JME

Journal of Mining & Environment,
Vol.7, No.2, 2016, 251-259.

Numerical analysis of energy transmission through discontinuities and fillings in Kangir Dam

A. Siamaki[1] and H. Bakhshandeh Amnieh[2*]

1. Department of Mining and Metallurgical Engineering, Amirkabir University of Technology, Tehran, Iran
2. School of Mining Engineering, College of Engineering, University of Tehran, Tehran, Iran

Received 16 September 2015; received in revised form 30 December 2015; accepted 3 January 2016
**Corresponding author: hbakhshandeh@ut.ac.ir (H. Bakhshandeh Amnieh).*

Abstract

A considerable amount of energy is released in the form of shock wave from explosive charge detonation. Shock wave energy is responsible for the creation of crushing and fracture zone around the blast hole. The rest of the shock wave energy is transferred to rock mass as ground vibration. Ground vibration is conveyed to the adjacent structures by body and surface waves. Geological structures like faults, fractures, and fillings play important roles in the wave attenuation. Studying the mechanism of ground wave propagation from blasts gives a better understanding about the stress wave transmission and its effect on the near structures. In this research work, the stress wave transmissions from discontinuities and fillings were evaluated using a field measurement and a Universal Distinct Element Code (UDEC). A single-hole blast was conducted in the Kangir dam, and the resulting vibrations were measured in many points before and after the faults. Numerical simulation shows the effects of geo-mechanical properties of fillings on the reflection and refraction rate of the stress wave. There are more energy reflections in the rock boundaries and soil fillings, and more energy is absorbed by soil fillings compared with rock fillings. Furthermore, there is a close correlation between the ground vibration records for the Kangir dam and the numerical results. The maximum relative error between the actual records and the simulated ones was found to be 18.5%, which shows the UDEC ability for the prediction of blast vibrations.

Keywords: *Peak Particle Velocity, Discontinuity, Filling, Attenuation, Blasting.*

1. Introduction

Blast-induced shock wave contains a sufficient amount of energy, which is transmitted to the rock, causing crushing and fracture zones around the bore hole. Then expanded gas flows through radial fractures caused by the shock wave, and cause more fragmentation in the rock mass. Since the compressive energy of shock wave is more than the dynamic compressive strength of the rock, a crush zone of about 2-4 times the hole diameter is created around the hole. The stress wave energy attenuates rapidly, and the wave energy is decreased. Therefore, radial fractures are developed in the rock due to the tangential stress energy of the wave. Finally, the stress wave is transferred through the rock and coveys energy to the surrounding structures via body and surface waves. Geometrical and material damping cause a decrease in the wave amplitude and absorbance of the wave by the rock as strain energy. In addition, discontinuities act as dampers and change the energy flux. Discontinuities in the fractured domains have an important effect on wave propagation in the rock. Stress waves experience more attenuation in the fractured rock than the continuum domain due to wave reflection, wave refraction, and energy dissipation in the boundaries of discontinuities. These boundaries filter the high frequencies of pulses and reduce the wave amplitude [1].

Nowadays, single-hole blasting has been increased in the mines and construction projects because it gives a good vision about the wave propagation, attenuation, and dominant frequencies. A single-hole ground vibration record helps blasters to design a pattern with minimum blast vibration. Joshi et al. (2013) used single-hole blasting to measure blast-induced vibration, and therefore, resonance frequency of pit wall. They adjusted the blasting pattern with electric detonators to gain higher frequencies than the pit wall resonance frequency [2]. Blair (2015) assessed the influence of blasting on the bench slope damage by measurement of single-hole blasts. He simulated the blasting process using the Heelan radian model. Based on the simulation and measurement results, the top-primed charge induced more damage to the rock rather than the base-primed charge [3].

