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Guided wave formation in coal mines and associated effects to buildings

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Abstract. The common prospect in diminishing mine-blast vibration is decreasing vibration with increasing distance. This paper indicates that, contrary to the general expectancy, vibration waves change their forms when they are travelling through the low velocity layer like coal and so-called guided waves moving the vibration waves to longer distances without decreasing their amplitudes. The reason for this unexpected vibration increase is the formation of guided waves in the coal bed which has low density and low seismic velocity with respect to the neighboring layers. The amplitudes of these guided waves, that are capable of traveling long distances depending on the seam thickness, are several times higher than that of the usual vibration waves. This phenomenon can many complaints from the residential areas very far away from the blasting sites. Thus, this unexpected behavior of the coal beds in the surface coal mines should also be considered in vibration minimization studies. This study developed a model to predict the effects of guided waves on the propagation ways of blast-induced vibrations. Therefore, vibration mitigation studies considering the nearby buildings can be focused on these target places.

Keywords: surface coal mine; blast vibrations; guided waves; evanescent waves; coal bed

1. Introduction

Compared with the surrounding rocks, coal layers having low seismic velocity and density (Aksoy, Kose *et al.* 2004), behave like a channel (Essen, Bohlen *et al.* 2007). Seismic waves induced from blasting in or above the coal layer, are totally reflected beyond the critical angle (when the angle of refracted waves is 90°, the angle of incidence is called critical angle) in the coal layer and behave like a guided waves in itself (Ravindra and Cerveny 1971). Seismic energy can be trapped within this type of low-velocity layer, like coal. In fact, trapped seismic wave behaviors change according to rock mass properties (Aksoy, Ozacar *et al.* 2010, Aksoy 2008). This situation happens when total or near total reflection occurs at the layer boundaries and it may happen if the velocity contrast is exceptionally high or if the angle of incidence exceeds the critical angle (Sheriff and Geldard 1982). These waves are generally dispersive with different frequency components travelling at different velocities. The result is that, an impulsive input becomes a long

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wave train, after travelling for some distances. For this reason, guided waves can propagate over distances of about 1000 times the seam thickness in favorable cases (Lavergne 1989).

Theory of the propagation mechanism of blast-induced waves, their potential effects on structures and seismic response of the structures to those vibrations have been investigated by many researchers (Zhang, Lin *et al.* 2005, Ewing, Guillin *et al.* 2009, Constantopoulos, Wessem *et al.* 2012, Mahmoud 2014, Oncu, Yon *et al.* 2015). Blast-induced vibration effects are increased several times, if blasting is prepared in or above the coal layer continuing under the settlement areas. Because, coal layer behaves like a channel and guides the blast-induced vibrations to long distances with small decrease in magnitudes. This circumstance displays that vibration amplitude-distance relation in the coal blasts is not a simple and uniform reduction relation. Therefore, in order to minimize the blast-induced vibrations in coal mines in which guided waves occur, the nature of those waves and their effects on settlement areas should also be studied.

Guided waves have been investigated for different aims in the literature: Krey (1963), Findlay, Goulty *et al*. (1991), Greenhalgh, Cao *et al.* (1992), Yang, Ge *et al.* (2009) indicate that, guided waves are used to find the faults and other structural discontinuities. Gritto (2003), Wang (2005) and Yancey (2006) used the guided waves to determine the voids in the rocks. Haberland, Agnon *et al.* (2003), Fohrmann, Igel *et al.* (2004) used the advantages of guided waves to analyze the low-velocity units and fault zones. Dobroka (2001), Essen, Misiek *et al.* (2005), worked on the determination of complex underground structures and reservoir characteristics by analyzing guided waves. Buchanan, Davis *et al.* (1983), Liu, Queen *et al.* (2000) investigate the absorption, dispersion and anisotropy of guided waves. This study was the first usage of guided wave theory to understand the unexpected behavior of coal beds where blasting operations are conducted.

This study focused on a special case in which blasting operations are performed in or above the coal bed. In this case, it is claimed that, coal bed which continues under the settlement area behaves like a channel and guides the waves to long distances. Those waves should be carefully analyzed. This paper presents some modeling studies prepared to analyze the behavior of guided waves. Appropriateness of the field measurements and the model results encourages us.

Field works were conducted in Turkish Coal Company Yenikoy Coal Mine, Turkish Coal Company Soma Eynez Surface Coal Mine and Turkish Coal Company Can Surface Coal Mine, Turkey.

2. Materials and methods

In this study, unexpected behavior of the coal beds where blast vibration wave travels are explained by "guided wave seismology", first defined by Krey (1963). After studying physical properties of coal and its neighboring rocks for a while, he realized that coal behaves like a guided wave, especially in the form of "Love" type. According to him, greatest amplitudes of this type of waves are seen in the coal beds. The amplitudes decrease exponentially in neighboring rocks while moving away from the coal. This decrease is rapid especially at high frequencies.

This study used the theory of "formation mechanism of guided waves" to model the behavior of the vibration waves in the coal beds.

