Environ Geol (2006) 50: 1015–1023
DOI 10.1007/s00254-006-0274-5

ORIGINAL ARTICLE

Ali Kahriman
Umit Ozer
Mehmet Aksoy
Abdulkadir Karadogan
Gungor Tuncer

Environmental impacts of bench blasting at Hisarcik Boron open pit mine in Turkey

Received: 28 February 2006
Accepted: 21 March 2006
Published online: 11 April 2006

A. Kahriman · U. Ozer (✉)
M. Aksoy · A. Karadogan · G. Tuncer
Mining Engineering Department,
Istanbul University, 34320-Avcilar,
Istanbul, Turkey
E-mail: uozer@istanbul.edu.tr
Tel.: +90-212-4737070

Abstract This paper presents the results of ground vibration measurements carried out in Hisarcik Boron open pit mine located on the west side of central Anatolia near Kütahya province in Turkey. Within the scope of this study to predict peak particle velocity (PPV) level for this site, ground vibration components were measured for 304 shots during bench blasting. In blasting operations, ANFO (blasting agent), gelatin dynamite (priming), and delay electric detonators (firing) were used as explosives. Parameters of scaled distance (charge quantity per delay and the distance between the source and the station) were recorded carefully and the ground vibration components were measured for all blast events using two different types of vibration monitors (one White Mini-Seis and one Instantel Minimate Plus Model). The absolute distances between shot points and monitor stations were determined using GPS. The equation of square root scaled distance extensively used in the literature was taken into consideration for the prediction of PPV. Then, the data pairs of scaled distance and particle velocity obtained from the 565 event records were analyzed statistically. At the end of statistical evaluation of the data pairs, an empirical relation which gives 50% prediction line with a reasonable correlation coefficient was established between PPV and scaled distance.

Keywords Blasting · Environmental impact · Ground vibration · Air blast

Introduction

The environmental problems arising from ground vibration and air blast have been faced and discussed frequently in various industries such as quarry, mining, civil works, shaft, tunneling, pipe line, and dam construction where the blasting operations are unavoidable. For this reason, in bench blast design, not only the technical and economical aspects, such as block size, uniformity, and cost, but also the elimination of environmental problems resulting from ground vibration and air blast should be taken into consideration. The prediction of ground vibration components plays an important role in the minimization of the environmental complaints. In recent years, one of the problems encountered by technical personnel who are responsible for the excavation with blasting is rightful or unjustifiable complaints of people or organizations in the neighborhood (Felice 1993; Ozdemir et al. 2004; Tuncer et al. 2003).

The number of these kinds of real or psychological disturbances has gradually increased with the increase of the population and urbanization. Therefore, an economical and safe blasting should simultaneously eliminate these kinds of problems. For this reason, one of the significant aspects of a good blasting is to be safe in terms of environmental effects. One of the requirements to be met by blasting design is to determine maximum amount of explosive per delay for a certain distance especially in large blasts and to be able to realize controlled blasting for the elimination of these environmental problems (Johnston and Durucan 1994; Karadogan et al. 2004; Kahriman et al. 2005). Environmental problems arising from blasting have been experienced in the developed countries a long time ago when compared to Turkey. Therefore, systematic research programs have been carried out to solve these problems and to set standards related to this subject. As result of these researches, the principles of controlled blasting techniques have been revealed.

Experimental studies by explosive producers and users are being continued to determine the effects of ground vibrations and air blast induced by blasting and to be able to take necessary precautions. Legal regulations related to this subject are being developed (Singh 1993; Kahriman et al. 2002; Kahriman 2002).

The purpose of this research is to measure environmental problems such as ground vibrations and air blast induced by blasting on the basis of the shots fired during the overburden excavation works at Hisarcik Boron open pit mine that is located on the west side of central Anatolia near Kütahya province in Turkey, and also to evaluate whether surrounding structures will suffer from the damage because of the fact that the open pit mine is located very close to Hisarcik town, by as close as 400 m.

