

Influence of depth and geological structure on the transmission of blast vibrations

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Abstract Vibrations generated by blasting carried out during the quarrying of material induce dynamic stresses that can give rise to damage of diverse considerations in surrounding buildings and structures. The adverse effects of vibrations caused by explosives used in mining and civil works can be controlled by suitably planning blasting operations, appropriately managing and optimising the equipment used, and monitoring the processes that cause these vibrations. The aims of the present study were to discuss and test the existence of a damping of underground vibrations, besides defining a transmission law for such vibrations which will depend on the directionality between the blast and the measurement point. Besides, the damages that vibrations can produce on the rock mass are evaluated.

Their effects are very similar to those produced by an earthquake that disconnects the rock mass integral blocks.

Keywords Blasting · Vibrations · Control · Damping · Transmission log

Introduction

“Bahoto” is a limestone quarry producing aggregates situated in northern Spain, close to the town of Langreo (Asturias). An old railroad tunnel passes under one of the quarry benches. This tunnel forms part of the Langreo-Gijón railroad, nowadays transformed into a greenway for hikers. Accordingly, the regional government has required the company mining the quarry to conduct a vibration study to analyse the effect of blasting on the aforementioned tunnel.

The goal is to detect and record the vibratory movements—caused by stresses that can vary in magnitude and direction—that are transmitted to the ground as elastic waves and, hence, to any structure in contact with it. In the survey carried out, the aim was to monitor the levels of vibration caused by blasting in the quarry. The variable employed was the amplitude of vibrations and not the frequency analysis.

The dynamic effects that structures suffer due to vibrations caused by quarry blasting can be monitored by means of measurements and calculations (Wu et al. 1998; Ak et al. 2008). There exist national and international regulations limiting vibrations, (Hustrulid 1999) which, in some cases, define the set of actions to follow regarding blasting which could possibly affect a structure.

Numerous studies have been conducted in recent years which focus on the analysis of the effects that quarry blasting has on the surroundings. For instance, studies have been carried out on the vibrations and impacts generated by

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blasting in different types of mines in Turkey (Kahriman 2004) (Ak and Konuk 2008) predictions have been made regarding the influence of vibrations on structures in the vicinity of a mine so as to avoid damage (Kahriman 2004) (Mohamed 2009) and diverse assessments have been made of the damage caused by a limestone quarry (Kuzu and Ergin 2005).

The recommendations of the International Society of Explosives Engineers (IESE 1992) have been followed

when choosing the monitoring points, as well as in the method used to carry out measurements.

Description of the study area

The area under study is situated near the town of Langreo (Northern Spain), in the “Cantera Bahoto” quarry. The

Fig. 1 Location of the area under study

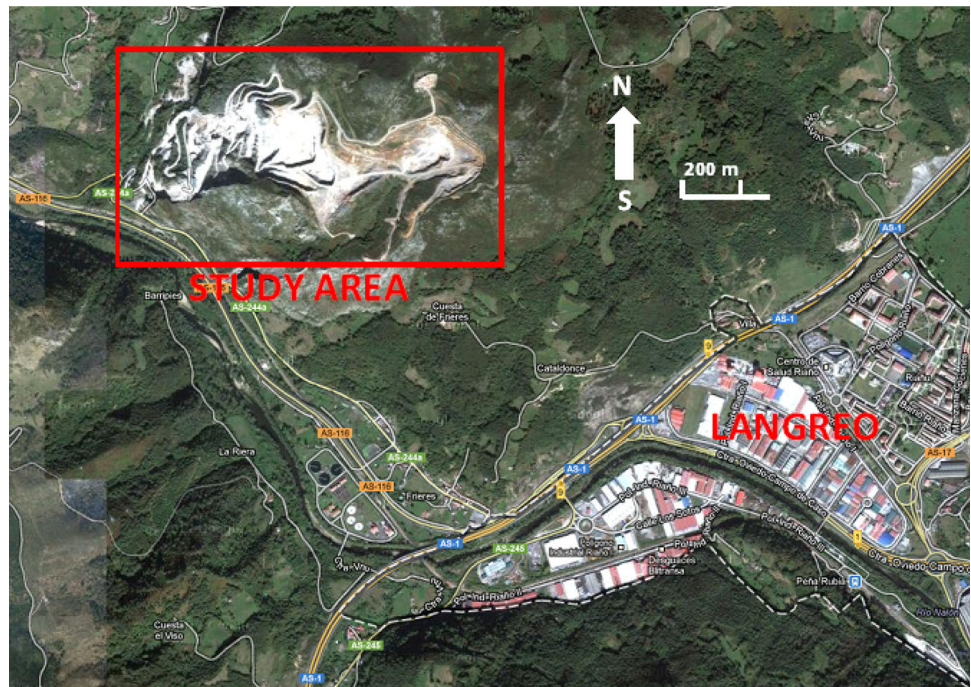
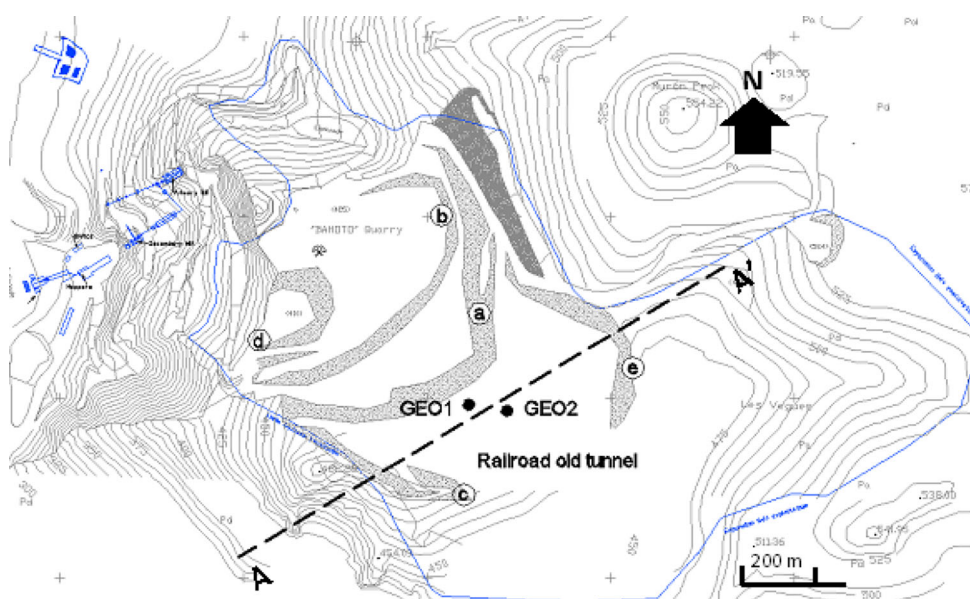


Fig. 2 Location of the old railroad tunnel



quarry is accessed via the AS-243 road (Oviedo–Frieres), kilometre point 9. Its approximate location is shown in Fig. 1. The most important elevation within the site is “La Peña Villa”, with a height of 591 m.

