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AN INTEGRATED OVERVIEW OF BLASTING DAMAGE CRITERIA FOR ENGINEERING STRUCTURES

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Abstract: Blasting applications are frequently used during the construction of engineering structures. In our country, damage assessment criteria created by reference to the Report of Investigations RI 8507 prepared by the United States Bureau of Mines (USBM) are used to control the impact of blast vibrations on existing structures or structures under construction. In this study, the structures in the database of that report of investigation and the points on which the damage criteria are based are examined. Moreover, in the light of the other studies carried out by different researchers about the blast damage criteria in engineering structures, the requirement of reevaluation of USBM damage criteria for reinforced concrete buildings, tunnels, pipelines and other engineering structures has been revealed.

Keywords: Blasting, Damage criteria, Peak particle, Velocity

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1. Introduction

The effects of blast-induced vibrations on existing or structures being built in our country are controlled by the Environmental Noise Management and Evaluation Regulation, which has been created with reference to the Research Report RI 8507 prepared by the United States Bureau of Mining Affairs (USBM).

However, USBM Research Report RI 8507 is based on data from the effects of blasting vibrations, particularly from coal mine operations, on wood-framed, plaster or gypsum-clad 1-2 stories buildings. Therefore, the research report in question loses its validity for reinforced concrete buildings, tunnels, pipelines and similar engineering structures.

Considering the criteria in the USBM Research Report RI 8507, the limit values selected for blast-induced vibrations are even below the vibration values that may be generated by construction machinery in some cases.

The researcher (Wiss, 1981) has given the vibrations of a 0.46 kg explosive depending on the distance in Figure 1 for reference with various construction machines, trucks, rock breakers. As can be seen in Figure 1, it is possible for a truck to pass at approximately 1 meter from a structure, to create a particle velocity of 25 mm/s in the structure.

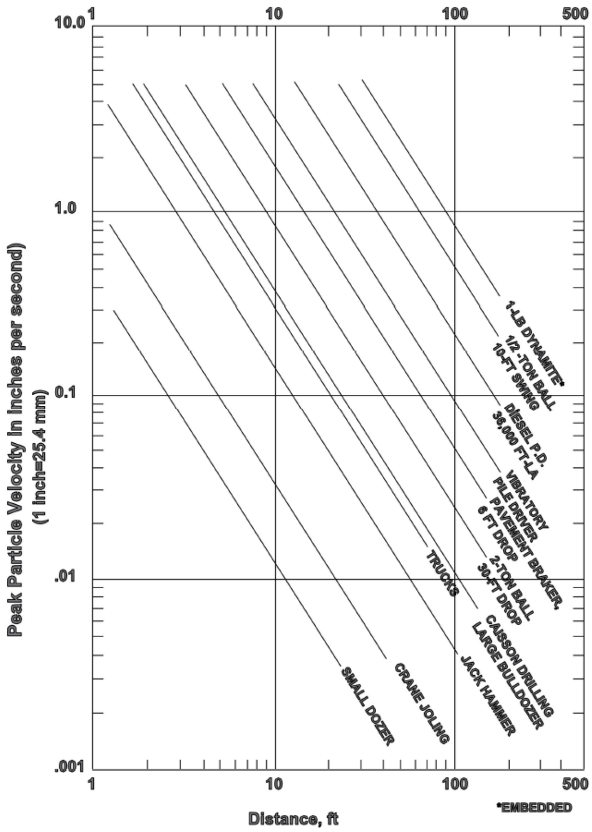


Figure 1. Relative magnitude of vibrations from construction machinery (Wiss, 1981).

These peak particle velocities are further increased by the effect of vibrations, especially in bridges built in the past with high oscillations. In addition, hydraulic breakers used right next to the buildings in excavations in the city can create particle velocities of about 100 mm/s. Similar effects apply to roller compacted concrete dams (RCD). In such dams, the concrete layer, which is usually 30-40 cm thick, is transported by large trucks (trucks), laid with dozers and compacted with rollers.

Considering that the trucks are as close as the layer thickness to the concrete, which has just gained a part of its strength, it is possible for the peak particle velocities to reach 50 mm/s. In addition to these, regardless of whether the concrete that is getting its setting is mass or structural concrete, or the concrete that has reached a certain age and is gaining its strength, the permissible vibration values may be chosen unnecessarily low, and the construction speed could be unnecessarily reduced, and accordingly, the construction costs increase. These considerations reveal the necessity of reviewing the USBM damage criteria for engineering structures.

The aim of this study is to reevaluate the damage criteria for reinforced concrete buildings, tunnels, pipelines, and similar engineering structures by examining the data on which the USBM Research Report RI 8507 damage criteria are based.

2. Damage Criteria of USBM RI 8507

The USBM damage criteria developed for the protection of wood-framed, gypsum or gypsum-clad 1-2-story buildings from blast-induced vibrations of open coal mines were adopted by the Open Mining Operations (OSM) Bureau in 1983 with little change. Later, the USBM damage criteria was made a part of Open Coal Mine legislation and entered into force throughout the USA in 2001.

In the USBM Research Report RI 8507, vibration limits are given for the most typical and common 1-2 stories buildings with wood frame, plaster or plasterboard cladding in the USA. Peak particle velocity (PPV) or displacement limits measured in the foundation soil close to the structure, which depend on the prevailing vibration frequency, are used to evaluate the possible crack formation in these structures (Siskind et al., 1980).

In the USBM Research Report RI 8507, blast points in an open coal mine operation; High amplitude low frequency cascading waves were considered surface waves when their closest distance to structures in the database was over 75 meters (or even 100 meters). The reason for this is probably 1.5-3 m thick soil covers (Siskind et al., 1980). In other measurements included in the USBM Research Report RI 8507, the thickness of the cover is 0-1.5 m in construction excavations, the distance to the measurement point is 10-50 m, and the thickness of the cover in the quarries is less than 3 m. The frequency distribution of the explosions is given in Figure 2.

At 15-75 m distances from the blasting point, the strongest waves are surface waves (Siskind, 2005). Rayleigh surface waves are created by the interaction of pressure (P) and shear waves (S) with geological structures, and by the ground-air interface effect. One of the characteristics of surface waves is that the amplitude of motion decreases rapidly with depth from the surface. The thickness of the surface layers and the propagation speed determine the frequencies of Rayleigh surface waves.