Test site descriptions

Within the scope of this study, ground vibrations and air blast have been measured at Hisarcik Boron open pit mine during the overburden excavation. The location of this site is shown in Fig. 1 (Kahriman et al. 2006) and the layout in Fig. 2.

The geology and mineralization

The geology and mineralization of Hisarcik deposit and Emet deposit was studied by Helvaci and Alonso (2000) and is described as follows:

The Miocene sequence in the Emet area rests unconformably on Palaeozoic metamorphic rocks comprising marble, mica schist, calc-schist and chlorite schist. This Miocene sequence consists of the following units in ascending order: conglomerate and sandstone; a thin-bedded lower limestone with lenses of marl and tuff; intermediate and acid volcanics, tuff, and agglomerate; a red unit containing conglomerate, sandstone, clay, marl, limestone with coal, and gypsum bands; clay, tuff, tuffite, and marl containing the borate deposits; an upper limestone containing clay, marl, and chert layers; and a capping basalt (Fig. 3).

Fig. 1 Location of the test site in Turkey

The borates are interlayered with tuff, clay, and marl with limestone occurring above and below the borate lenses. The principal borate mineral is colemanite with minor ulexite, hydroboracite, and meyerhofferite. Montmorillonite, illite, and chlorite are the only clay minerals that have been identified; montmorillonite is the dominant clay mineral in all the samples and occurs as Al-, Mg-, or Al–Mg–Fe montmorillonite. Illite is only a minor component and is distributed randomly. Chlorite is widely distributed within the deposits and is relatively abundant near or within the horizon of tuffs and tuffites. Zeolites are abundant along the tuff and tuffite horizons. Native sulfur, realgar, orpiment, and celestite occur in the borate zone throughout the area. Gypsum associated with borate minerals has been observed in the southern deposits. Calcite is also found in outcrops and adjacent to faults as a result of recent weathering of borates. Boron-bearing K-feldspar, clinoptilolite, illite,

Fig. 2 Layout of the test site and benches

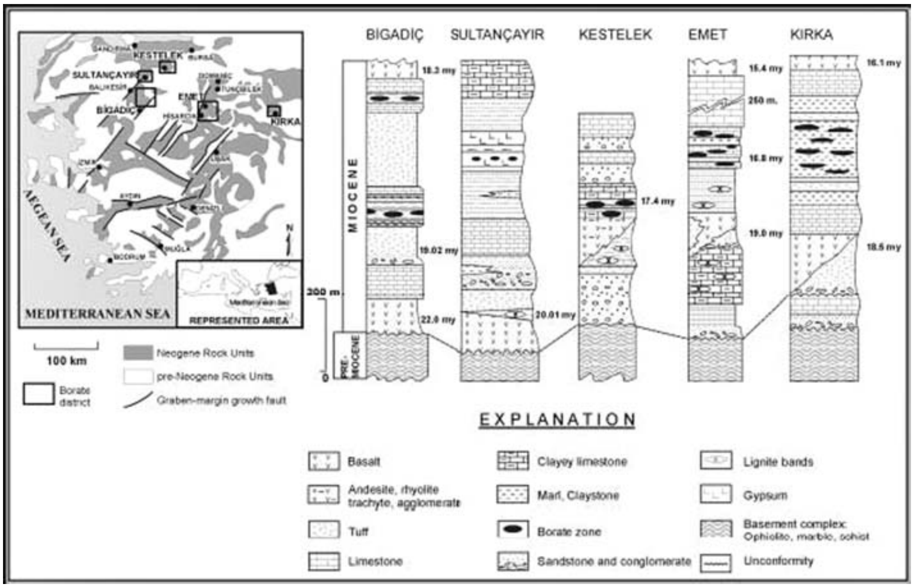

Fig. 3 Location of Miocene borate deposits in extensional rifts, and the stratigraphic sections of borate-bearing Miocene basins in western Turkey (Helvaci and Alonso 2000)

and smectite are the authigenic silicates detected in the tuffaceous samples. Volcaniclastic high sanidine and quartz are also present.

