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1 FULL TITLE

2 Blast wave induced spatial variation of ground vibration
3 considering field geological conditions

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15 **Keywords:** Blast wave propagation, PPV, Rock-soil interface, depth effect

1. Introduction

Drilling and blasting is one of the most used methods for large-scale excavation in rocks and soils. However, rock blasting can induce many adverse effects, and the typical influence of rock blasting on surrounding environment is illustrated in Fig. 1. Explosion induces ground and structures vibration [1, 2] and annoying noise. When the explosive is detonated, an extremely high pressure pulse from the chemical reaction induced energy is generated which is transmitted into rock mass adjacent to the blast hole, producing a dilatational wave that propagates away from the charge. Stress wave due to blasts may cause damage to the surrounding rock and, furthermore, when the wave reaches a free face or open fissure (non-transmission), it will be reflected and converted into tensile wave, which may produce tensile cracking and spalling if the tensile strength of the rock is exceeded by the tensile wave [3, 4]. Also due to the fact that some rock blasting projects are close to the inhabitant area, the surrounding buildings may be damaged due to blasting induced ground vibration if large strength wave propagates in the soil foundation and shock wave propagating through the air [5]. Disruption of some business activities, possible structural damage and emotional-traumatized residents are the problems that need to be addressed [2, 6]. Therefore, the influence of ground vibrations on surrounding buildings, sensitive devices and people in urban environments is a significant consideration in obtaining project approvals.

The magnitude of ground vibrations, often measured by the peak particle velocity (PPV), which generally has the form

$$PPV = H(D/\sqrt{Q})^{-n} \quad (1)$$

where H and n are fitting parameters representing the intercept on the log-log plot and the attenuation coefficient, respectively. D (m) and Q (kg) are the standoff distance to the blast hole and the maximum charge weight per delay, respectively. PPV is highly dependent on the blast design, the ground geological condition, e.g., heterogeneity, discontinuities, characteristics of wave propagation, material's response to dynamic wave propagation, and the distance from the blasting location [2, 7]. Geological conditions not

only affect the properties of rock mass significantly, but also determine the seismic responses [7]. Therefore, a proper predicting and monitoring scheme has to be considered and implemented during the blasting [2]. The research of blasting and its associated principles are especially significant for open field blasting, and a proper blast design can maximize the blast efficiency while minimize the induced adverse effects, thereby reducing the potential damage to surrounding buildings and minimizing the social and psychological impact to neighbourhood residents.

Over the years, many studies have been carried out, based on field tests [1, 7-16, 44], numerical simulations [4, 5, 16-35], and theoretical analysis [36]. Nevertheless, there is still a lack of comprehensive study on the geological effect on the blast wave propagation. While investigation of rock blasting and its effects by scaled or full size experiment is very expensive and time-consuming, the numerical method derived from rationale mechanical principles and validated against experimental data provides a promising approach to reveal blast induced ground vibration, given the rapid development of both numerical techniques and powerful personal computers.

The objective of the paper is to investigate the PPV attenuation in a mixed rock-soil field with special attention to the role of rock-soil interface on the blast wave propagation. The PPV attenuation along both horizontal and vertical directions is considered. Firstly, a rock blasting field test is described. A numerical model by finite difference method (FDM) considering the detail geological condition of the field test site is established to simulate the field test. After that, to demonstrate the effect of the geological condition on the wave propagation, a homogeneous numerical model with only rock material is assembled and simulated. The comparison revealed that the significance of the rock-soil interface on the wave propagation is not negligible. In addition, a parametric study based on various settings of the rock-soil model is performed. ~~At last, as an example, rock model with a circular tunnel, is carried out to demonstrate the importance of PPV field distribution to the engineering practices.~~

2. The field test

To investigate the blast wave propagation in the ground, an open field rock blasting test was conducted at a location in the western part of Singapore. The blast field had 60 blast holes which were 12 m in depth with 4 m stemming length. The hole spacing was 1.8 m. The detail bird-view of the blast holes is shown in Fig. 2. The charging weight of each hole was 30 kg. Since two holes were detonated in each delay, 60 kg ammonium nitrate/fuel oil (ANFO) charge per delay was actually applied. The on-site measured PPVs are listed in Table 1. From the location of the blasting area and the monitoring points, the geological profile between the blasting area and the monitoring points can be interpolated from the geological investigation report and presented in Fig. 3. The dimensions of the starting location, interface length and interface depth in Fig. 3 are 100 m, 100 m and 14 m, respectively.

