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Attenuation of blast vibration in tunneling using a pre-cut discontinuity

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ABSTRACT

A pre-cut discontinuity, similar to the pre-splitting around a tunnel periphery, is introduced to investigate the attenuation of the wave propagation due to tunnel blasting. For this, two empty holes were drilled to support the sawing jigs and a wire sawing machine with embedded industrial diamond wire was used to cut an artificial discontinuity near the initial blasting holes at the tunnel face. The peak particle velocity with/without pre-cut was measured during tunnel blasting and the effect of the pre-cut method was quantitatively accounted for, although, due to limited time and unfavorable field conditions, the cutting depth was not able to reach the initial design depth. Numerical analysis was also performed in order to model the tunnel geometry and blasting procedure. For this, a commercial package called UDEC was used and the accuracy of UDEC was initially proven by an analytical solution of the reflection and transmission of the incident wave. Various parametric studies including sequential detonations were performed and the reduction factor of attenuation with ideal cut-off discontinuity was shown to be 50%. Future work will concentrate on the improvement of the wire sawing machine to reduce the cutting time and three dimensional modeling of the blasting effect will also be performed.

1. Introduction

A high-speed rail tunnel in a remote area is somewhat free from civilian complaints regarding vibration and noise during drill and blast tunneling. However, vibration mitigation is one of the major issues in urban tunneling and quite a few approaches have been tried to reduce the vibration level. Mechanized tunneling or controlled blasting with precise delay times, for example, can be a substitute; even a non-blasting tunneling method such as the use of wedge-type fracturing machines can be considered when the tunnel face is located in a downtown area or near vibration-proof buildings. Furthermore, strict regulations on blast vibration are enforced and the limits are becoming more severe in recent years. Therefore, an efficient way to reduce the vibration level while maintaining construction time as well as cost will be necessary to overcome blast-related issues; a rather simple idea considering wave propagation is introduced in this study, namely a pre-cut method, that is used to reduce the vibration level by cutting certain rock masses before blasting. A field test, together with numerical analysis of the attenuation of the blast vibration, is performed to better understand the wave propagation through the discontinuity. Several parametric studies are also carried out to determine the effects of blasting on nearby areas.

When vibration due to tunnel blasting is of concern, several alternatives can be taken into consideration such as a Tunnel Boring Machine (TBM), a periphery–cutting machine (Hiller, 2011), an abrasive waterjet machine (Oh et al., 2012) and a hydraulic wedge-type fracturing machine, among others. Another possibility to reduce the blast vibration in the tunnel face is to create an artificial discontinuity near the blasting holes and, for this purpose, microwave energy (Henda et al., 2005) or high electric voltage (Vazhov et al., 2012) could be solutions to generate discontinuities within the rock masses. In this regard, Lengauer et al. (2000) showed that a rapid electric pulse induced a temperature rise within a small-sized ceramic material and that this caused a corresponding stress fluctuation. A brittle fracture due to the resulting tensile stress was expected both from the analytical solution (Vojta and Clarke, 1997) and from the three dimensional finite element analysis.

The fractures or discontinuities within a homogeneous medium will change the pattern of wave propagation initiated by rock blasting; a few analytical expressions are available to describe the transmission and reflection of the incident waves (Schoenberg, 1980; Pyrak-Nolte et al., 1990). Specifically, the property of the discontinuity, i.e., the stiffnesses of the rock joint in our case, will change the pattern of wave propagation, and attenuation of the particle velocity will be possible if a discontinuity with reduced stiffnesses is introduced near the tunnel periphery. This is a starting point of the proposed study because the conventional vibration prevention methods such as hydraulic wedge-type fracturing equipment and

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pre-splitting of the tunnel periphery with small amount of charges are rather expensive and time-consuming.

In this study, as a first trial to create a pre-cut within a rock mass, a sawing machine with an industrial diamond wire is introduced. The workability of the sawing machine according to the rock characteristics is another important research field; several attempts have been made to determine the efficiency of the rock cutting mechanism through experimental or numerical approaches. For example, Copur et al. (2011) concluded that the uniaxial compressive/tensile strength of the medium and the specific energy of the chisel-type sawing machine are the major factors to determine the performance of the field operation. Meanwhile, Yasitli et al. (2012) performed three dimensional numerical analysis to determine the performance of a circular sawing machine and established a relationship between advance rate and vertical reactional forces.

In a field test, an artificial discontinuity is created by drilling two boreholes to fit in the sawing jigs and by installing an industrial sawing chain within the boreholes. The location of the cutting line is just above the initial charging holes where the charge concentration is higher than that at the neighboring stoping holes so that the change of vibration level is clearly measured. Since the field experiment has to follow a regular tunneling schedule, the cutting time is required to be as short as possible and, therefore, the pre-cut is generated at the most effective area of the wave propagation, i.e., the upper part of the initial blasting holes. It is clear that, if the whole periphery of the tunnel is splitted by the sawing machine, the mitigation effect will be maximized although the time and cost cannot be neglected anymore. So far, the efficiency of the sawing machine is dependent on the rock strength, and the installation time of the jigs as well as sawing chains.