The Emet borate deposits were formed in two separate basins, possibly as parts of an interconnected lacustrine playa lake, in areas of volcanic activity, fed partly by thermal springs and partly by surface streams. Thermal springs associated with local volcanic activity are thought to be the source of the borates. The initial brines from which the borates crystallized are deduced to have been high in sulfite and sulfate and low in chloride, and hence it is assumed that they were fed at all times by abundant calcium and boron with minor amounts of arsenic, strontium, and sulfur. Realgar, celestite, and native sulfur are almost ubiquitous in borates and sediments, and appear to have formed at all stages during deposition and diagenesis. The unit of clay, tuff, tuffite, and marl containing the borate deposits has abundant realgar and orpiment in some horizons indicating that arsenic and boron have a genetic relationship and a volcanic origin at Emet.

The early colemanite, meyerhofferite, ulexite, and teruggite nodules were probably formed directly from brines penecontemporaneously within the unconsolidated sediments below the sediment–water interface and continued to grow as the sediments were compacted. Later generations of colemanite occur in vugs, veins, and as fibrous margins to colemanite nodules. Tunellite appears to have formed during diagenesis with enrichment of Sr in some places. Diagenetic alterations include the partial replacement of colemanite by veatchite-A, cahnite, hydroboracite, and calcite.

The bulk of the volcanic tuffs and tuffites appears to have been derived from volcanic terrains, but Tertiary limestone might also have been exposed, and erosion of these may have contributed Ca and Sr to the lake waters. Alternatively, Ca and Sr may have been leached from the underlying limestone and basement metamorphic rocks by thermal spring waters.

It may be assumed that the initial brines at all times contained an abundance of calcium and boron with minor amounts of arsenic, sulfur, strontium, magnesium, and sodium. All early precipitated minerals seem to have formed within the clastic sediments. The brines were evidently rich in Ca and B in both the northern and southern basins, and Ca borates are present at every horizon throughout the sequence. Field and petrological evidence demonstrates that Ca borates, ulexite, and teruggite crystallized within the sediments and did not precipitate from open water. The co-precipitation of ulexite and later diagenetic formation of tunellite apparently occurred infrequently in the northern basin and not at all in the southern area.

Field and textural evidence clearly indicates the sequence Ca borate → Ca–Na borate → Sr borate. Arsenic-bearing borates and Sr borates do not occur together in the Emet deposits, although arsenic sulfides do occur at the same horizon with Sr borates and sulfate. It is not known whether this condition reflects a genuine incompatibility or merely the scarcity of teruggite and cahnite. Both lateral and vertical changes from calcitemarls to colemanite-bearing clays have been observed and a gross zoning both laterally and vertically from calcite to colemanite and back to calcite seems to be typical of both areas. In the southern area, the sporadic occurrence of gypsum suggests that where sulfates are present, the sequence is calcite → gypsum → colemanite (Helvaci and Alonso 2000).

Test procedure

In this study, Schmidt hammer tests were initially performed as an addition to the observation of the blasting activities in order to determine the digging classification level of the overburden material (limestone) for Hisarcik Open-Pit Boron Mine (Table 1). Second, rock hardness descriptions were made by evaluating the Schmidt hammer test results according to the Rock Hardness Classification, which is approved by International Society of Rock Mechanics (ISRM).

These results and hardness values of the limestone proved that blasting is unavoidable for the excavation of these rock units because of technical and economic reasons.

Within the scope of the current research, ground vibration induced by blasting was measured for estimating damage risk and site-specific attenuation for Hisarcik Open-Pit Boron Mine. While measured distances were recorded for the 304 shots for this site, the ground vibration components were measured by using the two vibration monitors (one Instantel Minimate Plus Model and one White Mini-Seis Model).

In order to measure the environmental effects of these blasts, two station points were chosen at this site. The monitoring station point number 4 is located near the closest building. The location of the other station varied depending on the location of shot points along the open pit mine—in the direction of Hisarcik town.