2.1 Formation mechanism of the guided waves

Guided waves are formed in a low seismic velocity layer above or below in which there is a high seismic-velocity layer. Low-velocity layer allows for total reflection. The energy is trapped beyond the critical angle. Before the critical angle mode, leakage occurs. The low seismic wave velocity layers in which guided waves form can be considered as the water pipe: if there are some holes in the pipe, water will leak and the pipe will not take up all the water away. But beyond the critical angle, the low velocity seismic layer can take away the energy like a water pipe without any leakage. There is an important issue to be considered here; the waves, unlike the water in the water pipes, have mechanical movements. Water in the pipe is transmitted as an agent, it will not get out of the intact tube. However, coal with low seismic velocity layer, due to the mechanical action of the waves, can guide the waves but does not completely keep it in. In the literature, these types of waves are called evanescence waves (Sheriff and Geldard 1982).

The reason for seeing vibration effects in the settlements far away from the blasting location is the evanescence waves occurring in the coal seam underneath the settlements. Coal seams with low seismic velocity can guide and carry the blasting-induced vibrations to long distances without any reduction in amplitude. If the coal seams are similar to the water pipe, no vibration signals can leak during the transmission and the settlements are therefore not affected. However, the waves have mechanical movements, while traveling in coal seams. They seep upward in the form of evanescence waves and continue to threaten the upper settlements.

In this study, coal seam with low-velocity seismic layer guides the blasting-induced vibration waves and transmits the signals up to the Husamlar Village which is approximately 2000 m away from the Husamlar Lignite Mines, Muğla, Turkey. Since the wave has mechanical movement, coal layer guides the waves but cannot trap all the energy. The vibration wave seeps like an evanescence waves into the settlement while travelling underneath the coal layer.

Fig. 1 shows the derivation of reflection and refraction waves from the blasting above and below the coal layer. The blasting in this study was above the coal layer. Therefore, our case is an example of the situation given in Fig. 1. It is well known that, after blasting, omni-directional waves travel into the ground. Fig. 1 consists of 5 pieces of rays forming beyond the critical angle. Ray number 1, travelling in a short time due to a short distance, is the direct wave. These types of waves are long wavelengths. However, the short wavelengths, having high frequency, are bent and travelling into the layer by striking up and down the top and bottom of the layer. Therefore, they

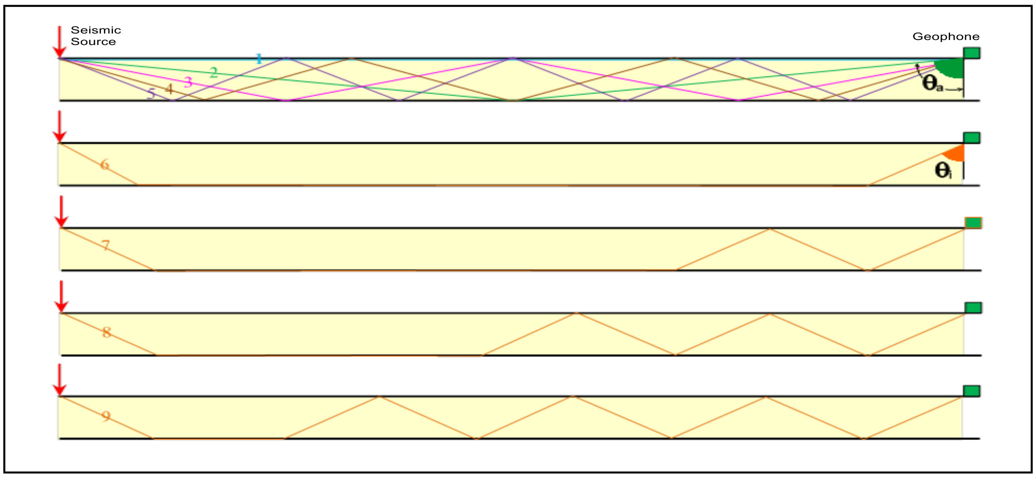

Fig. 1 Derivation of waves from the blasting above the coal layer

arrive later than the long wavelengths. This is called normal dispersion. Refracted waves also create a limited number of multiple reflections in low-velocity seismic layer, like coal.

In Fig. 1, no multiple reflections can be seen in the derivation of the ray, number 6. However, number 7 and 8 have two multiple reflections derived from refracted waves. Similarly, number 9 has three multiple reflections derived from refracted waves.

In this study, refraction and reflection of waves and multiple reflections thereof, were investigated to understand the event of interference in the channel, in our case, in the coal bed. In these views, layer thickness, distance, wave velocities, the dispersion factor and interference pattern depending on the frequency content of the sources (blasting), were examined. The evolution of the events in the coal bed is explained in the following formulas

$$G(\omega) = F(\omega)\, e^{-\alpha(\omega)x}\, e^{-iH\left[\ln e^{-\alpha(\omega)x}\right]}\, e^{-i\omega\frac{x}{v(\omega)}} \tag{1}$$

In Eq. (1), F (w) is the input wave, G (w) is the output wave. Since dispersion and absorption are frequency-dependent events, these operators are required to do in the frequency domain.

