Konya Mühendislik Bilimleri Dergisi, c. 10, s. 1, 1-17, 2022
Konya Journal of Engineering Sciences v. 10, n. 1, 1-17, 2022
ISSN: 2667-8055 (Electronic)
DOI: 10.36306/konjes.884110

PROPAGATION CHARACTERISTICS OF SURFACE AND IN-DEPTH VIBRATIONS IN SAND GROUNDS: A COMPARATIVE ANALYSIS

[1]Bilgehan KEKEÇ , [2]Dhikra GHILOUFI

Konya Technical University, Engineering and Natural Sciences Faculty, Mining Engineering Department, Konya, TÜRKİYE
[1]bkekec@ktun.edu.tr, [2]ghiloufi.dhikra@gmail.com

(Geliş/Received: 21.02.2021; Kabul/Accepted in Revised Form: 10.03.2021)

ABSTRACT: This paper aims to investigate the propagation characteristics of blast-induced ground vibrations in loose dry sand under surface and underground vibration conditions by monitoring the particle velocities and dominant frequencies of artificially generated ground vibrations. For this purpose, a ball drop apparatus was used to generate surface and underground vibrations at different depths. The free fall of the ball induced ground vibrations by impact. A total of 60 laboratory-scale ground vibration monitoring tests were performed on 4 physical models placed in a tank designed for this study. The vibrations were monitored on the surface of the sand filling the tank. The obtained results demonstrated that surface vibrations resulted in higher particle velocities than those generated by underground vibrations and that particle velocities measured on the ground surface decreased as the depth of the underground vibration source increased. The frequency analysis emphasized that only low frequencies (<40 Hz) were generated by surface ground vibration monitoring tests whereas 86.67% of those induced by underground vibration monitoring tests were high frequencies (>40 Hz). It was also determined that increasing the depth of the vibration source resulted in decreasing the dominant frequency range within the range of high frequencies (>40 Hz).

Keywords: *Blast-induced ground vibration, Sand, PPV, PVS, Dominant frequency*

Kum Zemin Yüzeyinde ve Derininde Meydana Gelen Titreşimlerin Yayılım Karakteristikleri: Karşılaştırmalı Bir Çalışma

ÖZ: Bu makale, gevşek kum zemin yüzeyinde ve derininde meydana gelen patlatma kaynaklı titreşimlerin yayılım karakteristiklerini, patlatma ile birlikte ortaya çıkan baskın frekans ve parçacık hızları gibi parametrelerin takibiyle araştırmayı amaçlamaktadır. Bu amaçla, titreşimlerin simülasyonunu sağlamak için, yüzeyde ve yer altında belirli seviyelerden düşerek buna kaynak oluşturacak bir çelik bilye kullanılmıştır. Bu bilye, serbest düşme aparatı yardımıyla istenilen derinlik seviyesinde zemin titreşim dalgaları oluşturmaktadır. Oluşturulan darbelerin yarattığı titreşim yayılımları, üst yüzeyde belirli noktalara yerleştirilen patlatma sismografı kullanılarak takip edilmiştir. Bu çalışma için tasarlanan bir tank içerisine kurulan 4 fiziksel model üzerinde laboratuvar ölçekli toplam 60 adet yer titreşim izleme testi gerçekleştirilmiştir. Elde edilen sonuçlar irdelendiğinde, yüzeyde oluşturulan darbelerin oluşturduğu titreşimlerinin yarattığı parçacık hızlarının yer altında oluşturulan darbelerin oluşturduğu titreşim değerlerinin yarattığı parçacık hızlarına göre daha yüksek olduğu gözlemlenmiştir. Ayrıca, yer altı titreşim kaynağının derinliğinin artmasıyla, zemin yüzeyinde ölçülen parçacık hızının da azaldığı gözlemlenmiştir. Frekans analizi sonuçları, yüzey zemin titreşim izleme testleri ile yalnızca düşük frekansların (<40 Hz) üretildiğini, yer altı titreşim izleme testlerinin ise% 86.67'sinin yüksek frekanslar (>40 Hz) olduğunu göstermiştir. Son olarak, titreşim kaynağının derinliğinin artmasının, yüksek frekanslar (>40 Hz) aralığında baskın frekans aralığının azalmasına neden olduğu tespit edilmiştir.

Anahtar Kelimeler: *Patlatma kaynaklı zemin titreşimleri, Kum, PPV, PVS, Baskın frekans*

1. INTRODUCTION

Drilling and Blasting (D&B) is regarded as the most effective and cost-efficient rock fragmentation technique in quarrying, mining, tunnelling and numerous civil engineering applications such as subway, highway and dam construction projects (Ozer, 2008; Wang *et al*., 2013; Singh and Singh, 2005; Silva *et al*., 2019; Kekeç and Bilim, 2014; Nateghi, 2012). Only 20-30% of the energy released by a blast ensures the breakage and displacement of the rock mass (Shi *et al*., 2016; Singh and Singh, 2005). The remaining energy spreads from the blastholes to the surrounding rock mass, structures and environment (Shi *et al*., 2016) translating into adverse effects such as ground vibration, airblast, flyrock, noise, backbreaks and overbreaks (Monjezi *et al*., 2011; Singh and Singh, 2005; Singh, 2004). Long considered as the most hazardous impact generated by blasting activities (Kekeç *et al*., 2015; Monjezi *et al*., 2010), blast-induced ground vibration (BIGV) has always been a major concern to planners and environmentalists (Nateghi, 2012) especially that an increasingly higher number of quarries and mines operate nowadays nearby urban areas (Ainalis *et al*., 2017). In fact, BIGV has a detrimental effect on adjacent and remote structures (Nateghi, 2011) such as buildings, dams, roads, railways, natural slopes, mine slopes and underground activities conducted in close proximity (Singh and Singh, 2005; Singh, 2004; Monjezi *et al*., 2010; Shi *et al*., 2016). Besides, ground vibrations induced by blasting activities can disturb the neighboring residents and cause complaints and lawsuits. Therefore, predicting and monitoring BIGV levels are essential steps towards adopting the necessary measures to minimize their harmful effects (Shi *et al*., 2016).

As recommended by numerous damage criterion standards such as the standard introduced the U. S. Bureau of Mine (USBM RI 8507), the German standard (DIN 4150), the Indian standard (Indian DGMS Standard) and the French standard (87/70558), the intensity (Peak Particle Velocity) and the frequency are the most commonly used parameters in the studies assessing BIGV damages. Peak particle velocity (PPV) is defined as the maximum instantaneous velocity of a particle at a point during a given time interval measured simultaneously along all three perpendicular components (Longitudinal, Vertical and Transverse) (Avellan *et al*., 2017). The following equation is used to predict PPV levels (Duvall and Petkof, 1959):

$$\mathrm{PPV} = \mathrm{k}\,(\mathrm{SD})^{-\beta} \qquad (1)$$

Where PPV is Peak Particle Velocity (mm/s), SD is the scaled distance (m/kg$^{1/2}$), k is a ground transmission coefficient and β is a specific geological constant.

$$\mathrm{SD} = \frac{\mathrm{R}}{\sqrt{\mathrm{Q}}} \qquad (2)$$

Where SD is the scaled distance (m/kg$^{1/2}$), R is the distance between the charge point and the monitoring point (m) and Q is the maximum charge per delay (kg).

