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Evaluation of Blast-Induced Vibration Effects on Buildings: Case Study

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Abstract:
Background: Mining is an essential industry for supporting economic and societal development, but it does not come without environmental consequences. One of the most significant environmental impacts of mining is the fact that blasting practices used to facilitate the extraction of ore, can wreak havoc on buildings and other structures located in and around the affected mine site. This paper discusses the effects of mining blast on buildings, including the force of the blast wave, vibrations caused by the blast. A proposed equation is evaluated using field measurements results obtained from the Multi-channel process. Also, the comparison of field results with International Building Codes and others is presented.
Key Word: Blasting; Blast Induced Vibration, Limestone Mine; Field Measurements.

I. Introduction

The force of the blast wave generated from mining is one of the most common factors that can damage buildings. Blast waves are generated by the detonation of explosives and the subsequent release of energy. The force of the blast wave causes pressure changes in the atmosphere, which can lead to fractures and breaks in building components and can disrupt the overall stability of the structure. The intensity of the blast wave typically decreases over a greater distance away from the mining site, however, making it more challenging to consider when mitigating damage.

Additionally, mining blasts generate vibrations in the environment that can cause further damage to buildings. The propagation of these vibrations can extend over a great distance, and they have the potential to result in vibrations, strong enough to damage structural components. Buildings that are adjacent to a mining site usually experience the most significant effects from vibrational damage, although vibrations may still occur at more moderate levels of intensity in structures located farther away.

One of the biggest challenges that face companies using blasting operations are limiting the vibration levels in order to minimize or eliminate the possibility of damage to the nearby structures. Therefore, proper blasting design is necessary to ensure both the safety of employees and the protection of nearby structures from the vibration effects [Ak., et al],

Quarry of vibrations caused by blasts breaking rocks with explosives is a very popular method of extracting rocks [Coltrinari, et-al and Jacko, et al]. The adjacent civil properties must be little affected by the blasting procedure. To lessen the harm to the buildings and the health of the populace, this is an essential requirement [Gheorghiosu, et al].

To break or fragment rock, explosive energy is employed. However, this energy is not used in an entirely efficient manner. A portion of the energy escapes into the atmosphere, causing vibrations or an air explosion. Ground vibrations are another way that some of the energy escapes the blast site through the bedrock and surface soil [Malbašic, et al]. The material and massif are disturbed by waves of vibration in the air and soil, which causes them to move and shake when they are exposed to buildings or other structures. Airwaves affect the home above the walls, and earth vibrations enter the house through the basement or foundations.

Numerous studies have been carried out by researchers to forecast and optimize blasting efficacy. The conventional forecasting techniques rely on empirical models. The Kuz-Ram empirical model was altered [Zhu, et al.] in order to increase blasting block prediction accuracy. In order to anticipate blast vibration, the Sadovsky formulation's performance is compared with those of other empirical models [Matidza, et al.]. The application of intelligent algorithms to forecast blast-induced outcomes has increased recently. These include the prediction of direct blasting results, such as block degree [Wang] and throwing distance [Yu, Z.; Shi, et al], as well as the prediction of unfavorable impacts, such as back break [Khandelwal, et al], dust emissions [Bakhtavar, et al], and vibration [Mostafa]. Additionally, blasting affects how different production segments in open-pit mines operate [Kinyua, et al]. Bulk ore extracted using blasting, for instance, necessitates higher loading, transportation, and crushing expenses [Sadiq, R, et al]. Bulkiness and blast cracking also have an impact on crushing and grinding [Nielsen, K].

The variance in blasting outcomes is primarily caused by the varying contributions of explosive energy; that is, a smaller portion of energy (about 20–30%) is used for rock removal and fragmentation, while the majority of the energy is wasted in many unfavorable impacts [Armaghani, et al]. Among all the negative consequences, blasting-induced ground vibrations are thought to be the most dangerous [Bui, X., et al], contributing around 40% of the explosive energy [Faradonbeh, R, et al]. In open-pit mines, for instance, blasting vibrations have an impact on the explosives and crushers [Bakhtavar, E, et al]. Therefore, blasting-induced ground vibration should be tightly managed when there are significant buildings and unstable terrain around the blasting location [Nguyen, H, et al]. Peak particle velocity (PPV) is typically regarded as a critical measure of the intensity of blast-induced ground vibration [Hasanipanah, M, el al]. Many empirical models have been created and validated over time and have shown to be successful in PPV prediction [Murmu, S, et al]. Nevertheless, a review of the literature revealed that empirical models have lower accuracy [Ghasemi, E, et al and Ainalis, D, et al]. Prediction accuracy is therefore increased by using clever algorithms and adding more variables influencing PPV to prediction models [Shirani Faradonbeh, R ae al and Zhou, J et al].

Standards and regulations have been established for managing and protecting constructions from the harmful effects of air and ground vibration. These regulations differ from country to country based on the kind and quality of building materials. Furthermore, other propagation equations and damage criteria have been developed with differing degrees of success [F.J. Lucca, et al and B.Müller et al].

This paper uses multi-channel process and results of field measurements obtained from vibration instruments for about 2 years. The site of the study is near the Egyptian Cement Company (ECC) plant located at 15th of May city at Plot 27. There is an attempt to evaluate equation for ground excitation raised from mining blast effect based on field measurements. A comparison of field results with International Building Codes and others is presented.