Blasting patterns being applied at the mine have been observed and investigated. As a result of investigations, it was understood that the blasting model is bench blasting. The blasting patterns, drilling patterns, and explosive charges at the shots have been observed and no changes have been done in these patterns and charge amount. In other words, both blasting pattern and the charging process were designed by blasters of the company and the vibrations have been measured simultaneously on the surface. Only necessary quantitative measurements and observations have been performed at the shots on which vibration monitoring will be based. The patterns and protocols applied by the company during the shots have been used in the derivation of the necessary data (Kahriman et al. 2006).

In blasting operations at this site, ANFO (blasting agent), gelatin dynamite (priming), and delay electric detonators (firing) were used as explosives. Applied design parameters for some of the shots are given in Table 2.

Table 1 Results of Schmidt hammer test

Test no.	1
Formation	Limestone
Hammer position	Horizontal
Number of points	10
Arithmetic mean	54.90
Standard deviation	±3.70
Rock hardness classification	Quite strong

In the predictions of ground vibration, although a lot of empirical relations have been established and used by different researchers in the past, the most reliable relations are those of accepting the scaled distance and particle velocity, which have been used as the basis in the present study. The scaled distance is a concept that utilizes the amount of explosive creating energy in air shock and seismic waves, and the effect of distance.

During the bench blasting, the distances between shot points and monitor stations were determined using GPS. The scaled distance is derived by a combination of distance between source and measurement points, and maximum charge per delay. The equation used for the scaled distance is given below:

$$\mathrm{SD} = \frac{R}{W_{\mathrm{d}}^{0.5}}$$

where: SD, scaled distance; R, distance between the shot and the station (m); and W_{d}, the maximum charge per delay (kg).

On the other hand, the formula given below, which is used extensively in most of the investigations, has been used as a predictor for the estimation of the peak particle velocity (PPV):

$$\mathrm{PPV} = K \times (\mathrm{SD})^{-\beta}$$

where: PPV, peak particle velocity; K, ground transmission coefficient; β, specific geological constant.

To assure the reliability of the second equation, the attenuation formula must be adjusted statistically to 95% confidence level and the "goodness of fit" or coefficient of determination (r) of the data should not be less than 0.7. The standard deviation, used in establishing the confidence level, should be as close as possible to zero. When the goodness of fit is too low, below 0.7 or so, this is an indication that there is some problem

Table 2 Applied design parameter for some of the shots

Shot no.	1	10	50	100	200	300
Bench	800	800	790	780	780	770
Number of holes	32	15	10	11	48	64
Diameter, d (mm)	171	171	171	159	89	89
Slope, α (°)	90°	90°	90°	90°	90°	90°
Bench height, K (m)	6	5	7	3	6	3
Number of lines	2	2	1	1	3	3
Hole length, H (m)	5	6.5	5.5	6	6	3
Burden, B (m)	5	4	4	5	2	2
Spacing, S (m)	4	5	5	6	3	3
Stemming, h_0 (m)	2	3.5	3.5	4	4	2
Priming (kg)	24	19	8	6	18	30
Total charge, Q (kg)	1,624	919	460	333	898	638
Maximum charge per delay, W_{d} (kg)	102	61	46	31	76	42
Number of detonators	32	15	10	11	48	64

or inconsistency in the data. When it occurs, a review of the data and test procedures is advisable and a series of additional tests must be carried out (Costa et al. 1996; Kahriman et al. 2006).

Measurement results

Within the scope of this experimental study, the shots for which the application conditions such as location, pattern, and charge are explained above in detail, the particle velocity of vibration inside the rock and frequency values have been recorded by using two vibration monitors. In the blasting records, the geophones were located at the measurement stations as mentioned above.

The results of ground vibration measurements of 565 events recorded in 304 shots carried out at the test site, including PPV, total charge per delay, distance, and scaled distance are presented in Table 3.