PPV is the most accepted and used parameter to quantify the intensity of BIGV and assess its potential structural damages (Konya and Walter, 2006; Alcudia *et al.*, 2007; Karadogan *et al*., 2014). However, Peak Vector Sum PVS (mm/s) is an equally effective indicator in the assessment of BIGV's intensity. In fact, numerous studies even highlighted the advantages of adopting PVS over PPV because of its higher safety factor (Gu *et al*., 2017; Gu *et al*., 2016; Torres VF *et al*., 2018) as it incorporates the effect of all the components which consequently increases its magnitude (Alcudia *et al.*, 2007). PVS defined as the square sum of the particle velocities measured along all three components (Longitudinal, Transverse and Vertical) is expressed as shown below:

$$\mathrm{PVS} = \sqrt{\mathrm{PVL}^2 + \mathrm{PVT}^2 + \mathrm{PVV}^2} \qquad (3)$$

Where PVS is Peak Vector Sum (mm/s), PVL is Particle Velocity Longitudinal (mm/s), PVT is Particle Velocity Transverse (mm/s) and PVV is Particle Velocity Vertical (mm/s).

Besides PPV and PVS, the frequency content also plays a primary role in the evaluation of BIGV. Numerous papers emphasized the importance of the frequency content in assessing the dynamic response of structures to BIGV (Yang *et al.*, 2016; Lu, 2005; Monjezi *et al.*, 2011). The frequencies generated by ground vibrations are affected by numerous parameters such as the physico-mechanical properties of the rock masses, the distance between the vibration source and the monitoring point, the technical specifications of the explosive material and the adopted blast design (Yang *et al.*, 2016). The dominant frequency of BIGV affect the persistence of the vibration and its amplification or reduction characteristics in structures (Singh and Roy, 2008). Potential structural damages and human disturbances caused by BIGV are determined by the particle velocity and the low-frequency portion of the seismic waves induced by the blast (Aloui *et al.*, 2016) because low frequencies (<40 Hz) are potentially more damaging than high frequencies (> 40 Hz) (Siskind *et al.*, 1980; Pal Roy, 1998; Zeng *et al.*, 2018). High damages are significantly correlated with the low frequency portion of the BIGV because of the resonance effect, which occurs when the frequencies of the seismic waves generated by a blast overlap the natural frequency range of the structure (5-16 Hz) and consequently amplifies the resulting vibration amplitude (Aloui *et al.*, 2016; Singh and Roy, 2008; Yang *et al.*, 2016).

Numerous scholars inspected surface and underground blast-induced vibrations in quarries and mines under different geological and geotechnical contexts and conducted comparative analyses on the resulting particle velocities and frequency contents. Shi *et al.* (2016) examined PPV values generated by bench blasting at the surface and in an underground transport tunnel of an open-pit mine and determined that for the same ground vibration distance, PPV levels recorded at the surface were in most cases higher than their corresponding values in the underground tunnel. Based on the obtained results, the authors established that BIGV waves undergo an energy loss (damping effect) as they travel from the surface to the underground. Singh *et al.* (2015) investigated BIGV in a zinc mine operating both open-pit and underground. In this study, the authors demonstrated that as a result of geometrical spreading and the presence of underground voids, for the same scaled distance, surface PPV values were higher than their corresponding values measured underground. The paper also illustrated that low frequency vibrations were recorded on the ground surface whereas high frequency vibrations were recorded in the underground openings. Dogan *et al.* (2013) carried out experimental blasting operations in a site formed of alternating layers of gravelly, sandy and clayey units. The obtained results indicated that for the same scaled distance, PPV values measured during the conduct of underground blasts were up to 95% lower than those recorded in surface blasts and that the dominant frequencies recorded underground were up to 78 % lower than those recorded on the surface. Based on data from 20 different mines in India, Pal Roy (1998) concluded that contrarily to surface blasting operations where both low and high frequencies are generated, underground blasts produce only high frequencies.

The aim of this research paper is to review the characteristics of surface and underground blast-induced vibrations in loose dry sand grounds located nearby hard rock blasting sites. This study presents a comparative analysis of PPV, PVS and the dominant frequency levels in loose dry sand under surface and underground vibration conditions. Furthermore, the effect of increasing the simulation depth of underground vibrations on the resulting particle velocities and dominant frequency ranges is examined and interpreted.

The findings of this paper provide an insight into the characteristics of blast-induced ground and underground vibration waves in loose dry sand grounds located nearby hard rock blasting sites. The obtained results allow a better understanding of the potential structural damages due to BIGV to structures built on loose dry sand grounds. Furthermore, the findings of this paper are of great value in the prediction of the responses of the inhabitants of these structures which allows adopting the necessary measures to minimize, if not eliminate, any potential damages.

2. MATERIALS AND METHODS

2.1. Sand Material

The experimental investigation conducted under the scope of this study falls within an extensive research project that examines the propagation mechanisms of BIGV in sand, clay and sand-clay layered mediums. Similarly, to the laboratory-scale experimental studies conducted on loose dry, compacted and water-saturated sand (Kekeç and Ghiloufi, 2021) and those carried out on loose dry clay and sand-clay layered media (Kekeç and Ghiloufi, 2020), the sand used in this study is a 0-4 mm washed sand obtained from a sand quarry operating on the road connecting the cities of Konya and Ankara in Turkey. Table 1 highlights the physical properties of the sand used in this study.

Table 1. Physical properties of the sand used in the study

Parameter	Value
Soil classification	SW
Effective particle size D10 (mm)	0.17
D30 (mm)	0.7
D60 (mm)	2
Uniformity coefficient Cu	11.77
Coefficient of curvature Cc	1.44
Specific weight (kN/m^3)	26.90
Loose dry bulk density $\gamma_{k,min}$ (kN/m^3)	14.20
Compact dry bulk density $\gamma_{k,max}$ (kN/m^3)	19.50
Minimum void rate e_{min} (%)	38
Maximum void rate e_{max} (%)	89

2.2. Tank

In order to conduct a comparative analysis on the blast-induced particle velocities and dominant frequency ranges in loose dry sand, laboratory-scale vibration monitoring tests were conducted on 4 physical models (Model 1, Model 2, Model 3 and Model 4) set up in a tank. The rectangular prism shaped tank designed for this purpose is 112.9 cm long, 39 cm wide and 80.8 cm high (Fig. 1). The front and the back of the tank are made of a 1.5 cm thick tempered glass. The bottom and the sides are made of iron.

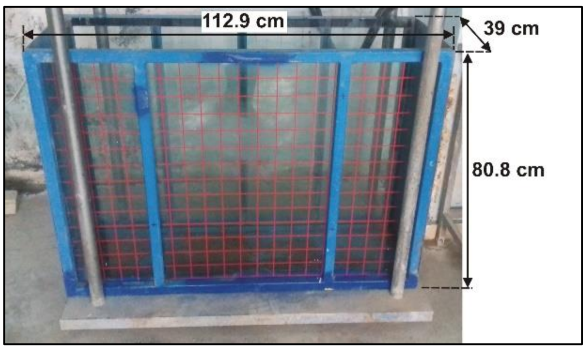


Figure 1. Dimensions of the tank used in the laboratory-scale vibration monitoring tests.

2.3. Simulation of Surface and Underground Blast-Induced Vibrations

Before starting the ground vibration monitoring tests on the above-mentioned physical models, the tank was first filled with approximately 370 Kg of loose dry sand up to the 60 cm level of the tank. A ball drop apparatus placed on top surface of the sand filling the tank enabled replicating BIGV generated by surface blasting activities (Fig. 2). The working principle of the ball drop apparatus consists of releasing a 102.8 gr steel ball from a specific height which enables the fall of this ball onto the sand filling the tank generating ground vibration waves similar to those induced by surface blasting activities. The apparatus consists of an aluminum pipe secured inside an 18.2 cm high and 24.5 cm wide wooden stand. The 55 cm long pipe allows dropping the steel ball from 5 different levels located at heights of 55 cm, 45 cm, 35 cm, 25 cm and 15 cm. A pin ensures holding the ball inside the pipe at the intended ball drop level. For each ground vibration monitoring test conducted under the scope of this study, the steel ball was released from the ball drop level located at a height of 45 cm from the surface of the loose dry sand filling the tank. It is important to emphasize that the fall of the steel ball from the same level always results in releasing the same amount of seismic energy in each ground vibration monitoring test (Kekeç, 2010).