II. Blast-induced ground vibration

A pressure wave is created around the blasthole's perimeter when an explosive charge detonates. By pushing the surrounding particles aside, the wave creates a seismic or vibration wave as it travels outward from the borehole. The measurement of this individual particle oscillation determines the intensity and level of blast vibration. Thus, ground vibration is the result of shaking caused by shockwaves dispersing out from blast holes, causing structural or aesthetic damage [Wyllie and Mah (2017)]. These seismic waves propagate outward and radially from the vibration source and quickly diminish with increasing distance from the source.

Engineers and regulatory bodies prioritize ground vibration above all other detrimental effects of blasting. This means that in order to reduce the possibility of blast disruptions, there must be sufficient control over explosive energy. The using delay detonators effectively is a great way to regulate vibration [Kaneko et al, Grobler, Schneider, and Cardu et al]. The authors emphasized that the use of detonators can reduce blast vibration, produce consistent and effective fragmentations, and alter the profile of blasted rocks to control over break, reduce comminution energy, and increase diggability.

Powder factor, the separation between the blast point and structures, the blast's geometry, and the structural characteristics of the rock mass are all directly related to blast-induced ground vibration [Joo et al.; Khandelwal and Singh; Elevli and Arpaz; Nateghi]. Although the distance to neighboring structures and the characteristics of the rock cannot be controlled, the powder factor can be estimated using models developed by different researchers [Langefors et al.; Duvall and Fogelson; Siskind et al.; Joo et al.; Dehghani and Ataee-pour; Mohammad Nejad et al.] in order to meet the maximum permissible limit of ground induced blast vibration.

The most popular and accurate predictor of blast-related ground vibrations is the peak particle velocity (PPV) [Kuzu and Ergin 2005; Dehghani and Ataee-pour 2011; Armaghani et al. 2014; Kumar et al. 2016). The basis for PPV evaluation is the observation that the total energy of ground motion produced after a blast varies inversely proportional to the square of the distance from the nearby structure to the blasting site and directly varies with the weight of detonated explosives.

Scaled distance (SD) has been used to estimate peak particle velocity of vibration with reasonable accuracy (Oriard 1971; Dowding 1985, 1992; Bui et al. 2019). The link between particle velocity and scaled distance is the most trustworthy way to relate blast geometry to ground vibration.

$$SD = \frac{R}{\sqrt{W}} \quad (1)$$

Where

W = the maximum mass of explosive detonated per delay (kg); and

R = the radial distance from the detonation point to the observation point (m).

The peak particle velocity is thus predicted using scaled distance, as shown in Eq. 2.

$$V = k(SD)^{\beta} = k\left(\frac{R}{\sqrt{W}}\right)^{\beta} \quad (2)$$

Where

V = peak particle velocity (mm/s);

k, β = site constants which are related to rock geologic factors.

However, the constants k and β are site specifics, The Standards Association of Australia (SAA, 1993) recommended (-1.6) for β, and suggested criteria for selecting k values as follows:

- (Under confined conditions) - hard or highly structured rock, k = 500;
- Free-face average (normal confinement), k = 1140;
- Heavily (over) confined, k = 5000.

III. Geologic setting

The studied area's formation (Figure 1) consists of marl and marly limestone with clay intercalations at its upper portion. The thicknesses of these layers comprise 50 to 80 meters. The Qurn Formation is divided into five units. As seen in the composite geological section (Figure 2), the first unit (at the base) is made up of large crystalline limestone interbedded with argillaceous limestone [Adel M.E. Mohamed and Abuo El-Ela A. Mohamed].