The statistical analysis of measurement results

When statistical analysis techniques are applied to blast vibration data pairs, PPV and scaled distance give a site-specific velocity attenuation equation. Statistically, a sufficient number of blasts (at least 30 events) have to be planned so that enough data can be gathered to develop a similar formula. Within the scope of this study, enough data sets have been obtained in accordance with the statistical rule of thumb (Kahriman et al. 2004).

In order to establish a useful relationship between PPV and scaled distance, simple regression analysis was performed using the 565 data pairs obtained from this site. In simple regression, linear, logarithmic, exponential, reciprocal, and power curve fitting approximations were tested. As a result, imposed field constants for prediction of PPV on controlled blasting activities at this site are explained by the equation with a reasonable correlation coefficient as given below:

$$\mathrm{PPV} = 561 \times \mathrm{SD}^{-1.432} \quad (r = 0.71)$$

From this, the field constants are determined as $K = 561$ and $\beta = -1.432$, respectively. In this study, an empirical site-specific relationship with a reasonable correlation has been established between PPV and scaled distance for this site.

The result of the regression and correlation are presented in Table 4, which shows the statistical calculations using the full data set. It presents standard

Table 3 Results of ground vibration measurements

Shot no.	Date	PPV (mm s^{-1})	F^{a} (Hz)	N^{b} (dB)	Q^{c} (kg)	W_d (kg)	R (m)	SD
1	18.12.04	9.65	14.6	*	1,624	101.5	104	10.32
2	18.12.04	31.49	12.1	*	515	39.0	44	7.05
3	20.12.04	3.56	10.0	*	916	87.3	246	26.33
4	20.12.04	2.54	12.1	*	538	38.4	204	32.91
5	21.12.04	2.54	4.9	*	1,625	101.6	286	28.37
10	07.01.05	1.14	85.0	119.2	919	61.0	679	86.94
20	21.02.05	1.02	100.0	114.8	1,789	204.0	552	38.67
30	14.03.05	2.54	7.7	*	919	77.0	313	35.67
40	22.03.05	1.02	21.3	118.0	1,173	102.0	494	48.91
50	25.03.05	1.02	11.9	110.0	460	46.0	589	86.84
60	31.03.05	1.02	102.4	100.0	615	39.0	320	51.24
70	04.04.05	7.87	7.8	123.2	1,457	102.0	384	38.02
80	07.04.05	3.43	10.0	115.6	818	51.0	178	24.92
90	11.04.05	3.17	9.1	112.0	563	51.0	209	29.27
100	29.04.05	1.02	100.0	110.0	333	31.0	244	43.82
120	06.05.05	9.40	13.0	114.2	256	25.7	183	36.12
140	13.05.05	0.38	100	110.2	255	51.0	253	35.39
160	23.05.05	109.00	7.1	129.1	712	44.5	69	10.34
180	07.06.05	35.20	18.0	127.6	463	51.0	65	9.17
200	05.07.05	8.25	7.8	130.9	898	75.9	151	17.36
220	08.07.05	4.57	16.0	142.6	1,027	153.8	311	25.07
240	13.07.05	11.20	11.0	126.5	1,027	102.7	234	23.13
260	17.07.05	13.30	16.0	125.6	1,033	82.6	295	32.48
280	21.07.05	1.78	11.0	121.9	1,338	115.6	235	21.82
300	30.07.05	48.90	34.0	144.0	638	42.3	137	21.06
304	30.07.05	23.90	51.0	113.5	722	42.5	84	12.91

[a]Frequency
[b]Air blast
[c]Total charge
*Microphone was not connected

summary output from an SPSS (Version 11.5) regression analysis performed within the data analysis tool. The R^2 quantity is a basic measure of the quality of the fit. In this case, a value of 0.5076 indicates that 50.76% of the PPV variability is explained by the linear regression.

The intercept coefficient is obtained from the linear regression in the log–log transformed space. Note that $10^{2.7490}$ equals 561, which is in agreement with Fig. 4. Finally, the critical slope value of −1.432 is easily extracted from the summary output.

It must be taken into consideration that its use in the blast design could give erratic results. In order to support this formula, more events should be monitored in various directions and the regression analysis should be updated, considering the results of further measurements.