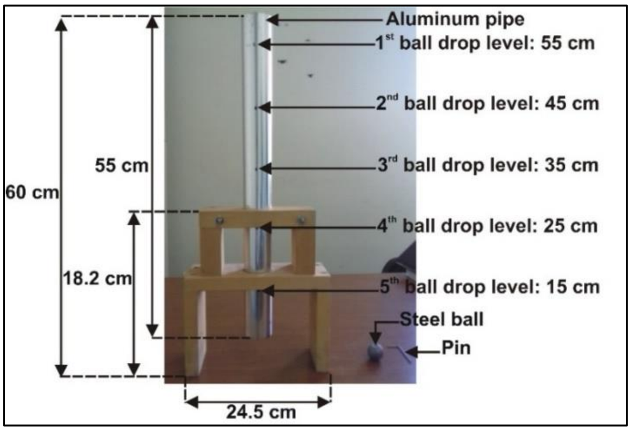


Figure 2. The Ball drop apparatus.

The ball drop apparatus was used in Model 1 to generate surface blast-induced vibrations. For models 2, 3 and 4, the ball drop apparatus was positioned above a PVC pipe placed inside the sand filling the tank to ensure simulating underground blast-induced vibrations at depths of 15 cm, 30 cm and 45 cm. To assess the effect of the depth of the vibration source on the resulting PPV values, PVS values and the dominant frequency ranges in loose dry sand, a 5 cm-diameter PVC pipe was placed inside the sand filling the tank. In models 2, 3 and 4, the length of the PVC pipe was 15 cm, 30 cm and 45 cm, respectively. Thus, as the pin was pulled from the ball release level located at a height of 45 cm from the base of the apparatus, instead of falling onto the surface of the sand filling the tank, the steel ball fell inside the PVC pipe creating underground vibrations at the intended depth. Fig. 3 emphasizes the 45 cm long PVC pipe placed inside the loose dry sand in Model 4.


Figure 3. Positioning of the PVC pipe inside the sand in Model 4.

2.4. Description of the Physical Models

Four physical models namely model 1, model 2, model 3 and model 4 were inspected under the scope of this study. A total of 15 ground vibration monitoring tests were carried out on each of these model.

The surface ground vibration events simulated in model 1 and the underground vibration monitoring events generated at depths of 15 cm, 30 cm and 45 cm in models 2, 3 and 4, respectively, were monitored using an Instantel Minimate Plus vibration monitor. The transducer (geophone) was placed on the top surface of the sand filling the tank at a distance of 60 cm from the ball drop apparatus. For each ground vibration monitoring test, particle velocity time history, Peak Particle Velocity Longitudinal PVV_L (mm/s), Peak Particle Velocity Transverse PVV_T (mm/s), Peak Particle Velocity Vertical PVV_V (mm/s) and PVS (mm/s) levels were monitored and recorded by the Instantel Minimate Plus seismograph. Fig. 4 displays a schematic presentation of the physical models investigated under the scope of this study.

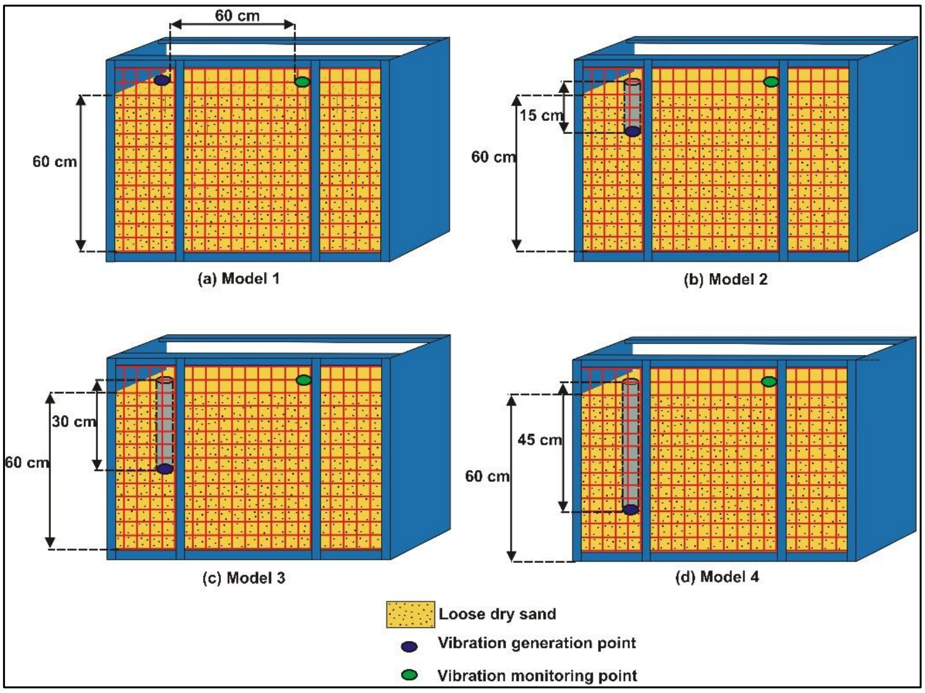


Figure 4. Schematic presentation of (a) model 1, (b) model 2, (c) model 3 and (d) model 4.

3. RESULTS AND DISCUSSION

The experimental investigation consisted of conducting 15 ground vibration monitoring tests on each of the 4 physical models defined and described in the preceding section. For each of the performed ground vibration monitoring tests, particle velocity time history, Peak Particle Velocity Transverse PVV_T, Peak Particle Velocity Vertical PVV_V, Peak Particle Velocity Longitudinal PVV_L and Peak Vector Sum PVS values were recorded by the Instantel Minimate Plus vibration monitor connected to a triaxial transducer (geophone). The geophone was set up on the top surface of the sand filling the tank at a distance of 60 cm from the ball drop apparatus as illustrated in Fig. 4. Data collected and stored by the monitoring unit of the seismograph were then transferred to the Blastware software, the companion software of the Instantel Minimate Plus vibration monitor that enables managing the recorded events and conducting different operations on the registered data sets such as waveform event and frequency analyses.

Fast Fourier analysis (FFT), one of the fundamental features of the Blastware software, ensured assessing the frequency content of the waveforms procured from the ground vibration monitoring tests by converting the vibration time history into the frequency domain. Thus, the Transverse dominant frequency F_T (Hz), Vertical dominant frequency F_v (Hz) and Longitudinal dominant frequency F_L (Hz) of each ground vibration monitoring event were quantified and the dominant frequency of each event was determined as the frequency corresponding to the highest PPV value.

3.1. Particle Velocity Analysis

Table 2 summarizes PVV_T, PVV_V, PVV_L, PPV and PVS values measured at each ground vibration monitoring event. For the purpose of reviewing both particle velocity descriptors i.e. PPV (mm/s) and PVS (mm/s) in loose dry sand under surface and underground vibration conditions, the maximum PPV and PVS values measured during the ground vibration monitoring tests of each physical model, referred to as PPV_{max} and PVS_{max}, were considered for the analysis and interpretation of the collected experimental data (Table 2).

To compare the evolution of particle velocity levels in loose dry sand under surface and underground vibration conditions, PPV_{max} and PVS_{max} values were plotted against the simulation depth of the vibration as emphasized in Fig.5 (the depth value 0 on the x-axis represents surface ground vibrations simulated on the top surface of the loose dry sand filling the tank).