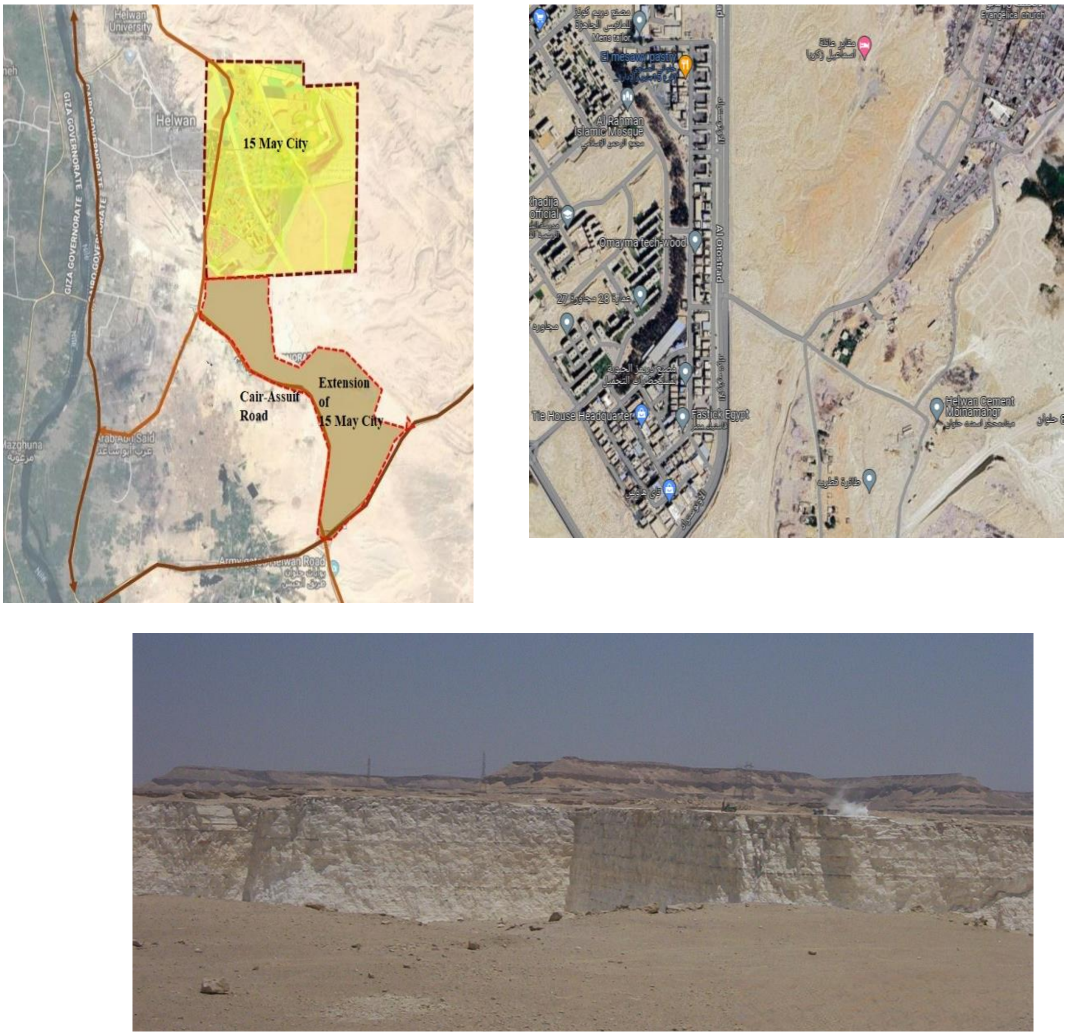

Fig. 1 Location maps and limestone mining of the studied area

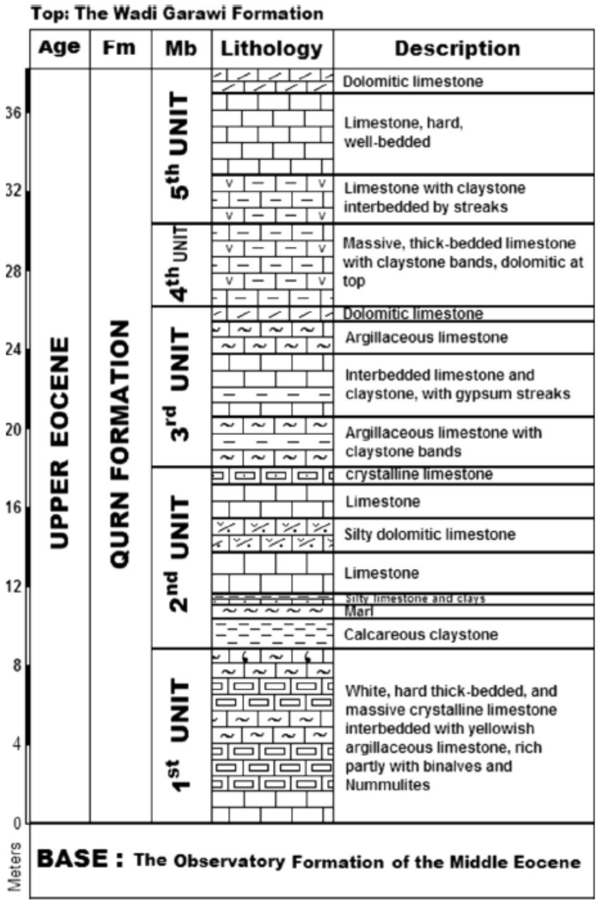

Fig. 2 The composite geological section at the area of interest [Adel M.E. Mohamed and Abuo El-Ela A. Mohamed].

IV. Instrumentation and data measurement

Direct in situ measurement systems are the technique used to measure the variation of PPA (peak particle acceleration). Blast-induced vibrations were monitored for the studied area along 8 months. The system used for measurements include three components:

1 Sensors for measurements.
2 Equipment for acquiring data: an electrical device called a data acquisition (DAQ) system is made to gather and store the data that measuring sensors pick up. In this work, two systems are used. The first one is LMS SCADAS Recorder system manufactured by Siemens [Tarek M. Alguhane- A.M. Ismail]. The second one is PULSE 3650-B manufactured by Bruel & Kjaer.
3 Efficient software to record and analyze field measurements.

Dynamic extraction cannot begin until recorded sensor data has been altered. Amplification, filtering, and signal conversion —such as from analog to digital, digital to analog, or frequency to voltage—are the common signal alteration techniques. The level of an electrical signal, which is indicated by variables like voltage, current, and power, is known as signal amplification. In order to avoid certain errors that stem from weak signals, the signal strength should consistently exceed a designated transmission threshold. Signal amplification can be employed to address some errors that arise from signal weakness. By removing some unnecessary signals, filtering enhances vibration monitoring and analysis performance. These signals are typically generated by noise in system components, error components in excitations, and various external disturbances. It is common to convert analog to digital. The system's general layout is shown in Figure 3. For eight months, blast-induced vibrations in the study area were observed. Only thirty-eight of the recorded values for blast magnitude, distance, PPV, and FFT analysis of the frequencies of vibration record are given in Table 1.

a. Typical setup of transducer-data acquisition pair | b. PCB 626B13 sensor

Fig. 3 Measurement system

Figure 4 shows results obtained from LMS SCADAS system. Some of the obtained blast time history record in the studied area are shown in Figure 5. Figure 6 shows the Fast Fourier Transform (FFT) analysis of the same blast event.