At the end of evaluation of the data pairs, an empirical relation, which gives 50% prediction line with a reasonable correlation coefficient was established between PPV and scaled distance. The prediction of particle velocity requires that average and upper bound values should be well known. The upper 95% prediction limit line, which was generated from standard error and data distribution curve, has been shown in Fig. 4.

Hence, given a particular scaled distance, it can offer a best guess as to the PPV as well as upper 95% prediction limit below which future blasts are expected to occur (Dowding 1985; Johnson et al. 2000; Kahriman et al. 2004).

This case study has proven that it can be possible to design reliable blasts using this formula on the site as an important approach when vibration monitor is not available as a PPV predictor.

The damage risk evaluation of the shots

According to peak particle velocities

The particle velocities and frequency values of all blast events are evaluated according to the United States Bureau of Mines (USBM) and German DIN 4150 norms in order to predict and compare the influence grades to the neighboring plants and structures due to the lack of a national standard in Turkey. Therefore, in our study, the damage risks are evaluated by applying the recommended equation in the prediction of the parameters of ground vibration; especially, maximum PPV gained a general acceptance in literature. However, during this evaluation, threshold damage limit was based on the conservative German DIN 4150 norm by taking all the negative conditions into consideration. This norm gives 3 mm s^{-1} particle velocity as a threshold damage limit of PPV for the damage risks of old structure and buildings.

The graph of measured maximum particle velocity versus frequency values of all events at both DIN 4150 and USBM norms is given in Fig. 5a, b. This figure shows that the PPV values of nearly half of the recorded events had exceeded damage limits of DIN 4150 norm. However, when the event records were investigated according to the location of station points, it was determined that most of these events had been recorded at the station point close to the shot points. Only a few of them had been recorded in the other station point located near the closest building. It can be also understood from the graph that most of the recorded values are below the damage limits of USBM norm.

If the recorded values given in Table 3 for some of the shots are examined in detail, it can be seen that some higher PPV values were recorded. However, most of these higher values were recorded in the station close to shot points, not in the station close to the buildings, and this can be understood by looking at distances (*R*). In order to explain this situation clearly, for example, the PPV, frequency, distance, and scaled distance values recorded in the station close to the buildings were 2.54, 6.20, 320, and 48, respectively, in shot no. 160.

The results of the analysis performed according to the threshold values are given Table 5. As it can be seen in Table 5, maximum amount of charge per delay with

Table 4 Summary of simple regression output from SPSS (Version 11.5) statistical software

Regression statistics					
Multiple *R*	R^2	Adjusted R^2	Standard error	Observation	
0.712	0.5076	0.5067	0.3036	564	
Analysis of variance (ANOVA)					
	df	Sum of squares	Mean square	*F*	Significance *F*
Regression	1	53.3817	53.3817	580.332	0.0000
Residual	563	51.7874	0.091985		
Total	564	105.1691			
Variables in the equation					
Parameter	Coefficients		Standard error	*T*-statistics	
Intercept	2.7490		0.095001	28.9369	
X variable	−1.432		0.059427	−24.0901	