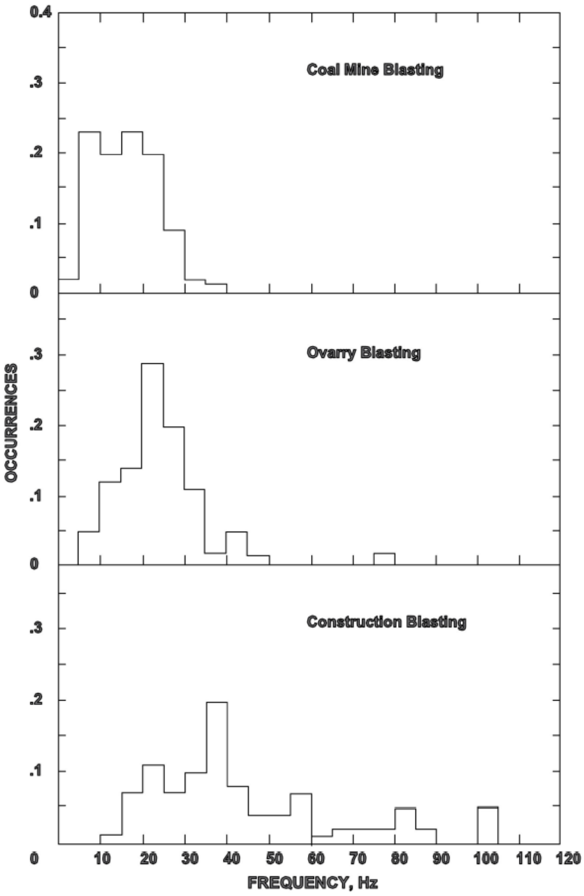
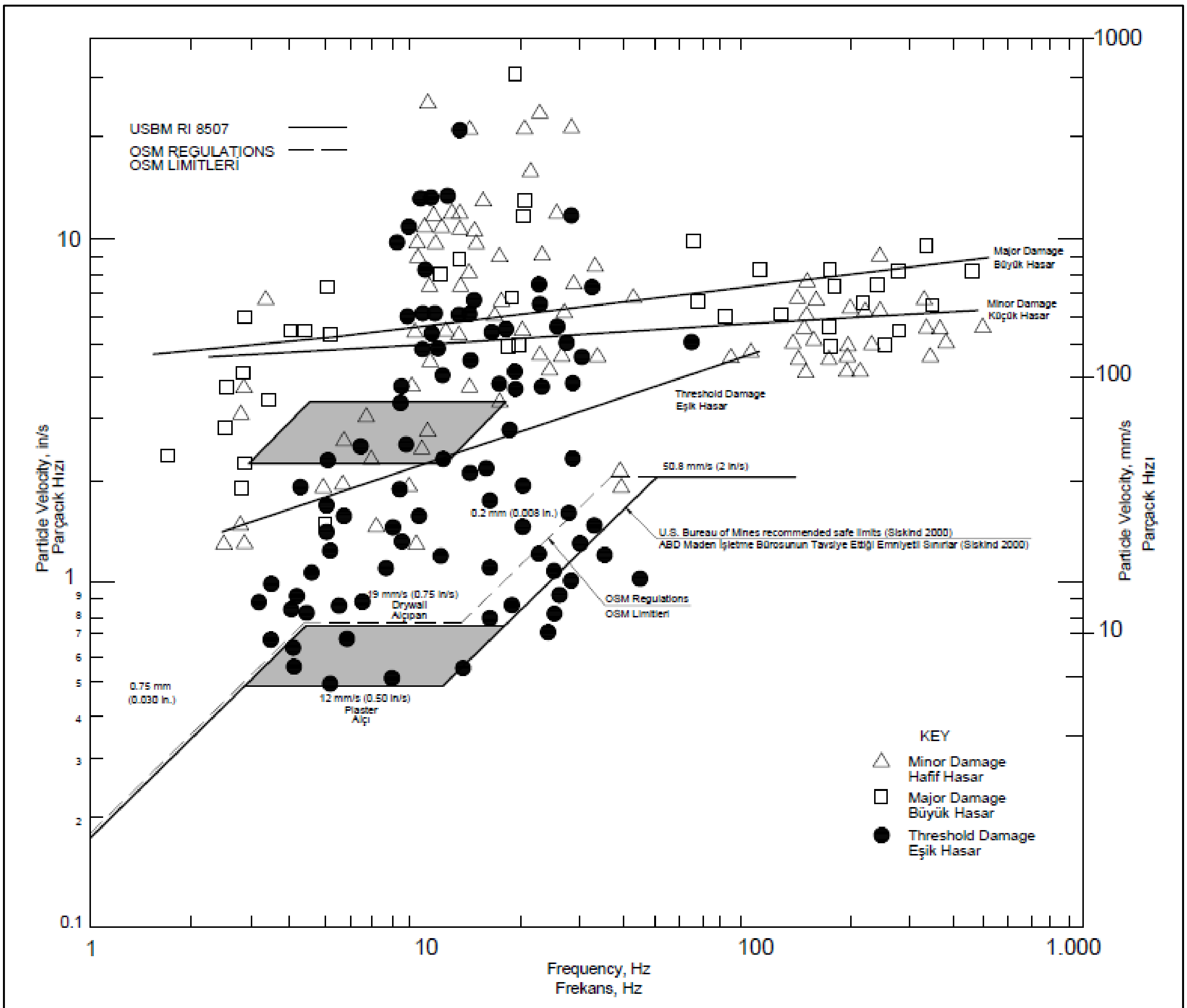


Figure 2. Frequencies of vibrations from coal mine, quarry, and construction blasting (Siskind et al., 1980).

The USBM Research Report RI 8507 does not evaluate the impact of vibrations on structures using structural vibration measurements. The main purpose of the USBM damage criteria is to prevent the formation of resonant horizontal frequencies since the frequencies created by the blasts in open coal mines may coincide with the natural frequencies of the structures in the database, and thus to prevent damage to these structures. Peak particle velocities in the USBM damage criteria are given as 12.7 mm/s and 19.0 mm/s, respectively, in the resonance region with a frequency band of 4 to 12 Hz for the structures in question. These limits, which were determined to prevent the formation of cosmetic cracks in buildings, were obtained from the division of ground vibrations with a maximum building amplification coefficient of 4.5.

In the USBM Research Report RI 8507, structural damage is classified based on the structure's response to ground vibrations. According to the definition of structural damage, damages are divided into 3 classes and are shown in Figure 3. These three types of damage identified are classified as follows: (1) Threshold: paint removal, small cracks in wall coverings at the corners of the building, growth of old cracks, (2) Slight damage: loosening and removal of wall coverings, openings in stone walls cracks close to partitions in places, cracks up to 3 mm, spillage of loose mortar materials, (3) Major damage: formation of many cracks larger than 3 mm, ruptures in arched structures, conditions causing structural weakness, spills in masonry walls, reduction in structural load carrying capacity.



