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New methodology to prevent blasting damages for shallow tunnel

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Abstract. From all of the environmental problems, blast-induced vibrations often cause concern to surrounding residents. It is often claimed that damage to building superstructures is due to blasting, and sometimes the building owner files a lawsuit against the company that perform blasting operations. The blast-vibration problem has been thoroughly investigated in the past and continues to be the subject of ongoing research. In this study, a tunnel construction has been performed by a construction company, according to their contract they must have used drilling & blasting method for excavation in tunnel inlet and outlet portal. The population is very condensed with almost tunnel below in the vicinity houses of one or two floors, typically built with stone masonry and concrete. This situation forces the company to take extreme precautions when they are designing blasts so that the blast effects, which are mainly vibration and aerial waves, do not disturb their surrounding neighbors. For this purpose, the vibration measurement and analysis have been carried out and a new methodology in minimizing the blast induced ground vibrations at the target location, was also applied. Peak particle velocity and dominant frequencies were taken into consideration in analyzing the blast-induced ground vibration. The methodology aims to employ the most suitable time delays among blast-hole groupings to render destructive interference of surface waves at the target location.

Keywords: shallow tunnel; drilling&blasting; blast-induced ground vibration; peak particle velocity; dominant frequencies

1. Introduction

Tunnels are required to be constructed for meeting different human needs such as transportation, power generation, underground storage, sewage etc. The predominant method of excavation, world over, is drilling and blasting owing to its capability to meet changing geo-technical conditions. Moreover, drilling and blasting procedures are easy and economic way. But blast-induced ground vibrations which are a serious issue for mining and construction industries have been investigated by researchers (Shi *et al.* 2009, Haciefendioglu *et al.* 2015, Oncu *et al.* 2015, Nam *et al.* 2015, Toy and Sevim 2017). Being an important engineering technology, blasting is increasing used in military; mining; and railway, highway, port, airport, tunnel construction and in other fields (Ak and Iphar 2009, Dindarloo 2015). Selection of an excavation method is a very important decision due to its direct effects on initial investment and project costs (Aksoy 2014, Aksoy *et al.* 2009). Three major areas of concern in drilling and blasting operations are productivity, occupational safety and environment (Cardu *et al.* 2015). Productivity means efficient and effective fragmentation with uniform or appropriate sized material and proper displacement. Safety considerations include explosive handling and blasting procedures as they could affect the safety and health of mine workers. Environmental problems are those that can affect neighbors include ground vibration, air-over-pressure/noise, fly rock, dust and fumes. From all of the environmental problems, blast-induced vibrations often cause concern to surrounding residents. It is often claimed that damage to building superstructures (e.g., cracks in walls) is due to blasting, and sometimes the building owner files a lawsuit against the company that perform blasting operations. The blast-vibration problem has been thoroughly investigated in the past and continues to be the subject of ongoing research (Kalantari 2011, Li *et al.* 2014, Zhang *et al.* 2014, Jeon *et al.* 2015, Han and Liu 2016).

Ground vibrations from blasting are acoustic waves that propagate through the earth (Siskind 2000). There are four types of ground vibration waves: compression or P-waves, transverse (shear) or S-waves, Rayleigh waves and Love waves. P and S waves are also called body waves. Rayleigh and Love waves are surface waves. Body waves of two types can propagate through the body of an elastic solid. P-waves propagate by compressional and dilatational uniaxial strains in the direction of wave travel. Particle motion associated with the passage of a compressional wave involves oscillation about a fixed point, in the direction of wave propagation. Shear waves, S-waves, propagate by a pure shear strain in a direction perpendicular to the direction of wave travel. Surface waves can propagate along the boundary of the solid. Rayleigh waves propagate along a free surface or along the boundary between two dissimilar solid media. Love waves are polarized shear waves with an associated oscillatory particle motion parallel to the free surface and perpendicular to the direction of wave motion. While body waves have low amplitude, high frequency and high velocity, surface waves, on the other hand, have high amplitude, low frequency and low velocity. This low

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frequency and low velocity properties of surface waves generate dangerous wave length which leads to resonance between ground and structure and causes amplification of vibration amplitudes (Kearey and Brooks 1991). For this reason, surface waves are more important in ground vibration minimization works than body waves.

Surface waves are dispersive waves. Their waveforms undergo progressive change during propagation as a result of the different frequency components travelling at different velocities. A compressed surface wave package originated from blast point expands with travelled distance. As a result of this expansion of surface wave package:

• Low frequency (long wavelength) waves hidden in the package become visible. This case is dangerous and unwanted case.

• Expansion of surface wave trains, increases the duration of vibration both at the ground and at the building so that especially joints in the buildings become tired (Aldas *et al.* 2006, Uyar and Babayigit 2016).

Blast induced vibrations differ from the ground vibrations caused by earthquakes in terms of seismic source, amount of available energy and distances travelled (Oriard 1989). The dominant frequency of blast-induced surface vibrations tends to be in the range 5-200 Hz, whereas the dominant frequency of ground vibrations caused by an earthquake is usually in the range 0.1-2 Hz (Scott *et al.* 1996). The study of blasting vibrations has become essential in providing guidelines for safe blasting in terms of minimizing damage to residential structures (Siskind *et al.* 1980).

The blasting seismic wave intensity can be evaluated by the vibration velocity, acceleration, displacement, frequency, etc. Currently the most widely accepted single measurement of ground vibration considered potentially damaging to structures is the *peak particle velocity (PPV)*, defined as the speed at which an individual earth particle moves or vibrates as the waves pass a particular location. Today it is state of the art to use seismographs to evaluate the response of blast-induced vibrations on houses and buildings in terms of PPV. PPV is the key for the environmental performances and it is strongly dependent upon the maximum charge per delay in the near field and the total charge in the very far-field (Blair 1990). Indeed, the study of blasting vibrations, the peak particle velocity in particular, has become essential in providing guidelines for safe blasting in terms of minimizing damage to residential structures (Siskind *et al.* 1980, Dowding 1996). The characteristics of blasting vibrations depend critically on the amount of explosives detonated at any given time, the delay intervals employed in the blast design and the prevailing geological conditions. Optimized delay between holes and rows can give better fragmentation and lower vibration levels (Singh *et al.* 1996, 2006). The proper combination of charge weight and delay timing is that which allows sufficient room for expansion of the rock mass (swelling) between rows in multiple row blasts (Zhang 2000). Any constriction in rock mass movement increases particle velocity and decrease blasting efficiency (Venkatesh 2005).