Figure 2 shows the ground plan position of the gallery, while Fig. 3 represents the A–A' longitudinal cross-section, in which the slope of the old railroad tunnel and its depth

with respect to the quarry can be seen. As this is an old tunnel, it doesn't have any support.

Geological materials that predominate in the study area are from the Paleozoic: Carboniferous and Devonian. In the study area there are also some Cretaceous materials, laying over the Paleozoic materials with an unconformity contact, as can be seen in Fig. 4.

Fig. 3 Topographical profile showing the slope of the old railroad tunnel

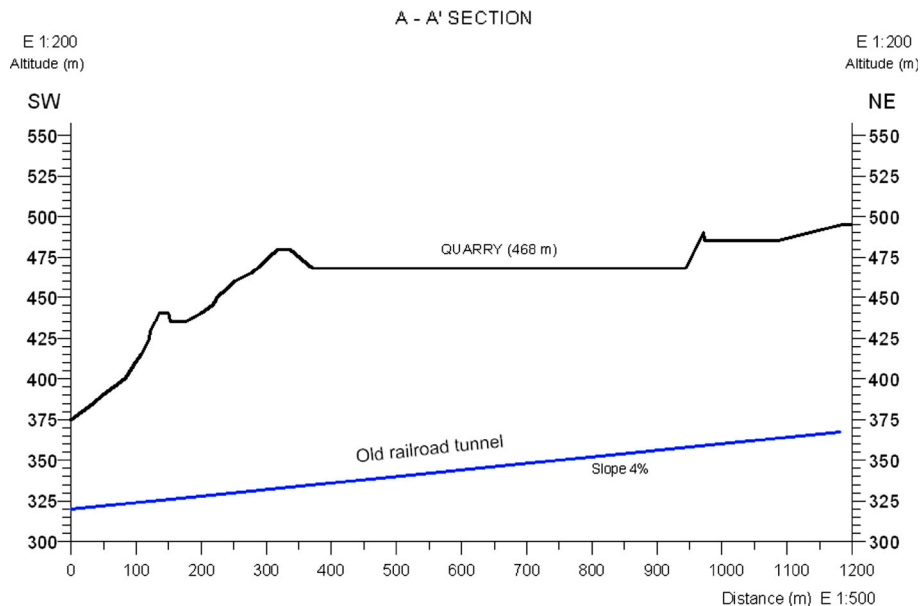
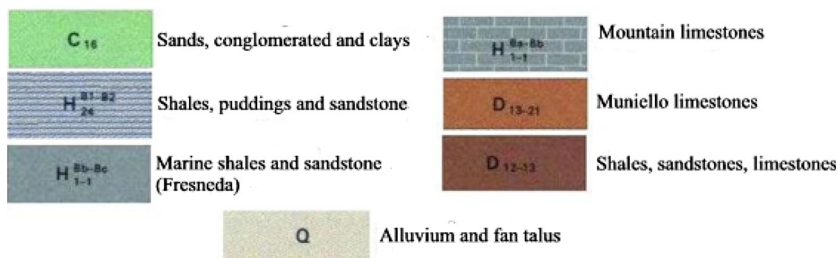
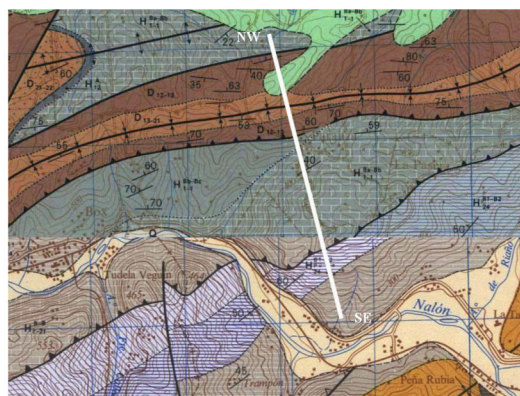