$e^{-\alpha(\omega)x}$ is the frequency-dependent attenuation term. *α*, is the absorption coefficient. *w*, angular frequency and the *x* is the distance. If the absorption function is only real, it loses its casual part. In order to make the function casual again, it is needed to add phase part. The part that makes the function casual is:

$e^{-iH\left[\ln e^{-\alpha(\omega)x}\right]}$ *H*: Hilbert transform

i: imaginary part

Normal dispersion part of the surface waves:

w: angular frequency, $e^{-i\omega\frac{x}{v(\omega)}}$ *v*: velocity

Eq. (1) was used to model the behavior of the vibration waves travelling in the coal bed. Modelling program prepared in this study examined the blasting induced direct waves, Rayleigh waves and guided waves. In the model, geometric spreading, dispersing, causal absorption, refraction and reflection phases in the channel, in our case in the coal bed, can be produced separately. The model works by linear theory. Generation of these waves and the details of the modelling studies can be found in Babayigit MSc. Thesis (Babayigit 2012).

3. Field study conducted to compare the model results

As stated in the previous section, the guided-channel wave theory to understand the unexpected behavior of blast-induced vibration wave travelling in coal beds was used. We modelled this guided wave generation in the coal beds by using channel wave theory (Krey 1963). Therefore, we could explain the unexpected vibration amplitude increases in our case study, illustrated below.

Field work for comparing our model illustrating the guided wave formation in coal beds were conducted in Turkish Coal Company Yenikoy Coal Mine, Turkey. Two group blastings were done above the coal layer which continues under Husamlar Village. The study area is within the boundaries of Milas, Mugla, Turkey (Fig. 2). Husamlar Village which is affected by the blasting activities of Turkish Coal Enterprises Surface Coal Mine is about 50 km away from Milas. In this

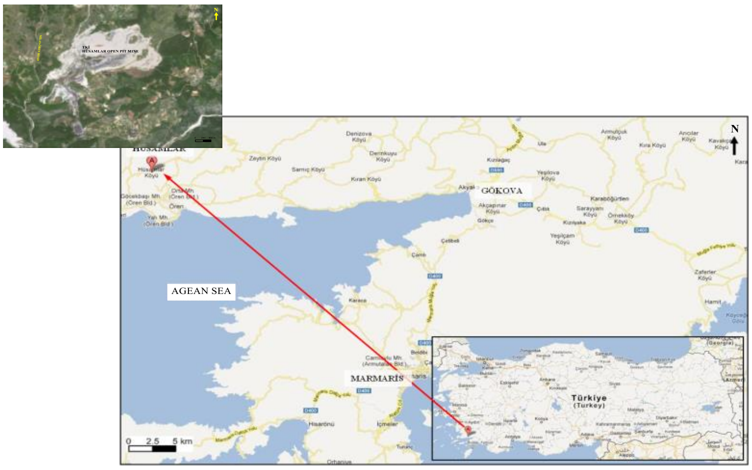

Fig. 2 Location map of the study area

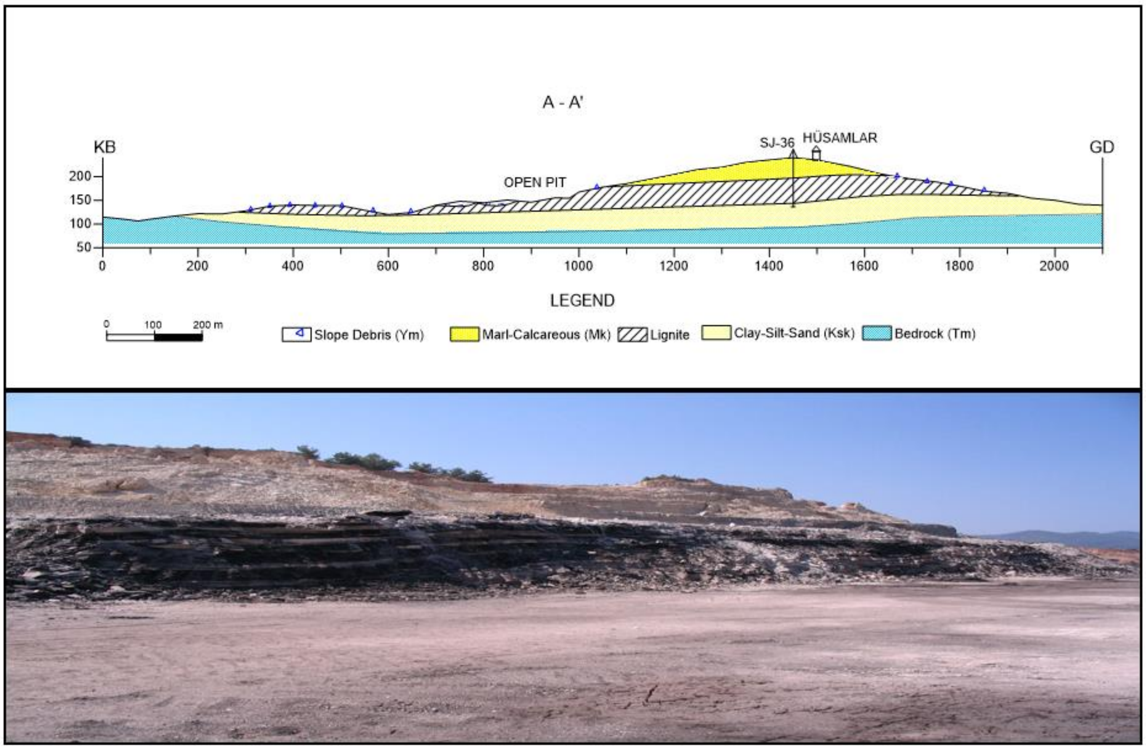

Fig. 3 Geological section of the coal layer below the Husamlar Village

field, topography ranges from 100 to 300 m. The basement rocks consist of Paleozoic metamorphic schists and Mesozoiclimestones (Yigitel 1981). The average coal thickness in the field of Husamlar is 18 meter.

