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Investigation of the structural damage caused by blasting activities in tunnels to surrounding buildings: The case of Gümüşhane belt highway

Tünellerde patlatma faaliyetlerinin çevre binalara verdiği yapısal hasarın incelenmesi: Gümüşhane çevre yolu örneği

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Abstract

Tunnels are road transport structures that reduce traffic and expropriation problems, noise, and possible damage to animals and plants, and provide safer, more comfortable, and faster transportation for vehicles compared to highways. However, some environmental problems occur during tunnel construction. These problems such as vibration, noise, rock throwing, etc. caused by the blasting process used during tunnel excavation on buildings and people should be well investigated. In this study, two buildings located close to the exit and entrance of two tunnels (T2 and T3 tunnels) on the Gümüşhane belt road were chosen to investigate. Firstly, the existing damages in the first building, which is 7 m away from the T2 tunnel exit, and the second building, which is 60 m away from the T3 tunnel entrance, were analyzed by considering criteria such as the geological and ground condition of the land and the building materials used during the construction of those building. In addition, the negative effects on the buildings were evaluated by calculating the vibrations after the blasting process in the tunnel with the help of various empirical formulas. Investigation on site showed that building 1 was built of masonry and building 2 was built of reinforced concrete, and that deep cracks had formed in the bearing systems of both buildings, spills occurred in the walls, and fractures in the windows. Also, calculations with empirical formulas showed that the vibration rates caused by blasting process in the 1st and 2nd buildings were as 385.68 mm/sec and 6.91 mm/sec, respectively, and these vibration values were above the standard values. The data obtained through examination on-site and empirical approaches show that it would be dangerous for people to be resident in both buildings.

Keywords: Damage assessment, Structural damage, Tunnel blasting, Vibrational hazard

Öz

Tüneller, trafik ve kamulaştırma sorunlarını, gürültüyü, hayvan ve bitkilere gelebilecek olası zararları azaltan, karayollarına göre araçların daha güvenli, konforlu ve hızlı ulaşımını sağlayan karayolu ulaşım yapılarıdır. Ancak tünel yapımı sırasında bazı çevre sorunları ortaya çıkmaktadır. Tünel kazısı sırasında kullanılan patlatma işleminin binalar ve insanlar üzerinde yaratacağı titreşim, gürültü, kaya fırlatma vb. problemleri iyice araştırılmalıdır. Bu çalışmada, Gümüşhane çevre yolu üzerinde bulunan iki tünelin (T2 ve T3 tünelleri) giriş ve çıkışlarına yakın konumda bulunan iki bina incelenmek üzere seçilmiştir. İlk olarak T2 tüneli çıkışına 7 m uzaklıkta bulunan ilk binada ve T3 tünel girişine 60 m uzaklıkta bulunan ikinci binada mevcut hasarlar arazinin jeolojisi ve zemin durumu ve bu binaların inşası sırasında kullanılan yapı malzemeleri ve gibi kriterler dikkate alınarak analiz edilmiştir. Ayrıca tünelde patlatma işlemi sonrası oluşan titreşimler çeşitli ampirik formüller yardımıyla hesaplanarak binalar üzerindeki olumsuz etkiler değerlendirilmiştir. Yerinde yapılan incelemede, 1. binanın yığma, 2. binanın betonarme olarak inşa edildiği, her iki binanın taşıyıcı sistemlerinde derin çatlaklar oluştuğu, duvarlarda dökülmeler ve camlarda kırıklar olduğunu göstermiştir. Ayrıca ampirik formüllerle yapılan hesaplamalar 1. ve 2. binalarda patlatma işleminden kaynaklanan titreşim hızlarının sırasıyla 385.68 mm/sn ve 6.91mm/sn olduğunu ve bu titreşim değerlerinin standart değerlerin üzerinde olduğunu göstermiştir. Yerinde inceleme ve ampirik yaklaşımlarla elde edilen veriler, insanların her iki binada da ikamet etmesinin tehlikeli olacağını göstermektedir.