There are number of factors affecting the seismic behavior of blast vibration. In vibration minimization works, those factors must be taken into consideration carefully. These are:

• Explosive-rock interaction: Fragmentation and deformation properties of blasted rock. This interaction determines how much energy is used for fragmentation and how much is spent as elastic waves.

• Guided waves: Some rock units behave like channel so that, they transmit blast waves from shot point to far distances with little energy decrease.

• Blast parameters: hole number, explosive amount/hole, explosive type, hole depth, hole design, delay, free face

• Shot point-target distance: Absorption and dispersion of seismic wave depend on distance between shot and target (measurement location).

• Effect of geology: Elastic properties of units in which seismic waves travel, geological structure (base rock depth, faults, bedding, tectonic..etc)

The construction of a tunnel at has been performed by a construction company according to their contract, they must have used drilling & blasting method for excavation in tunnel inlet and outlet portal. In this study, the population is very condensed with almost tunnel below in the vicinity houses of one or two floors, typically built with stone masonry and concrete. This situation forces the company to take extreme precautions when they are designing blasts so that the blast effects, which are mainly vibration and aerial waves, do not disturb their surrounding neighbors. This paper is related with the studies in the drilling and blasting stages of construction works to measure and analysis of blast-induced ground vibration and air shock at the surrounding houses.

2. Damage criteria related with blast induced ground vibration

Energy level of vibration is measured as i) particle displacement (mm), ii) particle velocity, mm/s iii), particle acceleration, mm/s^2 and iv) wave frequency, Hz.

Duration of blast-induced vibrations is short. Motion velocity of a particle in the ground is known as particle velocity. Particle velocity starts from zero, reachs to maximum level and diminishes. Therefore, particle velocity is very important in blast vibration analysis so that greater the particle velocity, greater vibration at the buildings.

Frequency is the number of occurrences of a repeating event per unit time. In other words, it is an oscillation number of a particle in 1 second. Unit of frequency is Hz. Frequency of blast-induced vibration is as important as particle velocity.

In this paper, particle velocity and seismic wave frequency is considered. Vibration frequency is affected mostly by two factors: i) geology, ii) delay between blast holes (Dowding 1985). Sometimes, even particle velocity is below 12.5 mm/s (damage level for USBM standart, Siskind et. al., 1980), complaints from vibration continue. This complaint is resulted from solely low frequency of vibration. Because humans feel low frequency vibration easily. When frequency is high, humans cannot feel so that they do not worry about it. Frequencies below 10 Hz produce large ground displacement and high levels of strain, and also couple very efficiently into structures where typical resonant frequencies are 5-12 Hz for the corner and

Table 1 Safe levels of blast-vibrations for residential type structures, USBM standard (Siskind *et al.* 1980)

Type of Structure	Ground Vibration, At low frequency (<40 Hz)	Peak Particle Velocity mm/s At high frequency (>40 Hz)
Modern homes, Drywall interiors	19.0 (solid line at Fig. 1)	50.8
Older homes, plaster on wood lath construction for interior walls	12.7 (dashed line at Fig. 1)	50.8

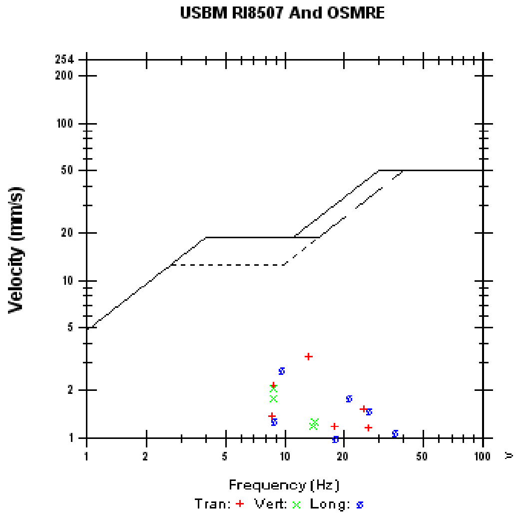

Fig. 1 USBM RI 8507 and OSMRE vibration Standard (Siskind *et al.* 1980). Dashed line illustrates the damage limit level for older homes, plaster on wood lath construction for interior walls. Solid line illustrates the damage limit level for modern homes, drywall interior. Tran (+), Ver (*x*), Lon (§) symbol indicate transversal, vertical and longitudinal components of vibration wave, respectively

racking motions. Construction techniques of buildings are also important in analyzing building damage due to vibration (Siskind *et al.* 1980).

Damage possibility due to vibrations at buildings depends on the relationship between ground frequency of vibration and natural frequency of the building. The most critical case at blasting is when ground vibration frequency is between 5-12 Hz (which is the natural frequency of 1-2 floor buildings). In this case, resonance starts at the buildings and structure continues to vibrate even exciting wave goes away. When the building is in resonance, no damage occurs in buildings if the particle velocity is below damage level. However, human feels and fears. When the building is in resonance, damage occurs in buildings if the particle velocity exceeds damage level.

2.1 Damage classifications

Three damage class is defined in USBM (United States Bureu of Mine) (Siskind *et al.* 1980, 1989) as i) threshold damage ii) light damage iii) serious damage. “Threshold damage” causes only very small cracks (hair like) at plaster and it only disturbs appearance, no damage to the walls. “Light damage” causes falling down of some plasters and cracks will be extended to 3 mm in width. Although this case is disturbing, those “light damages” do not threat

Table 2 Safe levels of blast-induced air_shock for residential type structures (Siskind *et al.* 1980)

Low frequency limit of measurement system	Maximum Air Shock level that cannot cause any damage
	dB
< 2 Hz	133
< 6 Hz	129

structural elements and bearing capacity of the buildings. “Serious damages” cause wide cracks and permanent deformation at the walls and whole buildings.

