ABSTRACT
The definition of allowable limits to the vibrations transmitted from construction works is not straightforward when sensitive structures are found. Two examples are discussed in which the observational method is used with this objective. In the first one, the construction of a tunnel in hard rock in urban environment, in which reasonable criteria based on field measurements of transmitted vibrations could be fixed. In the second case, the presence of a highly sensitive prehistoric cave with mural paintings posed a serious limitation to a nearby excavation, requiring a careful control of ground vibrations to peak particle velocities of a few microns per second.

INTRODUCTION
The noise associated to transportation facilities comes from two main sources: the normal traffic operation (circulation of trains and other vehicles), and construction of infrastructures. The second one is not restricted to the time of construction itself, but it extends to the whole life of the infrastructure, associated to maintenance or improvement operations.

The definition of allowable limits to the vibrations transmitted through the ground from has two main uncertainties. First, the attenuation laws with distance are highly dependent on the particular conditions in each case. The existing theoretical and empirical laws have a wide scatter, and they are highly influenced by the ground anisotropy and non-homogeneity. On the other hand, the prediction of the behaviour of sensitive structures is very difficult, because even at low vibration levels some damage can occur due to local failures.

In some instances, field observations of the actual behaviour of these structures under trial operations are possible and then the allowable limits can be reasonably adjusted. In other cases, the limits must be fixed in the absence of real field data, leading to over conservative limits. In this paper, two illustrative cases are presented. In both, the observational method [1] was used to define the tolerances and to assess the influence of some construction techniques.

Figure 1. Case A. Tunnel in urban area. Longitudinal section
CASE A. SHALLOW TUNNEL IN URBAN ENVIRONMENT

Problem description
A transportation tunnel was excavated in the city centre of Santander (Spain). The tunnel was 600 m long, with a horseshoe section, 12 m wide. The ground (Figure 1) consisted of Cretaceous rock, formed by an alternating series of soft to medium sandstone and shale in the first 400 m (0+850 to 0+480), and hard limestone and sandstone in the last 230 m (0+480 to 0+250). Due to the strict constraints in debris transport in the urban area (the South portal was situated in the city centre), the tunnel had to be excavated from North to South.

The excavation was divided in heading and bench. It was performed with a roadheader in the sandstone and shale series (units L2, L3 and L4), but drilling and blasting was required for the section through limestone (L1) and hard sandstone (L5), as it had been anticipated in the design phase. The entire zone was densely populated, with some old buildings in poor conditions located just above the tunnel. The minimum rock cover was 10 m.

The heading section was excavated in two stages: a central core (3.50 m x 3.75 m) and lateral enlargement. The total blast charge was 82.5 kg in the core and 134.5 kg in the enlargement. The initial design included micro delay blasting, with a charge of 3.6 to 4.9 kg per delay.

Damage criteria
Most of the existing criteria relate damage to the peak particle velocity. In the present case, the criteria given by Chae [2] for structural damage and by Oriard [3] for human response were used (Figure 2). Given the presence of old buildings, a limit of 12 mm/s was adopted as a rule. The attenuation laws used for blasting induced vibrations have the general expression:

\[ v_p = k \left( \frac{Q}{D^\alpha} \right)^\beta \]  

(Eq. 1)

where \( v_p \) is the peak particle velocity, \( Q \) the charge (weight of explosive) per delay and \( D \) the distance. The exponent \( \alpha \) is taken as 1.5 (‘Swedish rule’), 2 (quadratic law) or 3 (cubic law). In this case, the quadratic law (\( \alpha=2 \)) was used. The exponent \( \beta \) depends on the ground conditions. A value of 0.8 is usually considered for sound rock. The factor \( k \) depends on the features of the shot. For \( \alpha=2 \) and \( \beta=0.8 \), values between 200 and 3000 are found, when \( v_p \) is measured in mm/s, \( Q \) in kg and \( D \) in meters (obviously, a decrease in \( \beta \) implies a smaller value for \( k \)).