Fig. 4 Study area geology



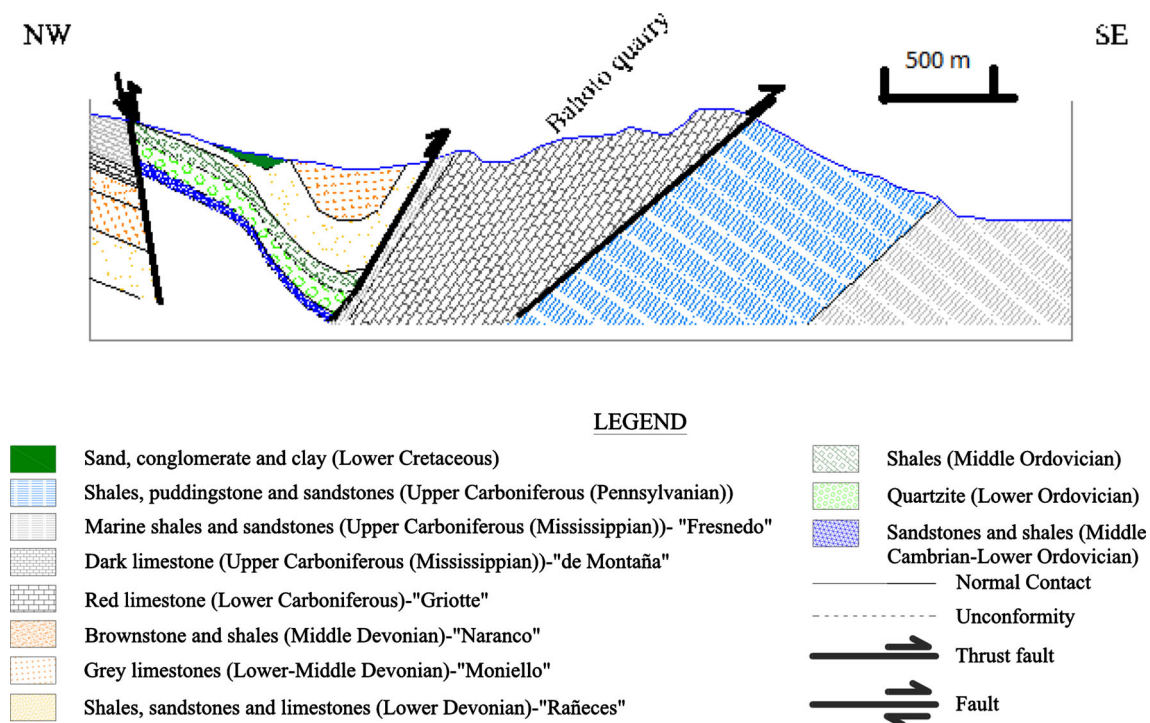


Fig. 5 Study area geological cross-section

In the quarry area, there are two types of lithologies. There are yellow sandstones, situated in the North part of the concession area (these materials are not mined) and massive limestones from the Valdeteja Formation, that form a continuous, isotropic and good quality rock mass.

The most important characteristics from a structural viewpoint of the area under study are presented next. The Bahoto Quarry is currently mining mountain limestone belonging to the Valdeteja formation. The surrounding materials are affected by two stages of deformation, within which diverse structures have arisen related to the Variscan orogeny.

The structure of the Paleozoic materials is determined by the existence of a series of thrust faults and folds. In the case of the over thrust faults, the thrusting strata are perhaps the most noteworthy cartographic structures, presenting a stepped geometry with large flats and small ramps affected by substantial sedimentary layers.

There is a thrust fault to the NW of the area under study, known as the Aramo Thrust Fault, which forks to the east of the outer quarry area. The face of the thrust fault, running NE–SW, is made up of Silurian materials that thrust over those of the Carbonaceous period and, more specifically, over the Barcaliente formation. The same thrust fault is located to the north of the quarry and runs E–W, placing the Barcaliente formation in contact with the carbonaceous formation of El Naranco.

The Veguín Thrust Fault is located to the southeast of the quarry area, running NW–SE. This means that the allochthonous or thrust formation, constituted by the Valdeteja formation, lies over materials from the Upper Carbonaceous period of Olloniego.

As regards the folds, the most outstanding example is the Veguín synform, the nucleus of which contains slates from the carbonaceous period of El Naranco flanked by the Barcaliente formation to the north and the Valdeteja formation to the south. On the other hand, a sequence of synform-antiform folds is observed within the Barcaliente formation, with axial traces of thrust faults the further south one advances. A general cross-section of the study area is showed in Fig. 5.

Control parameters, regulations and measuring equipment

The main vibration parameters to be measured are the triaxial variation of velocities and frequencies. These parameters are obtained by treating the data recorded by the measuring equipment. Once transferred to a computer, these data are analysed by specific software developed by the University of Oviedo Ground Engineering Research Group (its Spanish acronym, GITUO). This application allows simultaneous treatment of the signals provided by

the two types of equipment used, as each is made by a different manufacturer.

Once the data treatment has been carried out, two different graphs are obtained for each of the spatial axes (x , y , z). One of these graphs represents the velocity versus time curve and the other the fast Fourier transform (FFT) versus frequency. The FFT indicates the importance of each frequency of the vibration wave train. The dominant frequency is obtained via the analysis of the FFT, i.e., the frequency band with the highest amplitude value in the spectrum. This frequency depends on the rock mass that the waves pass through and is determined, to a major extent, by the existing geological conditions between the source and the receptor and by the distance from the source, as well as, to a lesser extent, by the design of the blasting and by the geometry of the borehole.

Numerous sets of regulations exist regarding vibrations which define the method to follow for their measurement and monitoring. However, they all present certain limitations as regards their application. The guidelines established by the Spanish Standard (Norma UNE 22381 1993) were followed in the present study, comparing the values obtained with the limits established in the Swiss Standard SN 640 312 (1978).

The information captured by two triaxial borehole geophones was used to analyse the blast-produced vibrations in the old railroad tunnel. ETNA high dynamic range triaxial stations were used to measure the surface vibrations. The triaxial borehole geophones transform the mechanical energy of the vibration into electrical energy, the intensity of which is proportional to the oscillatory movement of the ground. In this case, two geophones were used, both adapted for their insertion in their respective boreholes. Thus, by means of boreholes drilled on either side of the tunnel to a depth similar to that of the tunnel itself, it was possible to capture the vibrations the tunnel is subjected to as a result of the blasting carried out in the quarry.

The vibration events stored in the memory of the seismograph were transferred to a computer, where they were subsequently analysed by members of the GITUO team.

The triaxial stations used, the ETNA model manufactured by the firm Kinometrics, have a built-in memory for data storage.

Vibrations control and results obtained in the measuring survey

The vibrations generated by blasting in the quarry were recorded from October 2006 to May 2008 in the vicinity of the tunnel. The study of these vibrations was carried out both on the surface, using accelerometers, and underground, using geophones. The damping of the vibrations

with depth was thus assessed. The devices used to measure the underground vibration velocity were installed at the same depth as the old railroad tunnel and in close proximity to it. It was, thus, possible to measure the actual vibrations that the tunnel is subjected to and to test whether these comply with current Spanish regulations.

Initially, an analysis was conducted of the vibrations generated by blasting at the surface level. To do so, a measurement survey was carried out in which data from 17 blasts were recorded using the accelerometers. Data from another study of surface vibrations carried out previously by the GITUO, called *Survey 1*, were also incorporated in the analysis. We, thus, obtained a much clearer view of the situation thanks to the volume of information analysed.