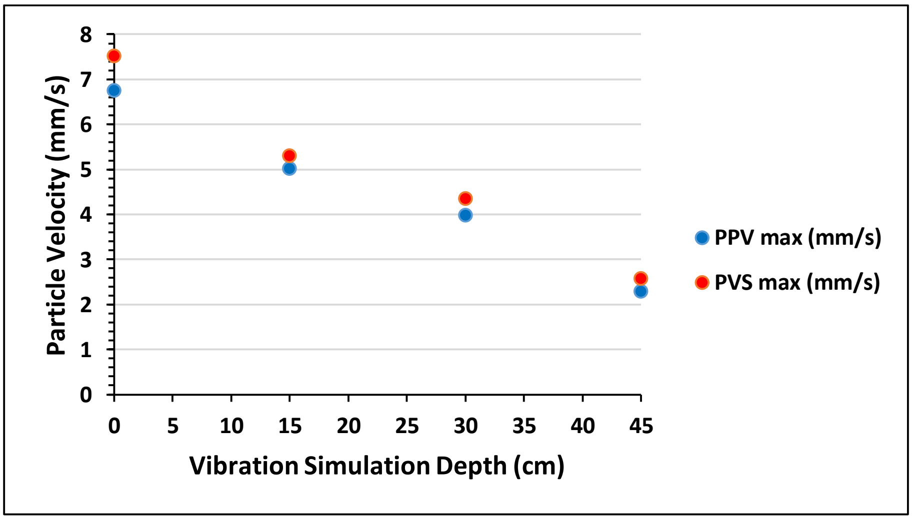


Figure 5. Evolution of PPV_{max} and PVS_{max} values in loose dry sand generated at different vibration simulation depths.

As emphasized in Fig.5, for both surface and underground vibrations recorded at the monitoring point placed on the top surface of the loose dry sand filling the tank at a distance of 60 cm from the ball drop apparatus, all of PVS_{max} values were higher than PPV_{max} values. The results of the ground vibration monitoring tests conducted on the first physical model (model 1) where surface ground vibrations in loose dry sand were simulated, indicate that PVS_{max} value (7.53 mm/s) was 11.39% higher than PPV_{max} value measured at the same monitoring point (6.76 mm/s). In models 2, 3 and 4 where underground vibrations were simulated at depths of 15 cm, 30 cm and 45 cm, the recorded PVS_{max} levels were respectively 5.57%, 9.55% and 12.17% higher than their corresponding PPV_{max} values.

These results demonstrate that for the same monitoring distance, PVS displays a higher safety factor than PPV. Therefore, when evaluating both surface and underground vibrations caused by hard rock blasting activities conducted nearby loose dry sand grounds, adopting PVS as the assessment parameter ensures safer prediction of ground vibration damages.

Table 2. Results of the ground vibration monitoring tests.

Physical Model	Test No	PPV_T (mm/s)	PPV_V (mm/s)	PPV_L (mm/s)	PPV (mm/s)	PVS (mm/s)	PPV_{max} (mm/s)	PVS_{max} (mm/s)
Model 1	1	2.44	1.48	4.43	4.43	5.16	6.76	7.53
	2	2.78	2.27	4.98	4.98	5.85		
	3	2.67	2.13	5.68	5.68	6.35		
	4	2.92	1.97	5.1	5.1	6.17		
	5	2.78	2	5.52	5.52	6.16		
	6	2.86	2.43	5.97	5.97	6.66		
	7	2.65	2.27	4.73	4.73	5.5		
	8	3.08	2.44	6.05	6.05	6.83		
	9	2.54	2.29	5.73	5.73	6.54		
	10	2.89	2.51	4.94	4.94	5.84		
	11	2.79	2.38	5.65	5.65	6.61		
	12	3.24	2.59	6.4	6.4	7		
	13	2.83	2.6	6.14	6.14	6.85		
	14	3.14	2.95	6.3	6.3	7.04		
	15	3.03	2.65	6.76	6.76	7.53		
Model 2	1	1.76	4.6	3.11	3.11	5.07	5.03	5.31
	2	1.52	4.71	3.38	4.71	5.24		
	3	2.68	4.16	3.1	4.16	4.31		
	4	2.7	3.14	3.05	3.14	3.45		
	5	2.48	4.38	3.11	4.38	4.85		
	6	2.08	3.13	3.54	3.54	3.86		
	7	1.41	3.37	2.52	3.37	4.01		
	8	1.83	3.91	3.1	3.91	4.44		
	9	1.49	4.19	2.54	4.19	4.61		
	10	1.86	3.68	2.48	3.68	4.03		
	11	1.84	3.76	2.21	3.76	4.2		
	12	1.7	5.03	2.22	5.03	5.31		
	13	1.92	4.38	2.41	4.38	4.99		
	14	2.05	4.97	2.13	4.97	5.15		
	15	2.54	4.29	2.24	4.29	4.4		
Model 3	1	1.86	3.13	2.65	3.13	3.72	3.98	4.36
	2	1.54	3.33	3.24	3.33	4.19		
	3	1.89	3.4	2.75	3.4	3.83		
	4	1.68	3.59	2.25	3.59	4.13		
	5	1.51	3.94	2.52	3.94	4.34		
	6	1.78	3.98	2.35	3.98	4.36		
	7	1.38	2.7	2.84	2.84	3.59		
	8	1.29	3.33	2.91	3.33	3.84		
	9	1.75	3.68	2.73	3.68	4.15		
	10	1.92	3.14	2.25	3.14	3.63		
	11	2.1	3.51	2.97	3.51	3.99		
	12	2.05	3.83	2.14	3.83	4.13		
	13	2.4	3.44	2.51	3.44	3.98		
	14	1.4	3.3	3.27	3.3	4.02		

	15	1.97	3.94	2.29	3.94	4.19		
Model 4	**1**	1.46	1.64	1.48	1.64	2.1	2.3	2.58
	2	1.43	1.84	1.89	1.89	2.28		
	3	1.62	2	1.89	2	2.49		
	4	1.41	1.56	1.4	1.56	2.04		
	5	1.71	2.03	1.52	2.03	2.31		
	6	1.13	1.86	1.29	1.86	1.98		
	7	2.3	1.89	1.49	2.3	2.32		
	8	2.25	1.86	1.33	2.25	2.3		
	9	1.49	1.92	2	2	2.4		
	10	1.86	1.68	1.64	1.86	2.43		
	11	1.89	2.08	1.75	2.08	2.58		
	12	1.81	1.76	1.38	1.81	2.34		
	13	1.62	1.94	1.79	1.94	2.47		
	14	2.27	1.57	1.48	2.27	2.51		
	15	1.94	1.71	1.29	1.94	2.14		

The highest PPV_{max} and PVS_{max} values were obtained in model 1 where surface ground vibrations were monitored. In this model, PPV_{max} and PVS_{max} levels were determined as 6.76 mm/s and 7.53 mm/s, respectively. These results indicate that in loose dry sand at the same monitoring point, surface ground vibrations generate higher particle velocities (PPV and PVS) than those induced by underground ones.

When the effect of the underground vibration source depth on the resulting particle velocity levels was examined based on the data collected from models 2, 3 and 4, it was observed that increasing the simulation depth of the underground vibration source led to a decrease in the recorded PPV_{max} and PVS_{max} values. At the same monitoring point placed on the top surface of the sand, the recorded PPV_{max} values generated at depths of 15 cm, 30 cm and 45 cm, were respectively 25.6%, 41.12% and 65.98% lower than their corresponding value induced by surface ground vibrations in model 1. Under the same experimental conditions, PVS_{max} levels generated at depths of 15 cm, 30 cm and 45 cm, were respectively 29.48%, 42.1% and 65.74% lower than their corresponding value induced by surface ground vibrations in model 1. These observations emphasize the major role played by the location (surface/underground) and the depth of the ground vibration source on the resulting particle velocity level. The equations describing the attenuation of PPV_{max} and PVS_{max} levels are presented in Fig. 6. These attenuation equations are expressed as follows:

For PPV_{max}: $y = -0.0962 x + 6.682$ (**R^2= 0.9918**) (4)

For PVS_{max}: $y= -0.1053 x+ 7.315$ (**R^2= 0.9789**) (5)

The attenuation equations of PPV_{max} and PVS_{max} are both characterized by high R-squared values. R-squared values reached 99.18 % and 97.89% in Eq. (4) and Eq. (5), respectively.