Analysis of performance
The rock cover decreased with tunnel advance, from 50 m at sta 0+480 to 10 m at sta 0+300 (Figure 1). This allowed using an observational method, with a gradual reduction in the explosive charge in order to meet the above requirement [4]. Ground vibrations were measured at the surface in all the shots using three geophones, directly above the tunnel face and 5 m ahead and behind it. Additionally, the most critical buildings were temporarily left empty.

The section between 0+480 and 0+400, where the tunnel depth was between 50 m and 42 m, was excavated using the initially adopted charge of explosive (4-5 kg per delay). The measured...
particle velocities (50 measures) were in the range of 2 to 7 mm/s (Figure 3). Using Equation (1), with $\alpha=2$ and $\beta=0.8$, the factor $k$ ranged from 230 to 1200, with an average of 700 and a standard deviation of 230. This is in very good agreement with the existing experience.

The predictions for the rest of the tunnel using Equation (1) are also shown in Figure 3. The limit of 12 mm/s would have been exceeded for a tunnel depth between 25 and 30 m. As a consequence, the charge for delay was gradually reduced, to 1.0 kg from 0+390, to 0.75 kg from 0+354 and to 0.45 kg from 0+332. These reductions were achieved shortening the advance (from 3.5 m to 1.0 m) and by multi-stage excavation.

The measured velocities are also shown in Figure 3. All of them were below the limit, with an occasional exception (only one of the three geophones). The deduced value of $k$ from Eq. (1) is presented in Table 1. It tends to be higher in the central section, but it is not possible to separate the influences of the charge, depth and lithology.

The tunnel excavation was completed with no significant damage due to the vibrations, and all the affected buildings were re-occupied after only minor repairs.

Table 1. Analysis of measured peak particle velocity

<table>
<thead>
<tr>
<th>Section</th>
<th>0+480 - 0+400</th>
<th>0+390 - 0+354</th>
<th>0+354 - 0+332</th>
<th>0+332 - 0+300</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (m)</td>
<td>50 - 42</td>
<td>37 - 28</td>
<td>28 - 22</td>
<td>22 - 10</td>
<td>50 - 10</td>
</tr>
<tr>
<td>Charge, $Q$ (kg)</td>
<td>4 - 5</td>
<td>1.00</td>
<td>0.75</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>$k$ (best fit)</td>
<td>667</td>
<td>1029</td>
<td>1518</td>
<td>782</td>
<td>824</td>
</tr>
<tr>
<td>(min)</td>
<td>235</td>
<td>289</td>
<td>467</td>
<td>241</td>
<td>235</td>
</tr>
<tr>
<td>(max)</td>
<td>1177</td>
<td>2094</td>
<td>2559</td>
<td>2923</td>
<td>2923</td>
</tr>
<tr>
<td>No. of observations</td>
<td>50</td>
<td>34</td>
<td>55</td>
<td>138</td>
<td>277</td>
</tr>
</tbody>
</table>

* From equation (1), with $Q$ in kg, $D$ in m and $v_p$ in mm/s, $\alpha=2$, $\beta=0.8$

**CASE B. EXCAVATION NEAR A PREHISTORIC CAVE**

**Problem description**

The new Museum and National Research Centre of Altamira was constructed in 1997 in Cantabria (Spain), in the neighbourhood of the Altamira caves, famous by their Palaeolithic rock paintings and engravings from the Magdalenian period (14000-12000 BC).

The main cave is 270 m long, and the paintings are concentrated in the ceiling of a lateral chamber near the entrance, 18 m x 9 m, with a height varying from 1.15 m to 2.65 m, at an elevation of +155 m. The cave is of secondary nature, formed by the progressive collapse of underlying karstic cavities, inducing openings between individual rock strata. The rock is calcarenite, with a marked stratification (orientation 110°/140°).
The cave is at present in one of the last stages of its evolution, characterised by a progressive decalcification, leading to the separation of the individual strata, which eventually can fracture and fall. The final collapse of the cave can take years or millennia, but there are many evidences of significant rock falls in some parts of the cave in historic times (in 1920 a roof support was placed in some parts). As a result, the cave is considered as highly sensitive to any kind of alteration of the equilibrium of the surrounding rock mass.