Given that the structure susceptible to being affected in this case is an old railroad tunnel, the recommendations of the International Society of Explosives Engineers were followed, in addition to surface monitoring. To do so, geophones were installed in two boreholes drilled in the vicinity of the tunnel and at the same depth as the tunnel. These were used to record the data from the 31 aforementioned blasts. Five of these blasts were also measured with the surface accelerometers so as to analyse the attenuation the vibratory movements that suffer with depth.

The surface measurements were carried out from October 2006 to July 2007, recording data from 17 blasts. The underground measurements were carried out from May 2007 to June 2008, obtaining data from 31 blasts. Five of the blasts were simultaneously recorded using surface and underground devices.

Surface vibrations control

To record the vibrations transmitted on the surface, accelerometers were placed at different points in the quarry, as shown in Fig. 6. In all, 27 recordings were made, as data were obtained in ten of the blasts using two accelerometers situated in different areas of the quarry.

One was permanently installed in a station denominated E1, which is situated on the right-side of the tunnel. The other device, E2, was moved along the surface following the course of the tunnel, passing along a zone of the quarry, so as to be able to obtain recordings at different distances from the controlled blasts. Figure 6 shows the locations of both devices.

Recordings of five blasts were made from May to July 2007 using another device located on the place of the quarry (E3) as can be seen in Fig. 6.

Once the geophones were installed, these readings were taken to establish an “in situ” comparison between the surface and underground measurements. Accordingly, the accelerometer was placed at the side of the mouth of the borehole in which geophone 2 was installed.

Fig. 6 Location of the accelerometers (E1, E2 and E3)

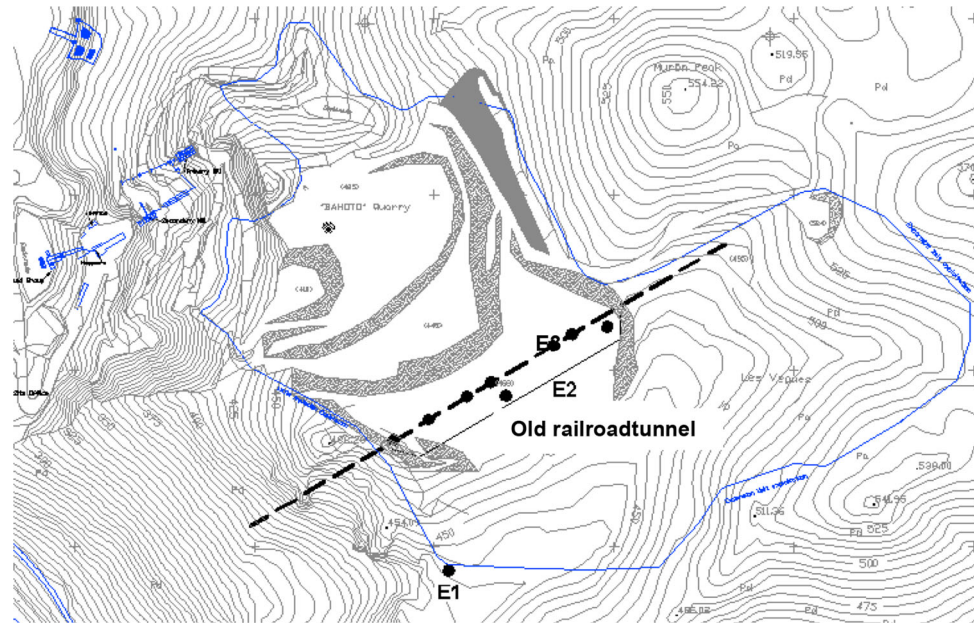


Table 1 Summary of readings obtained on the accelerometers

Blast	Q maximum charge by delay (kg)	Station	D distance (m)	PPV (mm/s)	V_{max} (mm/s)	F (Hz)
1	46	E1	193	5.0	5.9	21
		E2	210	19.3	19.8	16
2	246	E1	325	2.6	3.5	22
		E2	412	5.9	6.2	12
3	116	E1	139	9.3	15.0	23
		E2	262	7.1	10.5	10
4	147	E1	149	10.9	14.2	18
		E2	569	4.6	4.7	15
5	82	E1	148	8.1	13.3	21
		E2	277	12.1	12.4	18
6	70	E1	344	9.4	9.5	18
		E2	562	0.3	0.5	13
7	48	E1	200	9.5	10.5	16
		E2	468	4.0	4.2	9
8	151	E1	67	9.1	13.4	10
		E2	474	4.0	4.2	10
9	52	E1	55	13.8	18.8	13
		E2	371	4.2	4.3	12
10	124	E1	133	9.1	14.2	16
		E2	427	4.4	7.4	12
11	256	E1	197	7.1	11.2	11
12	17	E1	206	0.4	0.7	15
13	94	E3	276	7	9.27	11
14	94	E3	280	5.3	7.68	14
15	45	E3	365	5	2.60	20
16	91	E3	286	7.3	10.31	20
17	227	E3	289	9.2	12.23	17

The main vibration parameters to measure were velocity and frequency.

Table 1 summarises the following fundamental parameters for each of the recordings:

- The first column identifies the blast.
- The second column (Q), represents the maximum charge by delay referenced to plastic explosive expressed in kg.
- The third column indicates the measuring station.
- The fourth column (D), gives the distance between the blast and the recording device.
- The fifth column shows the maximum value of the vibration velocity in its greatest component for each recording, that is the Peak Particle Velocity (PPV).
- The sixth column gives the maximum value of the modulus of the velocity vector (V_{max}).

- The seventh column gives the dominant frequency of the vibration (F).

Using the data obtained from the accelerometers, Fig. 7 shows the existing relation (in blue) between the PPV per unit charge and the distance of the measuring device from the blast. It can be observed that the PPV per unit charge (Q) decreases as the distance between the measuring point and the blast location increases. The data from the vibration study carried out in *Survey 1* are represented in green in Fig. 7. It can be seen that the readings obtained in both cases are of the same order.

Underground vibrations transmission control

The study of the velocity of vibration underground was carried out by installing two geophones at the same depth as the old railroad tunnel and in close proximity to it. The two devices, thus, recorded exactly the same vibrations to which the tunnel was subjected. In May 2007, two boreholes were drilled until tunnel depth was reached to install the geophones called GEO1 and GEO2. Each was situated on its respective side of the tunnel, as shown in Fig. 8.