Pyrak-Nolte studied the laboratorial experiments carried out on the seismic waves passing through natural fractures, and obtained comprehensive results for the effects of fractures under elastic and viscous conditions on the seismic waves [4]. Chen and Zhao studied the fracture effect on rock mass and ability of discrete element code (UDEC) in the blasting wave propagation simulation. They assumed dry fractures, and inspected the effects of fracture spacing and their stiffness on the wave propagation [5]. Cai and Zhao examined the effect of parallel discontinuities on wave attenuation in a rock. Damping occured due to reflection and refraction of waves in the fractures, and since the problem was considered to be linear, the reflected and refracted waves showed the same frequencies [6]. The equations obtained from analytical solutions for the determination of reflection and refraction coefficients were similar to those obtained by Pyrak-Nolte and Schoenberg [4, 6, 7]. Zhao et al. considered compressive wave propagation through parallel discontinuities with the linear deformation, and evaluated the wave amplitude and shape for the reflection and refraction waves for different fracture stiffness values [8]. Lei et al. presented a new model for prediction of the wave energy transmission rate and superposition of the reflected and refracted waves between two cracks. For this purpose, they used UDEC to model blasting in the underground storage surrounded by the fractured rocks. They conducted a test in a quarry mine, and recorded the peak particle velocities to validate the results of the numerical modeling [9]. Wang et al. studied the effects of blasting on the sensitive underground storages numerically, and analyzed the compressive wave propagation in rock domains with discontinuities, fillings, and separations. Since their purpose was to examine the blast effects on the sensitive military structures and their protection against blasting, instead of using a filling, they used a solid steel plate. The results obtained showed the effects of thickness, elastic modulus, and plate density on the blasting energy transmission [10].

Ma and An (2008) simulated the process of blasting and the resulting fractures. J-H (Johnson-Holmquist) used the material model for modeling a rock. The crack propagation and spall formation in the rock boundaries in smooth blasting were simulated, and the results obtained showed a major crack formation in the rock interface. Many other researchers simulated single-hole blasts but the importance of rock faults with different material fillings have been less considered by the researchers [11].

The aim of this work is to examine the blast energy transmission from discontinuities and fillings. A single hole was blasted in the Kangir dam, and its PPV records before and after faults were measured. The simulation results showed the great effect of discontinuities on wave attenuation.

2. The Kangir Dam

The Kangir dam is located 115 km SE of Kermanshah city, 70 km NE of Ilam city, and 25 km NW of Ivan city. This dam was constructed in order to provide water for irrigation of the agricultural lands in the Zarneh and Somar regions. This Dam is located in the crushed zone of Zagros Mountains in the west and SW of Iran plateau, and is limited by the Minab fault in the SE.

A single hole was blasted in the Gachsaran formation, which consists of Asmari limestone. Figure 1 shows the fault filling with a thickness of 20 cm. Table 1 shows the geo-mechanical characteristics of rock mass regarding the field tests obtained by drilling to a depth of 25 m.

3. Single-hole blasting in Kangir Dam

A single hole of 64 mm diameter was drilled to a depth of 3 m. ANFO was used as the charge with a density of 2.7 kg/m and a dynamite cartridge as a primer. The charge and hole properties are shown in the Table 2.

The peak particle velocity (PPV) of blasting was recorded at 4 points before and after the faults using the 3-axial geophones model PG-2002 (Figure 2). Geophones recorded particle velocity *vs.* time, and the maximum vibration value was determined as PPV. The information of one sensor was missed out, and just the blast vibration information for 3 sensors was recorded (Table 3).

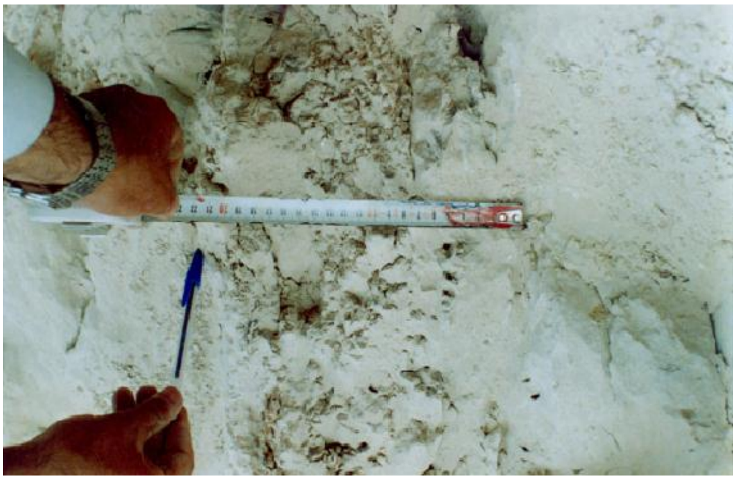


Figure 1. Fault thickness in Kangir Dam, Iran.

Table 1. Geo-technical properties of rock mass in Kangir Dam, Iran.