Ground vibrations generated by blasting and structural damage summary: solid lines are regressions representing data means, and symbols shown are positive damage observations. Data and plot were adapted from RI 8507 (Siskind et al. 1980).

Patlama ile oluşturulmuş zemin titreşimli ve yapısal hasarın özeti: sürekli çizgiler verilerin ortalamasını temsil eden regülasyonlar olup hasar gözlemleri olan semboller gösterilmiştir. Veri ve çizim RI 8507 araştırma raporundan adapte edilmiştir (Siskind et al. 1980).

Figure 3. Damage Criteria of USBM and OSM (Siskind et al., 1980; Svinkin, 2015)

Siskind (2005) created the damage graph in Figure 3 by reporting 233 boundary, minor and major damage from blast-induced vibrations belonging to a total of 718 opencast mines and quarries. The maximum allowable particle velocity is over 51 mm/s and the data without any damage were not included in the study. When the data are examined, it is seen that the damage depends on the dominant frequency of the blast and the peak particle velocity. In the study in question, the frequency of vibrations and the frequencies of structures do not overlap in regions where the frequency is between 2-5 Hz and 60-450 Hz. In these regions, the response of the structure to blast-induced vibrations is determined by the soil-structure interaction. Peak particle velocities that can damage the structure are between 33-191 mm/s in the region where the frequencies are between 2 and 5 Hz, and between 102-254 mm/s in the region where the frequencies are between 60-450 Hz, which is considerably higher than the USBM damage limit values (Svinkin, 2007). In this case, for cases where the natural frequency of the structure and the frequency of blasting vibrations do not coincide, the USBM limits are set on the very safe side, and it unnecessarily limits the applications in practical life.

The amplitude, frequency and significant vibration duration of the blast-induced vibration waves recorded on the ground vary depending on the location of the blasting application. Among the most important reasons for this change are the encountering of vibration waves with different geological structures as they progress, the spread of vibration waves over a larger area, and the absorption of motion, especially at high frequencies. The blast design and excavation geometry, the delay interval, the amount of explosive used in each delay interval, the direction of the blasting, the thickness of the blasted unit and the distance between the blast holes determine the characteristic of vibration waves in the regions close to the blast source. The impact of the blast design on the characteristics of vibration waves decreases in regions far from the blasting source whereas the effect of the transmitting ground rock and the soil cover layer on this rock increases (Siskind et al., 1980).

The damage criteria created by the Ministry of Environment and Urbanization with reference to the USBM Research Report RI 8507 are given in the Environmental Vibration Principles and Criteria section of the Environmental Noise Management and Evaluation Regulation. In this section, blasting in mines and quarries and areas where similar activities are carried out should not damage the surrounding structures. It is stated that the vibration level to be measured on the ground next to the closest building to blasting cannot exceed the values given in Table 1. It is seen that the values given in Table-1 are the values determined by the USBM damage criteria.

Table 1. The highest allowable values of the vibrations that will occur due to blasting in mines and quarries and similar areas, the closest very sensitive (Annex: RG-27/4 / 2011-27917) and ground vibrations that will be created outside the sensitive area of use)

Vibration Frequency (Hz)	Maximum Allowable Peak Particle Velocity (mm/s)
1	5
4-10	19
30-100	50

3. Damage Criteria

3.1. Crandell Damage Criteria

The first studies on the establishment of damage criteria were made by Crandell. Energy Ratio (E.R.) defined by Crandell (1949). The relationship between particle velocity and energy ratio is presented in Equation 1.

Crandell Energy Ratio = $E.R. = \frac{a^2}{f^2}$ (1)

Where, a= acceleration (ft/s²), f= frequency (Hertz).

Since the relationship between displacement (D) and particle velocity (V) in a harmonic wave motion is given as D=V/(2πf) depending on the frequency (f), the displacement also changes depending on the change in frequency. Thick soil cover and long distances on the rock cause low frequency and long duration wave movements. As a result, this change in motion increases the building response and the potential for damage to nearby structures (Siskind et al., 1980). It is possible to calculate the Energy Ratio for sinusoidal motion with the help of Equation 2.

$$E.R. = \frac{a^2}{f^2} = \frac{4\pi^2 f^2 v^2}{f^2} = 4\pi^2 v^2 \quad (2)$$

As can be seen from Equation 2, the Energy Ratio is proportional to the square of the peak particle velocity and is independent of the frequency, unlike the USBM criterion. Crandell Energy Ratio suggested the E.R.= 3 limit as the safe limit, which corresponds to a peak particle velocity of approximately 83.8 mm/s (3.3 inch/s) (Figure 4). However, the more commonly used Energy Ratio value is E.R=1, and according to this value, the peak particle velocity becomes 48.3 mm/s (Bollinger, 2018).

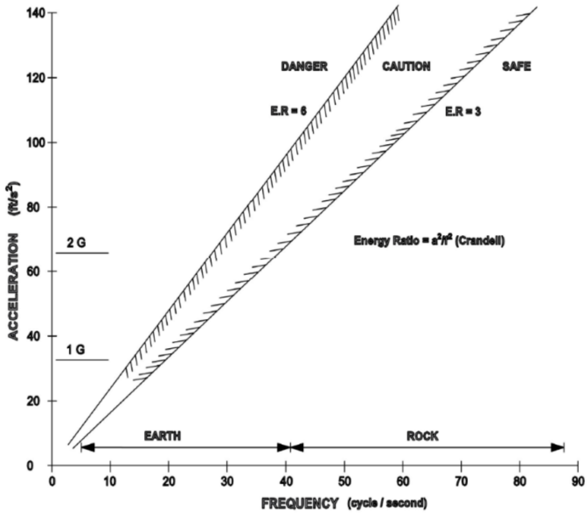


Figure 4. Damage prevention limits of Crandell

3.2. Approach of Edwards VE Northwood's Particle Velocity

Edwards and Northwood conducted experimental studies on brick structures with masonry basements resting on sandy-clay and glacial deposits in Canada. Based on the findings of these studies, it was determined that the best damage criterion for all soil types was the peak particle velocity (PPV), and the damage occurred between 101.6 mm/s (4 inch/s) and 127 mm/s (5 inch/s). As a result of the study, they recommended that the safe limit value be taken as 50.8 mm/s (2 inches/s) [8]. Damage criteria based on their results are given in Table 2.