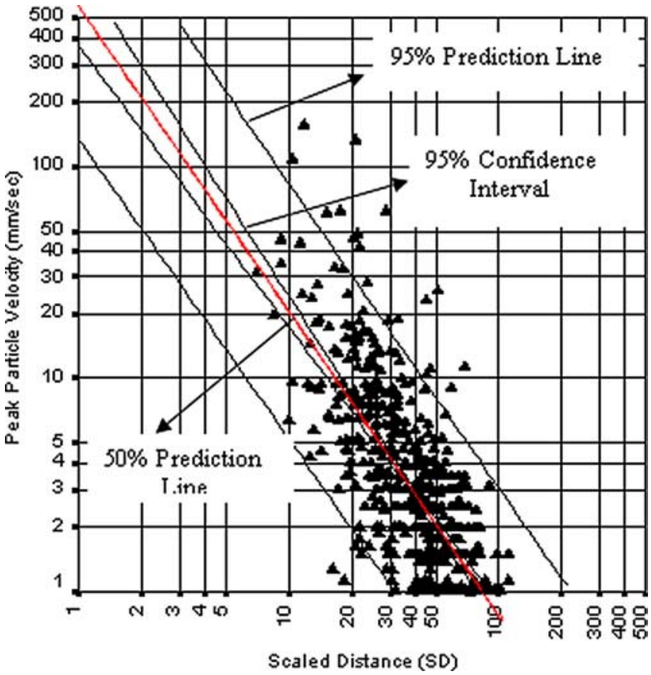

Fig. 4 Peak particle velocity versus scaled distance

respect to both norms was calculated according to 50% and upper bound 95% prediction line for the occurrence of threshold damage limit at different distances, respectively, by using the equation to predict PPV.

In addition, the maximum PPVs that will be obtained in the case of using different maximum amounts of charge per delay with both 50% average line and upper bound 95% prediction line are given in Table 6 for different distances.

When the shots are investigated, it is determined that the amounts of the charge per delay used in the shots are much lower than the amounts calculated. In light of the results of this investigation, it is understood that there are no damage risks of the shots fired during this study to distant residential areas and stations close to the shots.

According to air blast

The air blast can cause loud disturbances, window breaking, and structural damages, if the recorded value is more than 140 dB (Siskind et al. 1980). During the study, air blast values were recorded for 176 shots by planting the microphone of the monitor on the ground. The percentages of recorded air blast values are given in Fig. 6. As it can be seen from Fig. 6, only 1% of recorded air blast exceeded this limit and 59% of them were recorded between 110 and 120 dB. It has been observed that these shots did not cause any damage to the neighboring structures.

Human response to blast vibrations and air blast

Hisarcik open pit mine was opened in 1958. Since then, blasting has been extensively used in the mining activities. It is thought that the people of this town have been accustomed to psychological effects of blasting, and also there were no legal complaints filed against Emet Bor Company during this study. In fact, the contractor company responsible for overburden excavation is forced to comply with the DIN 4150 norm (3 mm s^{-1} limit) by Emet Bor Company to prevent any legal issues that can arise during the excavation activities. The contractor had designed the blast design accordingly.

Conclusion

Environmental issues arising from blasting restrict the mining operations increasingly. So, monitoring the shots and measurements of ground vibration are extremely important in eliminating the environmental problems.

Fig. 5 Peak particle velocities versus frequencies

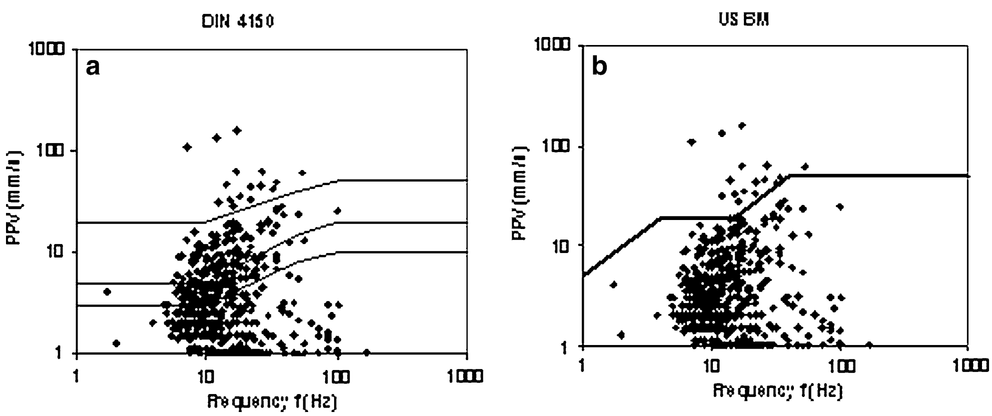

Table 5 Maximum amount of charge per delay calculated according to threshold damage beginning limit