The visits to the cave were strictly limited to only 20 persons per day. The cave was closed on Mondays. Besides this paintings cave, there is another one at a lower level (el. +145), called the stalactites cave, with no known rock art, but also of tourist interest by its karstic formations.

The works for the new museum were located at a distance of 150 m from the paintings cave and 100 from the stalactites cave (Figure 4). They comprised an open excavation in rock, 10 m deep, and construction of the building and access roads.

**Damage criteria. Design provisions**

There are few data on the tolerance of underground openings to vibrations. Lined tunnels behave relatively well during seismic motions, with reported damages only under very severe actions [5]. However, unlined natural cavities are more sensitive. Berta [6] presents a case where a limit of 7.1 mm s⁻¹ was adopted for a cave with delicate karstic structures.

![Figure 4. Case B. General plan showing the caves and construction works](image)

![Figure 5. Measured ground vibrations during the design phase](image)
In the present case, the paintings form a thin layer of clay and other substances adhered to the rock surface, and any local loss of bond can lead to a severe deterioration. In any case, the uniqueness of the monument and its particular conditions described above implied that the consequences of a small local failure would be unacceptable. This lead to the condition of "no perceptible vibration in the cave" due to the works. To meet this requirement, the design included the specification that the construction could not produce at the cave any vibrations higher than the pre-existing ground vibration levels.

During the design phase, a field campaign was carried out aimed to the determination of the existing vibration level. A portable system was used [7], and natural vibrations were recorded with triaxial geophones under different conditions. Figure 5 shows the results of the measurements inside the cave. The maximum peak particle velocity was found to be of only 3.5 \( \mu \text{ms}^{-1} \) (microns per second). This was considered as an initial limit, for a range of frequencies 0.1 Hz to 100 Hz. This limit is three orders of magnitude lower than the usual ranges (Figure 3).

Some construction constraints were adopted in the design: Blasting, percussion drilling and use of impact hammer were forbidden. Traffic was not allowed in the path surrounding the cave, and limited to 10 km/h (5 km/h for heavy vehicles) in the rest of the area. Progressively, these restrictions were relaxed, depending on the location, after assessment that the imposed vibration limit was not exceeded. Blasting was forbidden under any circumstances.

In the main excavation, expansive mortar in pre-drilled holes was used to fragmentate the rock. For small excavations (footings), a small roadheader was also employed.

**Vibration control**

Ground vibrations in the caves were continuously monitored during all the construction stage [8]. A fixed control system was installed, to check that the adopted limit was not exceeded. The system would also serve to assess the level of natural ground vibrations in a longer time basis (the total recording time during the design phase had been 100 seconds in runs of 5 seconds). The sensitivity required excluded the use of standard geophones, and so the system was based on the measure of accelerations, that are then integrated in the time domain to obtain the velocities. The installed system consisted of:

- Three ground accelerometers, mounted in a triaxial (xyz) arrangement inside the paintings cave: measuring range 0.1-200 Hz, \( \pm 1 \mu \text{g} \); sensitivity \( \pm 1 \mu \text{g} \).
- Three ground accelerometers, mounted in a triaxial (xyz) arrangement inside the stalactites cave: measuring range 0.1-1000 Hz, \( \pm 0.5 \mu \text{g} \); sensitivity \( \pm 5 \mu \text{g} \).
- A central system, installed at the works office, composed of a data acquisition unit, with three AD acquisition boards, each of them with three conditioning module channels and a memory board, programmable triggering level and recording time, and a computer (PC) with software for time integration, signal storage, discrimination of events (see next paragraph) and alarm control.

![Figure 6. Record of events during a Sunday](image)
Criteria for the analysis
A first campaign of trial measurements showed that the rock mass anisotropy was very important in the attenuation of vibrations with distance. For the range of distances involved, the attenuation (in terms of peak particle velocity) was found to be five times greater in the direction normal to bedding than parallel to it, due to the loss of energy at the discontinuity planes. As the rock structure was very uniform, a system of virtual distances between any two points was easily defined, by assigning a weight factor of 5 to the component across the stratification.