2.2 Safe levels of blasting vibrations for residential type structures

From the practical point of view, the blasting engineer is not interested so much in the shape of the wave but in the negative effects of a wave. These are defined by the position of the frequency-peak velocity pairs of all the cycles or half-cycles that constitute the wave, in a graph that represents the damage criteria ((in Turkey this is established by 25862 no. Official Gazette “Guide of Determination and Administration of Environmental Noise (CGDYY 2005), in Spain this is established by Standard UNE 22381:1993 (AENOR 1993), equivalent to, for example BS 7385 (British Standards Institute 1993), DIN 4150-3 (Deutches Institut für Normung 1983), or RI 8507 (US Bureau of Mines, USBM 1980)). In the damage criteria there are certain limit lines for the particle speed, depending on the vibration fundamental frequency and the type of structure to protect. For many standards, the structures are classified into groups: For example, for USBM standards (and for Turkish standards), structures are divided into two groups, defined in Table 1 and Fig. 1.

In this study, USBM standards (Siskind *et al.* 1980) (and Turkish standards (CGDYY 2005), which is the same as USBM’s standart) were used to analyze blast induced vibration.

According to USBM, safe vibration levels for blasting are given in Table 1, being defined as levels unlikely to produce interior cracking or other damage in residences. Implicit in these values are assumptions that the structures are sited on a firm foundation, do not exceed 3 stories and have the dimensions of typical residences, and that the vibration wave trains are not longer than a few seconds (Siskind *et al.* 1980).

Safe blasting criteria were developed for residential structures, having two frequency ranges and sharp discontinuity at 40 Hz (Table 1). There are blasts that represent an intermediate frequency case, being higher than the structure resonances (4 to 12 Hz) and lower than 40 Hz.

2.3 Safe air shock level for residential structures

According to USBM (Siskind *et al.* 1980), safe air shock levels for residential structures are given in Table 2.

3. Problem definition

A construction company carried out excavation on the

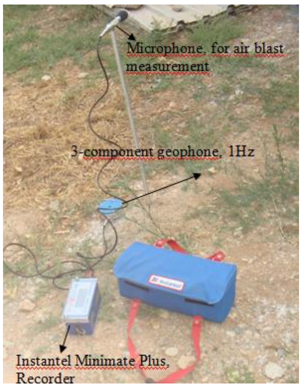

Fig. 2 Instantel Minimate Plus Seismograph with 3-component geophone and microphone

Fig. 3 Blasting area at tunnel outlet portal

Table 3 Blast parameters and measured vibration frequencies belong to blast at tunnel outlet portal

Date	20.07.2011
Location	Outlet portal
Hole length	7 m
Number of blast holes	24
Hole diameter	89 mm
Explosive	12.5 kg/ hole ANFO)2 kg/hole powergel magnum 365 as primer)
Explosive per delay	12.5 kg/hole x 12 hole= 150 kg
Delay between rows	200 ms
Distance between blast and measurement location	350 m
PPV (peak particle velocity) measured at target	Transversal: 1.51mm/s - Vertical: 1.43 mm/s - Longitudinal: 0.984 mm/s
Dominant frequencies	Transversal: 8.75 Hz -Vertical: 5.75 Hz -Longitudinal: 9.50 Hz

tunnel inlet and outlet portal and according to their contract they are required to use the drilling & blasting method for excavation. But around tunnel there are settlements in one or two storey houses mostly built with stone walls and concrete. Because of this, the company has taken many precautions to avoid disturbing the neighbors around the blast effects, which are mainly vibration and aerial waves, when designing detonations. Vibration measurement and analysis have been carried out in tunnel inlet, outlet portal and in the surrounding houses, and a new methodology (Aldas and Ecevitoglu 2008) has been applied to minimize the ground vibrations induced by blasting on the surrounding buildings.

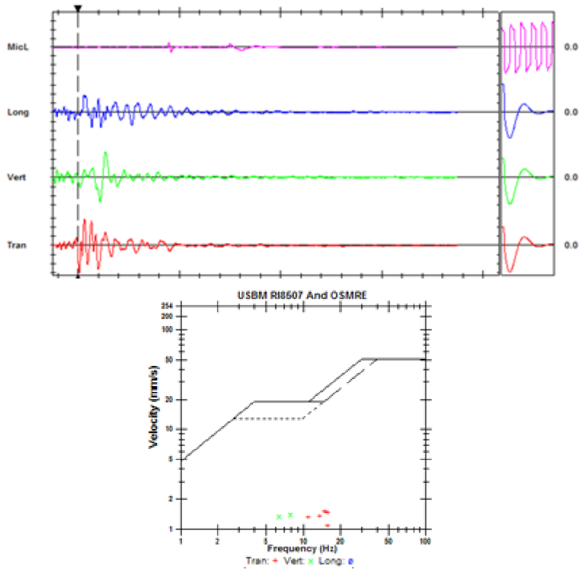

Fig. 4 Event report of the blast at tunnel outlet portal (20.07.2011)

3.1 Field studies

On 20 and 21 of July 2011, number of four blasts, two at tunnel outlet and the other two at tunnel inlet portal, were performed and blast induced ground vibration together with air shock were measured by Instantel Minimate Plus Seismographs. It has three components (transversal, vertical, longitudinal) geophone. The geophone frequency of the seismograph is 1 Hz. Three seismographs were used at field study (Fig. 2).

3.1.1 Blasts at tunnel outlet portal

Blast on 20.07.2011

Fig. 3 shows the blasting area at tunnel outlet portal.