The analytical solution and numerical prediction model are employed to calibrate the measurement results. Next, a few parametric studies on wave propagation, including various blasting patterns, are undertaken to simulate the measurement results for the particle velocity. For this, a two dimensional distinct element software called UDEC (UDEC, 2006) is mainly used throughout the parametric studies although a finite element based approach (Torano et al., 2006) or a bonded particle model (Resende et al., 2010) can equally be employed. The results show that the peak particle velocity (PPV) before and after the pre-cut does not significantly change, partly because the pre-cut depth was not deep enough to reflect the incident wave and partly because small amounts of charges were used near the area of concern. However, the results of the numerical analysis, proven using appropriate analytical solutions, show that a significant reduction of PPV can be achieved if the ideal conditions are met in the field.

Future work will be concentrated on the improvement of the wire sawing machine; specifically, the cutting efficiency needs to be upgraded so that the total amount of excavation time will not be delayed. For this, a new approach on the sawing method either using electricity or employing high temperature can be considered although development of a rock fracturing method without mechanical power will be a challenge to overcome the current technical shortcomings.

2. Wave propagation across rock discontinuity

It is well known that pre-existing rock discontinuities such as rock joints and faults change the characteristics of propagating waves, and quite a few research works on wave propagation as well as attenuation have been attempted so far. As mentioned in the Introduction, our interest is focused on the attenuated velocity of incident waves and we begin with analytical expressions of the ideal case in the following section. For simplicity, a one-dimensional wave propagation across a discontinuity, based on the assumption of displacement discontinuity, is considered; the corresponding magnitudes of the reflection as well as the transmission coefficient are as follows (Schoenberg, 1980):

$$|T_p(\omega)| = \left|\frac{\frac{2k_p}{Z_p}}{-i\omega + \frac{2k_p}{Z_p}}\right|; \quad |R_p(\omega)| = \left|\frac{i\omega}{-i + \frac{2k_p}{Z_p}}\right| \tag{1}$$

where T_p and R_p are the transmission and reflection coefficient, respectively, and Z_p is the seismic impedance expressed by

$$Z_p = \rho_r C_p \tag{2}$$

with density of rock ρ_r and compressional wave speed C_p. Meanwhile, k_p and ω are the stiffness of the discontinuity and the circular frequency of the incident wave, respectively. It should be noted that the subscript p denotes the compressional wave and can be replaced by sh or sv according to the properties of the incident wave. Slightly different expressions are available when the viscosity at the discontinuity is accounted for Pyrak-Nolte et al. (1990). Eq. (1) shows that, as the stiffness of the discontinuity is increased, T_p approaches 1, i.e., all the energy related to the wave propagation is fully transmitted across the *welded* discontinuity. Meanwhile, if k_p has a negligible value, all the waves are reflected at the discontinuity and the PPV across the discontinuity will be significantly diminished. This is the triggering point of the pre-cut method and, in fact, according to a critical thickness of the pre-cut where k_p becomes zero, the transmission of incident waves is theoretically no longer possible. Further development of the wave mitigation has been mainly focused either on the nonlinear behavior of the discontinuities (Zhao et al., 2008) or on the complex wave forms that result from multiple discontinuities (Zhu et al., 2013). Recent semi-analytical modeling trends have been extensively documented in Perino et al. (2012) in which an equivalent medium model, based on the Voigt model concept, has been compared with other displacement discontinuity models through the use of numerical examples.

Eq. (1) can be used to validate the efficiency of UDEC and, for this, one dimensional simplification of an ideal bar having a through discontinuity is introduced. Proper viscous boundary conditions as well as mesh design based on the wave length of the incident wave are the main issues during the numerical verification; the input wave pulse, either in the form of stress or velocity, should be compatible with the associated boundary conditions (UDEC, 2006). Fig. 1(a) shows a typical verification model using a one dimensional bar that includes a discontinuity. The material properties listed in Table 1 were obtained from field tests; the dynamic properties of the elastic moduli and Poisson's ratio are used in the analysis. In fact, the field tests were undertaken at the tunnel site and the material properties in Table 1 will be extensively used in this study. Modeling of the one dimensional bar can be realized by imposing y-directional constraints shown in Fig. 1 and both ends of the bar are assumed to have the viscous boundary condition for eliminating possible reflection of the waves. Meanwhile, the mesh size is directly related to the accuracy of wave propagation and, in our case, the element size is smaller than one-tenth of the wavelength associated with the input frequency, which is approximately one-hundredth of the bar length.

As can be seen in Fig. 1(b), the numerical prediction using UDEC is in good agreement with the theoretical values in Eq. (1) and similar results have been demonstrated by Zhao et al. (2008) and Zhu et al. (2013), among others. So far, our interest has been confined to the one dimensional simplification of the wave propagation, but if fully jointed rock masses are of concern, the two dimensional verification is possible (Zhu et al., 2013) and various parametric studies on the wave propagation through jointed rock masses have also