Density	ρ_r	gr/cm^3	2.61
Elastic Modulus	E_r	GPa	19.8
Poison	υ	-	0.17
Bulk Modulus	K	GPa	30.23
Shear Modulus	G	GPa	24.53
UCS	σ_c	GPa	73.1
Dynamic Elastic Modulus	E_d	GPa	58.04
Compressive Wave Velocity	V_P	m/s	4013
Shear Wave Velocity	V_s	m/s	3069

Table 2. Explosive and hole properties.

ANFO Density	ρ_r	gr/cm^3	0.85
Detonation Velocity	VOD	m/s	3200
Hole Radius	b	mm	32
Hole Depth	h	m	3
Stemming	T	m	2
Charge Density	M	Kg/m	2.7
Charge Volume per Meter	V_e	cm^3/m	3216.9

Table 3. Vibration records from single-hole blast, Kangir Dam, Iran.

Record No.	**Distance from Blast Point (m)**	**PPV (mm/s)**	
1	18.87	Vertical	1.76
		Radial	2.55
		Tangential	4.32
2	23.81	Vertical	1.33
		Radial	2.7
		Tangential	3.8
3	32.19	Vertical	0.483
		Radial	0.527
		Tangential	0.022

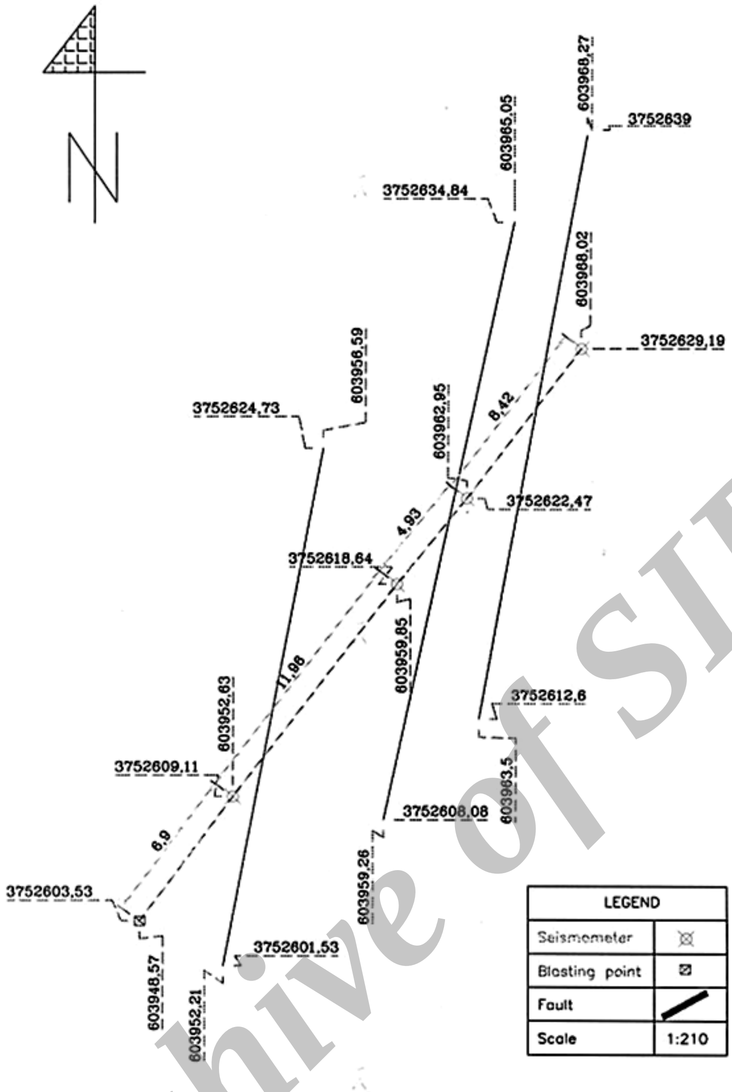


Figure 2. Blasting and geophone locations relating to faults.

4. Numerical model of single-hole blasting

What makes a discrete element method (DEM) an appropriate tool for simulation in discontinum domains is its helps to analyze block movements relating to each other and the contact mechanism. Furthermore, DEM codes like UDEC are very strong tools for solving dynamic problems with little simulation time, usually 1 ms to 1 s, like blasting.

A model with dimension of 42 m * 21 m was designed for simulation of a single-hole blast in the Kangir dam. The model contained 3 inclined faults having 20 cm fillings, as shown in Figure 3. The middle fault was filled by rock material, and the other two faults were filled by soil (crushed and altered rock).