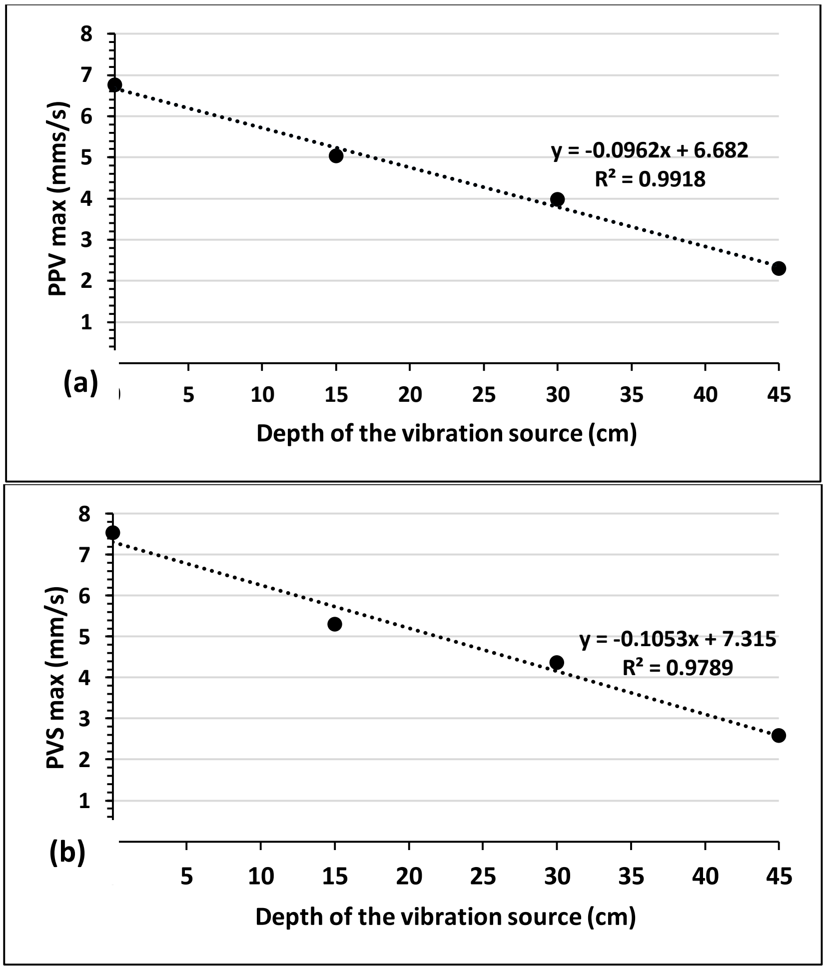


Figure 6. Attenuation equations of (a) PPV_{max} and (b) PVS_{max} in loose dry sand.

The gradual decrease in PPV_{max} and PVS_{max} values as the vibration source was simulated deeper under the ground surface is caused by seismic attenuation. Because of seismic attenuation also known as absorption, particle velocities (PPV and PVS) decrease as the distance between the vibration source and the monitoring point increases. In model 1, the geophone was placed at a distance of 60 cm from the ground vibration simulation point. In models 2, 3 and 4 the distance between the underground vibration simulation point and the geophone placed on the top surface of the sand filling the tank was 6.18 cm, 6.7 cm and 7.5 cm, respectively (Fig. 7). These distances were calculated using the Pythagorean Theorem. The obtained results demonstrate that in loose dry sand, increasing the simulation depth of ground vibrations results in increasing the distance separating the vibration source and the monitoring point placed on the surface which consequently induces a decrease in the resulting PPV and PVS values.

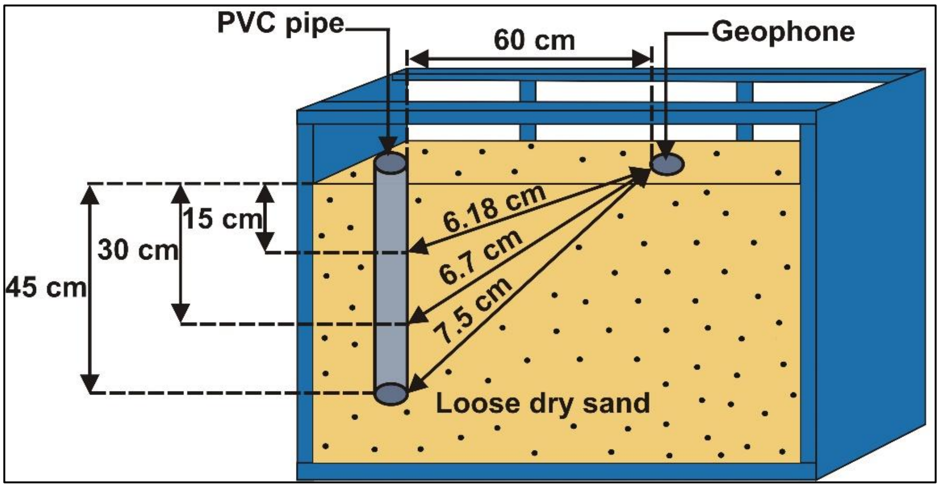


Figure 7. Distance between the vibration simulation point and the geophone in models 1, 2, 3 and 4 (scale non respected).

3.2. Frequency analysis

Analyzing the frequency content of surface and underground blast-induced vibrations is a substantial aspect of assessing their potential structural damages and human responses to these vibrations. Frequencies below 40 Hz are correlated with high structural damaging potentials and human disturbances and those below 10 Hz are particularly notorious because of the large ground displacement and high strain levels they cause (Siskind *et al*. 1980). Furthermore, contrarily to high frequencies which do not pose any stability or safety risks (Zeng *et al*., 2018), low frequencies can overlap with structures' natural frequencies (5-16 Hz) which amplifies the resulting ground motion and further increments their damaging potentials. This phenomenon is known as the resonance effect. Thus, evaluating the frequency content of the seismic waves generated by a blast is a crucial process in the assessment of the potential damages caused by BIGV.

Numerous methods such as the inversion of time periods, response spectrum techniques, Zero-Crossing method (ZC) and Fast Fourier Transform (FFT) can be used to analyze the frequency content of BIGV events. Fast Fourier Transform (FFT) considered to be the most accurate among these techniques (Çakmak, 2007; Kalaycı *et al*., 2014), enables the analysis of the frequency content of the waveforms released by the vibration source and transforms the vibration time history (a time based function) into the frequency domain (a frequency based function). The FFT method ensures examining the distribution of the frequency content, identifying the dominant frequency and determining the frequency band potentially responsible for damages and disturbances (Pal Roy, 1998).

For each of the 4 physical models investigated under the scope of this experimental study, 15 ground vibration tests were monitored and interpreted. Fast Fourier Transform (FFT) analysis was conducted on each ground vibration event using Blastware software, the companion software of the Instantel Minimate Plus vibration monitor. Fig. 8 displays an FFT analysis example conducted by Blastware software. Table 3 emphasizes the results of the FFT analysis conducted on the 60 ground vibration monitoring events investigated within the framework of this study. Each event is characterized by its Transverse dominant frequency F_T (Hz), Vertical dominant frequency F_V (Hz), Longitudinal dominant frequency F_L (Hz) and dominant frequency (Hz). Herein, similarly to the frequency analysis approach adopted by (Dogan *et al*., 2013), the dominant frequency of each ground vibration event was determined as the frequency corresponding to the highest PPV value.