Table 2. Damage criteria according to Edwards and Northwood's particle velocity approach (Edwards and Northwood, 1960)

Particle particle velocity (mm/s)	Damage
<50.8	None
50.8-101.6	Minor
>101.6	Major

3.3 Approach of Bauer and Calder

Bauer and Calder have given the possible damages that may occur in solid rock depending on the peak particle velocity in Table 3, and the particle velocity-related damage estimates for various equipment and various types of structures are given in Table 4 (Calder, 1977).

3.4. Swedish Standard

Standardization methods for guide levels for vibrations in buildings from blasting are done in two ways. The more common practice is to regulate the guide peak particle velocities by frequency, as buildings are more likely to be damaged by resonance with low-frequency vibrations. The second type, much less used, is the determination of peak particle velocity guide levels based on the distance and the type of ground beneath the building. The Swedish Standard is one of three countries in the world that sets guide levels taking into account distance and ground type (Jansson, 2018). In the Swedish Standard, vertical particle velocity is used because it generally gives the higher value. It is recommended to measure particle velocity vibrations at the foundation of the building (Jansson, 2018).

Table 3. Damages that may occur in solid rock depending on the peak particle velocity (Calder, 1977)

Peak particle velocity (mm/s)	Effects on hard rock masses
>2500	Complete break-up of rock masses
635-2500	Strong tensile and some radial cracking of rock
250-635	Minor tensile slabbing in rock
<250	No fracturing of intact rock

Table 4. Damage criteria depending on the type of structure (Calder, 1977)

Type of structure	Type of damage	Peak particle velocity at which damage starts (mm/s)
Houses	Plaster cracking	51
Concrete block as in a new house	Cracks in blocks	200
Cased drill holes	Horizontal offset	380
Mechanical equipment pumps, compressors	Shafts misaligned	1000
Prefabricated metal building on concrete pads	Cracked pads, building twisted and distorted	1500

According to the Swedish Standard, the following equation is used to calculate the guide levels for vibrations caused by blasting (SS 4604866, 2011).

$$v = v_0 \times F_b \times F_m \times F_d \times F_t \quad (3)$$

Where, v_0 is the uncorrected velocity under the building depending on the ground type, F_b is the building coefficient showing the vibration sensitivity, F_m is a coefficient depending on the weakest material forming the structure, F_d is the distance between the building and the blasting source, and F_t is a factor depending on the duration of the blasting job.

The uncorrected peak particle velocity v_0 can be obtained from Tables 5, 6 and 7 and Figure 5 depending on the soil type, or it can also be obtained as mm/s by dividing the P wave velocity in m/s by 65 (Jansson, 2018).

Table 5. Guideline limits for vertical PPV in different substrata (Jonson, 2012)

Substrata of foundation	Substratum	Vertical PPV, v_0 mm/s
Loosely layered moraine, sand gravel, clay	Clay	18
Compactly layered moraine, schist, soft limestone	Moraine	35
Granite, gneiss, hard limestone, quartzitic sandstone, diabase	rock	70

Table 6. Vibration sensitivity factors for different structures, F_b (Jonson, 2012)

Class	Building	Building Factor, F_b
1	Heavy constructions such as bridges, quays, defense installations, etc.	1.7
2	Industrial and office buildings, consisting mainly of prefabricated elements	1.2
3	Normal residential buildings	1.0
4	Especially sensitive buildings and buildings with high vaults or constructions with large spans	0.65
5	Guideline values for especially sensitive heritage buildings, installations or environments identified in the investigation shall be determined separately. (Per special investigation.)	≤0.5

Table 7. Vibration sensitivity factors for different materials. F_m (Jonson, 2012)

Class	Material	Material factor, F_m
1	Reinforced concrete, steel, wood	1.20
2	Plain concrete, brick, concrete hollow blocks, lightweight-aggregate concrete	1.0
3	Autoclaved aerated concrete, plaster, lath-and-plaster stucco, renedr, etc.	0.75
4	Sand-lime brick, tiled oven with sensitive joints	0.65

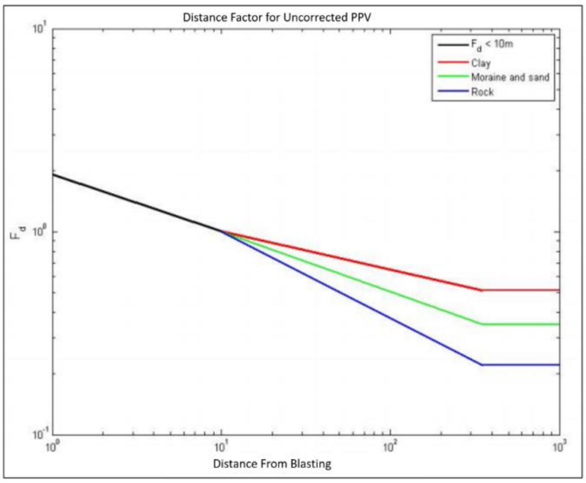


Figure 5. Change of distance factor (F_d) depending on ground type according to Swedish Standard (SS 4604866, 2011).

The Ft time factor used to consider the duration of the blasting work is taken between 1 for construction operations such as tunnels and highways, and 0.75-1 for quarry and mining operations.

3.5. DIN 4150 German Standard

In DIN 4150 German Norm, the peak particle velocity values are determined depending on the frequency. Permissible values according to the structure type are given in Table 8. While the allowable velocity is lowest in unsound structures such as old and worn historical monuments, it reaches its highest value in reinforced concrete and steel structures (Schillinger, 1996; Karadoğan, 2008).

3.6. British Standard

The values given in Table 9 of the British Standard BS 7385 give the maximum allowable levels to avoid cosmetic damage under temporary vibrations that do not cause resonance in low-rise buildings. If the vibration is continuous and occurs at small frequencies that may cause resonance, it is recommended to use low limits and reduce the values given in Table 9 by 50% (BS7385, 1993).