Table 3 shows the blast parameters applied to the blast at tunnel outlet portal. Blast induced ground vibration and air shock were measured at a nearby house complaining about the blast. Table 3 also indicates the measured vibration level in peak particle velocity and their dominant frequencies. Explosive per delay was 150 kg in this blast. In such vibration analysis, it must be clearly understood that, the important explosive amount which cause ground vibration is explosive per delay, not total amount. Therefore, one must analyze the effects of 150 kg explosive per delay in this blast. The dominant frequencies are low (between 5-10 Hz) as expected from this type of surface blasts, peak particle velocities are also low. They all are below the USBM damage level (see Fig. 4).

Fig. 4 illustrates the USBM damage level graph together with waveforms. Particle velocities are very low in all three vibration component (transversal: red sign, vertical: green sign, longitudinal: blue sign, longitudinal component is below threhold level so that it cannot be seen in the graph). Although the dominant frequencies of the vibration waves are resonance frequencies of 1-2 story houses, particle velocities are so small that cannot cause any damage to the nearby structures. This case is clearly seen in the Fig. 4:

Table 4 Blast parameters and measured vibration frequencies belong to blast at tunnel outlet portal

Date	21.07.2011
Location	Tunnel outlet portal
Hole length	6m
Number of blast holes	40 Blast location: 38 430708 E, 4026748 N
Hole diameter	89 mm
Explosive	12.5 kg/ hole ANFO (1 kg/hole powergel magnum primer)
Explosive per delay	12.5 kg/hole x 12 hole= 150 kg
Delay between rows	600 ms
Distance between blast location and target place	350m
PPV (peak particle velocity) measured at target and dominant frequencies	Serial no:12270 (38 429611 E, 4025849 N) T: 1.35mm/s, 15.7 Hz V: 0.286mm/s, 3.5 Hz L: 0.873mm/s, 15.6 Hz Serial no:12269 (38 429744 E, 4026453 N) Below tresh hold level Serial no: 14465(38 430062 E, 4026246 N) T: 1.06 mm/s, 23 Hz V:0.571mm/s, 9.25 Hz L: 0.778 mm/s, 9.25 Hz

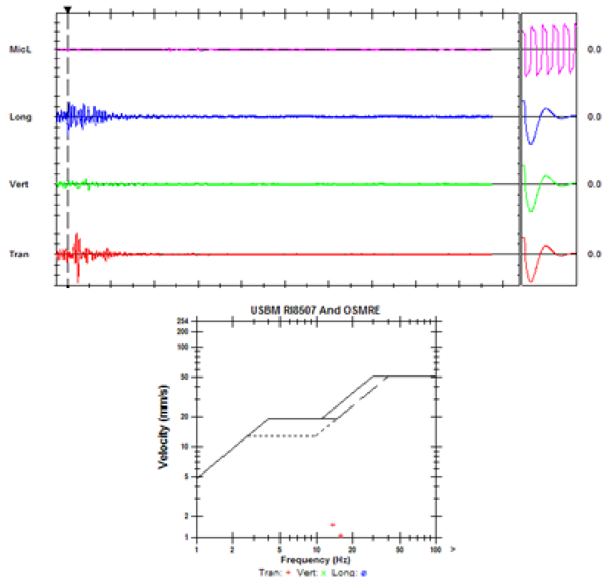

Fig. 5 Serial no: 12270. Event report of the blast at tunnel outlet portal (21.07.2011)

particle velocities in three components are below both the dashed line (damage level for old houses, 12.5 mm/s) and solid line (damage level for modern houses, 19 mm/s) for the frequencies 5-20 Hz. Dominant frequencies determined by FFT analsis are between 5.75, and 9.50 Hz.

<u>Blast on 21.07.2011</u>

On 20.07.2011, 24 blast holes were exploded at tunnel outlet portal. Explosive per delay was 150 kg. Resultant particle velocities, considering the dominant frequencies and safe standards, were very low. Therefore, total number of blast holes on 21.07.2011's blast were increased to 40. Three rows of blast-holes were designed. The delay interval between the first and second row was 600 ms. The third row, however, was blasted 100 ms after the second row. Therefore, explosive per delay did not exceed 150 kg (12.5 kg/hole x 12 hole=150 kg), same as 20.07.2011's blast. Regarding the particle velocities generated from 24 and 40 blast-holes, it is seen that, blast with 24 blast-holes created

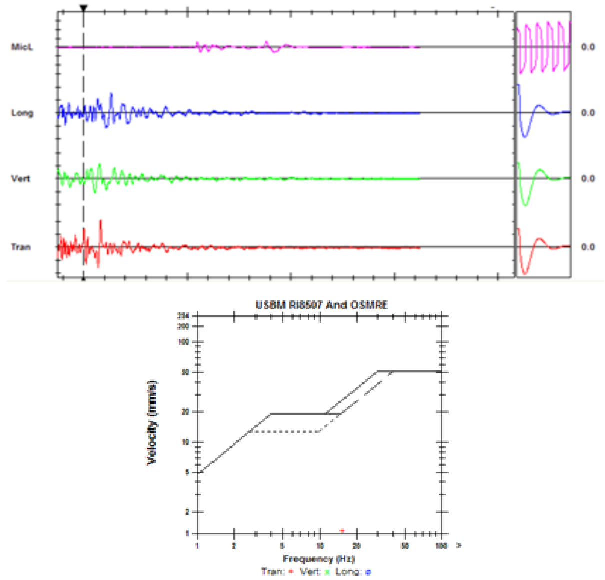

Fig. 6 Serial no: 14465. Event report of the blast at tunnel outlet portal (21.07.2011)

Table 5 Air shock levels of blasts on 20.07.2011 and 21.07.2011

Blast Date	Serial # of Seismograph	Air shock, dB
20.07.2011	14465	6.00 Pa (L): 109.54 dB
21.07.2011	12270	2.00 Pa (l): 100 dB
21.07.2011	12269	Below treshold level
21.07.2011	14465	7.00 Pa (L): 110 dB

little bit higher particle velocities (1.51 mm/s (Trans), see Table 3, Fig. 4)) as compared to blast with 40 blast-holes (1.35 mm/s (Trans), see Table 4, Fig. 5). Although their explosive used per delay was same, 150 kg, blast with 40 blast-holes generated more free surface to expand the explosion than blast with 24 blast-holes. Therefore, it used most of their explosive energy to fragment rock, not for vibration. It is recommended to use 40 blast holes instead of 24 holes within the pattern providing that explosives per delay do not exceed 150 kg. Peak particle velocities from blast with 40 blast-holes did not exceed USBM damage criteria (Fig. 5, Fig. 6). Dominant frequencies determined by FFT analsis are between 3.5, and 23 Hz.