Once the boreholes had been drilled and these had been checked using a video camera to assess the state of the rock mass, they were lined with PVC tubing. The geophones were then installed. A steel cable was used to slide them down inside the tubing until reaching the bottom of the borehole. Once installed, they were buried in sand. As the devices were fixed in position, they could not be aligned with the blast due to the fact that the direction of propagation of vibrations is variable.

The benches in which the blasts were recorded are identified in Fig. 8 by the letters a, b, c, d and e.

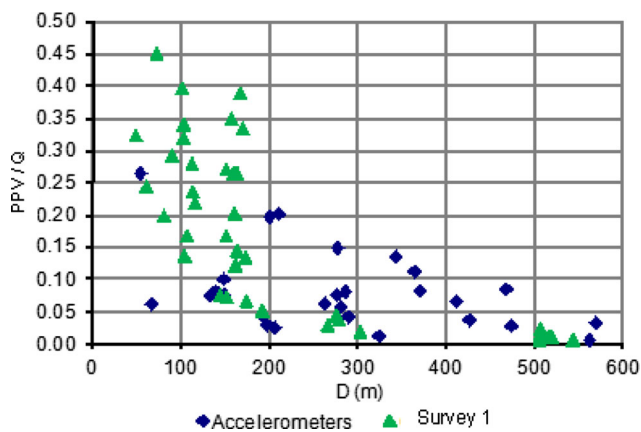


Fig. 7 Graphical representation of the PPV per unit charge. Data from the accelerometers and the measurements obtained in *Survey 1*

Fig. 8 Location of the geophones and the analyzed blasting benches

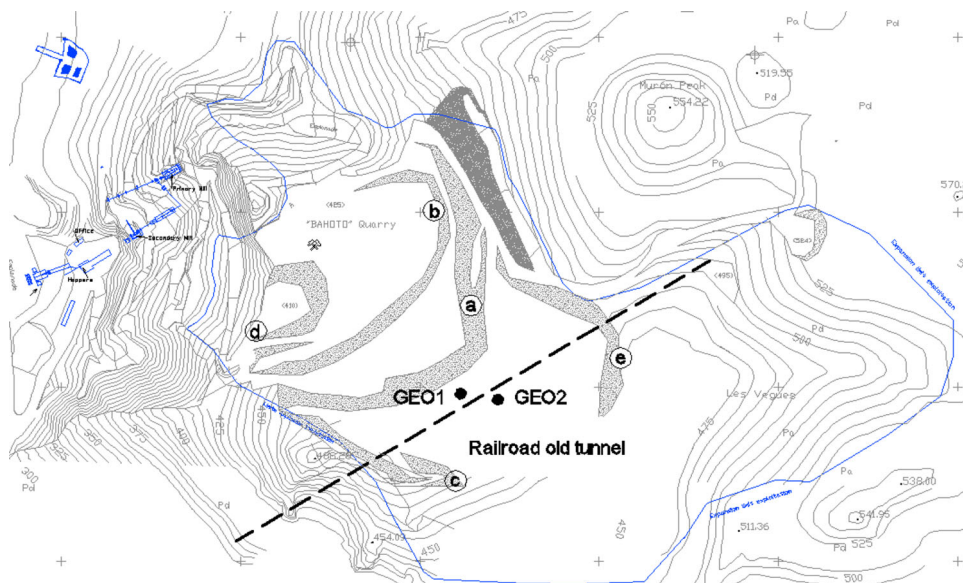


Table 2 Data on the assessed blasts and the measures obtained using geophones

Blast	Bench	Geophone	Q Maximum charge by delay (kg)	Distance to GEO1 (m)	Distance to GEO2 (m)	PPV (mm/s)	V_{\max} (mm/s)	F (Hz)
1	b	1	94	277	275	1.4	1.5	12
		2				1.4	1.5	13
2	b	1	94	280	278	1.3	1.4	13
		2				1.9	2.1	13
3	a	1	45	321	367	1.5	1.6	17
		2				1.3	1.3	16
4	b	1	94	283	281	1.7	1.8	16
		2				2.3	2.4	10
5	b	1	92	286	284	1.8	2.1	11
		2				2.0	2.0	13
6	c	1	229	402	371	1.4	1.5	18
		2				1.5	1.6	18
7	b	1	227	289	287	1.5	1.9	14
		2				1.8	2.1	7
8	a	1	149	165	168	5.6	6.8	18
		2				4.8	5.2	2
9	b	1	222	311	290	2.5	2.7	15
		2				2.9	3.0	11
10	b	1	149	230	228	4.8	5.9	16
		2				5.1	5.4	2
11	b	1	222	314	292	2.5	2.6	17
		2				3.1	3.1	15
12	b	1	222	317	295	4.7	5.5	14
		2				6.0	6.0	2
13	b	1	222	319	298	1.8	2.2	7
		2				2.3	2.8	12
14	b	1	222	322	301	3.1	3.1	11
		2				1.8	2.2	3
15	b	1	222	325	304	2.0	2.3	12
		2				1.5	1.6	8
16	c	1	96	409	374	1.9	2.4	10
		2				2.0	2.6	10
17	a	1	147	186	193	1.8	2.0	20
		2				1.3	1.3	14
18	a	1	149	147	146	2.2	2.4	12
		2				1.4	1.7	10
19	a	1	149	150	149	1.9	2.2	14
		2				0.9	1.1	18
20	e	1	149	296	310	6.1	7.6	16
		2				7.7	7.7	16
21	c	1	94	412	376	1.1	1.2	14
		2				1.0	1.2	14
22	a	1	141	154	157	5.5	7.1	19
		2				6.0	6.5	19
23	d	1	98	414	379	1.0	1.1	16
		2				0.9	0.9	14
24	e	1	147	296	307	5.5	6.9	10
		2				6.8	7.2	11