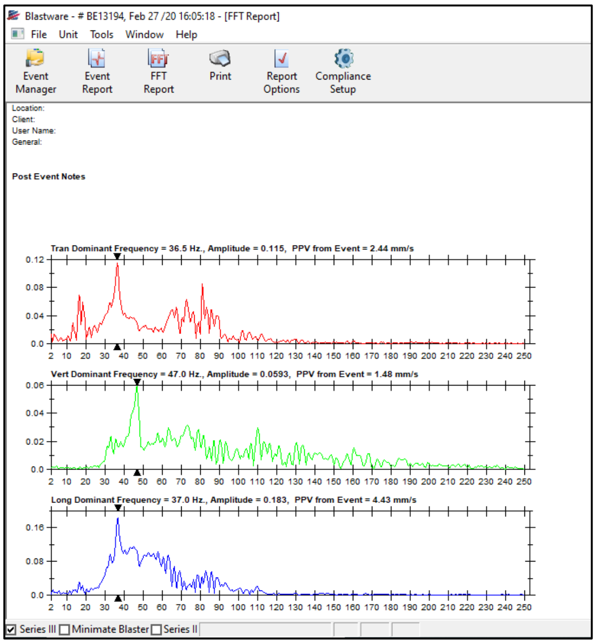


Figure 8. Example of an FFT analysis report computed by Blastware software (Model 1, 1st ground vibration monitoring test).

For each ground vibration monitoring event, F_T (Hz), F_V (Hz), F_L (Hz) and the frequency corresponding to spectral maximum in power spectrum (Zhen-xiong *et al.*, 2016) i.e. the dominant frequency, were identified as shown in Table 3. The obtained dominant frequencies were then statistically analyzed to determine their distribution ranges for each physical model. Fig. 9 illustrates the distribution of the dominant frequencies values generated by surface and underground vibrations in loose dry sand.

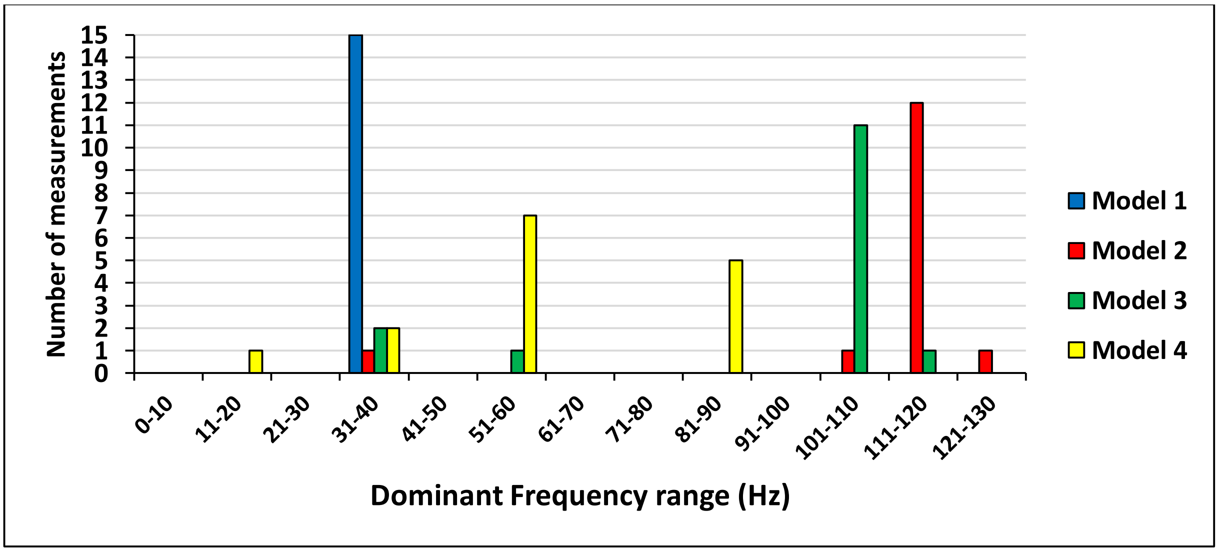
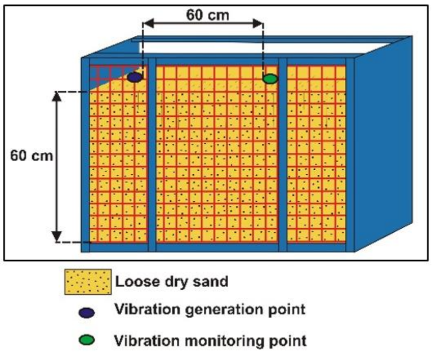
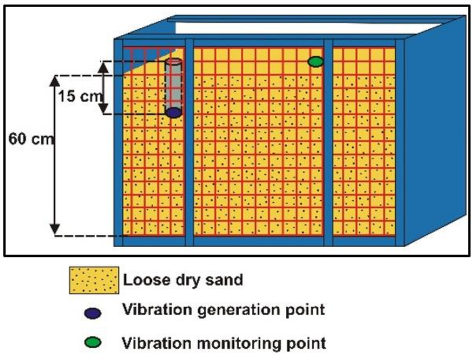
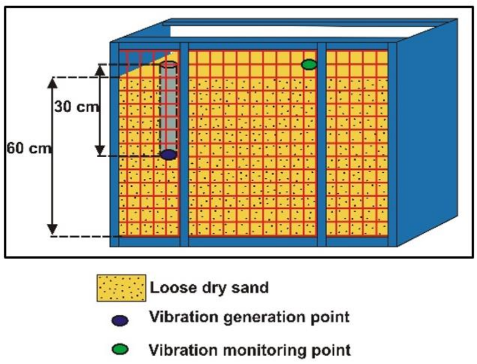
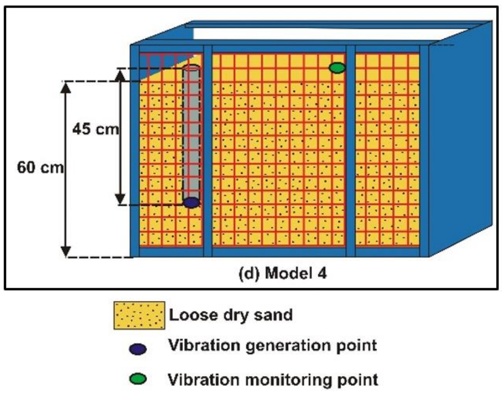


Figure 9. Distribution of the dominant frequency values in loose dry sand.

Table 3. Results of the FFT frequency analysis conducted on models 1, 2, 3 and 4.