<u>Air shock measurement</u>

According to USBM (Siskind *et al.* 1980) safe air shock levels for residential structures (see Table 2), both of the blast induced air shocks were under damage level. Since the geophone frequency of the seismographs used is 1 Hz, damage level can be selected as 133 dB (see Table 2).

3.1.2 Blasts at tunnel inlet portal

<u>Blast on 20.07.2011</u>

Table 6 shows the blast parameters applied to the blast at tunnel inlet portal. Blast induced ground vibration and air shock were measured at a nearby house complaining about the blast. Table 7 indicates the measured vibration level in peak particle velocity and their dominant frequencies. Table 8 shows the air shock level. Fig. 7 shows the blast pattern.

Table 6 Blast parameters applied to the blast at tunnel inlet portal (left tube)

Date	20.07.2011
Location	Tunnel inlet portal (left tube)
Hole length	3m
Number of blast holes	79
Hole diameter	45mm
Total explosive used	180 powergel magnum 365 (38x400 mm, 545 gr/cartridge)
Delay number	(see Fig. 13) 1: 100 ms 2: 200 ms 4: 400 ms 5:500 ms 6:600 ms 7:800 ms 8:1000 ms 9:1200 ms 10:1400 ms
Explosive per delay	19 kg (2 kg-2.5 kg/hole, max. 8 holes (number 1) were blasted at the same time)
Distance between blast and measurement location	90 m in depth

Table 7 PPV and dominant frequencies of blast at tunnel inlet portal (20.07.2011)

Measurement location	Vertical Distance from shot	PPV Transversal (mm/s)	PPV Vertical (mm/s)	PPV Longitudinal (mm/s)	PVS (mm/s)	Dominant Frequency, Hz
Haydar Selim (14460)	90	4.81	5.73	5.81	7.66	33.6 Hz at Transversal 81 Hz at Vertical 101 Hz at Longitudinal
Hoşevi İbrahim (12270)	100	2.91	1.79	4.84	5.25	62.1 Hz at Transversal 36.9 Hz at Vertical 90.3 Hz at Longitudinal
Haziran Salah (12269)	120	2.19	1.30	1.59	2.58	36.8 Hz at Transversal 36.8 Hz at Vertical 46.3 Hz at Longitudinal

Table 8 Air shock level for the blast at tunnel inlet portal (20.07.2011) 1Pa=1 N/m^2= 94 dB (SPL: sound pressure level)

Blast Date	Serial # of Seismograph	Air shock, dB
20.07.2011	14465 (Haydar Selim)	6.25 Pa (L): 109 dB
20.07.2011	12270(Hoşevi İbrahim)	3.75 Pa (L): 105 dB
20.07.2011	12269 (Haziran Salah)	3.00 Pa (L): 103 dB

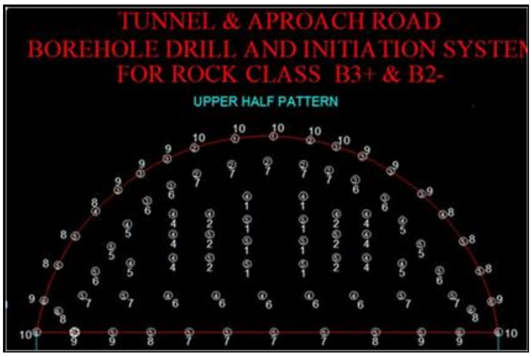

Fig. 7 Blast pattern of the blast at tunnel inlet portal (left tub (20.07.2011). 1 (4) means: cap no:1 having 4 cartridges: 0.5 kgx4=2 kg/ hole. Some holes contain 5 cartridges, 0.5 kgx5=2.5 kg/hole

Tables 7 and 8 represent the blast-induced peak particle velocities and air shock levels, respectively. Particle velocities are below the damage level. Moreover, the dominant frequencies are high (higher than resonance frequencies of buildings). As it is said earlier, the low frequencies with high vibration amplitudes have a danger of possible damage to the structures. However, in our case, the vibration amplitudes are low, frequencies are high. For this