Table 2 continued

Blast	Bench	Geophone	Q Maximum charge by delay (kg)	Distance to GEO1 (m)	Distance to GEO2 (m)	PPV (mm/s)	V _{max} (mm/s)	F (Hz)
25	a	1	136	152	155	1.5	1.7	9
		2				1.1	1.2	18
26	c	1	178	417	482	1.2	1.3	19
		2				0.9	1.0	18
27	a	1	135	157	160	3.9	5.4	16
		2				4.6	5.4	18
28	e	1	90	299	311	2.5	3.0	19
		2				1.4	1.8	18
29	e	1	65	302	313	3.2	3.4	15
		2				2.4	2.5	19
30	e	1	65	305	315	3.0	3.6	18
		2				2.4	2.6	19
31	a	1	137	160	163	2.7	4.5	15
		2				3.9	5.8	15

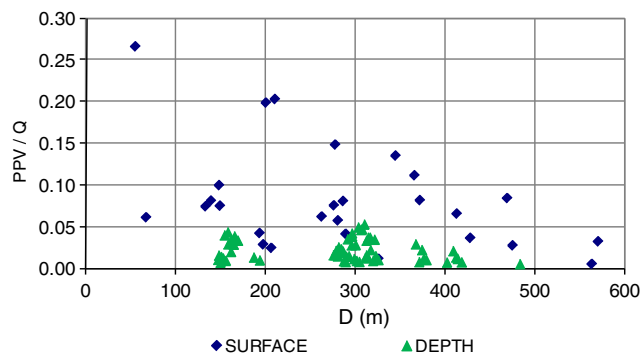


Fig. 9 Representation of PPV per unit charge versus the distance from the surface accelerometers or the underground geophones

The main characteristics of the blasts were studied: in particular, the maximum charge by delay and the distance of the blast from the measuring devices.

Table 2 summarizes the data from the assessed blasts, including the date, the bench in which they were carried out, the maximum charge employed and the distance between each of the measuring devices and the blast. Once the recordings had been obtained, the following values were determined: the PPV following standard UNE 22381 1993. The modulus of the maximum vector of the vibration velocity (V_{max}) following standard SN 640 312, 1978 and the design frequency, i.e., the dominant frequency (defined in standard UNE 22381 1993 in the interval of resonance of the tunnel, ranging between 10 and 20 Hz. These values shall be required for comparison with the limit values established by Spanish regulations and Swiss regulations, respectively.

Table 3 Simultaneous readings from the two geophones and the accelerometer

Blast	PPV GEO1 (mm/s)	PPV GEO2 (mm/s)	PPV ETNA (mm/s)	V _{max} GEO1 (mm/s)	V _{max} GEO2 (mm/s)	V _{max} ETNA (mm/s)
1	1.40	1.40	7.00	2.02	2.14	9.27
2	1.27	1.90	5.30	1.92	2.32	7.68
3	1.52	1.27	5.00	2.29	1.67	6.80
4	1.78	2.02	7.30	2.94	2.78	10.31
5	1.52	1.78	9.20	2.43	2.35	12.23

Study of the damping of vibrations with depth

Verification of the existence of damping of vibrations with depth was carried out by jointly analysing the data obtained on the surface and underground. Figure 9 shows the values of the PPV per unit charge by delay versus the distance of the measuring device from the blast, for both the measurements on the surface and those carried out underground.

Although Fig. 9 shows, in the majority of cases, that lower values are obtained underground than on the surface for the same distance, it should be borne in mind that only five measurements were taken simultaneously using the geophone and the accelerometer. That is, the geometric conditions of the quarry, atmospheric conditions, the water table and all the other parameters that may influence the propagation of vibration waves were exactly the same in only five blasts.

Therefore, in order to verify that damping of vibrations with depth exists, Table 3 shows the values of the PPV and

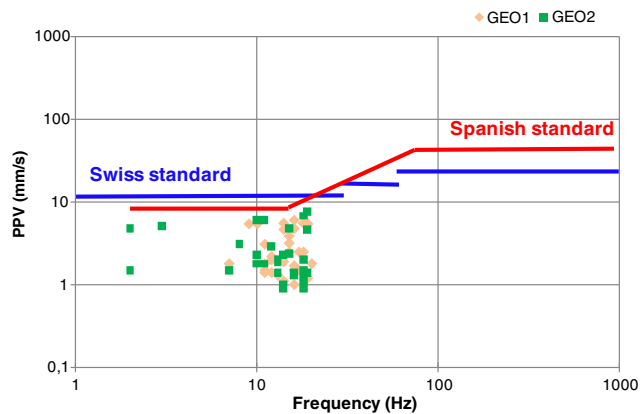


Fig. 10 Representation of vibrations in relation to standards UNE 22381 [10] and SN 640 312 [11]

of the maximum vibration velocity vector modulus (V_{\max}), obtained by means of an accelerometer and the two geophones on the five days simultaneous measurements were taken. It can be seen that, whether taking PPV or V_{\max} as a reference, the recordings obtained on the surface are between 70 and 80 % higher than those registered underground.

The assessment and valuation of the underground vibrations was carried out comparing the PPV obtained using the geophones—given that these were the devices that recorded the vibrations that might affect the old railroad tunnel—with the permissible limits specified in Spanish Standard UNE 22381 (1993). To do so, the tunnel was considered as a structure that belong to Group II, as defined in the standard, the PPV permitted in each case has been evaluated, seeing as these depend on the frequency with which the vibration is calculated.

Furthermore, the structure of the tunnel was considered to be framed, in accordance with Swiss Standard SN 640 312 (1978), within the group corresponding to structures with a low susceptibility to blasts or tremors, due to the nature of the construction itself, and with a frequency of loadings generated by vibrations corresponding to an intermediate level denominated as “recurring” in the standard.

Figure 10 shows the situation of all the pairs of vibration frequency-velocity values corresponding to the maximum components recorded in each of the blasts. In addition, the maximum permissible values established by the standards UNE 22381 (1993) and SN 640 312 (1978) are also represented in this figure. It can be seen that 100 % of the recordings of the blasts analysed are situated below the level of vibrations set by both standards for this type of structure. Moreover, it must be taken into account that for setting the most unfavourable situation, lower frequencies (more destructive) have been selected.

Determination of the laws of transmission of vibrations

Having proven the suitability of measuring the underground vibrations to which the structure to protect is subjected, new vibration recordings were subsequently made using the two geophones in a number of quarry benches. The main characteristics of the blasts were studied, especially the instantaneous maximum charge and the distance of the blast from the measuring devices, as well as the variation in the vibration velocity versus said parameters.