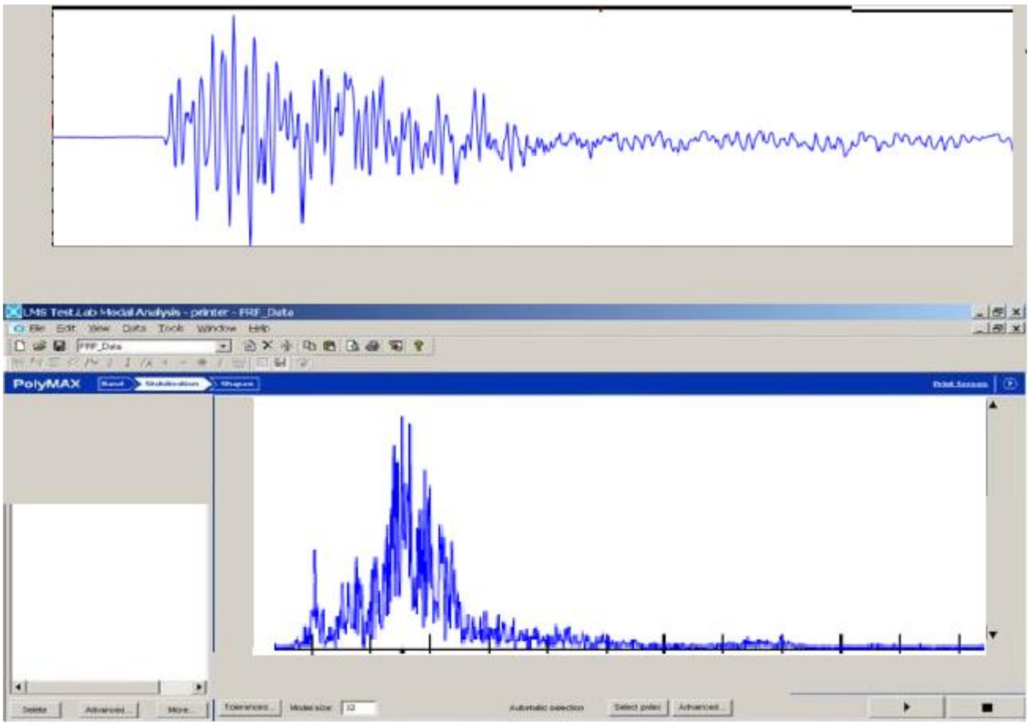

Fig. 4 LMS SCADAS sample record

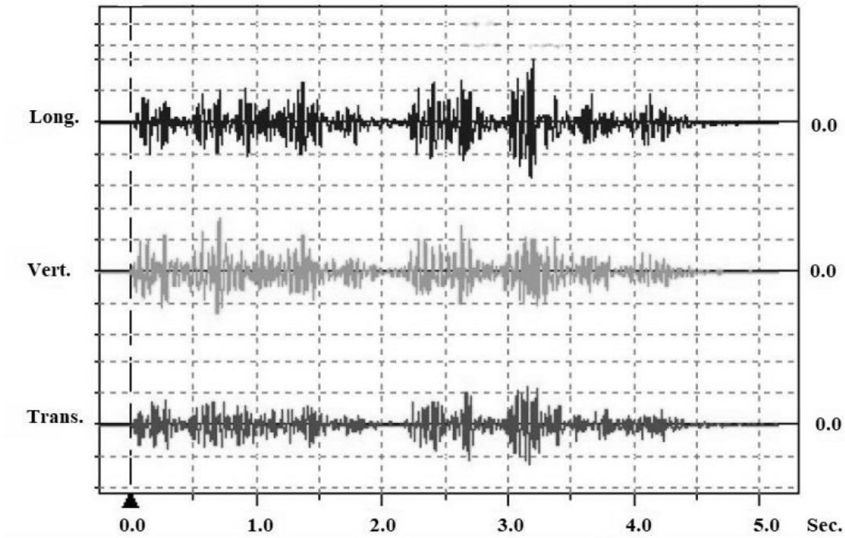

Fig. 5 Typical blast time history

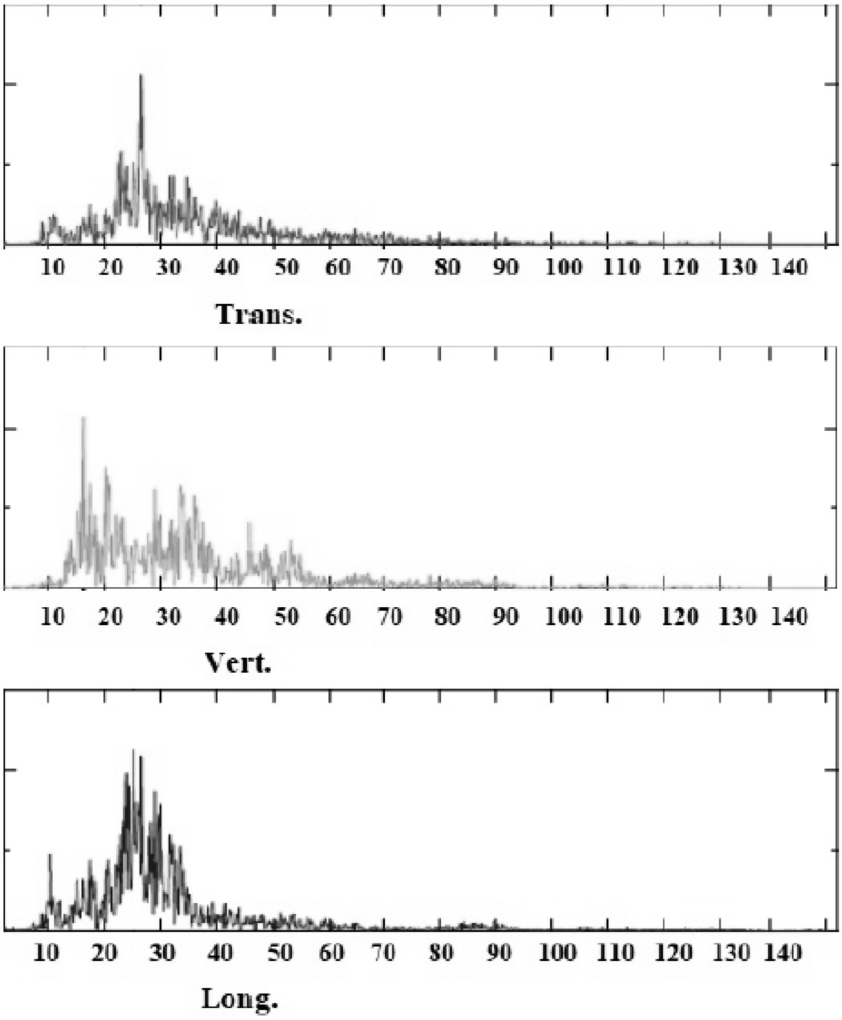

Fig. 6 FFT analysis of frequencies of vibration record

Table 1 The parameters of the 38th recorded events due to quarry blasting

No.	W(kg)	R, m	Long.		Trans.		Vert.	
			PPV (mm/s)	*f* (Hz)	PPV (mm/s)	*f* (Hz)	PPV (mm/s)	*f* (Hz)
1	2547	352	58	31	54	7	20	6
2	4664	454	60	11	57	23	30	14
3	4665	560	47	5	44	8	10	42
4	4660	616	41		39	8	14	7
5	4656	616	41	7	39	8	14	56
6	4657	616	41	10	39	9	14	56
7	4655	616	41	6	39	8	14	9
8	4661	616	41	6	39	8	14	10
9	4653	616	41	7	39	7	14	10
10	1850	528	27	8	26	53	45	11
11	1850	728	17	41	17	32	46	33
12	1850	1000	11	25	11	30	43	52
13	960	600	14	23	14	23	43	33
14	1850	784	15	29	15	30	48	34
15	1850	776	16	29	16	30	46	34
16	3000	1456	9	26	9	27	25	38
17	1000	456	21	40	21	25	61	45
18	1000	552	16	38	16	46	61	59
19	1000	496	19	39	19	39	61	39
20	3000	1384	10	35	10	35	15	57
21	3355	1072	15	28	15	33	25	33
22	3355	1408	10	23	11	35	13	37
23	3355	1440	10	33	10	32	13	22
24	3355	1320	11	27	12	28	20	51
25	3355	1368	11	24	11	22	13	6
26	2985	1104	13	41	14	6	13	7
27	2985	1056	14	39	14	6	15	7
28	2985	1040	15	50	15	34	46	52
29	2985	1080	14	40	14	2	24	38
30	2985	960	16	46	16	43	15	8
31	2985	1048	14	43	14	3	28	32
32	2985	888	18	40	18	2	30	40
33	2985	1048	14	5	14	5	10	5
34	3720	2500	5		5			
35	2800	1200	12		12			
36	2640	2500	4		4			