Model	Test No	Dominant frequency Transverse F_T (Hz)	Dominant frequency Vertical F_V (Hz)	Dominant frequency Longitudinal F_L (Hz)	Dominant frequency (Hz)	Schematic representation
Model 1	1	36.5	47	37	37	
	2	36.5	47.5	36.5	36.5	
	3	36.5	47	36.5	36.5	
	4	36.5	46.5	36.5	36.5	
	5	36.5	47	37	37	
	6	37	47	37	37	
	7	36.5	47	36.5	36.5	
	8	17.5	47	37	37	
	9	17.5	46	36.5	36.5	
	10	36	47	37	37	
	11	36	46.5	36.5	36.5	
	12	36.5	47	36.5	36.5	
	13	35.5	47	36	36	
	14	36	47	36.5	36.5	
	15	35	47	37	37	
	Avg.	**33.73**	**46.9**	**36.66**	**36.66**	
Model 2	1	19.5	119	40.5	119	
	2	19	119	40	119	
	3	19.5	116	40	116	
	4	19.5	118	40	118	
	5	19.5	115	40.5	115	
	6	19.5	118	40	40	
	7	20	123	40	123	
	8	19.5	118	39.5	118	
	9	19.5	119	40.5	119	
	10	19.5	116	40.5	116	
	11	19.5	120	39.5	120	
	12	19.5	115	19.5	115	
	13	19	118	39.5	118	
	14	19	104	98.5	104	
	15	19.5	119	41	119	
	Avg.	**19.43**	**117.13**	**42.63**	**111.93**	
Model 3	1	19	108	94.5	108	
	2	19.5	108	50.5	108	
	3	19.5	105	91	105	
	4	82	104	98	104	
	5	19.5	105	68	105	
	6	19.5	107	94.5	107	
	7	19	114	39.5	39.5	
	8	19.5	107	39.5	107	
	9	19.5	106	95	106	
	10	19	114	82.5	114	
	11	19.5	105	39.5	105	
	12	19.5	108	97.5	108	
	13	19.5	51.5	98	51.5	
	14	19.5	105	39.5	39.5	
	15	85.5	107	94.5	107	
	Avg.	**27.96**	**103.63**	**74.8**	**94.3**	
Model 4	1	19.5	53	40	53	
	2	19.5	52.5	40	40	
	3	82	52	40	52	

	4	19.5	52.5	71	52.5
	5	20	52.5	39.5	52.5
	6	20.5	52	39.5	52
	7	82	52	66	82
	8	82	52.5	39.5	82
	9	19.5	52	40	40
	10	19.5	52.5	40	19.5
	11	20	52	40	52
	12	82	52.5	40	82
	13	19	52	40	52
	14	82	52.5	39.5	82
	15	82	52	39.5	82
	Avg.	**44.6**	**52.3**	**43.63**	**58.36**



The evaluation of the distribution of the dominant frequency values in Model 1 demonstrate that all of the frequencies generated by surface ground vibration events were lower than 40 Hz ranging between 36 Hz and 37 Hz. Therefore, surface hard-rock blasting activities are expected to generate low frequency vibrations (below 40 Hz) in the nearby loose dry sand grounds. These low frequency vibrations are known for their high damaging potentials.

In models 2, 3 and 4, the effect of underground vibrations on the distribution of the dominant frequency values in loose dry sand was examined. For this purpose, blast-induced underground vibrations were simulated at depths of 15 cm, 30 cm and 45 cm in order to compare the obtained dominant frequency values to those induced by surface vibrations and to examine whether the depth of the blast-induced underground vibration source affects the resulting dominant frequency ranges. It was observed that except only 1 ground vibration monitoring event in model 2, 2 events in models 3 and 3 events in model 4, 39 events i.e. 86.67% of the underground vibration monitoring events in loose dry sand displayed dominant frequencies above 40 Hz.

In model 2 where underground vibrations generated at a depth of 15 cm inside the loose dry sand filling the tank were examined, the statistical analysis conducted on the resulting dominant frequencies indicated that 80 % of the dominant frequencies were in the range of 111 Hz-120 Hz, 6.66% were between 121 Hz and 130 Hz, 6.66% were in the range of 101 Hz-110 Hz and 6.66% were between 31 and 40 Hz. In model 3 where underground vibrations generated at a depth of 30 cm inside the loose dry sand filling the tank were investigated, it was demonstrated that 73.33% of the dominant frequency values were between 101 Hz and 110 Hz, 13.33 % were in the range of 31 Hz-40 Hz, 6.66% were between 111 Hz and 120 Hz and 6.66% were in the range of 31 Hz - 40 Hz. In model 4 where underground vibrations were simulated at a depth of 45 cm inside the loose dry sand filling the tank, the conducted analysis has shown that 46.66% of the dominant frequency values were in the range of 51 Hz and 60 Hz, 33.33% of these frequencies were between 81 Hz and 90 Hz, 13.33% were in the range of 31 Hz-40 Hz and 6.66% were in the range of 11 Hz-20 Hz. These results demonstrate that in the great majority of the cases, underground hard-rock blasting activities are expected to generate high frequency ground vibrations (above 40 Hz) in the nearby loose dry sand grounds which considerably reduces the risks of resonance, structural damages and human disturbances if the intensity of these vibrations do not exceed the damage threshold.

When the effect of the depth of the underground vibration source on the distribution of the dominant frequency ranges was examined in models 2, 3 and 4, it was observed that increasing the depth of the vibration source resulted in decreasing the dominant frequency range within the range of high frequencies (> 40 Hz). The dominant frequency range in models 2 determined as 111-120 Hz decreased to 101-110 Hz in model 3. In model 4, the dominant frequency range further diminished to the ranges of 51-60 Hz and 81-90 Hz. These results confirm that in loose dry sand, similarly to PPV and PVS, the dominant frequency range also decrease as the depth of the vibration source increases. As illustrated in Fig.7, the distance between the underground vibration source and the monitoring point in models 2, 3 and 4 was determined as 6.18 cm, 6.7 cm and 7.5 cm, respectively. Increasing the depth of the vibration source results in increasing the distance separating it from the monitoring point placed on the top surface of the sand filling the tank which increases the high-frequency absorption of the seismic waves as they increasingly travel a longer distance before reaching the monitoring point.

4. CONCLUSIONS

The findings of this paper can be summarized as follows:

- For the same monitoring distance, PVS_{max} levels generated by both surface and underground blast-induced vibrations in loose dry sand were up to 12.17% higher than PPV_{max} values. Thus PVS displays a higher safety factor than PPV.
- In loose dry sand, for the same monitoring distance, surface vibrations generated higher PPV_{max} and PVS_{max} values than those induced by underground vibrations.
- In loose dry, for the same monitoring distance, increasing the depth of the ground vibration source resulted in decreasing PPV_{max} and PVS_{max} values because of seismic attenuation (absorption). In fact, increasing the depth of the vibration source led to increasing the distance separating it from the vibration monitoring point placed on the ground surface which consequently caused an increased absorption of the seismic energy before reaching the monitoring point.
- The equations describing the attenuation of PPV_{max} and PVS_{max} levels in loose dry sand were developed as follows:

  For PPV_{max}: $y = -0.0962\,x + 6.682$ (**R^2= 0.9918**)

  For PVS_{max}: $y = -0.1053\,x + 7.315$ (**R^2= 0.9789**)

The R-squared value of the PPV max and PVS max attenuation equations reached 99.18% and 97.89 %, respectively.

- The analysis of the distribution of the dominant frequency values in loose dry sand has shown that while surface vibrations generated only low frequencies (<40 Hz), 86.67% of the frequencies generated by underground vibrations were high frequencies (> 40 Hz).
- In loose dry sand, increasing the depth of the vibration source resulted in decreasing the dominant frequency range recorded on the ground surface within the range of high frequencies (> 40 Hz). The decrease in the dominant frequency range is explained by the high-frequency absorption of the seismic waves that proportionally increases as the distance separating the vibration source from the monitoring point increases.

5. ACKNOWLEDGMENT

This research was supported by Konya Technical University *Scientific Research Projects Coordination*.

REFERENCES

Alcudia, A. D., Stewart, R.R., Eliuk, N., Espersen, R., 2007, Vibration and air pressure monitoring of seismic sources, *CREWES Research Report 19*.

Aloui, M., Bleuzen, Y., Essefi, E., Abbes, C., 2016, "Ground Vibrations and Air Blast Effects Induced by Blasting in Open Pit Mines: Case of Metlaoui Mining Basin, Southwestern Tunisia", *Journal of Geology & Geophysics*, Vol. 5, pp. 1-8.