***Anahtar kelimeler**: Hasar tespiti, Yapısal hasar, Tünel patlatma, Titreşim hasarı*

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1. Introduction

Tunnels are defined as underground structures that allow a part of the highway or railway to be built underground when it is not technically or economically feasible to construct over the ground (Öztürk, 2007). The province with the highest number of tunnels in Turkey's road network because of its mountainous geography is Gümüşhane. Gümüşhane city center is located on a valley between steep mountains. Therefore, it is possible to provide safe and comfortable transportation with highway tunnels. Within the provincial borders, there are a total of 52 tunnels open to traffic and under construction, and 15,803 m of the 496 km highway is crossed by tunnels. After the completion of the tunnels under construction, 30 km of the highway network will be passed through tunnels. When the projects are completed, transportation in 9% of the city's road network will be provided by tunnels.

Tunnels are usually built by blasting. Blasting activities also have some negative effects on the environment and people. Blasts that may occur in or near structures (especially in masonry brick walls with a brittle collapse mechanism) cause serious structural damage or collapse, cause serious economic losses and, more importantly, endanger public safety (Altunışık et al., 2021). Any situation that arises during the usage period of a building is defined as damage in general terms if it exceeds the tolerance limits (Demir, 1999). Structural damage can be defined as the partial loss of standard or defined properties of a structure or a building element due to any reason during use (Yüksel, 2008).

The first damages in reinforced concrete structures start with thin plaster cracks and continue with the pouring of small pieces of plaster. These cracks do not affect the structural system safety of the building. The fact that the crack has been repaired and the crack is reopened after the repair indicates that the effect that created the crack continues. With the continuation of the effect, if "X" shaped cracks occur in the walls, large pieces of plaster fall due to the enlargement of crack openings, slipping of roof tiles, cracks in the chimneys and some chimney parts falling down, the structures can be considered as moderately damaged structures. Moderately damaged structures can be reused by repair or reinforcement. The occurrence of large cracks in the walls and the collapse of the chimneys indicate that the structure is heavily damaged. The rupture of the building walls, the collapse of some parts of the building and the loss of connection of the parts separated by joints are defined as debris. The collapse of the buildings as a whole can be defined as heavy debris. Heavy damage to the structure indicates that the structural system elements (column, beam) are damaged. In this case, the bearing capacity of the structure or the load-bearing system decreases and it is likely that collapse or heavy debris damage may occur (Yüksel, 2008). Based on the detailed literature review, it is observed that the structural elements are too sensitive to the blast loading (Senthil et al., 2020).

Progress in mining and tunneling activities is achieved by excavation and blasting the rocks. The main purpose of blasting for the excavation process is to separate the rock from the ground. The shock wave energy, which provides disintegration by blasting, not only breaks the rock but also passes through the solid rock in seismic waves and propagates in the field until it is completely damped. There are two ways in which the energies of such waves can be damped. The first is the physical and geological resistance of the rock structure, the second is the geometrically spreading of the seismic wave to a wider area as it moves away from its source. In this damping process, energy waves can cause damage to buildings and anxiety for residents. The environmental problems here are an indication that not all of the explosive energy is used for blasting. During the propagation of shock waves, vibration frequency decreases as well as vibration energy (Karakuş, 2012). In the damage caused by the blast effect in the surrounding buildings, besides the vibration energy level, the building material, building dimensions, and the geological characteristics of the ground on which the foundation of the building is located are also effective. Energy propagation can progress in different directions and intensities according to geological formations within the rock.

Ground vibrations caused by blasting have earthquake-like effects. Therefore, the resulting structural damages are also similar. It is important to evaluate the vibration effects of seismic waves that occur as a result of blasting in areas close to buildings, on the aboveground and underground structures and slopes. The blasts carried out in the tunnel areas are very likely to damage the surrounding rural buildings (village houses, barns, etc.). Because explosive materials used in tunnel excavation works propagate different vibration waves around. The resulting vibration causes some adversities such as cracks and vibrations on the buildings and houses starting from the closest one in the vicinity.