Model discretization is an important step in solving the static and dynamic problems, which have direct effects on the numerical accuracy. The mesh size is a function of the dominant wave frequency and wave velocity in dynamic models. Kuhlmeyer and Lysmer (1973) stated that for logical and accurate modeling of wave propagation via numerical cods, element size for discretization of domain should obey the following rule [12]:

$$\frac{\lambda}{10} \leq \Delta l \leq \frac{\lambda}{8} \qquad (1)$$

where λ is the wavelength with the maximum frequency. In the current modeling, the element size was chosen to be 16 cm for the uniformity of discretization.

To avoid wave reflection from the model boundaries, free field boundary was used for the lateral boundaries, and the viscos boundaries were used for the up and down boundaries.

Furthermore, velocity was fixed on the lateral boundaries in the x direction and on the up and down boundaries in the y direction.

Blasting consisted of two stages, shock wave and gas flow. As the explosive is detonated, the shock wave impacts the rock and makes crush zone, fracture zone, and conveys blasting energy in the elastic manner to the rock. In the second stage, the gas from blasting is extended rapidly and flow to the fractures, which causes more complex fracture networks and also more fragmentation. Since this work concerned wave propagation in a discontinuum domain, just stage one was considered in the modeling. The shock wave intensity had to be applied by a pulse to the borehole wall in the UDEC modeling. The pulse intensity was obtained using the following equation [13]:

$$P_m = 1.62 \times (\rho_e \times VOD^2) \times (\frac{\rho_r \times V_P}{\rho_e \times VOD})^{0.25} \quad (2)$$

where ρ_e is the explosive density (gr/cm^3), VOD is the velocity of detonation (km/s), ρ_r is the rock density (gr/cm^3), V_p is the compressive wave velocity in the rock (km/s), and P_m is the maximum dynamic pressure on the hole walls ($Kbar$). With regards to the information in Tables 1 and 2 and using relation 2, the detonation pressure was about 2.015 Gpa for the ANFO charge.

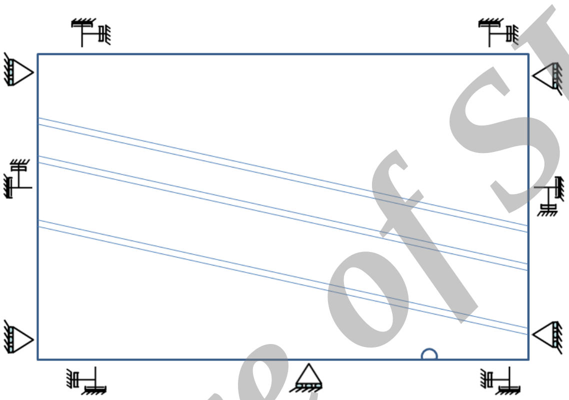


Figure 3. Geometrical modeling and boundary conditions.

5. Single-hole blast simulation

Single-hole blast simulation provides a better understanding about the vibration wave propagation from blasting and effects of discontinuities on the wave attenuation. Blast-induced shock wave was applied as a triangular pulse with a peak pressure of 2.015 Gpa and a rise time of 10 ms.

Figure 4-a shows the wave generation and its propagation 0.811 ms after detonation. The compressive wave propagated with a sphere shape front to fault 1. 1.19 ms after detonation, the wave front arrived fault 1. During this collision, a considerable amount of wave energy was absorbed and reflected in the fault boundary. Presence of soil filling with a lower impedance than rock caused a significant wave attenuation in the path of fault 1. As shown in Figure 4-b, a fraction of the incident wave transmitted through the fault. The reflected wave caused spalling in the fault and rock interface. Wave propagation continued till it arrived fault 2. The collision occurred 3.72 ms after blasting. Since fault 2 was filled with the rock, it provided a good conductivity between the two sides of the fault. Therefore, very limited reflection happened in the rock and fault interface. Finally, the wave reached fault 3 5.11 ms after blasting.

5.1. Peak particle velocity (PPV) variation during propagation

According to Figure 5-a, The PPV value 6.9 m away from the blast point was 37 mm/s. There was an increase in the PPV value at this point due to wave reflection from fault 1 and superposition. Point two 18.86 m from the blasting point experienced a PPV value of 2.8 mm/s, showing a severe energy absorption and wave intensity reduction in fault 1 (Figure 5- b).

As shown in Figure 5-c, the PPV value at point 3 between faults 2 and wave and 23.79 m away from the blasting point was 3.1 mm/s. Regarding the PPV value at this point, the wave amplitude decreased from point 2 to point 3 due to energy absorption in fault 2. However, the PPV amplitude increased rapidly because of superposition of the incident wave and the reflected wave from fault 3.