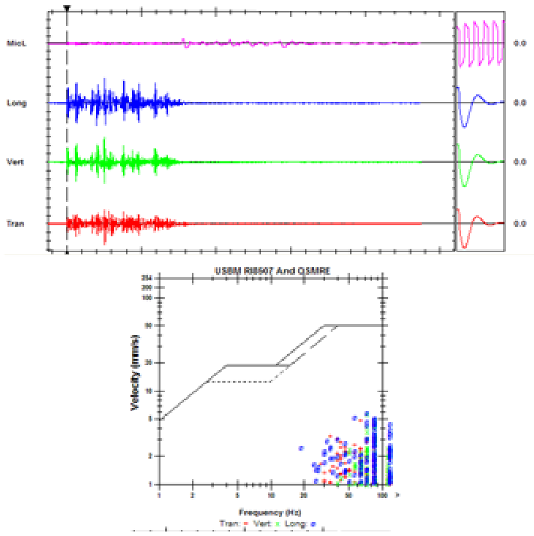

Fig. 8 Event report of blast vibration (20.07.2011) belongs to seismograph:14465

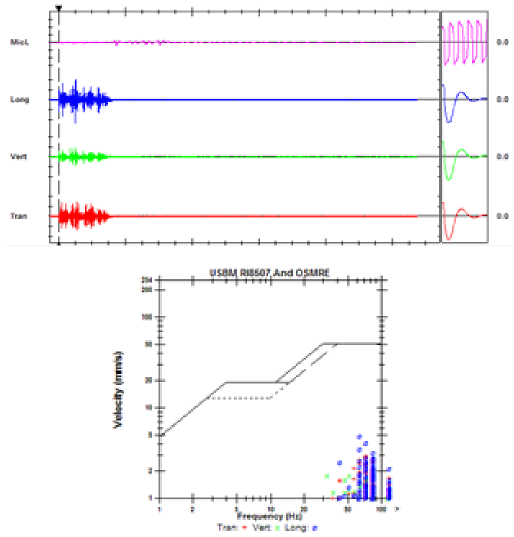

Fig. 9 Event report of blast vibration (20.07.2011) belongs to seismograph:12270

reason, the next blast on 21.07.2011 was planned as using 25 kg/delay explosive (previous one has 19 kg/delay explosive). Fig. 8 illustrates the event reports of vibration measurements belongs to seismograph 14465. Dominant frequencies determined by FFT analysis are between 5.13, and 101 Hz. Fig. 10 illustrates the event reports of vibration measurements belongs to seismograph 12270. Dominant frequencies determined by FFT analsis are between 36.9, and 90.3 Hz. Fig. 11 illustrates the event reports of vibration measurements belong to seismograph 12269. Dominant frequencies determined by FFT analsis are between 36.8, and 46.3 Hz.

Blast on 21.07.2011

Table 9 shows the blast parameters applied to the blast at tunnel inlet portal. Blast induced ground vibration and air shock were measured at a nearby house complaining about the blast. Table 10 and 11 indicate the measured vibration level in peak particle velocity and air-shock, respectively. Fig. 11 shows the blast pattern.

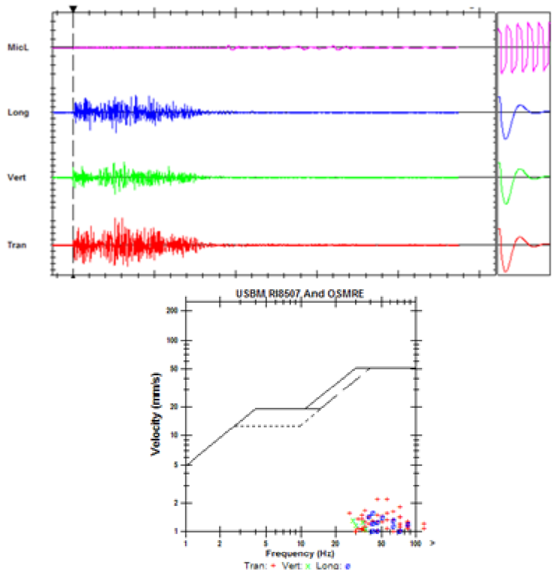

Fig. 10 Event report of blast vibration (20.07.2011) belongs to seismograph:12269

Table 9 Blast parameters applied to the blast at tunnel inlet portal (left tube)

Date	21.07.2011
Location	Tunnel inlet left tube
Hole length	4 m
Number of blast holes	79
Hole diameter	45 mm
Total Explosive used	240 powergel magnum 365
Delay number	
Explosive per delay	25 kg
Distance between blast location and target place	90 m

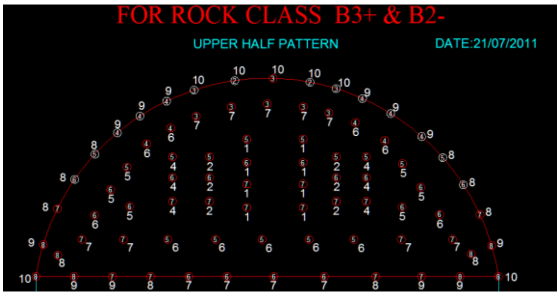

Fig. 11 Blast pattern of the blast at tunnel inlet portal (left tube) (21.07.2011). 1 (5) means: cap no:1 having 5 cartridges: 0.545 kgx4=2.5 kg/ hole. Some holes contain 7 cartridges, 0.545 kgx7=3.5 kg/hole.

Table 10 PPV and dominant frequencies of blast at tunnel inlet portal (21.07.2011)

Measurement location	Distance from shot	PPV Transversal (mm/s)	PPV Vertical (mm/s)	PPV Longitudinal (mm/s)	PVS (mm/s)	Dominant Frequency, Hz
Haydar Selim (14465)	90	6.86	5.70	8.13	8.52	67 Hz (T) 67 Hz (V) 102 Hz (L)
Ahmet Balındı (12269)	100	4.38	3.92	6.02	6.54	25.6 Hz (T) 85.5 Hz (V) 85.5 Hz (L)
Haziran Salah (12270)	120	2.44	2.11	2.37	2.51	51 Hz (T) 57 Hz (V) 43 Hz (L)

Table 11 Air shock level for the blast at tunnel inlet portal (21.07.2011)

Blast Date	Serial No of Seismograph	Air shock, dB
21.07.2011	14465 (Haydar Selim)	15.5 Pa (L): 117 dB
21.07.2011	12269 (Ahmet Balındı)	7.25 Pa (L): 111 dB
21.07.2011	12270 (Haziran Salah)	5.25 Pa (L): 108 dB

(1Pa=1 N/m^2= 94 dB (SPL: sound pressure level))