Damaging effects such as rock throwing, dust emission, air shock, and noise caused by the blasting process are reflected in the nearby environment in a very short time. However, the vibration caused by seismic shock waves arising from blasting can be felt in a wider area by spreading in a certain speed, frequency and amplitude in the blasted rock unit as in the air. The speed of movement of a particle in the ground is called the peak particle velocity (PPV). Particle velocity starts at zero, reaches its highest value, and gradually damps. Therefore, one of the most important features in ground vibration studies is the highest particle velocity. Because the higher the speed value, the more severely the structure or ground is shaken. A greater area or distance is required for a greater particle velocity to be damped. The greater the vibrations cause them to be felt from an area farther from the blasting point, while the more destructive effect it has on structures in the near regions. The propagation of shock waves continues until their energy is exhausted. Transport of seismic waves depends on various factors: distance traveled, ground investigation, geology, wave type, discontinuities, frequency, refractive angle, source structure, spherical propagation and elastic properties of the environment (Gümüşçü et al., 2016). In homogeneous structures, the wave spreads more easily, and some part of the wave is reflected back in fractured structures or fault layers (Figure 1). Based on this information, another parameter that should be considered while preparing the blasting pattern is the geological characteristics of the area.

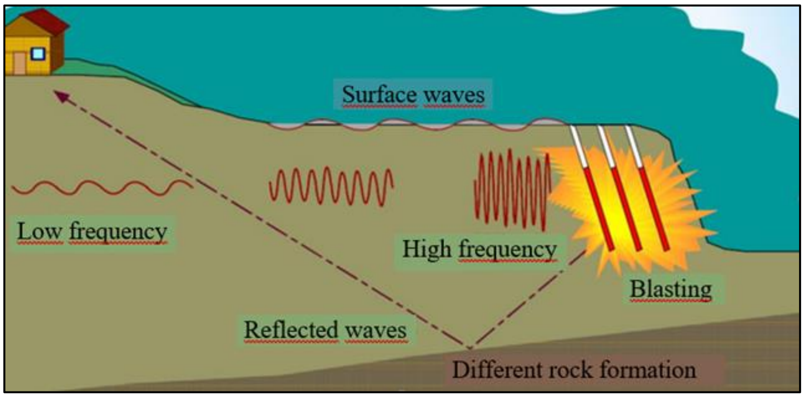

Figure 1. Vibration waves caused by blasting (Gümüşçü et al., 2016)

According to German DIN 4150-3, for frequency values lower than 10 Hz, the maximum permissible vibration (high particle velocity) value is determined as 3 mm/sec for protected structures and 5 mm/sec for buildings and similar structures. According to this specification, damage in the form of visible plaster cracks in buildings occurs when the vibration velocity exceeds 20 mm/sec and 12 mm/sec, respectively, for gypsum and sand plaster. For people to feel the vibrations, the vibration velocity must be greater than 0.25 mm/s (DIN, 1999).

According to the classification of building damage that may occur due to the blasting effect developed by U.S. Department of the Interior Bureau of Mines (USBM), damage to buildings is defined in three ways: threshold damage, slight damage and heavy damage (Siskind et al., 1993). Threshold damage covers only visual damage, which consists of hairline cracks in paint and plaster. Slight damage is damage that can be seen in the form of plaster falling and cracks expanding up to 3 mm, but that does not affect the strength of the structure and the load-bearing capabilities of the structural elements. Heavy damage is the damage that causes wide cracks in the building walls, stone and bricks fall from the walls and chimneys, resulting in permanent deformations in the building and weaken the structure. Table 1 gives the values that safe vibration speeds should be according to the frequencies depending on the types of structures. The values in the table are chosen lower than the values observed to occur threshold damage. If these values are met, it is accepted that the probability of surface crack formation can be at most 5% (Küçük & Aksoy, 2017).

Table 1. Safe vibration speed levels according to USBM (Küçük & Aksoy, 2017)

Building type	Vibration speed, mm/sec	
	Low frequency (< 40 Hz)	**High frequency (>40 Hz)**
Modern structures	19	50.8
Old buildings (with wooden elements)	12.7	50.8

In Turkey, "Regulation on Assessment and Management of Environmental Noise (RAMEN) (RAMEN, 2010)" has been prepared which covers the principles and procedures for environmental vibrations and environmental noise that people exposed to. According to this regulation, the highest permissible values of ground vibrations that will be caused by vibrations that will occur due to blasting in mines and quarries and similar areas outside the closest very sensitive area of use are given in Table 3. In the relevant regulation, the damage limits vary according to the vibration frequency generated by the blasting. The ground vibration level cannot exceed the limit values in the Table 2.