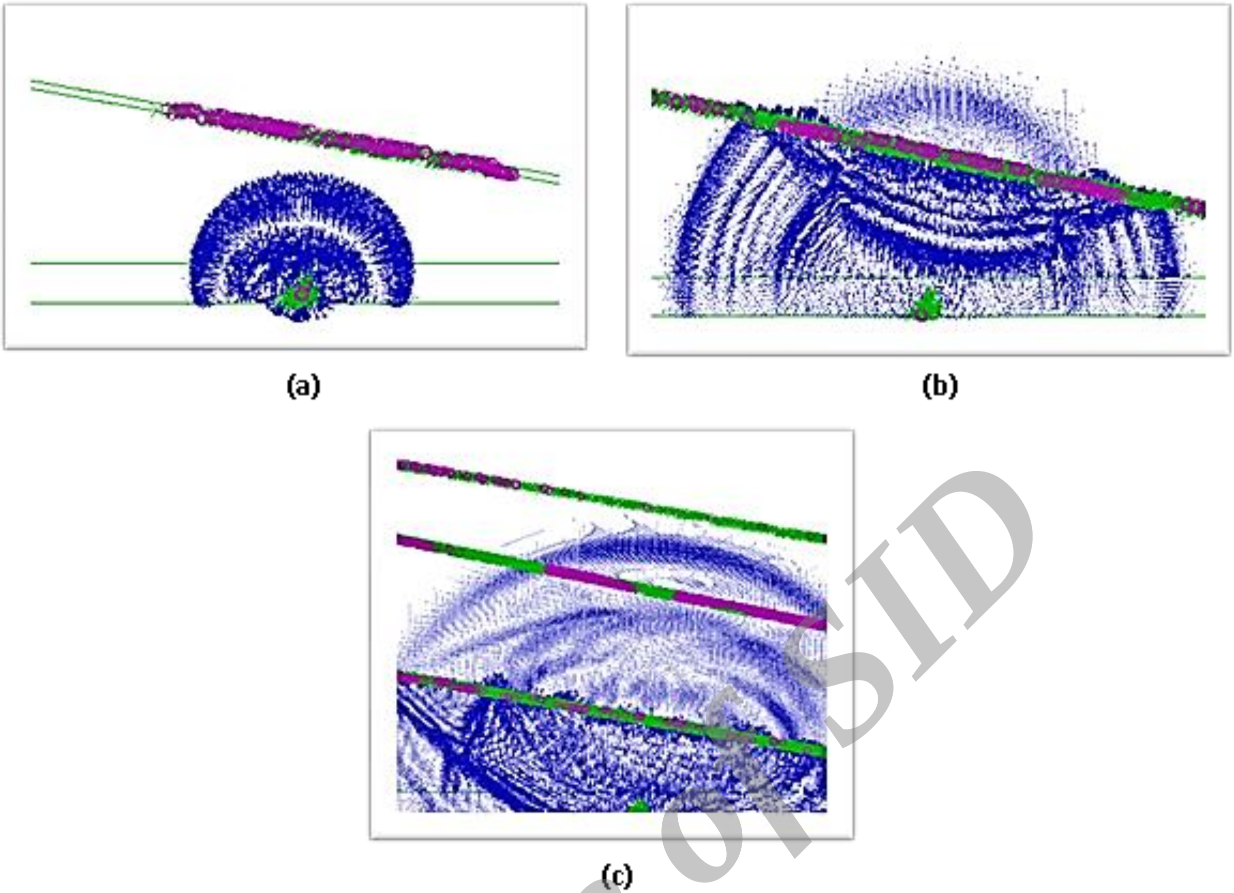


Figure 4. Wave propagation: a). 0.811 ms after blasting, b). 2.47 ms after blasting and c). 5.11 ms after blasting.

Finally, 5.21 ms after detonation, the wave front was achieved in fault 3. In this region, the fault was filled by very loose materials with low impedance, which caused high levels of wave reflection and absorption. Figure 6 shows the transmitted wave from fault 3 and the repeated reflections between faults 2 and 3, between faults 1 and 2, and from fault 1, showing the impact of discontinuities on the wave propagation.