37	3140	1800	7		7			
38	2480	1600	7		7			

V. Improved Expression to Estimate PPV (mm/s)

Equation 2 represents the general formula for PPV in (mm/s), as was mentioned in the introduction. In which k, β = site constants are related to rock geologic factors. By using the regression analysis technique for the recorded events gives the following values:-

K=725

β = -1.318, the Equation 2 will be (for the studied events and area):-

$$V = 725\left(\frac{R}{\sqrt{W}}\right)^{-1.318} \quad (3)$$

The ratios between the revised observed and predicted values of the PPV (mm/s) from Equation 3 are displayed in Figure 7. This figure makes it evident that the adjusted observed and predicted PPV show a strong association.

The statistics' goodness of fit has been examined. Table 2 displays these checked regression analysis results together with the associated mathematical features.

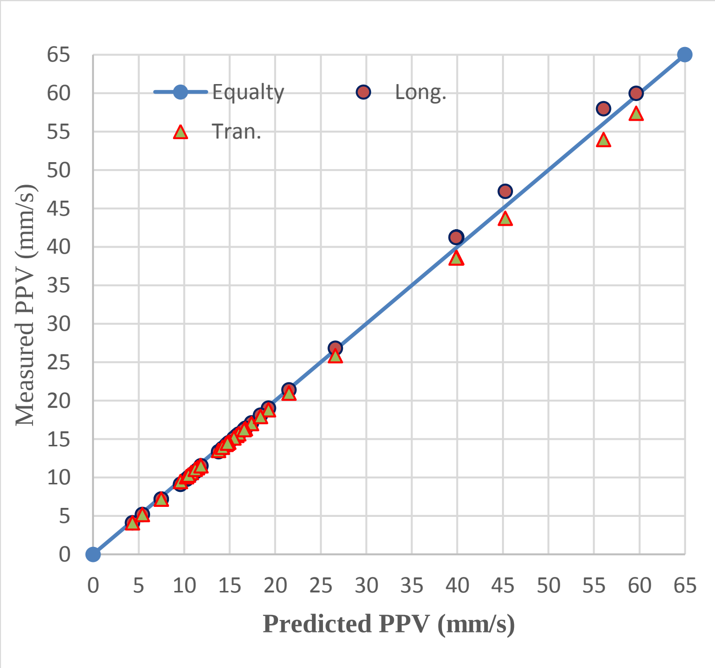

Fig. 7 Verification of PPV obtained from proposed equation $V = 725\ (\frac{R}{\sqrt{W}})^{-1.318}$

Table 2 Regression Variable Results

Variable	Variable Value	Standard Error	t-ratio	Prob. (t)
k	725	43.11	16.82	0.0
β	-1.318	2.576E-02	51.15	0.0

VI. Safe Limit Criteria

The International Standards ISO 4866-1990 enumerates several principal ground vibration rules for various building types. Moreover, it has long been maintained that damage may be connected to the ground vibration's PPV (Duvall and Fogelgon; Wiss; IEE, 1998).