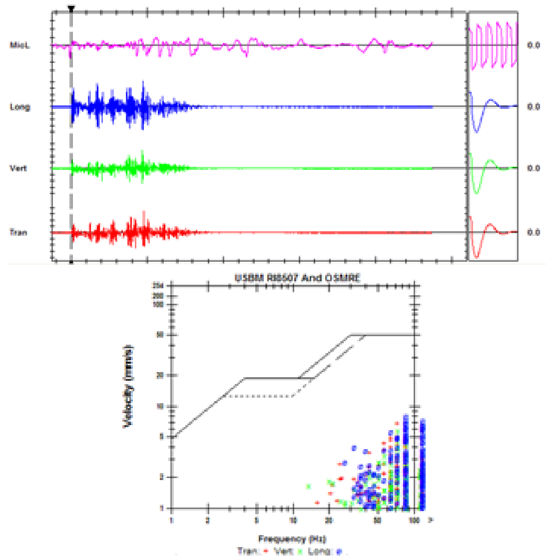

Fig. 12 Event report of blast vibration measured by seismograph 14465

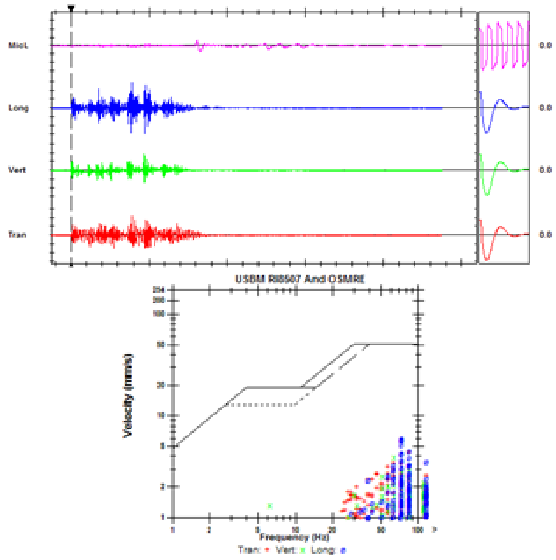

Fig. 13 Event report of blast vibration measured by seismograph 12269

4. New methodology used for vibration analysis

In this study, a new methodology (Aldas and Ecevitoglu 2008) in minimizing the blast induced ground vibrations at the target location, was also applied. The methodology aims to employ the most suitable time delays among blast-hole groupings to render destructive interference of surface

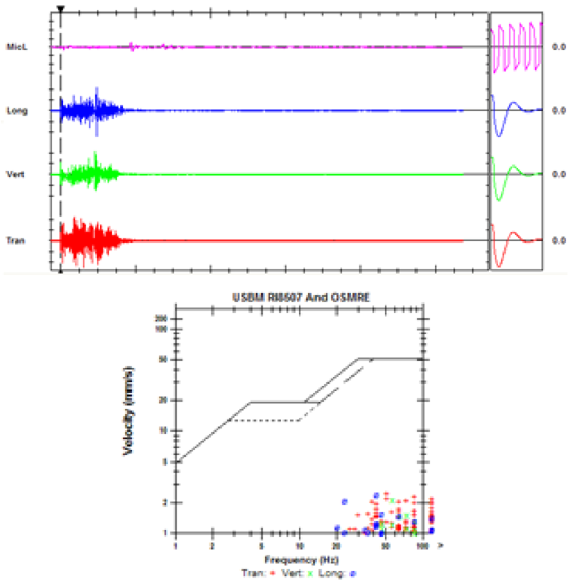

Fig. 14 Event report of blast vibration measured by seismograph 12270

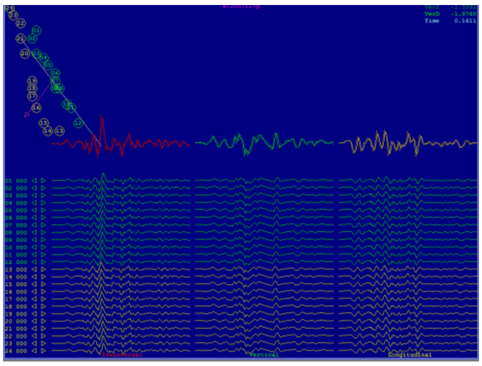

Fig. 15 Blast vibration analysis screen. There are two groups (green and yellow). At this stage no delay applied to the blast holes

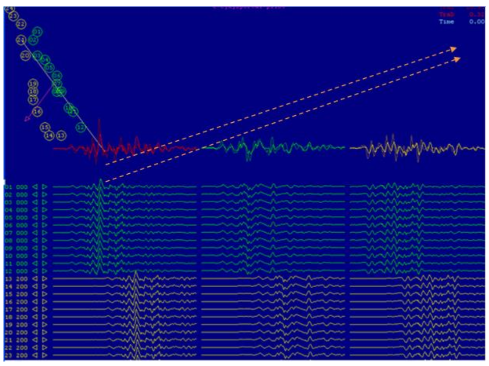

Fig. 16 Blast vibration analysis screen. There are two groups (green and yellow). At this stage 200 ms delay applied to the second group blast holes. Notice the vibration reduction especially at the transversal component (In case of Tran (z): zero delay: vibration is 10.41 unit, in case of Tran (D): 200 ms delay, vibration is 0.32 unit)

waves at the target location (where the blast-induced vibrations are to be minimized).

The crucial point of the methodology is to use a pilot-blast signal. The pilot-blast is constituted of a single or a few neighboring blasts in the vicinity of the group-blast. The pilot-blast signal embraces the seismic properties of all complex geology between the blast and the target locations. Therefore, the methodology does not require any geological model or assumption; it is based on two seismic records related to: (1) Pilot-blast, (2) Group-blast. The group-blast is made up of pilot-blasts, i.e., a gathering of pilot-blasts representing the group blast. The seismic records obtained from pilot and group-blasts share the same blast-design properties, such as explosive types and amount, hole-diameter and depth, etc. We assume that seismic waves initiated from pilot and group-blasts should travel along the same geological structures, such as lithology, stratigraphy and tectonics. Since the pilot-blast carries all the information related to the above stated factors, there is no need to take in account all the details of the complex geology. The data analysis technique used in this work is based on Linear System Theory (Oppenheim and Schafer 1975, Karu 2002), and its immediate result: The Superposition Principle.