The testing site is in Bukit Timah formation with residual soil covered on the top of Bukit Timah granite. The Bukit Timah granite is mainly an acidic igneous rock formed during the Triassic period [40]. The residual soil is from the weathering of the Bukit Timah granite due to chemical decomposition under the humid tropical climate [41]. For the residual soils, the total density ranges from 1600 to 2000 kg/m³ [40] and the undrained Young's modulus ranges from 1 to 100 MPa [42]. For the Bukit Timah granite, the total density and the Young's modulus are in the ranges of 2140 to 2660 kg/m³ and 5.4 to 65 GPa, respectively [43]. The properties of the residual soil and the Bukit Timah granite used in the simulations are listed in Table 2.

3. Numerical simulation procedures

In the field blasting test, since two holes are detonated simultaneously, the two holes may be simply replaced by one equivalent hole in the 2-dimensional Finite Difference Method (FDM) modelling. Based on the amount of charge per delay and the blast hole depth, the radius of the equivalent single blast hole may be calculated as:

$$r = \sqrt{\frac{Q}{h\pi\rho_e}} \quad (2)$$

where Q is the charge per delay (60 kg), h is the ANFO charging length (8 m), ρ_e is the ANFO charging density (820 kg/m³). Taking all the parameters into Eq. (2), the equivalent blast hole radius is obtained to be 54 mm.

In order to calculate the pressure on the blast hole wall, ANFO velocity of detonation (VOD) is needed. Sources and Vitello (2004) [37] conducted experiments on ANFO explosion. The obtained experimental relationship between the radius of cylindrical ANFO and VOD is shown in Fig. 4. The fitting curve for the relationship is:

$$VOD = -0.1514r_e^2 + 44.272r_e + 874.74 \quad (3)$$

where r_e is the radius of ANFO. Thus, the VOD for ANFO with radius of 54 mm is 2823 m/s. Since it is fully coupled between the blast hole and the charging ANFO in the field blasting test, i.e., there is no gap between the explosive and the wall of the blast hole, ANFO explosion pressure acting on the blast hole wall can be calculated as [38]:

$$P_e = \frac{\rho_e \times VOD^2 r_c^{2\gamma}}{8} \quad (4)$$

where r_c is the coupling ratio (=explosive diameter/blast hole diameter), γ is the adiabatic exponent, which is usually adopted to be 1.5 [3]. Therefore, the blast hole wall peak pressure is 816.92 MPa. It is noted that in Eq. (4), the pressure is the peak pressure on the wall of the blast hole. In a typical pressure-time history on the wall of the blast hole, there are two main parts, i.e., rise and decay parts. The rise time is very short and the decay time is relatively longer. In this paper, the blast wall pressure evolution during the blasting is assigned to follow the optimized pressure-time profile by Saharan and Mitri (2008) [38] using the peak pressure calculated in Eq. (4). Considering the charging coupling ratio and the fact that ANFO is non-ideal explosive, the evolution is adopted as

shown in Fig. 5. It can be seen that the pressure rise time is 0.1 ms, and it takes 0.15 ms to drop the blast hole wall pressure to 10% of the peak pressure. And it takes 0.25 ms to further decline to 1% of the peak pressure.

The numerical model built is as shown in Fig.3, with the overall dimension of 125×400 m². The technique of the mesh size selection used in reference [4] is followed: for accurate representation of wave transmission through a model, the spatial mesh size must be smaller than approximately one-tenth to one-eighth of the wavelength associated with the highest frequency component that contains appreciable energy. The left, right and bottom boundaries of the model are set as viscous boundaries. The pressure history presented in Fig. 5 is applied on the left boundary as indicated in Fig. 3. The PPVs at the locations which are the same as the monitoring points in the field test are recorded to calibrate the model. In addition, some selected locations along horizontal directions (i.e., $x = 32, 64, 128$ and 256 m) at various depths (i.e., $y = 5, 10, 15, 20$ and 25 m) of the model are investigated as well.

4. Simulation results

The material properties used in the simulations are tabulated in Table 2 based on the site investigation data and some published literature. Since the objective of the paper is to investigate the ground vibration attenuation law, elastic model is used in the simulations. The model is calibrated by comparing the PPVs from the numerical simulations and the field monitoring points as shown in Table 1. Natural dynamic system contains some degree of damping of the vibration energy partly due to energy loss from internal friction and interface slippage; otherwise, the system would oscillate indefinitely when subjected to driving forces [39]. The calibration parameter in this simulation is the damping ratio. The damping scheme used in the simulation is local damping, where a constant is used for the entire model (both soil and rock) in the mixed rock-soil model to apply a velocity-proportional damping force to each node. Therefore, the damping ratio used in the simulation is an equivalent value. The local damping ratio calibrated is 0.03 in the mixed rock-soil model.