After wave passing from fault 3, PPV changes at point 4, 32.21 m away from blast point, was recorded, and the maximum PPV was obtained to be 0.61 mm/s. Figure 7 shows the PPV record at point 4, and regarding this figure, there was a high energy absorption in fault 3.

Comparison of the measured PPV and numerical simulation results shows the importance of the numerical methods in the simulation of complex processes like blasting. Table 4 compares the results of the numerical model with the records in the Kangir dam. The results obtained showed that the maximum relative errors between the actual records and the simulated ones were less than 20%. The difference between the values is due to the geological and geo-mechanical heterogeneities in this area and the complexities of wave propagation and attenuation.

Figure 8 shows the plastic yielded area around the blast hole. This plastic zone shows a crack propagation around the blasting hole with 4 major cracks for the semicircle hole. The maximum length of these cracks was 70 cm, which had a good correlation with the field measurement results (76 cm).

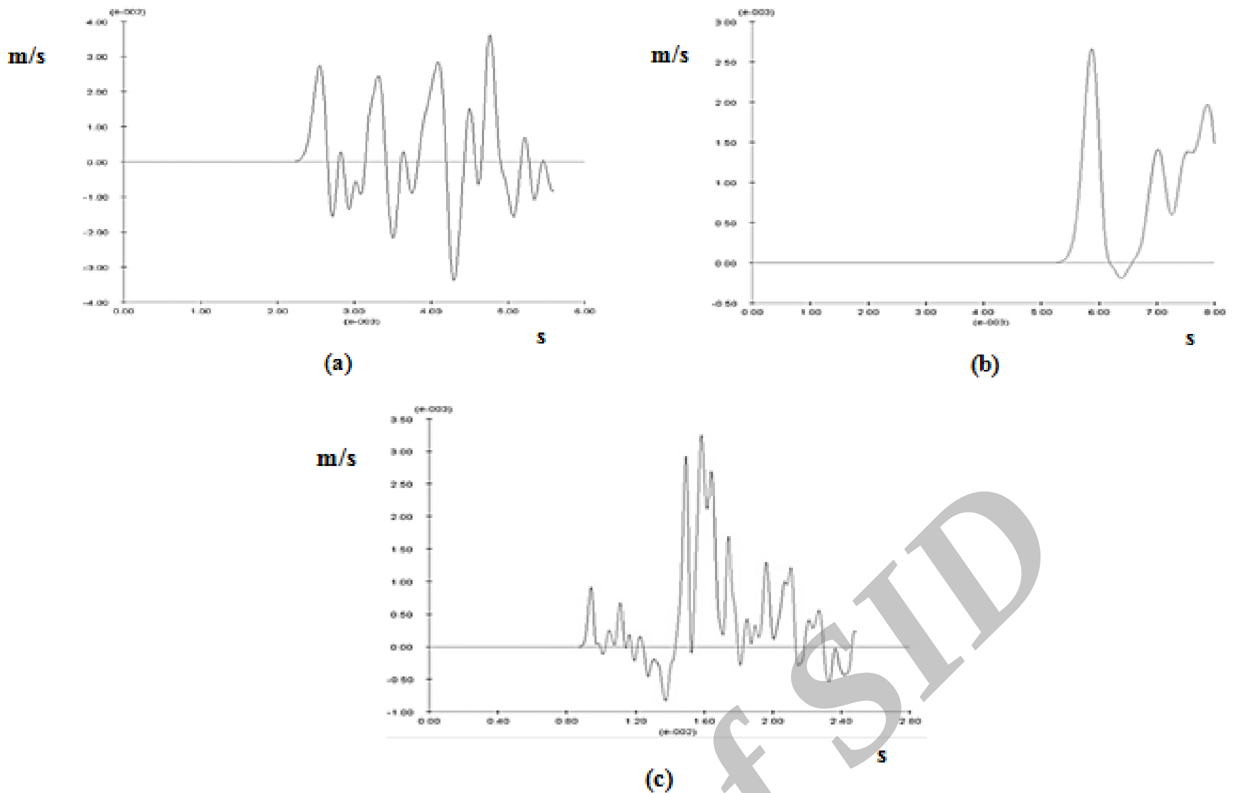


Figure 5. PPV changes via Time: a). 6.9 m away from blasting, b). 18.86 m away from blasting and c). 23.79 m away from blasting.