Table 2. The vibration speeds depending on the blasting frequency (Forssblad, 1981)

Vibration frequency (Hz)	Maximum permissible vibration speeds (Peak value-mm/sec)
1	5
4-10	19
30-100	50

It is possible to measure the effect of the vibration generated by the blast on the surrounding structures and air shock and vibration measuring devices are used for this. However, the estimated peak particle velocity that may occur after blasting can be calculated by using the "Devine Equation", thanks to the data obtained from the blasting designs in areas where blasting has not yet been performed or measurement has not been made during blasting (Equation 1).

$$V = k \times \left(\frac{D}{\sqrt{W}}\right)^{-\beta} \quad (1)$$

Here; V; vibration speed propagated in the rock (in./sec), k; coefficient depending on the rock type (26-260), β; is site constant, D; the effective distance between the blast point and the surrounding buildings (feet), W; is the amount of explosive in a lag interval (pounds) (1 feet=0.3048 m, 1 pound=0.4536 kg, 1 in.=25.4 mm).

Vibration values are calculated taking into account the total amount of explosives per lag interval. The coefficient "k" in the relation is the rock's capacity to transmit vibration. The variability of the units between the blast source and the sensitive point, the density of discontinuities such as fractures, faults, and cracks affect the coefficient k. While the coefficient k is around 260 in homogeneous units, the intensity of tectonic effects and the coefficient for each different unit passed is around 26.

Vibration speed values are based on the closest building unit according to the distances found with the Devine Relation. Vibration speed at the foundation of the building is expressed as V_0 1/2 to 1/5 times the vibration speed in the rock (V) is accepted as the V_0 value (Forssblad, 1981). Vibration speeds occurring in building foundations (V_0) depending on the evaluation of the building types that may be damaged due to blasting are given in Table 3.

Table 3. V_0 values that may occur depending on the building types (Forssblad, 1981)

Building type	V_0 (mm/sec)
a- Very old historical buildings that are about to collapse	2
b- Plastered briquette, adobe, masonry brick buildings	5
c- Reinforced concrete buildings	10
d- Industrial buildings with very solid structures such as factories	10-40

Studies in the literature have shown that the Devine equation alone is not sufficient, due to the changes in rock parameters and uncertainty of in situ conditions. It has been determined that there is another study using a total of 1089 blast data published by various researchers in different rock areas. In this study, a new generalized empirical model for PPV (Equation 2) is proposed, taking into account the effects of rock parameters such as unit volume weight (γ), rock quality definition (RQD), geological strength index (GSI) and uniaxial compressive strength (UCS) (Kumar et al., 2016).

$$v = \frac{(0.3396 \text{ x } 1.02^{GSI} GSI^{1.13})^{0.642} D^{-1.463}}{\gamma} \tag{2}$$

where v is the PPV (m/s); D is the scaled distance ($m/kg^{1/2}$), which is defined as the ratio of distance from charge point, R (m), to the square root of charge mass, Q (kg), expressed in TNT net equivalent charge weight, i.e. $D=R/Q^{1/2}$.

2. Material and method

Gümüşhane is located on one of the important transit routes of the historical Silk Road. This route connects the Eastern Black Sea ports to the Eastern and Southeastern Anatolia Region and Southeast Asia. However, due to unsuitable terrain conditions, the single carriageway with two lanes undivided highway passing through the city is also used as a transit way until 2019. Averages of 8.000 vehicles per day are transiting this highway. This situation led to both the locking of urban traffic and the decrease in traffic safety. A high-standard belt highway is built in 2019 to ensure that the vehicles using the highway in the city for transit purposes can participate in the intercity traffic fluently. At the same time, vehicles going to the Bayburt-Erzurum direction or Trabzon direction do not enter the traffic in the city by using this road. As a result, while the traffic density in the city highway is decreased, driving comfort, shorter travel time, fuel saving and higher traffic safety are provided for the vehicles using the belt highway. Satellite image of the highway passing through the city and belt highway are given in Figure 2.