Fig. 3 shows the geological section of the coal layer below the Husamlar Village.

Two group blastings were carried out. The vibration amplitudes were measured by four

Table 1 Blasting pattern applied in Husamlar Surface Coal Mine.

Blasting Pattern	
Blast#1: number of holes	30
Blast#2: number of holes	20
Number of row in both blasts	2
Explosive used in both blasts	50 kg Anfo, 0.5 kg dynamite per hole
Charge/delay	100 kg
Hole length	7 m
Hole diameter	13 cm
Burden and spacing	3 m – 3.5 m
Stemming	3 m
Delay intervals	500ms (inhole) /25ms (surface)

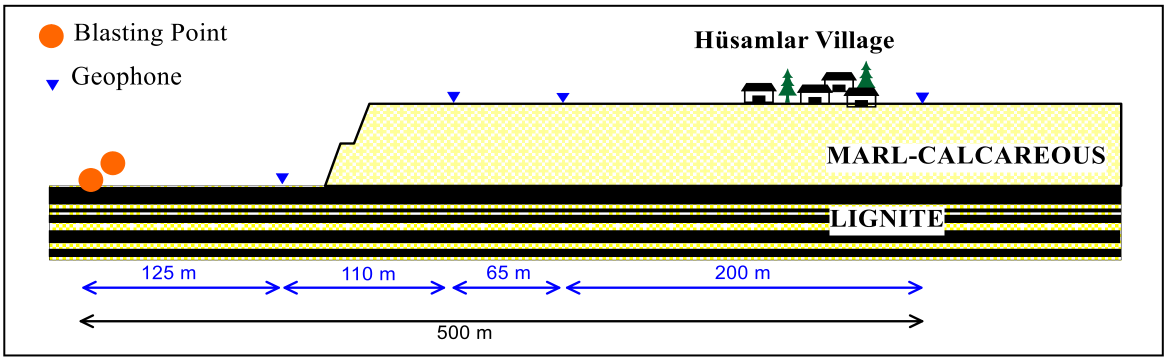

Fig. 4 Blasting and geophone locations (without scale)

seismographs and compared with the model results. Table 1 shows the blasting pattern. Fig. 4 illustrates the blasting and geophone locations (without scale).

Guided wave effects of blast induced vibration were modelled by using the Eq. (1). Then, experimental group blasts were done and the effects of blast induced guided waves were observed in the blast-induced waveforms, as it is stated in the model. Two group blasts were carried out in the field. In the first blasting, 30 holes were detonated. Three component particle velocities recorded from 4 geophones belonging to the first blasting are seen in Fig. 5.

Here, the amplitude increase in the curve formed by the vertical component in 300 meters is noteworthy. This increase, is thought to be due to the guided wave effects formed in the coal. Towards the end of the axis, the upward trend of transverse and longitudinal components suggest that the guided wave effect is also effective in these components.

In the second blasting, 20 holes were detonated. Three component particle velocities recorded from 4 geophones are seen in Fig. 6. The distance axis of longitudinal component shows that up to 230 m, low slope is observed. In other words, slow rate of amplitude decline is observed after 230 m. This is also interpreted as guided wave effect. In transversal component, opposite of the expected trend, amplitude increase can be seen towards the end of the axis and this is also due to the effect of guided waves.