The generally accepted standard for the safe-limit vibration against structural and threshold damage of buildings resulting from ground vibrations created by blasting was developed during the course of a ten-year study program of the United States Bureau of Mines (USBM). 51 mm/s was chosen as the safe limit for the resulting PPV within the frequency range of 3–100 Hz. This cap was unable to stop the numerous complaints from locals about construction/mining blasting.

An alternative USBM frequency-based safe limit was presented to account for the effect of the dominant vibration frequency when assessing the ground vibration effect on structures. This criterion, which protects against blast-related ground vibrations, is called USMB-RI 8507 (Figure 8). The US Office of Surface Mining (OSM) modified the USMB-RI 8507 criterion. It is graphically displayed in Figure 8 and contrasted with the USMB-RI 8707 criterion.

Figure 9 plots the British Standard BS 7385 criterion for the safe limit against blast-related ground vibrations and compares it to the OSM criterion. It closely complies with OSM and USBM-RI 8507 requirements. Depending on the kind of building, BS 7385 uses one of two lines for the safe limit: line 1, which is used for big commercial buildings regardless of the frequency of vibrations, and line 2, which is frequency based, is used for smaller or residential buildings.

Figure 9 also plots the DIN 4150 and the Swiss Standards for safe limits against ground vibrations caused by blasting. It is clear that these two standards are noticeably stringent. The DIN 4150 criterion is said to be non-damage-based; rather, its goal is to lessen the complaints and perceptions of dwelling occupants who are close to blasting sites.

Graphs for the limiting of PPV against the explosive charge's weight and related distance are provided by Egyptian Code 202/6-2001. It also provides an investigative reference for anticipated building element damage or human impact in comparison to the PPV. Egyptian Code 202/6-2001 did not consider ground movement frequency for determination of safe limit.

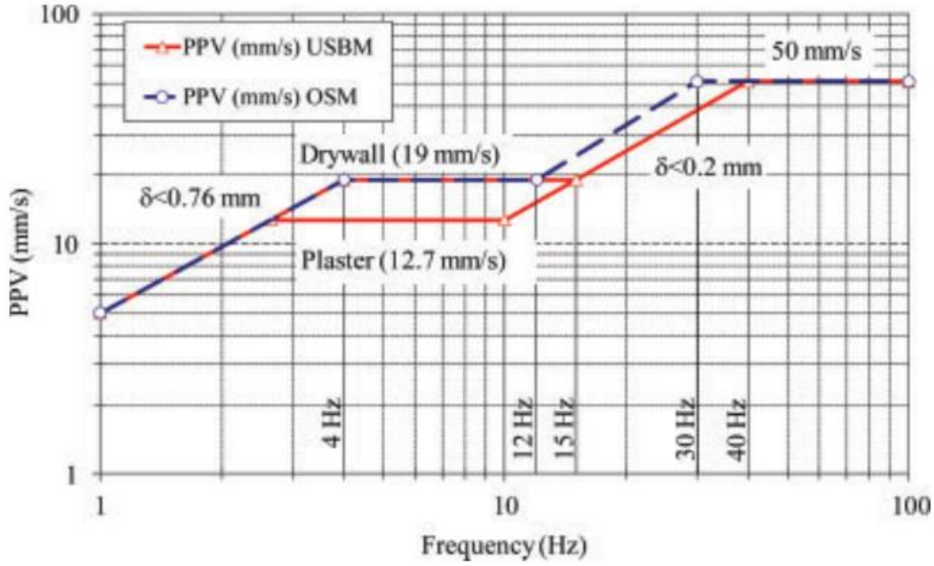

Fig. 8 USBM and OSM safe limit criteria against ground vibrations due to subsurface blasting.

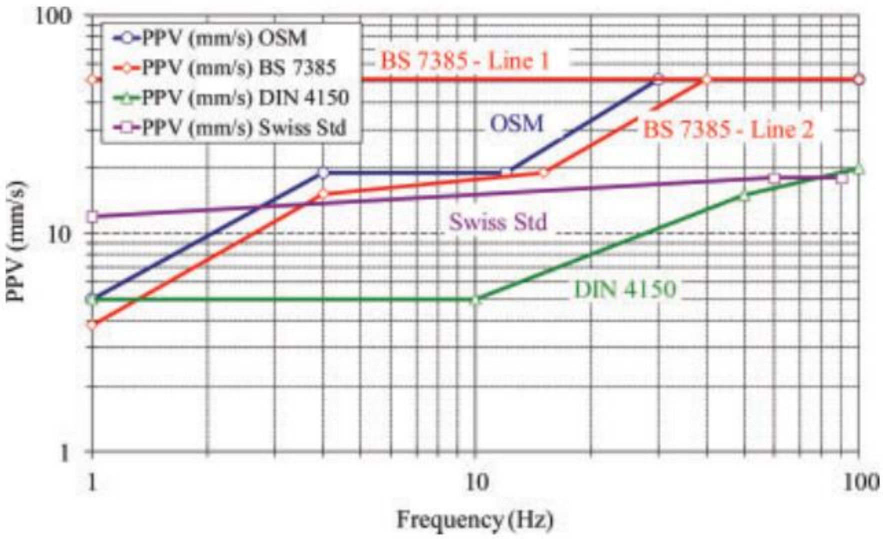

Fig. 9 Safe limit criteria against ground vibrations due to subsurface blasting.