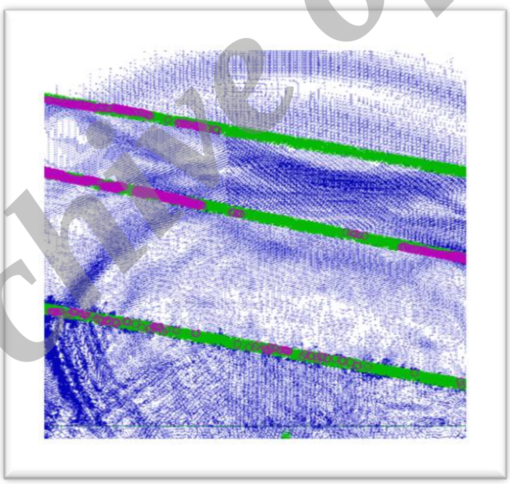


Figure 6. Wave reflection and refraction 6.87 ms after blasting.

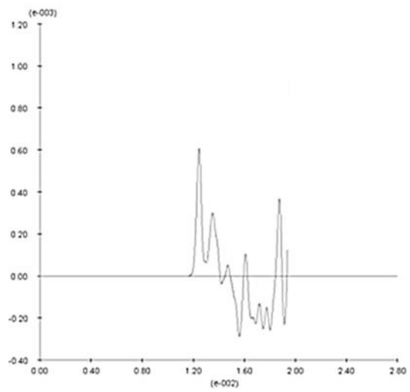
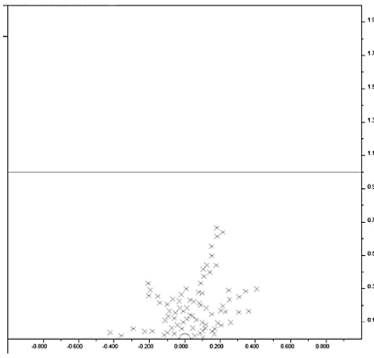


Figure 7. PPV changes in point 4.

Table 4. Comparison between blasting records and numerical simulation ones.

Record No.	Blasting Record (mm/s)	UDEC Result (mm/s)	Relative Error (%)
1	2.55	2.8	9.8
2	2.7	3.2	18.5
3	0.527	0.610	15.7



(a)

(b)

Figure 8. a). Fracture propagation around hole in UDEC simulation and b). fracture propagation around hole in Kangir Dam, Iran.

6. Conclusions

Blasting, as a main operation in construction projects, may have an effect on the adjacent structures and buildings. Therefore, evaluation of blast-induced vibrations helps to assess the intensity of ground vibrations due to blasting and control its effects. Discontinuities in the rock structures play an important role in the wave filtration and attenuation. In this research work, a single-hole blast was fired in the Kangir dam, and the blast-induced vibration was measured before and after the faults near the blast hole. The process of single-hole blasting and ground vibration propagation was simulated by UDEC. The simulation results gave a better understanding about the importance of discontinuities in the wave energy absorption. The results obtained showed that the faults with a loose filling like soil attenuated a significant portion of the wave amplitude but the faults with rock material fillings conveyed ground vibration wave with minimal attenuation. In addition, as the simulation results showed, the presence of discontinuities and wave reflection caused spalling and weakness in the interface of the rock and filling and increased the PPV of the points before fault because of wave superposition. The good correlation between the field measurement and PPV simulation results indicates the ability of UDEC in blast simulation. The maximum relative error between the measured PPV value and its actual value was about 18.5%, which is acceptable due to the geological heterogeneity and complexity.

References

[1]. Myer, L.R., Pyrak-Nolte, L.J. and Cook, N.G.W. (1990). Effects of single fracture in seismic wave propagation. in: Proceedings of ISRM Symposium on Rock Joints. Balkema, Rotterdam.

[2]. Joshi, V.P., Tripathi, A., Konidina, R. and Misra, V. (2013). A case study on wall stability at Rampura Agucha Mine using electronic blasting systems. Rock Fragmentation by Blasting. India.

[3]. Blair, D.P. (2015). Wall control blasting. Rock Fragmentation by Blasting. Australia, Taylor & Francis Group. pp. 13- 26.

[4]. Pyrak- Nolte, L.J. (1998). Seismic visibility of fractures. University of California, Berkeley.

[5]. Chen, S.G. and Zhao, J. (1998). A study of UDEC modelling for blast wave propagation in jointed rock mass. International Journal of Rock Mechanic and Mining Science. 35: 93-99.

[6]. Cai, J.G. and Zhao, J. (2000). Effects of multiple parallel fractures on apparent attenuation of stress waves in rock masses. International Journal of Rock Mechanic and Mining Science. 37: 661-682.