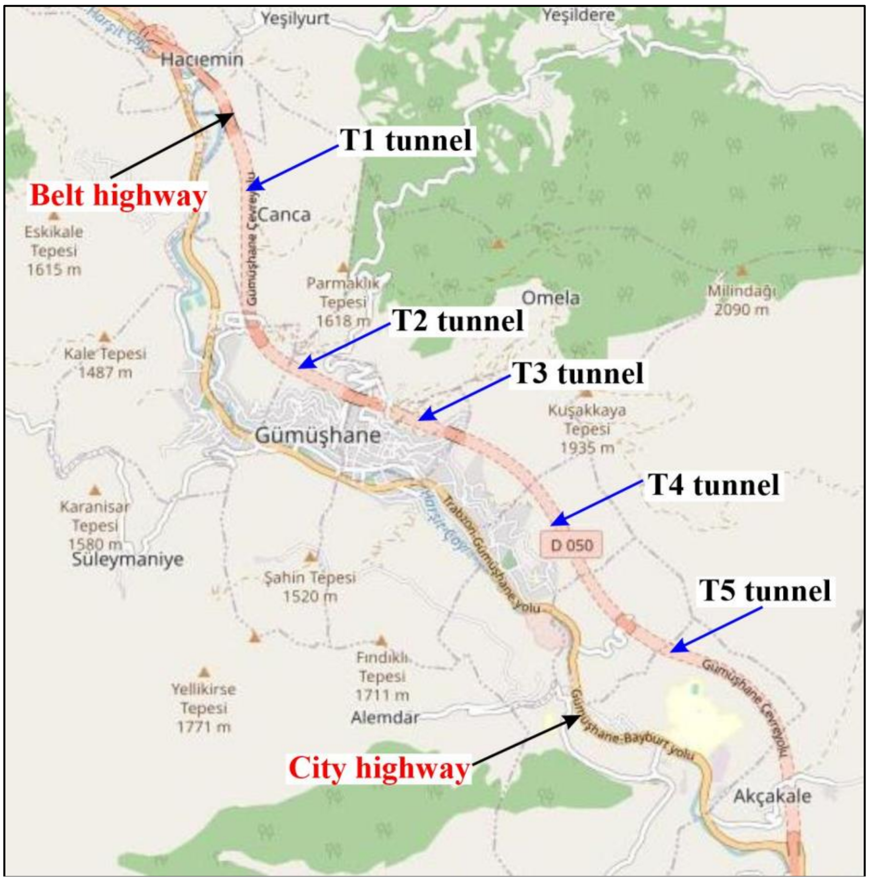

Figure 2. Satellite image of Gümüşhane city highway and belt highway

Five dual-tube highway tunnels named T1, T2, T3, T4 and T5 are built on the belt highway. Some information about these tunnels is shown in Table 4. The method to be selected is the New Austrian Tunneling Method (NATM). Drill and blast method is used for the excavation. There are many residential areas on the belt highway route (Liu et al., 2020). In this study, the effect of blasting in the belt highway tunnels on the surrounding buildings is examined.

Table 4. Highway tunnels on the Gümüşhane belt highway

Tunnel	Number of tubes	Tube lengths (m)	
		Left tubes*	Right tubes*
T1	2	1.725	1.700
T2	2	929	936
T3	2	754	665
T4	2	2.255	2.245
T5	2	2.564	2.538

** Designations are made according to Gümüşhane-Bayburt direction*

2.1. Study area

Two sample buildings, at the entrance and exit of the belt highway tunnels in the Central District of Gümüşhane Province, are selected as the study area. T2 and T3 tunnels are examined as they are the closest tunnels to the buildings (Figure 3).