VII. Applicability of the safe limit criteria of international standard (codes) on the measured events

For the studied area at 15th of May City plot 27 under ten recorded events, the Egyptian Code ECP202/6-2001 shows that these events do not affect the main structural elements as PPV is less than the effected values for most events as shown in Figure 10. There are less than five percent of events that require attention. However, complaints were made from many people who blamed the blasting operation for causing threshold cracks to their houses. Applying ECP202/6-2001 demonstrates, as Figure 11 illustrates, that human suffering exists.

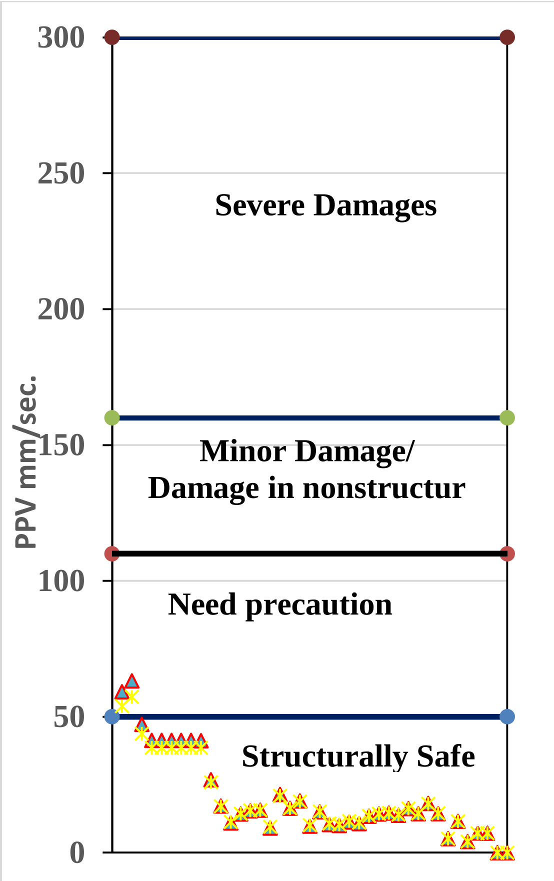

Fig. 10 Guide for the estimation of the probability of damage due to subsurface blasting (ECP-202/6-2001-pp58)

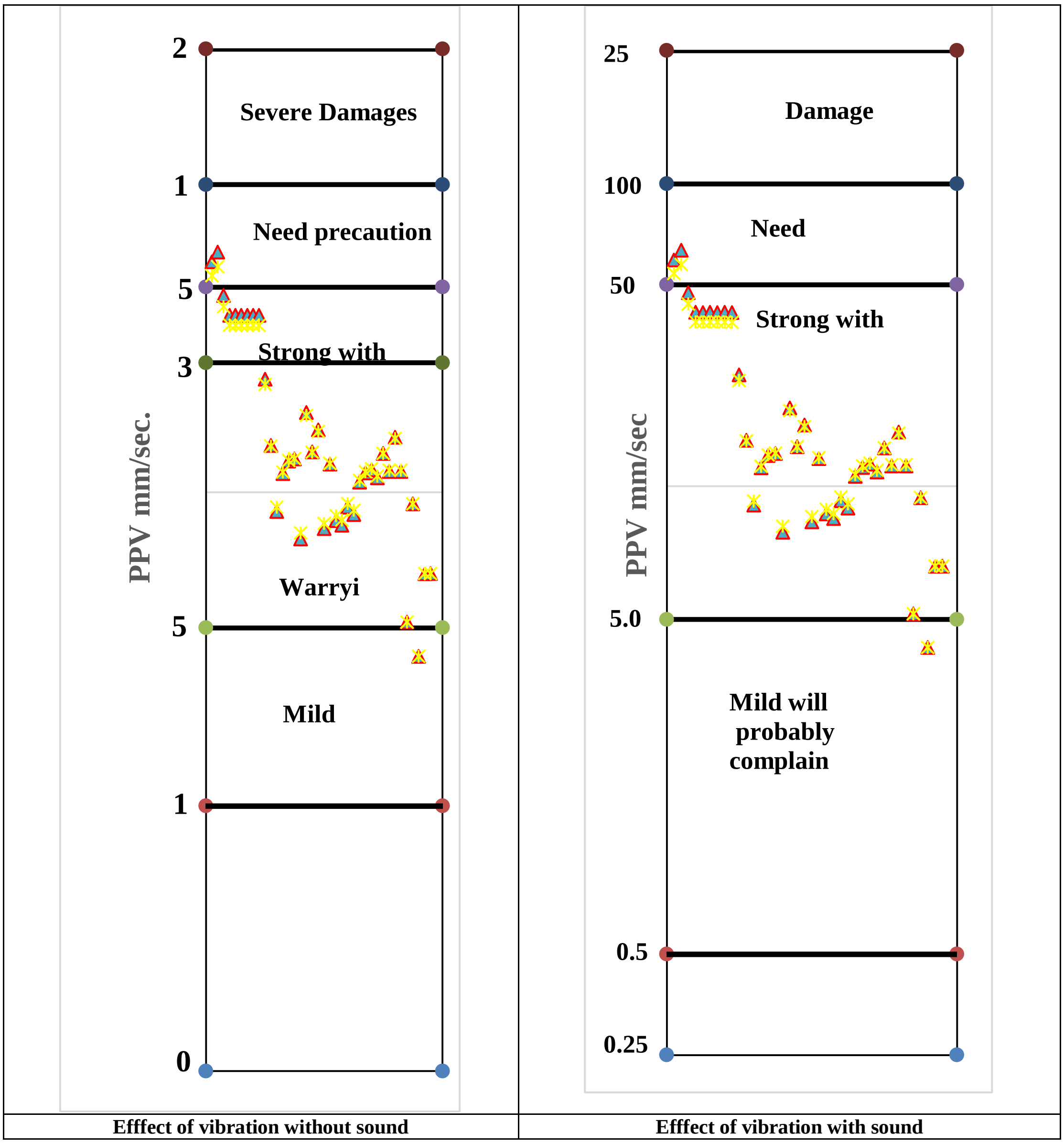

Fig. 11 A guide for estimating the harm that a subsurface blasting would bring to human comfort (ECP-202/6-2001-pp60)