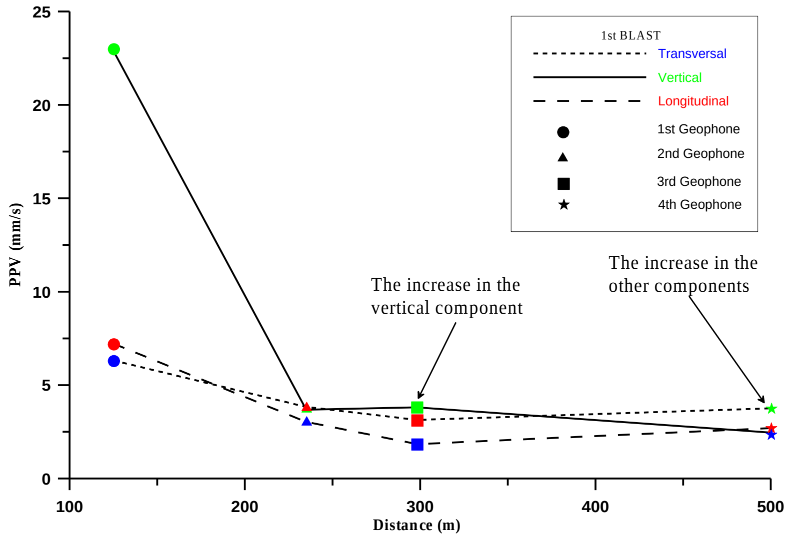

Fig. 5 Peak Particle Velocity (PPV)-distance graph of the first blast

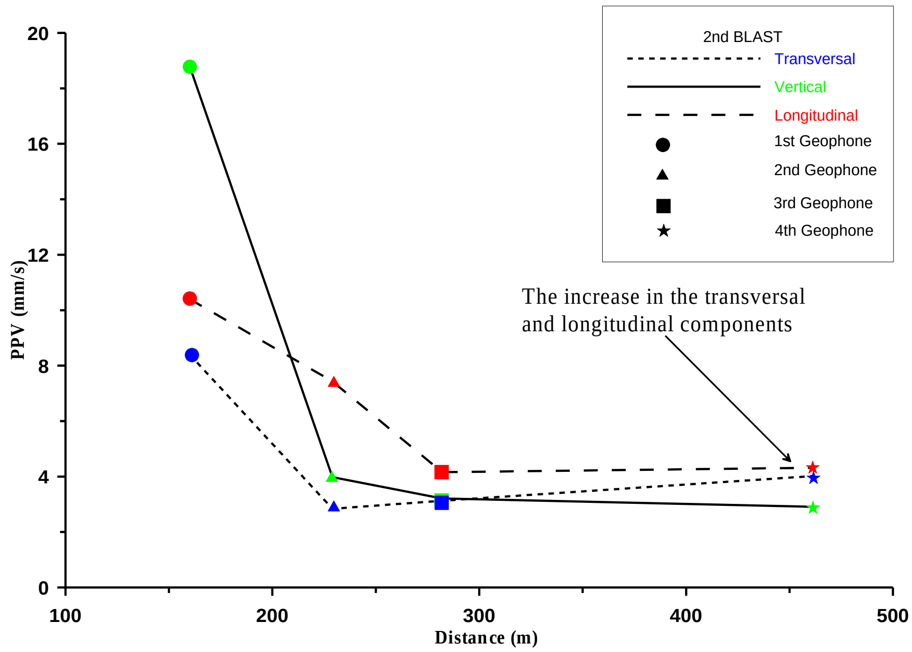

Fig. 6 PPV-distance graph of second blast

Fig. 7 indicates the Peak Particle Velocity (PPV) values of two blasts and curve obtained from the model. Point symbol represents PPV values induced by blast#1 and triangle symbol represents PPV values from blast#2. Curve, however, illustrates the total expected amplitudes (direct waves, surface waves, reflected and refracted channel waves in total) from the model. Running the model