Table 8. Particle velocity limits according to structure type and frequency in German Standard DIN 4150 (Schillinger, 1996)

Frequency (Hz)	Peak particle velocity (mm/s)	Type of building
0-10	3	Historical building
0-10	5	Durable building, Masonry brick
0-10	20	Reinforced concrete, Steel construction
10-50	3-8	Historical building
10-50	5-15	Durable building, Masonry brick
10-50	20-40	Reinforced concrete, Steel construction
50-100	8-10	Historical building
50-100	15-20	Durable building, Masonry brick
50-100	40-50	Reinforced concrete, Steel construction

Table 9. Temporary vibration guide levels for cosmetic damage (BS7385, 1993)

Type of building	Peak component particle velocity in frequency range of predominant pulse	
	4 Hz to 15 Hz	15 Hz and above
Reinforced or framed structures Industrial and heavy commercial buildings	50 mm/s at 4 Hz an above	
Unreinforced or light framed structures Residential or light commercial type buildings	15 mm/s at 4 Hz increasing to 20 mm/s at 15 Hz	20 mm/s at 15 Hz icreasing to 50mm/s at 40 Hz and above

Note 1: Values referred to are at the base of the building.
Note 2: For unreinforced or light framed structures at frequencies below 4 Hz, a maximum displacement of 0.6mm (zero to peak) should not be exceeded.

3.7. Indian Standard

The Indian Standard has been regulated by DGMS (Tech) (S&T) (1997) Circular No. 7, published on August 29, 1997, regarding vibrations caused by blasting. It is desirable that measurements be made adjacent to the structure. Permissible peak particle velocities are determined according to the dominant frequency of blast-induced vibrations and the types of structures (Table 10).

Table 10. Maximum allowable particle velocities in mining areas (DGMS, 1997)

Type of structure	Dominant excitation frequency, Hz		
	<8 Hz	8-25 Hz	>25 Hz
A) Buildings/structures not belong to the owner			
(i) Domestic houses/structures (kuchha brick and cement)	5	10	15
(ii) Industrial buildings (RCC and framed structures)	10	20	25
(iii) Objects of hşstorical importance and sensitive structures	2	5	10
B) Buildings belonging to owner with limited span of life			
(i) Domestic houses/structures (kuchha, brick and cement)	10	15	25
(ii) Industrial buildings (RCC and framed structures)	15	25	50

3.8. France Standard

In the French Standard, allowable peak particle velocity is determined according to the structure type and frequency (Karadoğan, 2008).

Table 11. Highest peak particle velocity according to French Standard (Karadoğan, 2008)

Type of structure	Peak particle velocity (mm/s)		
	4-8 Hz	8-30 Hz	30-100 Hz
House	8	12	15
Sensitive	6	9	12
Very sensitive	4	6	9

4. Damage Criteria for Different Engineering Structures in Literature

In studies based on the USBM Research Report RI 8507, the maximum allowable particle velocity is given as 50 mm/s, taking into account the structures in the database. The damage criteria given for different engineering structures in the literature are summarized below.

In AASTHO Designation R 8-96, it is stated that it is common to apply the USBM damage criteria to other types of structures from the database on which they are based, but it is not the right approach to apply the USBM damage criteria to foundations, buried pipelines and underground structures (AASTHO Designation, 2004).

Svinkin (2015) points out that the USBM criteria are valid for 1-2-storey buildings with wood skeletons, plaster or gypsum boards, but do not cover structures such as concrete, electricity poles, pipelines, bridges. Hendron, (1977) and Langefors and Kihlstrom (1978) give the damage criterion as 10-12 in/s (250-300 mm/s) for tunnels and pipelines.

Olofsson (1990) suggests the permissible peak particle velocity of 150 mm/s for reinforced concrete structures resting on rock. Wiss (1981), on the other hand, states that concrete that has taken full strength can resist up to 125 mm/s particle velocity levels without being damaged. According to the measurements he made, it has been determined that high pressure pipelines can withstand particle velocities of 250-500 mm/s without being damaged.

Francini and Baltz, 2008) suggest values between 125-250 mm/s as permissible peak particle velocity for pressure pipelines constructed of steel. The vibration limit for the second line built parallel to the 1368 km long high-pressure gas pipeline currently in operation was chosen as 305 mm/s and the blasting process was successfully applied without damaging the existing pipeline (ISEE, 2011).

Crawford and Ward (1965) state that the peak particle velocity does not cause any damage up to 250 mm/s in concrete structures and up to 75 mm/s in mortar masonry structures. Moreover, the unit displacement values corresponding to these particle velocities are given as 100 μ and 30 μ, respectively. Persson et al. (1981) gives the allowable peak particle velocity for pulses with a vibration duration of less than 0.5 s, as 200 mm/s for reinforced concrete tanks resting on rock, 100 mm/s for modern steel or reinforced concrete tall structures, 70-100 mm/s for 15-18 m span underground galleries, 70 mm/s for brick or masonry buildings, and 25 mm/s for Swedish National Museum buildings. These values have been chosen low enough so as not to cause damage to the structures. However, even the lowest value is large enough to be felt by the people around.

(Siskind, 2005) stated that the peak particle velocity can be taken as 300 mm/s for underground structures, including the interaction of tunnels opened close to each other, and 125 mm/s for pressure pipes in multiple blasting. However, referring to the studies of (Oriard, 1994), he states that a peak particle velocity of 300 mm/s is appropriate in case of blasting one hole at a time, provided that the hole diameter does not exceed 63.5 mm for blasts to be made at distances closer than 6 meters.

In the Tennessee Valley Authority (TVA) specification, allowable peak particle velocities depending on the age of the concrete are given in Table 12 (Oriard and Coulson, 1980). The biggest difference that distinguishes this study from similar studies is that the concrete strength is determined depending on the frequency by using the Distance Factor. As the distance increases, the geometric spread and the damping frequency in the rock decrease. The falling frequency also increases the particle velocity and hence the unit displacement. By using the values in Table 12, the permissible particle velocity is found to be 300 mm/s if MF=0.6 is used for long distances of concrete aged 10 days and older, which has largely gained its strength. This is in line with the values given in the studies (Hendron, 1977; Langefors and Kihlstrom, 1978). TVA has been using the values given in Table 12 for many years without any problems (Oriard, 2002).

It should also be taken into account that the TVA specification includes 3 types of ground conditions, and these ground conditions impose some limitations. In the first case, blasting is carried out in the rock at higher elevations than the concrete. In this case, there is no question of any damage to the concrete and the data in Table 12 can be used exactly. In the second and third cases, blasting is done at lower levels than the concrete. In this case, if there is a slope flatter than 1 Vertical to 2 Horizontal slope between the lower level of the concrete and the lowest level where the explosive is placed, the data in Table 12 can be used exactly without the need for any operation. However, if the slope in question is steeper or if the blasting is done adjacent to the concrete, then blasting can be done, but subject to the approval of the authorities. Also, tall structures built above ground can amplify movement on the ground floor. In this case, half of the values given in Table 12 are used (ISEE, 2011).