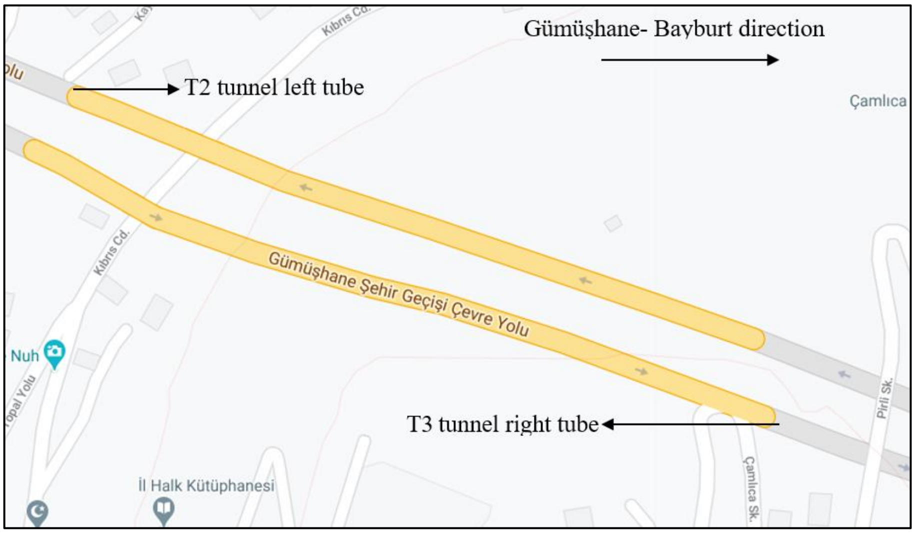

Figure 3. Satellite image of the examined tunnels

The building on the left tube side at the exit of T2 tunnel in Hasanbey District on the belt highway route in the direction of Gümüşhane-Bayburt is named as the 1st building, and the building on the right tube side at the entrance of the T3 tunnel in the Çamlıca District in the same direction is named as the 2nd building. Satellite image of the locations of the buildings is given in Figure 4, the location of the 1st building to the tunnel entrance is given in Figure 5a, and that of the 2nd building is given in Figure 5b.

Figure 4. Satellite image of the buildings

Figure 5. The positions of the structures to the tunnel entrance; a) 1st and b) 2nd buildings

The 1st building is built in masonry style and is plastered both inside and outside. The building is single storey. The 2nd building is built in reinforced concrete style and is plastered inside and outside. This building consists of two floors, including the penthouse. The buildings are about 40-45 years old. General views of the buildings are given in Figure 6.

Figure 6. General views of the buildings; (a, b) 1st and (c, d) 2nd building

The buildings are subject to the 1975 Turkey Earthquake Regulations as of the period they are built. There is no static or architectural project belonging to the buildings, and the structures are not built-in accordance with the requirements of the regulation.

2.2. Geology of the study area

Alibaba Formation (Tokel, 1977) is observed in the area where the 1st building 7 m northwest of the left tube exit of the T2 tunnel. This formation mainly consists of andesite, basalt and their pyroclasts. Although the rocks in the formation are generally observed in fissured and fractured structures, the andesitic rocks at the basement of the 1st building are massive (Figure 7a). The distance between the 2nd building and the explosion/excavation site (entrance of T3 tunnel right tube) is measured as approximately 60 m. In addition, the distance of the building to the direction of the tunnel is measured as 7 m The geological units in the building area and the tunnel construction site are similar. Besides, Gümüşhane Granitoid (Yılmaz, 1972; Topuz et al., 2010), which outcropped generally as fractured and formation of sand by weathering (arenization) of granite, are observed in the area of the 2nd building and T3 tunnel (Figure 7b).

Figure 7. Field view of (a) the fissured and fractured andesite and (b) arenization of granite

3. Analysis of vibration data

The increase in the magnitude of blast load will significantly increase the intensity of damage to be caused to the tunnel and the surrounding ground media (Senthil, 2021). The maximum amount of explosive used in a hole in the drilling and blasting process carried out in the tunnel construction of Gümüşhane belt highway is 15 kg.

Field and laboratory studies were carried out by (Alemdağ et al., 2011; Kaya et al., 2011; Alkan & Dağ, 2018) to determine the rock mass and material properties of the Gümüşhane Granitoid and Monzogranite. In field studies, rock masses were classified according to the degree of weathering in accordance with the ISRM (1981) definition criteria. RQD values for moderately and heavily weathered granite were found to be 70% and 59%, respectively. With the help of data obtained from field and laboratory studies, rock masses were classified according to RMR89 (Bieniawski, 1989) and Q (Barton et al., 1994) rock mass classification systems and GSI (Sönmez & Ulusay, 2002) values were determined. GSI values for moderately and heavily weathered granite were found to be 39 and 28, respectively (Alemdağ et al, 2011). GSI values for andesite were found to be 64 (Alemdağ & Kanık, 2020).