The simulated ground surface PPV attenuation in the rock-soil model is shown in Fig. 6(a). The vertical black line in each figure of Fig. 6 indicates the scaled distance of the interface at the ground surface. It can be seen that a good agreement between the simulated PPVs and the field monitoring ones are obtained. The numerical PPV attenuation law along the ground surface can be fitted by the following equation based on the four points at $x=32, 64, 128$, and 256 m:

$$PPV = 6553976SD^{-4.06} \text{ (mm/s)} \quad (5)$$

with the coefficient of determination (R^2) being 0.94. In the equation, SD is the scaled distance and expressed as $(D/\sqrt{Q})$ with D (m) the distance between the blast hole and the monitoring point, and Q (kg) the charge per delay.

To investigate the significance of the rock-soil interface in the rock blasting site, a revised model is constructed where the dimension is identical to the mixed rock-soil model, but the interface is removed and the whole problem domain contains only rock material (Fig. 6b), with all the material parameters the same as the mixed rock-soil model. However, the local damping ratio used in the rock-only model is 0.01 after considering the fact that the real damping of hard rock is smaller than that in the soil. The simulated relationship between SD and PPV is plotted in Fig. 6(a) and the fitting curve can be expressed as:

$$PPV = 42236SD^{-1.137} \text{ (mm/s)} \quad (6)$$

with the coefficient of determination (R^2) 0.98. It is shown in Fig. 6(a) that the interface plays a significant role in the blast wave propagation along the ground surface, in terms of both PPV value and the attenuation trend. The PPV after the interface in the mixed rock-soil model is declined drastically so that the PPV is lower than that in the rock-only model after the interface, although the PPV in the mixed rock-soil model is initially larger than those in the rock-only model before the interface. Therefore, the blast wave is attenuated faster in the mixed rock-soil model compared to the rock-only model.

More ground surface PPVs numerically monitored in the two models containing the near field (i.e., $x = 2, 4, 8$ and 16 m) and far field ($x > 256$ m) locations are plotted in Fig. 6(b). It is noted that, the PPV initially increases in the near field before it decreases in both models. This can be accounted for by the expanding phenomenon of the blast wave propagation in a cylindrical charging manner. The cylindrical explosive is buried 4 m below the ground surface with centre at the depth of 8 m. The explosion-induced blast wave reaches the ground surface with the largest PPV at a location which is at a certain distance away from the blast hole. After the interface, the PPV in the mixed rock-soil model is decreased abruptly until 256 m standoff distance, followed by gently descent in the far field (i.e., $x > 256$ m).

Fig. 7 presents the blast wave attenuation for the mixed rock-soil model and rock-only model at various depths. In the following discussions, the y -coordinate starts at the depth of 25 m, i.e., $y = 25$ m indicates the ground surface. It can be seen that the PPV attenuates at different rates at different depths in both models. By curve fitting the PPV attenuation for different depths in Fig. 7 (i.e., $y = 20, 10$, and 5 m) and $y = 25$ and 15 m, the parameters of H and n in Eq. (1) can be found and plotted in Fig. 8. It can be seen that generally the parameters H and n have similar trend with the depth in the mixed rock-soil model, i.e., decrease with increase of depth. However, the H value is less sensitive to the depth in rock-only model. The n value overall increases with the depth in the rock-only model. In other words, the wave attenuates faster in deeper level. The H value in the mixed model is much larger than it in the rock-only model, especially when the depth = $0, 5$, and 10 m.

To show the significance of charging location and the depth effect, the near field PPVs are also monitored (i.e., $x = 2, 4, 8$, and 16 m). Fig. 9 presents the numerically monitored PPV evolution along the vertical orientation at different standoff distances from the blast hole. It manifests that the evolution of PPV along the vertical direction is extremely dissimilar in the two models, especially for large standoff distance. It is found that the PPV in the rock-only model is not necessarily larger than the mixed rock-soil model if the depth is large. Taking the PPV at $y = 5$ m for example, the PPV in the mixed

model is about 30 times that in the rock-only model when the standoff distance is 2 m. However, the PPV in the mixed rock-soil model increases to around 1747 times that in the rock-only model when the standoff distance is 128 m before it decreases to around 704 when the standoff distance is 256 m. More ratios of PPV for the mixed rock-soil model to rock-only model can be found in Table 3.