Hulshizer and Desai (1984), Kwan and Lee (2002) and Ahmed (2016) found similar results with Oriard and Coulson (1980) in their studies on fresh concrete. For 0-3day old concrete, China limits the vibration rate to 15-20 mm/s for frequencies below 10 Hz, while it gives 25 mm/s for 50 Hz. On the other hand, Finland allows peak particle velocities of 45-90 mm/s, Norway 5-50 mm/s, and Sweden 30mm/s without limiting frequency (Ahmed, 2016). Ahmed (2016), after reviewing all the studies, emphasizes that 60 mm/s peak particle velocity is suitable for 0-0.5day old concrete, and a particle velocity of 140 mm/s for 0.5-3day concrete do not harm the concrete.

It is necessary to be very careful when using the values in the standards of some countries. Because while determining the limits, damage limits can be kept lower than necessary in order to manage social perceptions and complaints about blasting rather than technique. This also applies to the preparation of the DIN 4150 Standard. The limits in this standard are not damage limits (Siskind, 2005).

Table 12. Blast damage criteria for mass concrete (Oriard and Coulson, 1980)

Age of concrete (from batching time)	Allowable particle velocities from blast induced vibrations, mm/s
0- 4 hours	100 x DF
4 hours- 1 day	150 x DF
1 to 3 days	225 x DF
3 to 7 days	300 x DF
7 to 10 days	375 x DF
10 days or more	500 x DF

DF= distance factor.

Distance factor as defined below;

Distance factor	Distance from blast to concrete, Meters
1	0-15
0,8	15-50
0,7	50-75
0,6	Greater than 75

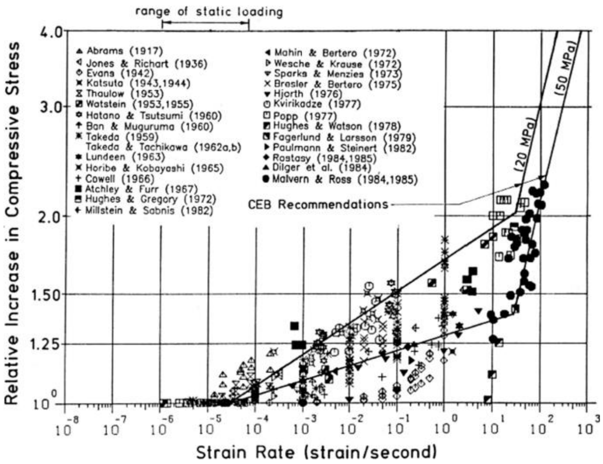


Figure 6. Effect of loading speed on concrete strength (Bischoff and Perry, 1991).

Along with the curing time, the loading speed is among the factors that determine the concrete strength. As the frequency of vibration increases, the concrete strength increases as the loading speed increases. While the strain rate is 10^{-5} per second in static loads, this rate is between 100 and 1000 per second in blast-induced loads (Bischoff and Perry, 1991). This increase in loading rate leads to a 1.5-to-3.5-fold increase in the compressive strength of concrete, called the Dynamic Increase Factor (DAF), as shown in Figure 6 (Bischoff and Perry, 1991).

The increase in the loading speed leads to an increase in the tensile strength of concrete about 2 times more than the increase in the compressive strength of the concrete (Ahmed, 2016). These increases in compressive and tensile strengths of concrete under loading speeds under the influence of blast-induced vibrations are one of the main reasons why buried concrete tunnel linings or structures resting on bedrock perform well without being damaged under high peak particle velocities.

Therefore, shotcrete for several hours withstands vibration rates of 500-1000 mm/s without cracking (Ahmed, 2016).

Isaac and Bubb (1981), based on their own experience and the findings of researchers in Scandinavian countries, determined that the allowable peak particle velocity increases in parallel with the strength of concrete. They showed that concrete with a strength of 40 MPa could withstand a peak particle velocity of 187mm/s, depending on the ductility of the concrete and the surrounding rock conditions.

In some nuclear power plant constructions in Spain, the allowable peak particle velocity has been determined depending on the concrete strength in the constructions carried out simultaneously with the concrete pouring (Jimeno ~~Carcedo~~ et al., 1995). Mass concretes are subjected to vibrations after 8 hours passed from the time of pouring. The peak particle velocity is increased in parallel to strength gained. Allowable peak particle velocity reaches 100 mm/s when the strength of concrete becomes 15 MPa. Similarly, in structural concretes, when the strength exceeds 25 MPa, the permissible peak particle velocity is risen to 60 mm/s but it cannot go beyond 100 mm/s.

(Karadoğan, 2008) found the accepted values of the Environmental Noise Evaluation and Management Regulation published by the Ministry of Environment and Urbanization to be high for Türkiye. The referred values have been adapted from USBM Norm of the United States. The reasons for these high values are that the field constants, frequency values and response levels of the residents in Türkiye and the natural frequency values of the building stock in the country are different from the data on which the USBM Norm of the United States is based. Although the residences in the USA are generally one or two floors and have high frequencies, the residences in our country are generally five floors and above and their natural frequencies are low. In the measurements made in the field, the frequency of blast-induced vibrations was measured close to the frequencies of the building stock. Based on these findings, Karadoğan et al. (2014) ~~[35]~~ developed the damage criteria for Türkiye depending on the building type as in Figure 7.

5. Identification of Damage Criteria Using Response Spectrum

The ratio of the structure size to the wavelength of the blast-induced vibration determines which of the displacement, velocity and acceleration vibration limits will cause damage first. If the dimensions of the structure are very small compared to the wavelength of the vibration, the criterion that determines the damage will be the displacement, while if the size of the structure is too large compared to the wavelength of the vibration, the criterion that determines the damage will be acceleration. In the region between these two, the speed determines the damage. Damage criteria for buildings resting on solid rock can also be expressed in terms of frequency. In this case, at frequencies lower than 20-50 Hz, the damage determining criterion is displacement, while when the frequencies exceed 200 Hz, the damage determining criterion is acceleration. Between these two, peak particle velocity damage is the determining criterion (Figure 8).