Avellan, K., Belopotocanova, E., Puurunen, M., 2017, "Measuring, Monitoring and Prediction of Vibration Effects in Rock Masses in Near-Structure Blasting", *Procedia Engineering,* Vol. 191, pp. 504-511.

Çakmak, B. B., 2007, *Investigation of ground vibrations induced by production blasting at Uşak Kışladağ gold mine,* M.S. Thesis, Middle East Technical University, Turkey.

Dogan, O., Anil, O., Akbas, S.O., Kantar, E., Tuğrul E. R., 2013, "Evaluation of blast-induced ground vibration effects in a new residential zone", *Soil Dynamics and Earthquake Engineering,* Vol. 50, pp. 168-181.

Duvall, W. I., Petkof, B., 1959, Spherical propagation of explosion-generated strain pulses in rock, *Report for the United States Bureau of Mines (USBM),* Report No. BM-RI-5483.

Gu, W., Wang, Z., Liu, J., Xu, J., Liu, X., Cao, T., 2017, "Water-Depth-Based Prediction Formula for the Blasting Vibration Velocity of Lighthouse Caused by Underwater Drilling Blasting", *Shock and Vibration*, Vol. 2, pp. 1-9.

Gu, W. B., Wang, Z. X., Chen, J. H., Liu, J. Q., Lu, M., Xu, H. M., 2016, "Influence of charge structure on the energy transfer of blasting vibration and explosive effect", *Journal of Vibration and Shock,* Vol. 35, No. 2, pp. 207-211.

Kalaycı, U., Ozer, U., Karadogan, A., Ozyurt, M. C., "Investigation of Dominant Frequency by Vibration Monitors", *VIth Global stone Congress,* Antalya, Turkey, *22-25 October 2014.*

Karadogan, A., Kahriman, A., Ozer, U., 2014, "A new damage criteria norm for blast-induced ground vibrations in Turkey", *Arabian Journal of Geosciences*, Vol. 7, pp. 1617-1626.

Kekeç, B., 2010, *Blasting induced ground vibration determination according to some rock materials and rock mass properties*, PhD Thesis, Selcuk University, Graduate School of Natural And Applied Science, Konya, Turkey.

Kekeç B., Bilim N., 2014, "Evaluation of Blast Induced Vibration and Air Blast Measurements Nearby a Residential Area", Mine Planning and Equipment Selection, Drebenstedt C., Singhal R. (eds). Springer, Cham, 719-727.

Kekeç, B., Gökay, M. K., Bilim, N., 2015, "Evaluation of the effect of vibrational wave propagation of different artificial discontinuous planes in rock samples", *Arabian Journal of Geosciences*, Vol. 8, pp. 6399-6407.

Kekeç, B., Ghiloufi, D., 2020, "Propagation mechanisms of blast-induced ground vibration (BIGV) in clay and layered sand-clay media", *Manuscript submitted for publication.*

Kekeç, B., Ghiloufi, D., 2021, "Propagation Mechanisms of Blast-Induced Ground Vibration (BIGV) in Different Ground Conditions", *International Journal of Ecosystems and Ecology Science (IJEES)*, Vol. 11, No. 1, pp. 165-180.

Konya, C. J., Walter, E. J., 2006, Rock blasting and overbreak control manual, *Report for the U.S. Departement of Transportation Federal Highway Administration,* Publication No. FHWA-HI-92-001.

Lu, Y., 2005, "Underground blast induced ground shock and its modelling using artificial neural network", *Computers and Geotechnics,* Vol. 32, pp. 164-178.

Monjezi, M., Ahmadi, M., Sheikhan, M., Bahrami, A., Salimi, A. R., 2010, "Predicting blast-induced ground vibration using various types of neural networks", *Soil Dynamics and Earthquake Engineering*, Vol. 30, pp. 1233-1236.

Monjezi, M., Ghafurikalajahi, M., Bahrami, A., 2011, "Prediction of blast-induced ground vibration using artificial neural networks", *Tunnelling and Underground Space Technology,* Vol. 26, No. 1, pp. 46-50.

Nateghi, R., 2011, "Prediction of ground vibration level induced by blasting at different rock units", *International Journal of Rock Mechanics & Mining Sciences*, Vol. 48, pp. 899-908.

Nateghi, R., 2012, "Evaluation of blast induced ground vibration for minimizing negative effects on surrounding structures", *Soil Dynamics and Earthquake Engineering,* Vol. 43, pp. 133-138.

Ozer, U., 2008, "Environmental impacts of ground vibration induced by blasting at different rock units on the Kadıköy–Kartal metro tunnel", *Engineering Geology,* Vol. 100, pp. 82-90.

Pal Roy, P., 1998, "Characteristics of ground vibrations and structural response to surface and underground blasting", *Geotechnical and Geological Engineering*, Vol. 16, pp. 151-166.

Shi, X., Qiu, X., Zhou, J., Huang, D.,Chen, X., Gou, Y., 2016, "A Comparative Study of Ground and Underground Vibrations Induced by Bench Blasting", *Shock and Vibration*, Vol. 2016, pp. 1-9.

Silva, J., Worsey, T., Lusk, B., 2019, "Practical assessment of rock damage due to blasting", *International Journal of Mining Science and Technology*, Vol. 29, pp. 379-385.

Singh, P. K., Roy, M. P., 2008, "Damage to surface structures due to underground coal mine blasting: apprehension or real cause", *Environmental Geology,* Vol. 53, pp.1201-1211.

Singh, P. K., Roy, M. P., Paswan, R. K., Dubey, R. K., Drebenstedt, C., 2015, "Blast vibration effects in an underground mine caused by open-pit mining", *International Journal of Rock Mechanics & Mining Sciences*, Vol. 80, pp. 79-88.

Singh, T. N., 2004, "Artificial neural network approach for prediction and control of ground vibrations in mines", *Mining Technology*, Vol. 113, No. 4, pp. 251-256.

Singh, T. N., Singh, V., 2005, "An intelligent approach to prediction and control ground vibration in mines", *Geotechnical and Geological Engineering,* Vol. 23, pp. 249-262.

Siskind, D. E., Stagg, M. S., Kopp, J. W., Dowding, C. H., 1980, Structure response and damage produced by ground vibration from surface mine blasting, *Report for the U.S. Bureau of Mines*, Report of Investigatons 8507.

Torres, V. F.,N., Silveira, L. G. C., Lopes, P. F. T., De Lima, H. M., 2018, "Assessing and controlling of bench blasting-induced vibrations to minimize impacts to a neighboring community", *Journal of Cleaner Production,* Vol. 187, pp. 514-524.

Wang, Z., Fang, C., Chen, Y., Cheng, W., 2013, "A comparative study of delay time identification by vibration energy analysis in millisecond blasting", *International Journal of Rock Mechanics and Mining Sciences,* Vol. 60, pp. 389-400.

Yang, J. H., Lu, W. B., Jiang, Q. H., Yao, C., Zhou, C. B., 2016, "Frequency comparison of blast-induced vibration per delay for the full-face millisecond delay blasting in underground opening excavation", *Tunnelling and Underground Space Technology*, Vol. 51, pp. 189-201.

Zeng, Y., Li, H., Xia, X., Liu, B., Zuo, H., Zuo, H., Jiang, J., 2018, "Blast-induced rock damage control in Fangchenggang nuclear power station, China", *Journal of Rock Mechanics and Geotechnical Engineering*, Vol. 10, No. 5, pp. 1-10.

Zhen-xiong, W., Wen-bin, G., Ting, L., Jing-lin, X., Xin, L., 2016, "Blasting Vibration Generated by Breaking-Blasting Large Barriers with EBBLB", *Shock and Vibration*, Vol. 2016, No. 3, pp. 1-13.