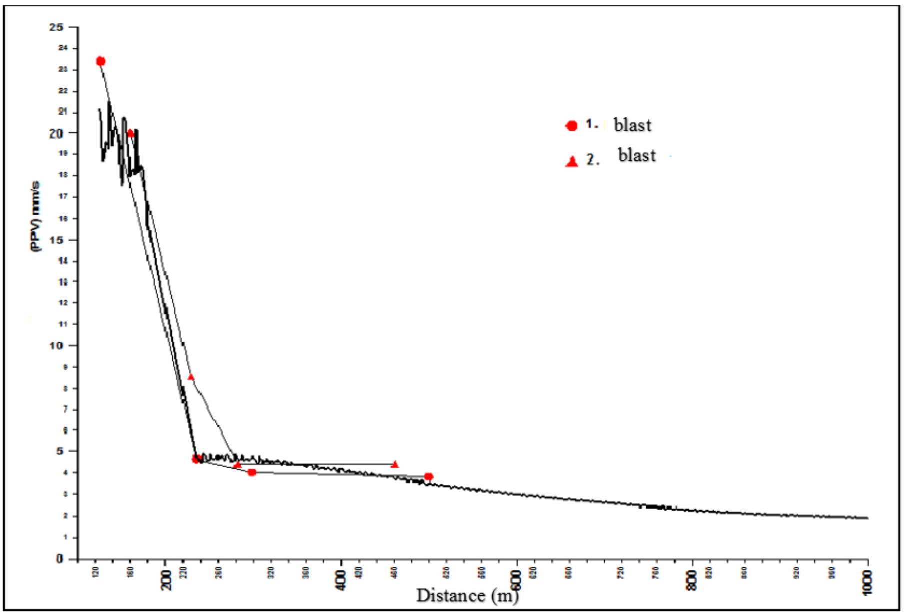

Fig. 7 Comparison of model curve with two blast's results

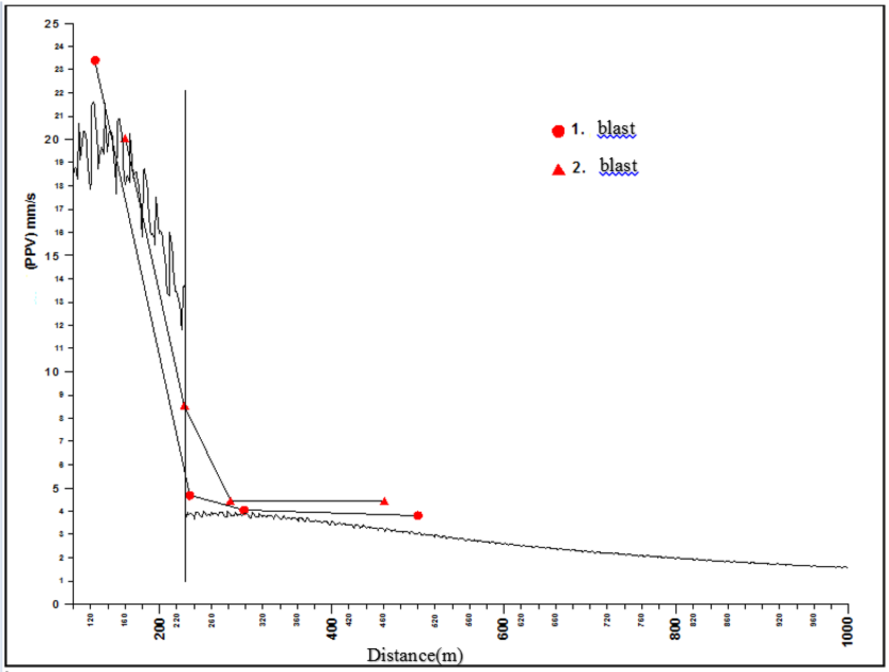

Fig. 8 Total channel wave effects calculated from the model program and blasting induced PPV's of two blasts

program, topography indicated from Fig. 3 was taken into consideration and input parameters were arranged. As it is seen in Fig. 3, the first geophone was on the coal layer and others were on the overburden, 40 m above the coal. Therefore, models were run for geophone#1 and for other geophones separated and derived amplitudes were combined appropriately considering the recording distance from the blasting locations. Fig. 7 shows that peak particle velocities (PPV) obtained from the two blasts were overlapped with the calculated curve from the model.

Fig. 8 shows the total guided wave effects calculated from the model program and blasting induced PPV's of two blasts. The curve from the left side of the vertical line in the Fig. 8 was calculated from the model. In the model, in order to simulate actual case in the field, no overburden above the coal was assumed. It is clear that guided wave effect is high when overburden layer is thin. The curve from the right side of the vertical line in the Fig. 8 illustrates that increasing the overburden decreases the guided wave effects.

A crack in the wall of a house in Husamlar village is shown in Fig. 9. This house is 500 m away from the blasting site. Normally, it can be thought that, this distance is far enough in order not to damage the building when blasting operations are carried out as it is illustrated in Table 1. However, due to guided wave and evanescent wave formation, the amplitude of blast induced wave increase again at that distance and may damage to the building.

Fig. 9 Damages in some village house, located 500 m away from the mine

Fig. 10 Location of the basting place and geophone

Table 2 Blasting pattern and blast vibration data

Blast #	Hole diameter, inch	Hole length, m	Q, kg	R, m	Tran, mm/s	Lon, mm/s	Vert, mm/s	Freq. Hz
Blast-1	9	7	100	310	3.56	1.78	2.94	5
Blast-2	9	7	150	735	0.508	0.254	0.381	4.5

4. Other fields where guided wave effects of coal beds are seen

This unexpected behavior of the coal beds was observed in Turkish Coal Mine Company's Can Lignite Surface Mine and Soma Eynez Surface Mine.

4.1 Turkish coal mine company can surface lignite mine

In this mine, in order to understand the wave propagation mechanism, two pilot blastings were arranged, Blast-1 and Blast-2 in Fig. 10. Table 2 illustrates the blasting pattern and blast-induced vibration particle velocities of these blasting operation.

Q: explosive amount per delay

R: distance between blasting and measurement location.

Tran, Lon, Vert: Transversal, longitudinal, vertical component of blast vibration particle velocities.

In blast-1, since vibration amplitudes of the transversal component is higher than the others, the signal of this component was investigated in Fig. 11. The amplitudes are high up to 0.5 second and then they start to decrease. However, at around 1.5 sec, their amplitudes show an increasing trend again (Black circle in the Fig. 11).

The other blasting operation is seen in Fig. 10 as "blast-2". The signal belonging to this blasting was measured at "measurement-2". Fig. 12 shows the transversal component of the vibration

