; Received in revised form 8 August 2017; Accepted 16 August 2017

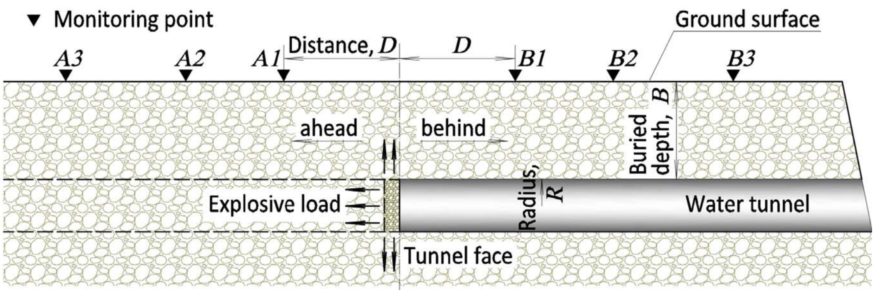

Fig. 1. Configurations of blast tests and ground vibration measurements.

each pair of symmetry points. The PPV of the point behind the tunnel face (see Fig. 1) is generally greater than that of the symmetry point ahead of the face. The ratio between the two PPV values can reach as high as 3.5 (Cai et al., 2015; Yang, 2012). It is the so-called cavity effect or hollow effect and this effect will act up to 40 m on the ground (Yang, 2012). Due to its action, the general attenuation law of ground vibrations does not apply to the cases containing underground blasts. Little reports have been found on this topic, though it is of great interest to experts who are supposed to carry out safety and stability analysis and design of surface structures (Feldgun et al., 2014).

In the present work, the cavity effect of a water tunnel and its influencing factors have been investigated at the construction site of a nuclear power plant in China. The blast vibrations are magnified by this effect when they reach the ground. The problem is that, several building structures are being and have been built on the ground surface, inside which vibration sensitive instruments have been installed. Besides, there are still several tower cranes in operation just above the tunnel (see Fig. 2). The blast vibrations may have adverse effects on these facilities. Their safety and performance are the primary concern. Therefore, the ground vibrations must be controlled under a certain limit in the whole process of tunnel driving. For this purpose, it is essential to investigate the amplifying effect of the tunnel, based on which an accurate prediction of blast vibrations can be made and a vibration control area is thus determined for the sake of ground structures.

2. Descriptions of vibration measurements and cavity effect

The circular shaped water tunnel links the foundation pit of pump house and a water reservoir. It is approximately 1000 m long and 15 m deep, with a radius of 3.5 m. The construction site mainly consists of lightly to moderately weathered granite, no macro cracks or faults running through. The tunnel excavation starts from the rock slope of the foundation pit and advances to the reservoir. At the present stage,

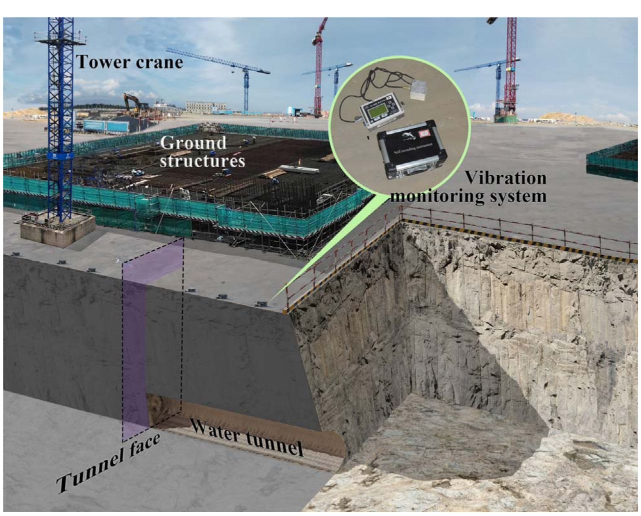

Fig. 2. Underground water tunnel and ground structures near the construction site.

the working face is close to the point right beneath several ground structures and facilities (Fig. 2). Their safety and normal operation are the primary concern and the adverse effect of tunnel blast vibrations deserves great attention.

Blast tests and vibration measurements have been conducted in order to study the propagations and amplifications of vibration waves after they pass through a void space. 3–5 pairs of monitoring points (MP) were placed on the ground surface along the longitudinal axis of the water tunnel, each installed with a set of vibration sensor and data-logging instrument. Here a pair of MP refer to the two symmetry points about the tunnel face, like the ones of B1 and A1, B2 and A2, and so on in Fig. 1. It is obvious that one of the pair (B1, B2, B3) is located behind the tunnel face and the other one (A1, A2, A3), ahead of it. The velocity time histories of all MP were recorded in each blast test by the vibration monitoring system. The amplifications of blast vibrations can thus be analyzed by comparing the monitoring results of each pair of points.

According to the research findings of Tao et al. (2013) and Zhang et al. (2005), an amplifying coefficient of ground vibrations has been introduced here to describe the cavity effects of the water tunnel, which is given by

$$f = \mathrm{PPV}_b/\mathrm{PPV}_a \tag{1}$$

where PPV_b and PPV_a are the PPV values of each pair of symmetry points **b**ehind and **a**head of the tunnel face, respectively.

3. Analysis on the test results of cavity effect

As a demonstration, the velocity time histories of two symmetry points A1 and B1 in Test 1 are presented in Fig. 3(a), for which the PPVs are determined as 3.41 and 6.02 cm/s, respectively. The amplifying coefficient is thus worked out as 1.77 according to Eq. (1). The other f values have been derived by the same method. Table 1 presents all the measurement results of the 9 groups of blast tests, in which Q stands for the explosive charge weight, being in the range of 13–25 kg; D denotes the horizontal distance between either one of the symmetry points and the tunnel face (see Fig. 1). The distribution of cavity effect is taken as the variation of amplifying coefficient with the MP distance along the tunnel axial direction, as is graphically presented in Fig. 4. It is observed that the amplifying coefficient rapidly rises to a peak value of 1.95 at a critical distance of 7 m, meaning that the ground vibrations were nearly doubled due to the action of cavity effect. It must be taken into consideration in the prediction of blast vibrations.

The f-D relation could be fitted to a segmented Gaussian function given by

$$f = 1 + (f_{\max}-1)\mathrm{e}^{-0.5\left(\frac{D-D_{\mathrm{cri}}}{w}\right)^2} \quad \begin{cases} w = w_1 & D \leqslant D_{cri} \\ w = w_2 & D > D_{cri} \end{cases} \tag{2}$$

where $f_{\max}$ is the maximum value of amplifying coefficient f, and D_{cri} denotes the critical distance, being 1.95 and 7 m for the current case, respectively. w is a constant depicting half width information of Gaussian function. A fitting result with 95% confidence is given by

$$f = 1 + 0.95\mathrm{e}^{-0.5\left(\frac{D-7.0}{w}\right)^2} \quad \begin{cases} w = 2.85 & D \leqslant 7.0 \\ w = 7.96 & D > 7.0 \end{cases} \tag{3}$$