The recorded data were used to determine the vibration velocities and the frequency of design generated by the blasts at each location where the devices were installed. As with the previous blasts, verification was made as to whether these complied with the requisites specified by standard UNE 22381 (1993) and that said blasts did not manage to affect in any case whatsoever the Group II structures in which the tunnel is included.

Using the readings from the two geophones, the law of transmission of vibrations was established considering the type of rock mass, the explosive charge and the distance. This law must be defined to prevent and control the vibrations resulting from blasting.

Besides the purely geometric phenomenon of dispersion of energy as the wave travels away from its origin, the not fully elastic nature of the rock mass and the presence of water filling cavities intervene in the damping of the waves. Two studies were carried out. In one, the “scaled distance” was used to calculate the velocity of vibration as a function of the load and the distance (conventional law of transmission). In the other, the existing relation between the vibration velocity per unit charge by delay and the distance from the blast was studied (law of transmission per unit charge).

In general terms, the level of vibration received at a certain point, expressed as the vibration velocity “PPV”, is a direct function of the maximum charge by delay employed “ Q ”, and is inversely related to the distance between the blasting point and the recording point. With the aim of finding a mathematical expression that defines the law of vibrations, the scaled distance (relation between the distance and the energy of the explosive charge) was calculated first as:

$$D_{\text{scaled}} = \frac{D}{\sqrt{Q}},$$

where D_{scaled} is the scaled distance, D is the existing distance between the points at which the vibrations are emitted and received in m, and Q is the energy of the explosive expressed in kg of plastic explosive.

An empirical relation is then obtained between the peak particle velocity in mm/s (PPV) and the scaled distance, which takes the following form:

$$PPV = K \times (D_{\text{Scaled}})^\alpha = K \times \left(\frac{D}{\sqrt{Q}}\right)^\alpha$$

To determine the value of the constants K and α , which will depend on geological conditions, the values obtained for PPV and D_{scaled} are plotted and the equation of the regression curve that best fits the plot is obtained.

The law of transmission of vibrations was obtained using the readings of the blasts from the two geophones. Figure 11 shows the pairs of values formed by the scaled distance and the PPV for each of the recorded blasts and at each of the geophones. Using the equation of the regression curve in Fig. 11, the following *transmission law of vibrations for the “Bahoto Quarry” area* is obtained:

$$PPV = 479.9 \times \left(\frac{D}{\sqrt{Q}}\right)^{-1.78}$$

Furthermore, a new equation is proposed, established via the following expression relating the velocity of vibration produced per unit charge of explosive with distance:

$$\frac{PPV}{Q} = M \times D^\beta$$

Q is the charge by delay referenced to plastic explosive expressed in kg and D is the existing distance in metres between the points at which the vibrations are emitted and received. M and β are two parameters that will depend on the geological conditions and are obtained by the statistical fitting of the equation of the obtained curve.

Calculating the regression curve of the pairs of values plotted in Fig. 12, we obtain the following *underground law of transmission of vibrations per unit charge*:

$$\frac{PPV}{Q} = 283,8 \times D^{-1.78}$$

Analysis of the influence of the rock mass on the vibrations

With the fittings obtained for the calculated laws of transmission of vibrations, it may be stated that the analysed rock mass presents a fairly uniform structure. Nonetheless, if the recordings of the blasts are analysed bench-by-bench, areas may exist with a slightly different law of vibration in response to a geological structure. Specifically, the law of vibrations was analysed for benches c and e , between which there is a fault whose alignment is shown in Fig. 13. This fault presents a small slip (few meters). The fault zone is very weathered, filled with limestone small blocks of limestone and clays. In Fig. 14a detailed cross-section of the quarry geology is represented, and in Fig. 15, fault zone aspect can be observed.

The slight difference that exists between the laws of the two benches can be observed, that of bench c being lower than that of bench e . This fact seems to result from the

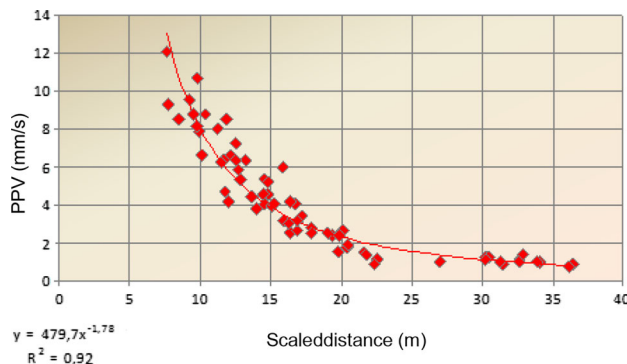


Fig. 11 Relation between the PPV and the squared scaled distance for underground vibrations

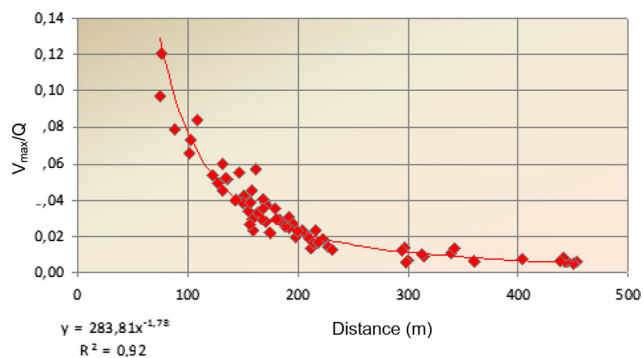


Fig. 12 Underground law of transmission per unit charge

presence of the aforementioned fault, and especially for its weathered zone. As bench e is situated on the same side of the fault as the two geophones used to take measurements, the readings of the blasts in this bench are higher than the readings of the blasts in bench c , which is located on the opposite side of the fault. For this reason, the vibrations generated in the latter bench are damped before being registered by the geophones.

Figures 16 and 17 shows the conventional law of transmission and the law of transmission per unit charge for benches c (blue) and e (red), respectively. In both of them, for the same scaled distance (Fig. 16) or distance (Fig. 17), it is clear on the figures that points c (triangles) are over points e (round), and the regression curves confirm that. We would say that attenuation is stronger for red points that for blue points. However, a greater quantity of analysis realised in benches e gives rise to a greater deviation of the results and from that a mistaken appreciation of the relation between the results.