Plotting the observed PPV with associated FFT response to British Standard BS 7385 OSM, USBM-RI 8507, DIN 4150, the Swiss Standards requirements, and Seoul Subway requirement is done while taking into account the frequencies of subsurface blasting, as seen in Figure 12. Approximately 18% of the occurrences did not satisfy the safe limitations of BS 7385, OSM, USBM, DIN 4150, and Seoul Subway, depending on the kind of construction. Furthermore, it could trigger safer damage in non-structural items like DIN 4150. Since almost 60% of the recorded occurrences did not meet the necessary safe threshold, the Swiss criterion is more stringent.

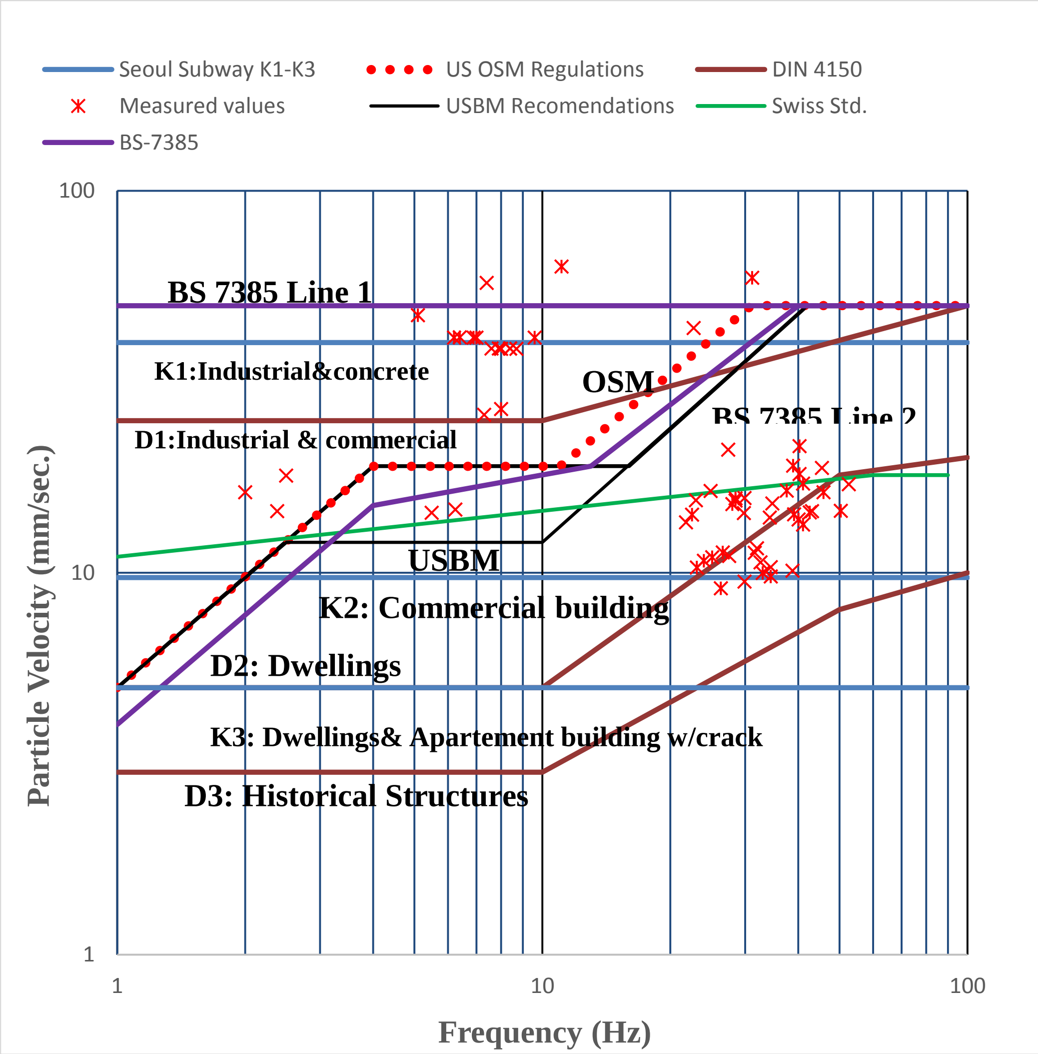

Fig. 12 Subsurface blasting effects vs international standards

VIII. CONCLUSIONS

The overall goal of this research has been to develop empirical formula for forecasting blast-induced vibration in limestone mines for the studied area developed from field measurements. The field measurement findings were analyzed and interpreted using the commonly used peak particle velocity predictors after the necessary data and parameters were recorded.

The paper discussed the currently accepted safe limit standards for vibrations caused by subsurface blasting that occur above ground. None of these requirements addresses resonance or damage in structural elements, which can happen to a residential structure when it is exposed to low-frequency ground vibrations. To ensure the safe limit criteria, frequency effects must be added to the ECP202 subsequent generation.

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