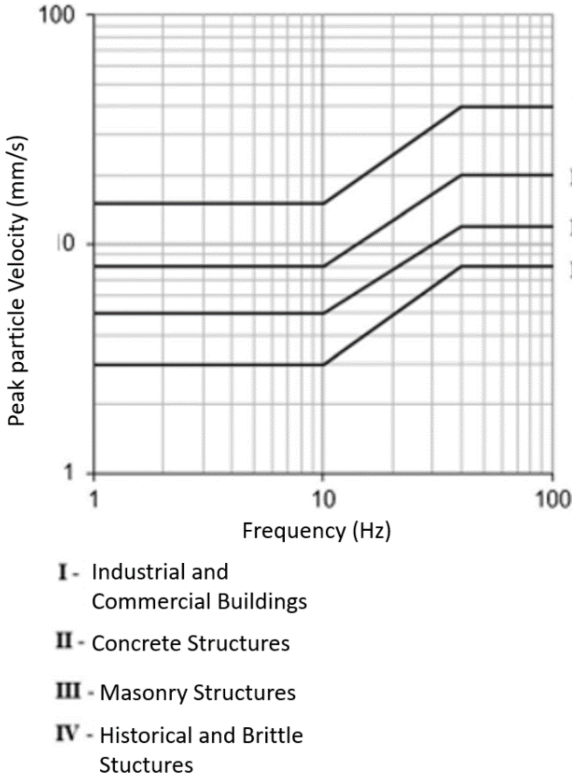


Figure 7. Damage criteria for Türkiye (Karadogan et al. 2014)

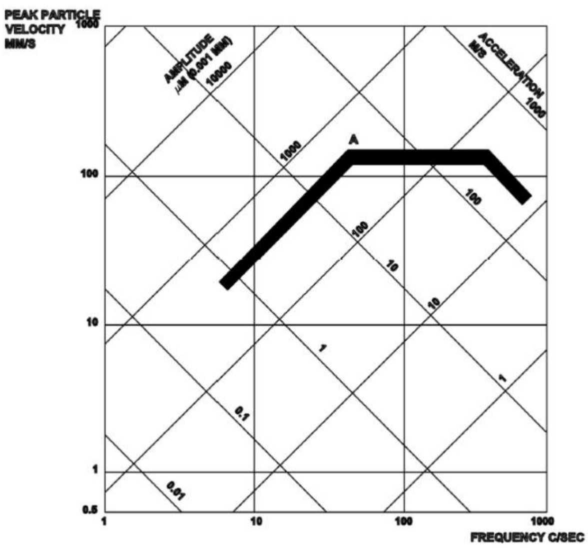


Figure 8. Frequency-dependent variation of displacement, velocity and acceleration limits of damage criteria for structures on rock (Persson et al., 1981).

In reinforced concrete structures, permissible damage criteria can be determined with the help of response spectrum based on the damage values given by TVA for mass concretes. In this case, the allowable particle velocity given for mass concrete can be divided by the building's response coefficient to determine the allowable peak particle velocity to be measured outside the building. For the same purpose, measurements can be made at critical openings and points inside buildings. Measurements made inside the buildings emerge as a safer approach, as they will include the response of the foundation ground sitting on different types of soils other than the rock, as well as the response of the building to blast-induced vibrations. However, this process may not always be possible in practice as it will require structural analysis and measurement in the right places.

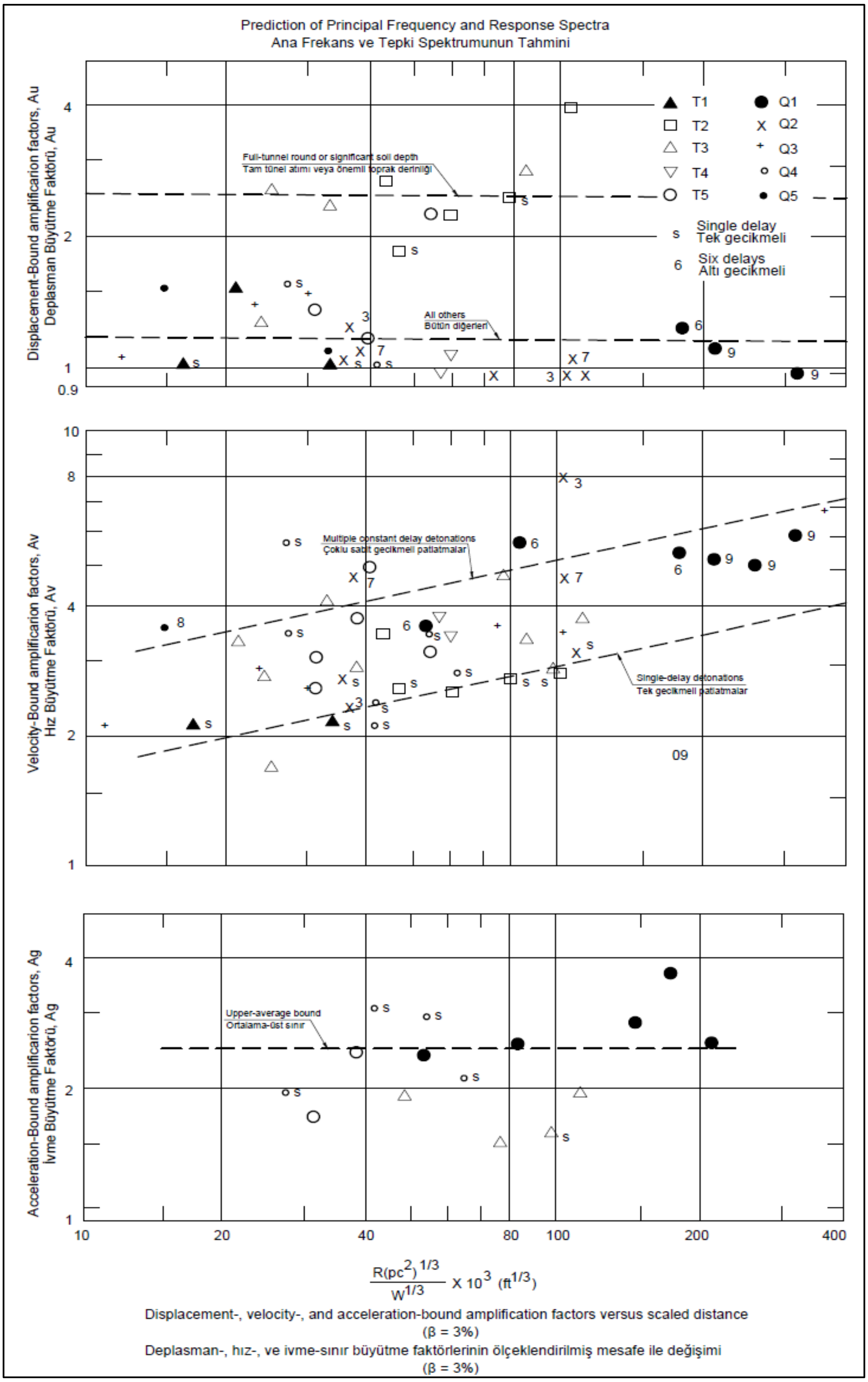


Figure 9. Variation of magnification coefficients with scaled distance (Dowding, 1985).