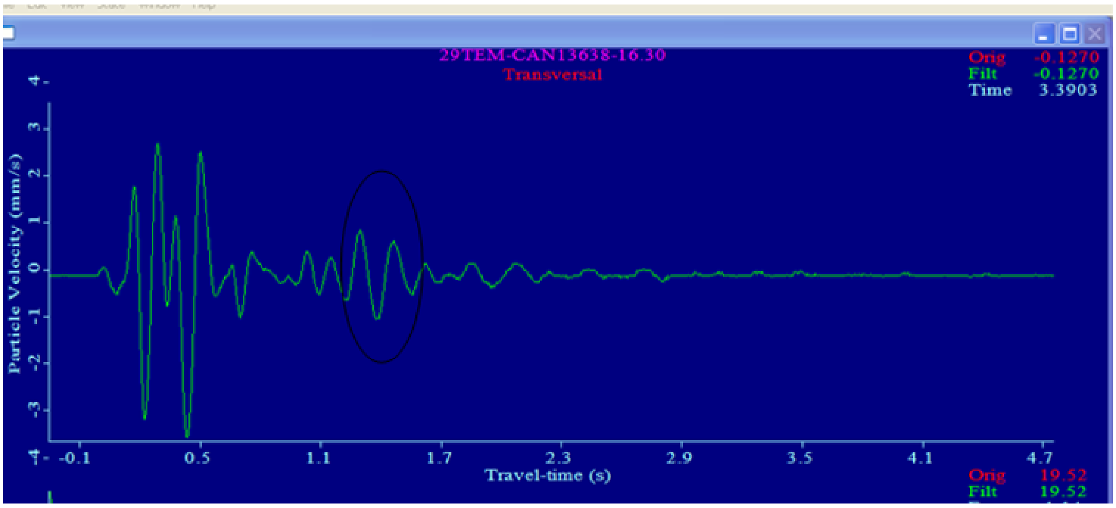

Fig. 11 Transversal component of the vibration signal of blast-1

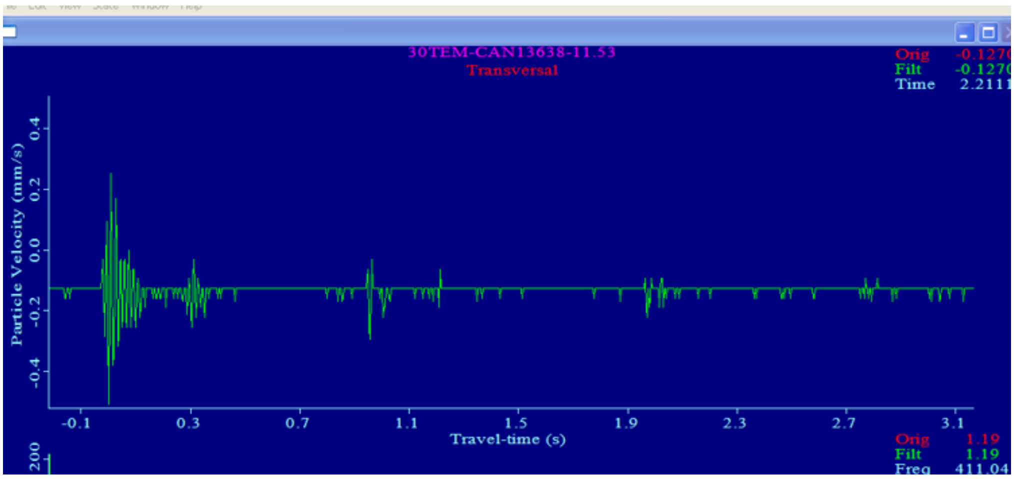

Fig. 12 Transversal component of the vibration signal of blast-2

signal generated by blast-2. It is noteworthy that, after decreasing the first big amplitudes, vibration waves start to increase at 0.3 sec, 0.9 sec, 1.3 sec, 2.1 sec and 2.8 sec.

4.2 Turkish coal mine company soma, eynez surface coal mine

Similar unexpected behavior of coal beds was seen in the study conducted at Turkish Coal Mine Company Soma Eynez Surface Coal Mine Blasts. In order to understand the propagation mechanism of blast induced waves, a group of blast holes (8 holes) was blasted at the upper level of the surface mine and their vibration signals were measured at lower levels. Fig. 13 illustrates the blasting and measurement locations.

The measurement geophone at P1 location was at the coal level. Table 3 shows the blasting pattern.

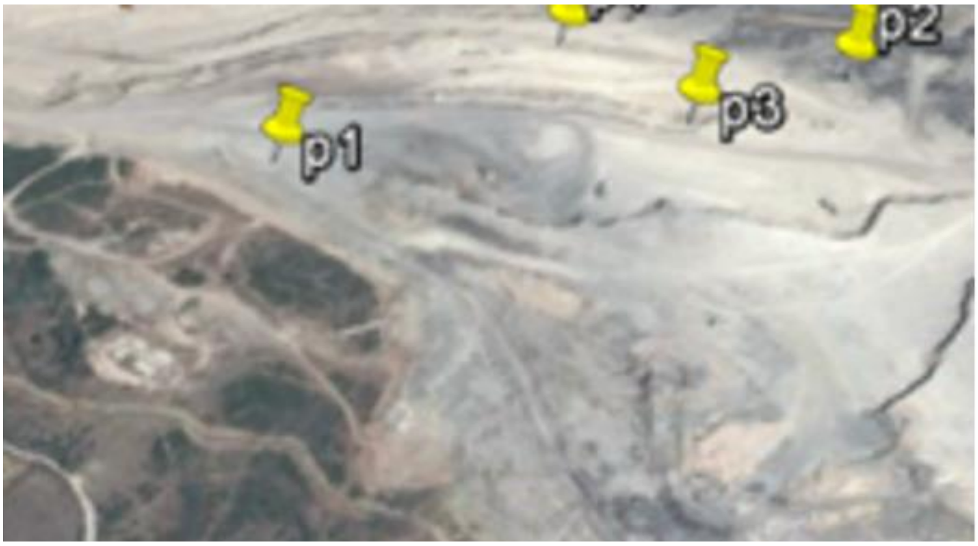

Fig. 13 Blasting and measurement locations. P2 is the blasting locations (506m above the see level). P3 (455m above the see level) and P1 (430m above the see level) are the measurement locations

Table 3 Blast design parameters

Blast design	parameters
Hole diameter, *D*	9 inch
Hole length, *H*	14 m
Hole number	8
Burden, *B*	5 m
Spacing, *S*	6 m
Explosive, Anfo	200 kg
Primer	2.5 kg
Delay per hole	42ms

Table 4 Blast vibration particle velocities

Date	Measurement location	Q, kg	R, m	Tran mm/s	Vert mm/s	Lon, mm/s	Freq., Hz
10 .11.2015	P3	200	51	1.78	2.54	3.94	4-5
10 .11.2015	P1	200	76	3.05	4.19	2.03	4-6

Table 4, shows the blast-induced vibration particle velocities measured at the two seismographs.