Shot distance (m)	Damage beginning limit (mm s^{-1})		Maximum amount of charge per delay, W_d (kg)			
			According to 50% average line		According to 95% prediction line	
	DIN 4150	USBM	DIN 4150	USBM	DIN 4150	USBM
50	3	20	1.6	24	0.2	4
100	3	20	6.7	95	1	14
200	3	20	27	380	4	55
300	3	20	60	855	9	124
400	3	20	107	1,520	16	220
500	3	20	168	2,375	24	344
1,000	3	20	670	9,500	97	1,377

Table 6 Maximum peak particle velocities (*PPV*) calculated for different distances

Distance (m)	Calculated PPV (mm s^{-1})											
	According to 50% average line						According to 95% prediction line					
	Maximum amount of charge per delay, W_d (kg)						Maximum amount of charge per delay, W_d (kg)					
	10	50	100	200	500	1,000	10	50	100	200	500	1,000
50	10.8	34.1	56.0	92.0	177.2	291.1	42.9	135.8	223.0	366.3	705.8	1,159.2
100	4.0	12.6	20.7	34.1	65.7	107.9	15.9	50.3	82.7	135.8	261.7	429.7
200	1.5	4.7	7.7	12.6	24.3	40.0	5.9	18.7	30.7	50.3	97.0	159.3
300	0.8	2.6	4.3	7.1	13.6	22.4	3.3	10.4	17.2	28.2	54.3	89.2
400	0.5	1.7	2.8	4.7	9.0	14.8	2.2	6.9	11.4	18.7	36.0	59.1
500	0.4	1.3	2.1	3.4	6.6	10.8	1.6	5.0	8.3	13.6	26.1	42.9
1,000	0.1	0.5	0.8	1.3	2.4	4.0	0.6	1.9	3.1	5.0	9.7	15.9

Since the particle velocity is still the most common single ground descriptor for regulating blast designs, parameters of the common empirical relationship between PPV and scaled distance were established for Hisarcik Boron open pit mine.

Within the scope of this study, an extensive research work was realized at Hisarcik Boron open pit mine during the overburden excavation. The blasting excavations are going to be continuous; the environmental issues will increase, too. So the results of this study will be more meaningful for finding a solution.

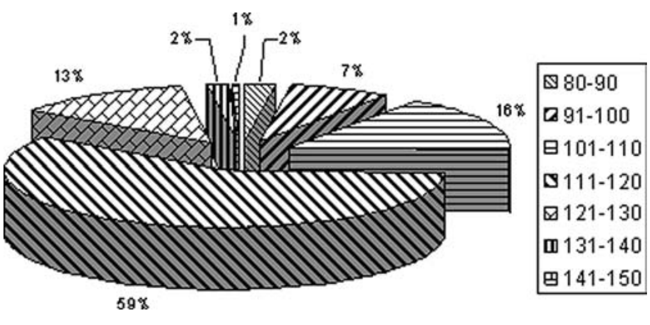

Fig. 6 The percentage distribution of recorded air blasts

Additionally, an empirical relation, which gives 50% prediction line with a reasonable correlation coefficient, was established and suggested for the test site. It should be taken into consideration that these formulae established just for prediction of particle velocity would give erratic results because of other effects. To support the reliability of these formulae, more events should be monitored in different directions and regression analysis should be updated by more measurement results depending on advances of time.

At the end of evaluations, it is determined that the amounts of the charge per delay used in the shots including the previous ones are much lower than the amounts calculated. In light of the results of this investigation, it is understood that there are no damage risks of the shots fired during this study to distant residential areas and stations close to the shots.

Acknowledgments This work was supported by the Executive Secretariat of Scientific Research Projects of Istanbul University (Project numbers are 429/13092005, UDP-134/25042003, UDP-217/24122003, UDP-286/29042004, UDP-405/15122004, UDP-659/23112005) and State Planning Organisation (Project number is 2005K120990). The authors are grateful to the Executive Secretariat of Scientific Research Projects of Istanbul University and State Planning Organisation for their financial support.

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