By using the peak particle velocities measured in the ground together with the response spectrum amplification factors, allowable peak particle velocity limits can be determined depending on the type of building. (Dowding, 1985) gives the building magnification factor approximately 3-4 for multiple blasts with scaled distance around 30-50 and damping rate of 3%. (Medearis, 1978) showed that 5% damping ratio would be more appropriate in his studies. The amplification factor corresponding to 5% damping rate for reinforced concrete buildings is calculated between 2-3, using the coefficients determined by (Dowding, 1985) and given in Table 13. (Medearis, 1978) gives the magnification factor between 2-3 for the mean +1 standard deviation for frequencies between 10 to 50 Hz; this value is very close to the values calculated by (Dowding, 1985) method.

Taking the Distance Factor (MF) into account, if the allowable particle velocity of 300 mm/s for the concrete (Oriard and Coulson, 1980) is divided by the amplification coefficient between 2-3 for buildings, the permissible value for the peak particle velocities measured on the ground is 100-150 mm/ s will be calculated between If blasting is done very close to the building, allowable particle velocities can be taken between 150-250 mm/s for relatively high frequencies. It is seen that these calculated limits are compatible with the values given by Hendron (1977), Olofsson (1990) and Persson et al. (1981).

Table 13. If the damping ratio of the response spectrum is desired for values other than 3%, the coefficients that must be multiplied by the factors obtained from Figure 9

β %	A_u	A_v	A_g
2	1.05	1.10	1.20
3	1	1	1
5	0.83	0.76	0.72
10	0.65	0.52	0.42

β % damping ratio; Au, Av, Ag are amplification factors for displacement, velocity, and acceleration, respectively.

6. Results and Discussion

In studies based on the USBM Research Report RI 8507, the maximum allowable particle velocity is given as 50 mm/s, taking into account the structures in the database of the mentioned research report. However, the damage criteria determined in the aforementioned report lose its validity for reinforced concrete buildings, tunnels, pipelines, mass concretes and similar engineering structures. Among the reasons for this are that the soil and structure amplifications are different from the structures in the database of the USBM Research Report RI 8507, the loading speed increases as the frequencies increase, and the material strength increases with the increase in loading speed. In addition to these, it should also be taken into account that the acceptance that fresh concrete is affected by vibrations too much and that the permissible peak particle velocities should be kept very low does not correspond to the real situation.

Deep foundations, buried pipelines, and underground structures do not amplify movement from the ground. Surface waves lose their effect rapidly as the depth increases, and that is, ground deamplification rather than ground amplification with depth occurs. For this reason, the application of USBM damage criteria to structures that do not have such amplifications will cause excessive design and will lead to an unnecessary reduction of construction speeds, since the building amplifications that are effective in determining the damage criteria of the USBM Research Report RI 8507.

The load-bearing system in reinforced concrete framed structures is less flexible than wood-frame structures on which the USBM damage criteria are based. In addition, stress concentrations observed in gypsum boards located at the corner points or junction points of wood-framed structures will be less in reinforced concrete-framed structures. Similarly, displacement differences caused by materials with different stiffnesses, such as wood and drywall react differently to vibration waves, but this type of differences are not expected to occur in reinforced concrete structures. For this reason, much less damage will be observed in reinforced concrete structures that are exposed to the same vibration as wood-framed structures.

On the other hand, studies initiated especially by TVA and later confirmed by many researchers have shown that fresh concrete and mass concretes can withstand peak particle velocities well above the values in the specifications. Strength increases depending on the loading speed also reveal that higher peak particle velocities can be allowed, especially at high frequencies.

For all these reasons explained, it is considered that USBM damage criteria should not be applied to reinforced concrete buildings, tunnels, pipelines, mass concretes and similar engineering structures, and cost increases should not be created by unnecessarily reducing construction speeds.

Allowable peak particle velocities for these structures are given below. TVA has been applying the allowable particle velocity of 300 mm/s for mass concretes that have gained 28-day strength without any problems for many years. This value is a value that can be used safely for mass concretes resting on the bedrock, buried structures and tunnel linings. In pressure pipes, the permissible particle velocity can be taken as 250-300 mm/s for single blasting, and a value between 125-150 mm/s, which is approximately half of this value, for multiple blasting.

The loading rate of concrete is 10-100 million times higher than static loading in vibrations caused by high frequency blasting (Bischoff and Perry, 1991). This situation increases the compressive strength of concrete 1.5-3.5 times, and the tensile strength about 2 times more than the increase in compressive strength. Thus, at high frequencies, concrete can withstand particle velocities up to 1000 mm/s without being damaged (Oriard, 2002).

By using the peak particle velocities measured in the ground together with the response spectrum amplification factors, allowable damage limits can be determined depending on the type of building. Considering the studies of Dowding (1985) and Medearis (1978), the magnification factor can be taken between 2-3 for 5% damping rate and frequencies between 10-50 Hz.

Considering the response of reinforced concrete structures, that is, amplification of movement from the foundation level, allowable particle velocities for reinforced concrete structures can be taken between 100-150 mm/s. Permissible particle velocities for single blasts can be increased to between 150-250 mm/s if blasting is done very close to the building.

7. Conclusions

The USBM Research Report RI 8507 is based on data from the effects of blasting vibrations, particularly from coal mine operation, on wood-framed, plaster or gypsum-clad 1-2 story buildings. The damage criteria were determined in such a way that structure would not be damaged by the effect of the resonance occurring as a result of the overlapping of the frequencies of the blast-induced surface waves and the frequencies of the structures in the database of the mentioned research report.

In studies conducted by different researchers in the literature for different types of engineering structures, it has been revealed that 50 mm/s particle velocity, which is the upper limit of the USBM damage criteria, can be selected higher.

Although it is common to apply the USBM damage criteria to structures other than those in the database on which the study is based, it is not the right approach. Therefore, it is necessary to re-evaluate the USBM damage criteria for engineering structures.

Oriard and Coulson (1980) showed that USBM PPV criteria may be conservative even for fresh concrete because it was not as much affected by vibrations as thought.

Author Contributions

The percentage of the author contributions is presented below. The author reviewed and approved the final version of the manuscript.

	D.Y.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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