Fig. 14 illustrates the waveforms of the vibration record measured at P3 (upper) and P1 (lower) locations.

Table 4 indicates that, although the measurement location P1 is far from the blasting location according to the measurement location P3, particle velocities of transversal and vertical components of the vibration signals are higher. This fact is also seen in Fig. 14. Considering the upper figure of Fig. 14, the amplitudes of the signal have a decreasing trend at the time of 3 sec.

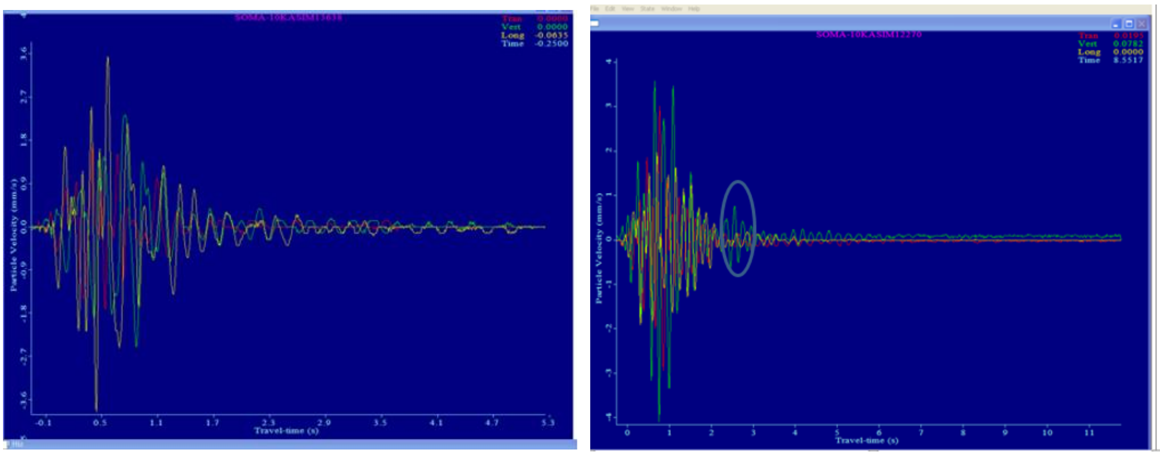

Fig. 14 The waveforms of the vibration record measured at P3 (left figure) and P1 (right figure)

However, the lower figure of Fig. 14 shows that, the vibration amplitudes start to increase again at the time of 3sec. The lower part of the figure belongs to the record measured at the coal level, P1. This unexpected increase in the amplitudes is thought to be due to channel wave generation behavior of the coal bed.

5. Results and discussion

Models used in this study were based on the guided wave formation theory. They do not depend on empirical approaches of field measurements. Models were tested by two group blast's vibration signals. Theory of guided wave formation has been proven many years ago and in this study, this knowledge was used in order to explain unpredicted vibration enhancements at long distances from the blasting points. Therefore, currently used methods for blast vibration minimization were adjusted for improvement.

Blasting study, the results of which were compared with the developed models, were carried out in the Turkish Coal Enterprises Yeniköy Lignites, Husamlar Surface Mine. Husamlar Village is located on the coal layer. Two group blasts were done in the mine and vibrations were recorded both in the mine and in the village.

When the results of blast#1 was examined, it became clear (in Fig. 5) that, the amplitude of the vertical component of the vibration signal starts to increase again after 300 m from the blast location although the amplitudes show decreasing trend until 300 m from the blasting. This unexpected case is also seen for other two components, transversal and longitudinal after 500 m from the blasting point. After 500 m, their amplitudes start to increase again.

Examination of vibration amplitudes of blast#2 gives the same conclusion: blast-induced vibration waves change their shape when they propagate in the coal layer and travel long distances, unexpectedly with increasing amplitudes. Fig. 6 shows that after 230 m, especially after 500 m, contrary to the expectations, amplitudes show an increasing trend.

Established models were overlapped with real blast data.

The unexpected amplitude enhancements in vibration signals travelling in coal beds are also seen in two different cases, Can lignite mine and Soma Eynez Lignite mine. This study showed that blast vibration amplitudes have not always exponentially decreased with distance. In case of coal layer, as a result of constructive interference between the low-velocity coal and other layers, vibration amplitudes may increase at certain locations even far away from the blasting point.

6. Conclusions

In this study added a new perspective to the blasting vibration analysis. We tried to explain that, contrary to the expected case, blast vibrations may not decrease with distance in case of guided wave formation in the coal mine. Also, those vibrations may increase again from the certain distances from the blasting locations and may travel long distances without decreasing their amplitudes. Therefore, to understand the situation, models were produced considering the theory of formation of guided waves in low-velocity layers, in our case, coal. Overlapping the results of the models with PPV's of real blasts encouraged us because the prediction of the wave propagation mechanisms of the blast-induced vibrations in such areas like coal mine is very useful in vibration minimization studies. Knowing the distance in the channel, coal layer, where amplitudes increase due to guided wave effect and selecting this locations as target point to minimize the vibration by using appropriate delays are very important. In other words, determination of the guided wave effects will give an important input data for the people trying to minimize blast vibrations affecting structures.

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