Based on the above theory, a software, called SeisBlast V.2.0. was developed. The theory of the program is based on the Linear Superposition Principle. After obtaining the pilot-blast signal, the seismic signals of each blast-hole in the group-blast are simulated as if they were the same as the pilot signal. It is assumed that the linear superposition of signals from each blast-hole, which are actually the pilot signal, represents the group-blast signal. Using the mouse controlled program, we can easily adjust the time-delays between blast-holes. While doing this adjustment, we consider applying suitable time-delays that will cause destructive interferences between major wave lengths.

Fig. 15 shows the first analysis screen of the program. Upper left quadrant of Fig. 15 displays the blast-hole locations. Blast-holes are shown with two colored circles with hole-numbers in them. Blast-holes sharing the same color are blasted simultaneously. The red arrow points to the measurement location which is out of the figure's scope. The NW–SE oriented yellow-line segment represents the free surface of the blast-bench which should be taken into account while designing the group-blast. The right corner of Fig. 15 shows: first row: "TranZ" denotes the original ((Z)ero delay) seismic amplitudes of the pilot-blast at the time "Time" (third row). Second row: "TranD" denotes the seismic amplitudes after the implementation of the appropriate time-(D)elays to mitigate the vibrations. "Tran" denotes the Transversal seismic component. In the middle of Fig. 15, Transversal (red), Vertical (green), and Longitudinal seismic components (yellow) obtained from the superposition of the zero-delay pilot signals are shown. The bottom half of Fig. 15 shows: blast-hole numbers at the far left; next, the individual delays corresponding to each grouping in milliseconds (in this case, "000" denotes no-delay).

Fig. 16 illustrates the analysis subsequent to the application of appropriate time-delays. In this example, the applied delays are 200 ms. The purpose of this specific blast-design is: following the collapse of the center of the blast-area upon itself, appropriate time-delays are given to the individual blast-holes to minimize the remaining seismic amplitudes step-by step. Inspection of the transversal component reveals destructive interference of the seismic signal (Dark waves represent waves with no delay; light waves represent waves with delay). As it is seen in Fig. 16, considerable amount of vibration reduction was obtained when applying 200 ms delay interval between blast-hole rows.

5. Results and discussions

In this technique, the input wavelet is extracted from the real data and it is convolved with the time series containing time-delayed spikes corresponding to each blast in the group. This convolution gives a synthetic time-series representing the linear behavior, hence the elasticity. The plasticity, on the other hand, is represented by the actual field data. The energy may simply be defined by the sum of the squares of the amplitudes in a time series. Therefore, the ratio of the blast energy related to the plasticity and elasticity can easily be obtained. Since the ratio so obtained is deduced from the seismic signals, it is a measure of the elasticity. The plasticity is considered as the complementary of the elasticity. The proposed technique was applied to tunnel outlet and inlet portal blasts.

Two blasts, having 20 and 40 blast holes, were done at a tunnel outlet portal. All the blast parameters (Table 3 and 4), except total explosive, were same. Increasing the blast-holes, hence the total amount of explosive from 500 kg to 700 kg make only small increase on plastic energy.

Two blasts, were done at a tunnel inlet portal. Most of the blast parameters (Table 6), except explosive amount, delay intervals and drill hole length, were same. Increasing the total amount of explosive from 180 kg to 240 kg and increasing the delay intervals make no change on plastic energy.

6. Conclusions

Taking the project as the background, the field experiments of vibration effects of the ground in tunneling blasting have been done. Based on the measurement of the waveforms of the vibration velocity in different distances away from the tunneling blasting sources on the ground, the vibration characteristic of the ground and its varying laws are studied. Four blasting experiments, two for tunnel inlet, and two for tunnel outlet, were carried out and 9 waveforms of measured point vibration were obtained. Blast induced ground vibrations were measured especially at nearby houses owner of them complaints about the vibration.

Peak particle velocity and dominant frequencies were taken into consideration in analyzing the blast induced ground vibration.

USBM (Siskind *et al.* 1980) damage criteria were used in analyzing the data.

The results of the tests and analysis show that:

• At tunnel outlet portal, keeping the explosive per delay as 150kg, vibration of blasting of 24 blast-holes and 40 blast-holes do not give any damage to the nearby settlement. Blast with 40 blast-holes generated more free face to expand the explosion than blast with 24 blast-holes. Therefore, it used most of their explosive energy to fragment rock, not for vibration. It is recommended to use 40 blast holes instead of 24 holes within the pattern providing that explosives per delay do not exceed 150 kg. Peak particle velocities from blast with 40 blast-holes did not exceed USBM damage criteria.

• At tunnel inlet portal (left tube), based on the monitoring data of the explosion vibration, the vibration wave forms, velocities, dominant frequencies and fields of measure points were analyzed under the conditions of four locations (Houses of Haydar Selim, Ahmet Balındı, Haziran Salah and Hoşevi İbrahim) and different charge quantities (180 kg and 240 kg total charge).

• It is important to note that, explosive per delay, not total amount of charge, should be considered in analyzing vibration effect. Therefore one should compare the blast vibrations of two blast: 19 kg per delay (totally 180kg) and 25 kg per delay (totally 240kg).

• It is realized that, increasing the explosive per delay 19 kg to 25 kg did not make any considerable increase in vibration amplitudes. Vibrations of both of the two blasts at inlet portal were between 1.30 mm/s- 8.13 mm/s. According to the safety-judging standard of explosion vibration, the conclusion that the existing tunnel blast vibration (both inlet and outlet portal blasts) do not exceed damage levels (12 mm/s for USBM standards).

• Blast induced air shocks of all blasts (inlet and outlet portal blasts) were between 100 dB and 110dB. According to USBM (Siskind *et al.* 1980) safe air shock levels for residential structures, blast induced air shocks of all blasts (inlet and outlet portal blasts) were under damage level. Since the geophone frequency of the seismographs used is 1 Hz, damage level can be selected as 133 dB.

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