[7]. Schoenberg, M. (1980). Elastic wave behavior across linear slip interface. Journal of Acoustics Society of America. 68 (5): 1516- 1521.

[8]. Zhao, J., Zhao, X.B. and Cai, J.G. (2006). A further study of P-wave attenuation across parallel fractures with linear deformational behavior. International Journal of Rock Mechanic and Mining Science. 43: 776-788

[9]. Lie, W.D., Henfy, A.M., Yan, S. and Teng, J. (2007). A numerical study on 2-D compressive wave

propagation in rock masses with a set of joints along the radial direction normal to the joints. Computers and Geotechnics. 34: 508-523.

[10]. Wang, Z.L., Konietzky, H. and Shen, R.F. (2010). Analytical and numerical study of P-wave attenuation in rock shelter layer. Soil Dynamics and Earthquak Engineering. 30: 1-7.

[11]. Ma, G.W. and An, X.M. (2008). Numerical simulation of blasting-induced rock fractures. International Journal of Rock Mechanics and Mining Sciences. 45 (6): 966-975.

[12]. Kuhlmeyer, R.L. and Lysmer, J. (1973). Finite element method accuracy for wave propagation problems. Journal of Soil Mechanic & Foundations. 99: 421- 427.

[13]. Liu, Q. and Tidman, P. (1995). Estimation of the dynamic pressure around a fully loaded blast hole. Technical Report MRL, 95- 104, CANMET/MRL, www.nrcan.gc.ca.

تحلیل عددی انتقال انرژی حاصل از انفجار از ناپیوستگی‌ها و پرشدگی‌ها در سد کنگیر

علی سیامکی[۱] و حسن بخشنده امنیه[۲*]

۱- دانشکده معدن و متالوژی، دانشگاه صنعتی امیرکبیر، ایران
۲- دانشکده فنی و مهندسی، دانشکده معدن، دانشگاه تهران، ایران

ارسال ۲۰۱۵/۹/۱۶، پذیرش ۲۰۱۶/۱/۳

* نویسنده مسئول مکاتبات: hbakhshandeh@ut.ac.ir

چکیده:

بخش قابل‌توجهی از انرژی انفجار ماده منفجره به صورت موج ضربه آزاد می‌شود که تشکیل ناحیه خردشده و ناحیه شکسته شده در اطراف چال انفجاری را به دنبال دارد. انرژی باقیمانده به صورت امواج ارتعاشی سطحی و حجمی در ساختارهای اطراف محل انفجار انتشار می‌یابند. ساختارهای زمین‌شناسی نظیر گسل‌ها، درزه‌ها و شکستگی‌ها و پرشدگی‌های در مسیر امواج، نقش مهمی در میرایی آن‌ها ایفا می‌کنند. مطالعه مکانیسم انتشار امواج لرزشی حاصل از انفجار باعث دست یافتن به درک بهتری از چگونگی انتشار امواج و تأثیر آن‌ها بر ساختارهای اطراف می‌شود. در این تحقیق، انکسار امواج حاصل از انفجار از ناپیوستگی‌ها و پرشدگی‌ها با استفاده از اندازه‌گیری‌های صحرایی و نرم‌افزار المان مجزای UDEC مورد مطالعه قرار گرفته است. یک انفجار تک چال در سد کنگیر انجام شد و ارتعاش حاصل از آن در نقاط قبل و بعد از گسل‌های نزدیک محل انفجار اندازه‌گیری شد. شبیه‌سازی عددی اثر ویژگی‌های ژئومکانیکی پرشدگی‌ها را بر نرخ انعکاس و انکسار امواج نشان داد. انعکاس بیشتری در مرز بین سنگ و پرشدگی‌های خاکی وجود داشت و انرژی بیشتری توسط پرشدگی‌های خاکی نسبت به پرشدگی‌های سنگی جذب شد. بعلاوه، همبستگی بالایی بین ارتعاش زمین ثبت شده در سد کنگیر و نتایج شبیه‌سازی عددی وجود داشت. بیشترین خطای نسبی بین نگاشت‌های واقعی و مقادیر شبیه‌سازی شده ۱۸/۵٪ بود که نشان‌دهنده قابلیت نرم‌افزار UDEC در شبیه‌سازی ارتعاش انفجار بود.

کلمات کلیدی: حداکثر سرعت ذرات، ناپیوستگی، پرشدگی، میرایی، انفجار.