For any given event, the ratio between the peak velocities recorded at the paintings cave, \( v_p \), and at the stalactites cave, \( v_s \), was used to discriminate its possible origin. The virtual distance from the works to the paintings cave was about twice as the distance to the stalactites cave. Hence, only when the recorded vibrations ratio \( v_p/v_s \) was in the range 2.5-7.5 were considered as potentially produced by the works. This range was wide enough so that any event outside it is clearly not caused by the construction activities.

Interpretation of results
After some time, it became evident that the initial limit of 3.5 \( \mu \text{ms}^{-1} \) was exceeded very often in the absence of construction activities. A continuous record for a Sunday (no construction activities) is shown in Figure 6. There is a continuous vibration of the order of 3.5 \( \mu \text{ms}^{-1} \), in agreement with the design phase analysis. However, there are events of velocity of up to 42 \( \mu \text{ms}^{-1} \) during the day and up to 10-15 \( \mu \text{ms}^{-1} \) during the night. These events happen at an average pace of 15–20 per hour, with individual duration of about 0.2 seconds (this explains why these peaks were not detected in the design phase, with discontinuous measurements in runs of 5 seconds). Figure 7 shows the records corresponding to three typical days:
- Sunday (28-12-97), with no construction activities, and with visits to the cave in the morning and afternoon.
- Tuesday (23-12-97), with construction activities and visits.
- Monday (22-12-97), with construction but with the cave closed to visitors.

In these plots, the above range for attenuation, separating the vibrations potentially associated or not to the works is also shown. There are many peaks of velocity exceeding by far the limit of 3.5 \( \mu \text{ms}^{-1} \), with very low ratios (well below 1.0), indicating that they are originated at the paintings cave itself or its surroundings. It is evident from these results that the level of vibrations in the absence of construction activities was well above the initial adopted value. The dominant frequencies were in the range 30 – 40 Hz.
After a whole month of continuous recording, it was accepted that the pre-existing vibrations were in fact of up to 42 $\mu$m s$^{-1}$, most of them associated with the visits to the cave (the highest peaks correspond to opening and closure of the entrance door). So it was decided to increase the initial estimate of the "natural" vibrations, with some additional safeguards. The following scheme of alarms and warnings was finally adopted, based on the peak particle velocity at the paintings cave, $v_p$, and the duration, referred always to events potentially due to the works (ratio between the vibrations in the two caves in the range 2.5 - 7.5):

- Level 1: One or more events of $v_p > 21\ \mu$m s$^{-1}$ during more than 50 milliseconds. A visual and sound alarm is activated in all the working area. Any construction activity should be immediately stopped.
- Level 2: $v_p > 10.5\ \mu$m s$^{-1}$: one event during more than 1 second, or six shorter ones per minute. A light and a bell are activated at the office. The source must be identified and corrected as soon as possible.
- Level 3: $v_p > 3.5\ \mu$m s$^{-1}$: more than 10 events in 1 hour or more than 40 in one day. A light is activated at the office. It must be analysed and reported to the work director.
- Level 4: Any single event of $v_p > 3.5\ \mu$m s$^{-1}$ during more than 50 milliseconds, or any system malfunction is recorded and stored. A signal is activated at the computer.

Performance
With the above criteria, the works were carried out satisfactorily, according to the scheduled program. The initial severe restrictions to construction methods were progressively relaxed (with the exception of blasting), as commented above. The system for vibration control performed well, with only minor occasional problems, mainly associated with the transmission cables (the distance from the instruments to the works office was of several hundred meters). The average occurrence of events associated to the works was: level 1, none; level 2, less than one per month; level 3, less than three per week; level 4, about ten per day.

CONCLUSIONS
The above two cases constitute two extreme examples in the conditions of application of the observational method in geotechnical engineering, for the effects of vibrations on existing structures. They represent the ‘ductile’ and ‘brittle’ situations [9]. In the case A, the particular conditions allowed the progressive assessment of the risk, and the construction method could be adapted accordingly to meet the design requirements.

On the other hand, the case B the severity implied by any damage lead to the imposition of a highly conservative limit for the allowable limit. Even in this case, the observational method was used to refine the level of the pre-existing ground vibrations, and to control the effect of particular construction techniques.

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