The largest PPV values are detected at the location close to the explosive for both models (Fig. 9a, d). Especially, for the standoff distance of $x = 2, 4, 8$ and 16 m, there is a dramatic increase of PPV between $y = 10$ and 25 m. This is because the location of the ANFO is between $y = 13$ and $y = 21$ m. However, the difference between the two simulation results is that the PPV in the mixed rock-soil model is higher for the depth larger than 15 m in large standoff distance (i.e., $x > 16$ m). Specifically, for the ground surface, the PPV before the interface in the mixed rock-soil model is larger than that in the rock-only model. For the depths of $5, 10$ and 15 m, the PPV in the mixed rock-soil model is larger than that in the rock only model if the standoff distance is smaller than 64 m. However, the PPV at the depth of 20 m always has larger value in the mixed rock-soil model.

5. Conclusions

This paper investigated the influence of rock-soil interface on the blast wave propagation in the mixed rock-soil ground. As a comparison, a similar model but with only rock was simulated under the same boundary conditions. During the simulation, the PPV of monitoring points along horizontal and vertical direction were recorded. The simulation results revealed the significance of the rock-soil interface on the rock blast wave attenuation. A depth effect in PPV attenuation in the two models was also observed. ~~To investigate the configuration effect of the rock-soil interface on blast wave propagation, the interface starting location, depth and length are, respectively, studied. To demonstrate the importance of the study, an example—a tunnel buried at various depths in rock mass was analyzed.~~ The findings indicate that the ground surface PPV may not be

enough to assess the safety of the underground structures under rock blasting vibration without taking geological conditions into consideration.

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Fig. 1. A sketch of the typical impact of rock blasting to neighbourhood.

Fig. 2. The bird-view of the blast holes group (the dash line indicates the explosion excavation contour).

Fig. 3. Illustration of the field and numerical rock blasting profile (non-scaled).

Fig. 4. Experimental relationship between velocity of detonation (VOD) and ANFO radius [37].

Fig. 5. The blast hole wall pressure-time evolution.

Fig. 6. Simulated ground surface PPV attenuation law.

Fig. 7. The PPV attenuation at different depth level (a) mixed rock-soil model (b) rock-only model.

Fig. 8. The fitted H and n with depth for the two models (scaled depth equals to the ratio of charging centre depth to the y coordinate of the measurement level).

Fig. 9. PPV distribution of the monitoring points in the numerical simulations: (a to c) the mixed rock-soil model and (d to f) the rock-only model.

Fig. 10. Spatial distribution of PPV ratio of the mixed rock-soil model to the rock-only model.

Table 1 Ground vibration monitoring data.

Table 2 Material parameters used in the simulations.

Table 3 Ratio of PPV for the mixed rock-soil model to rock-only model.

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Fig. 6. The simulated ground surface PPV attenuation (a) without near and far field PPV and (b) with near field PPV (the vertical black line in each figure indicates the scaled distance of the interface at ground surface).

Fig. 7. The simulated PPV attenuation along horizontal direction at various depth levels: (a) mixed rock-soil model, and (b) rock-only model.

Fig. 8. The fitted H and n with depth for the two models.

Fig. 9. The simulated PPV distribution along vertical direction at various standoff distance: (a to c) mixed rock-soil model, and (d to f) rock-only model.

Table 1

Ground vibration monitoring data.

Monitoring location	VM1	VM2	VM3	VM4	VM5
Distance (m)	265	275	295	320	370
Measured PPV (mm/s)	3.20	2.50	2.44	2.13	1.89

Table 2

Material parameters used in the simulations.

Material	Rock	Soil
Young's modulus (MPa)	64×10^3	20
Poisson's ratio	0.16	0.3
Density (kg/m ³)	2650	1800

Table 3

Ratio of PPV for the mixed rock-soil model to rock-only model.

Ratio		y (m)				
		25	20	15	10	5
x (m)	2	2.28	1.06	1.68	2.81	30.00
	4	1.70	1.95	1.96	1.79	15.59
	8	1.58	1.66	1.67	1.78	14.44
	16	1.45	1.74	1.67	1.55	56.924
	32	1.34	1.34	1.33	1.41	386.674
	64	1.21	0.93	0.93	0.95	1363.81
	128	0.02	0.55	0.62	0.63	1747.01
	256	0.01	0.004	0.006	0.20	704.30