The methods proposed by ISRM (2007) were used to determine the physical properties of the rock material. The unit volume weights were determined by using the dry and saturated masses of the rocks. As a result of 30 different tests for Gümüşhane monzogranites and andesite, the unit volume weight value was found to be 25.66 KN/m³ and 25.13 KN/m³on average, respectively (Alkan & Dağ, 2018).

For weak rock masses, the RQD is zero (Kumar et al., 2016). In such cases, it is more beneficial to use the GSI value rather than the RQD value (Marinos et al., 2005). Introduced by (Hoek, 1994), GSI is a rock mass characterization system used to estimate rock mass strength for different geological conditions defined by field observations.

No measurement value was taken for the peak particle velocity (PPV) that will occur in the blasting process for the tunnel excavation carried out previously in this area. Therefore, the estimated PPV values are calculated according to the distance by using the blast design data in the Equation 2. Building foundation vibration speeds (V_0) due to blasting in T2 and T3 tunnels are calculated according to different distances (Table 5). While calculating, vibration values are calculated by taking into account the total amount of explosives per lag interval.

Table 5. Building foundation vibration speeds depending on distance

D (m)	W (kg)	γ (KN/m³)	V (mm/sec)	V_0(mm/sec) V*1/2	V*1/5
1st building (andesite, GIS:64 (Alemdağ & Kanık, 2020), γ: 25,13 (Alkan & Dağ, 2018)					
***7**			385.68	192.84	77.14
10			228.88	114.44	45.78
20	15	25.13	83.02	41.51	16.60
40			30.12	15.06	6.02
60			16.64	8.32	3.33
2nd building (granite, GIS:33.5 (Alemdağ et al., 2011) , γ: 25,66 (Alkan & Dağ, 2018)					
20			34.50	17.25	6.9
40			12.51	6.25	2.50
60	**15**	**25.66**	**6.91**	**3.45**	**1.38**
80			4.53	2.26	0.90
100			3.27	1.63	0.65

After the observations and examinations made in the field, the 1st building was determined as a class b (i.e., masonry brick buildings such as plastered briquette, briquette, adobe or brick house). These types of buildings are among the building types that can be damaged even at low vibration velocity that may occur after blasting. Therefore, the V_0 speed in the foundation of the building should not exceed 5 mm/sec according to Table 3. The vibration speed value generated by a blasting at the exit of the T2 tunnel calculated in Table 5 at a distance of 7 m was 385.68 mm/sec. It is observed that the vibration values on the foundation (V_0) of the 1st building created by this vibration are between 192.84 mm/sec and 77.14 mm/sec. The fact that these vibration values are above the limit value of 5 mm/sec indicated that the cracks that may occur in the 1st building may be caused by blasting.

As a result of the damage investigations carried out on the 1st building, it is determined that deep and surface cracks are formed in the load-bearing walls of the building, there are spillages in the wall plaster, fractures occurred in the windows, and the roof pillars in the attic are separated from the floor. The visuals regarding the damage detected on the building are shown in Figure 8.

Damaged parts detected in the building are also located on the masonry walls that form the load-bearing system of the building. Crack openings in the walls vary between 1-5 mm. Although it is necessary to renew the roof in order to eliminate the damage on the roof, the carrier system should be given priority when looking at the condition of the ceiling floor and walls on which the roof will sit. There are also damaged parts on the supporting walls. Considering the current condition, age and depreciation of the building, it will be appropriate and reliable to be demolished and rebuilt. Due to the severe damage to the building, accommodation is not suitable.

The 2nd building is classified as “c class; reinforced concrete building" among the types of buildings that can be damaged due to blasting depending on the vibration speed values. Therefore, the V_0 speed in the foundation of the building should not exceed 10 mm/sec according to Table 3. The fact that the V_0 speed calculated according to V*1/2 is 3.45 mm/sec showed that the vibration caused by the blasting cannot cause damage to the 2nd building. However, as the tunnel route is in the direction of the 2nd building, the distance from the blast point to this building become shorter and shorter as it moves through the tunnel, and the potential of the building to receive damage due to the effect of increasing vibration. It is known that seismic waves continue to propagate until their energy is depleted. There are two reasons for the energies of such waves to be extinguished. The first is the physical and geological resistance of the rock structure, and the second is the geometrical spread of the seismic wave to a wider area as it moves away from its source. Massive andesites in the area where the 1st building is located transmit the energies of seismic waves faster. On the other hand, cracked and weathered granites in the area of the 2nd building absorb the energies of seismic waves more quickly.