Conclusions

- There is damping of the vibrations recorded on the surface, along the axis of the tunnel, of between 70 and

Fig. 13 Location of benches *c* and *e* with respect to the fault running through the quarry

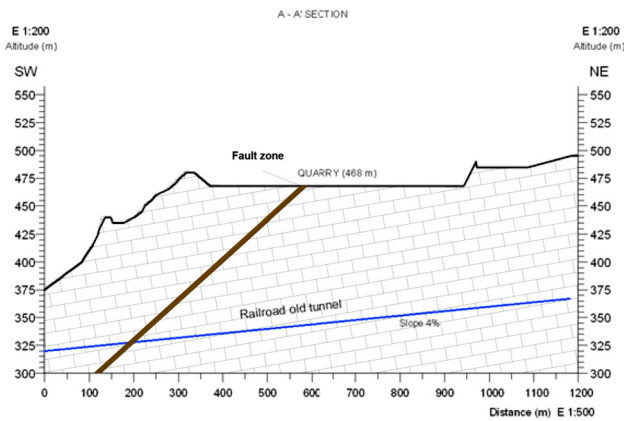
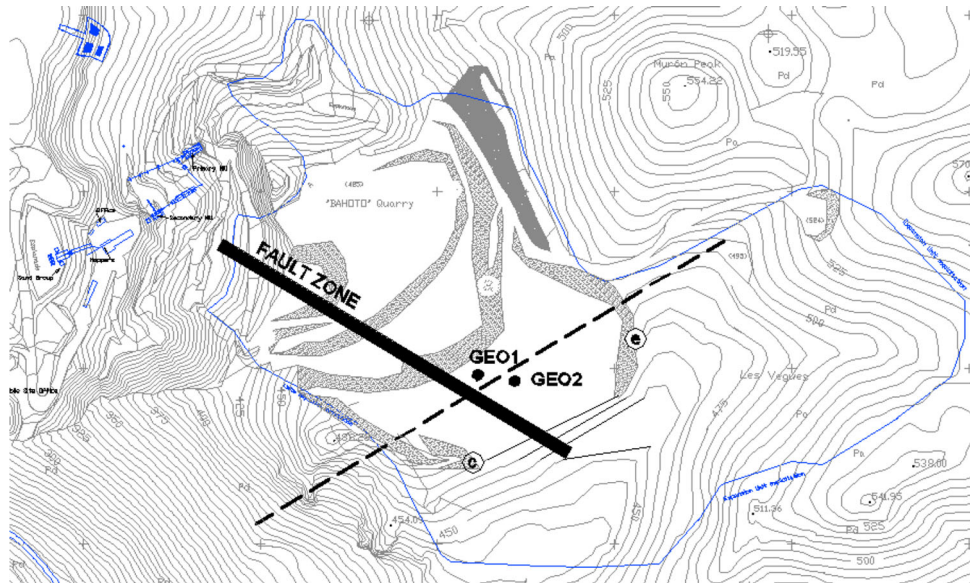


Fig. 14 Detailed geological cross section



Fig. 15 Fault zone aspect

80 % in relation to those recorded at the depth which the tunnel is located underground.

- As the old railroad tunnel is located at a certain depth, it is not correct to continue analysing the blasts on the

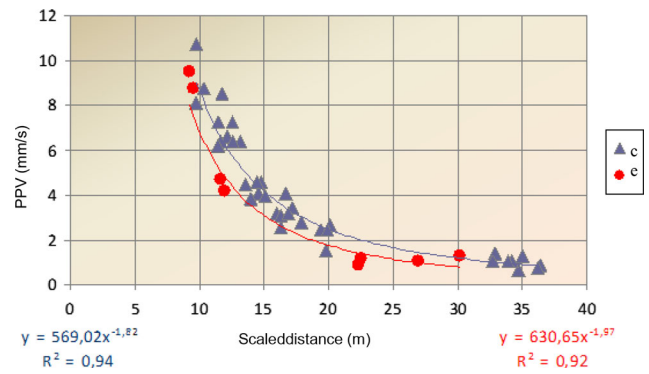


Fig. 16 Conventional law of transmission for benches *c* and *e*

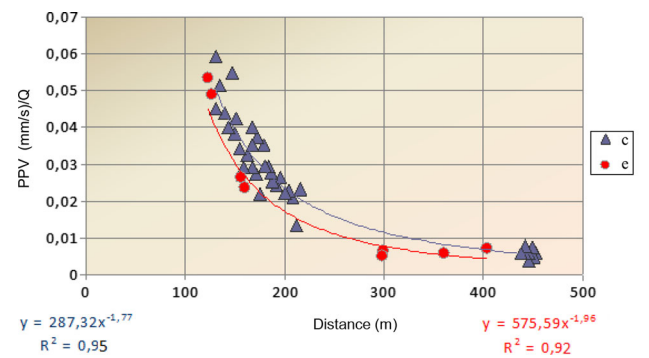


Fig. 17 Law of transmission per unit charge for benches *c* and *e*

surface, seeing as the measures are not representative of the blasting effect on the tunnel.

- The results of the analysis of the vibrations measured during blasting by the geophones situated in the vicinity

of and at the same depth as the tunnel indicate that these are always below the level of vibrations tolerated by standard UNE 22381 (1993).

- The laws of transmission of the calculated vibrations for the blasts recorded by the underground geophones present a good fit, indicating that the rock mass is fairly homogeneous.
- Differences observed between surface and depth measures probably are owing to two questions: at depth, rock mass is homogeneous and exists as an important confinement; however, at the surface level, surface waves are produced, and there are also important topographic changes. In any case, this question is meticulously being analyzed by the authors, by means of the study of the waves shape and its components at surface level and at depth.
- Despite the general homogeneity of the rock mass, the laws of vibration of the blasts located in quarry benches situated on opposite sides of a small fault running through the quarry differ. The blasts carried out in the bench situated on the opposite side to the fault where the geophones are located are slightly damped. This is due the presence of the fault zone, very weathered, that damps vibrations passing through it.

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