Figure 8. Damaged parts detected in the 1st building

As a result of the damage examination carried out on the 2nd building, it is observed that deep and surface cracks are formed on the load-bearing walls of the building, there are spillages in the wall plaster, deep cracks are formed in the surrounding pavements, and cracks are formed in the ceiling floors. The visuals of the damage detected on the building are given in Figure 9.

Figure 9. Damaged parts of the 2nd building

The damaged parts detected on the building are located on the masonry walls and ceiling reinforced concrete floors that form the carrier system of the building. Crack openings in the walls vary between 1-3 mm.

Considering the current condition, age and depreciation of the building, it will be more appropriate and reliable to demolish and rebuild it. As such, it does not seem appropriate to live in the building.

According to RAMEN, in the table of the highest permissible values of ground vibrations that will occur due to blasting in mines and quarries and similar areas outside the closest building, the maximum permitted vibration speed value at a frequency of 30-100 Hz is 50 mm/sec. Based on the calculated values, the probable vibration speeds due to blasting in the 1st building located 7 m away from the T2 tunnel exit and in the 2nd building 60 m away from the T3 tunnel entrance are calculated as 385.68 mm/sec and 6.91 mm/sec, respectively. Therefore, the possible vibration velocity to occur after blasting around 1st building is more than the values specified in the standard.

4. Discussion and conclusions

4. *Tartışma ve sonuçlar*

The results obtained depending on the determination of damage to the structures caused by the field geology and blasting effect of the two sample buildings located close to the T2 and T3 tunnels built on the Gümüshane Belt Highway route are as follows:

• Geological investigations showed that in the areas where the 1st and 2nd building are located, there are units of geological andesite, basalt and their pyroclasts with fractured and weathering of Gümüşhane Granitoid respectively.

• Considering that the distance between T2 tunnel exit and 1st building is 7 m; it is understood that the explosions made at the exit of the T2 tunnel caused the formation of cracks in the building.

• The vibration speeds due to blasting in the 1st and 2nd buildings are calculated as 385.68 mm/sec and 6.91 mm/sec, respectively, and these calculated values for 1st building are higher than the vibration values (5 mm/sec and 19 mm/sec) at 1 Hz and 4-10 Hz frequencies in the standards. It is determined that the vibrations that will occur at these frequencies have a high probability of damaging the surrounding 1st building. Because 1st building's vibration value are higher than the permissible maximum values of 50 mm/sec at 30-100 Hz according to Turkish Regulation on Assessment and Management of Environmental Noise (RAMEN).

• It is determined that the distance between the blast point and the 2nd building will be shortened with each blasting at the face of the tunnel and afterwards, as the T3 tunnel progress route is in the direction of the 2nd building, and therefore the damage effect of the vibrations on the building may increase.

• The German DIN 4150-3 norm is more protective than the Turkish damage classification. According to DIN 5140-3, the vibration at 5 mm/sec particle velocity should not be exceeded for reinforced concrete structures in open blasts where frequencies such as 1-10 Hz occur. However, according to the RAMEN, the limit value allowed at the same frequencies is a very high value, such as 19 mm/sec. This value is a destructive value for the village houses and non-reinforced concrete structures located around the mines and quarries. For this reason, it is very important to consider the German norms' damage limit values, which are on the safer side compared to the others, while performing the vibration analysis caused by blasting.

• As a result of the damage investigations, it is concluded that deep and surface cracks are formed in the walls and load-bearing elements of the buildings, there are spillages in the wall plaster, it is more convenient and safer to rebuild the buildings, considering the current condition, age and wear rate of the buildings.

Vibrations from blast excavations for tunneling activities can have devastating consequences for surrounding structures and people. For this reason, it is essential to conduct a good site investigation, increase the expropriation widths if necessary, and make accurate and complete analyzes to prevent financial losses and moreover, loss of life.

Author contribution

All authors contributed to all parts of the article.

Declaration of ethical code

The authors of this manuscript declare that the materials and methods used in this study do not require ethical committee approval and/or legal-specific permission.

Conflicts of interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

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