applied sciences

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Vibration Analysis and Empirical Law Definition for Different Equipment in a Civil Construction

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Received: 4 June 2020; Accepted: 2 July 2020; Published: 8 July 2020

Abstract: The potential affection of any construction, and especially historical sites, is of great concern for their long-term maintenance and stability. This study has determined the vibration behavior in poor-quality rock mass conditions generated by some of the most typical equipment used in construction: excavator, ripper, ripper vibrator, hydraulic hammer, bulldozer and vibrating roller. Several empirical expressions are proposed to know the maximum velocity at different distances for each type of equipment, taking into account the intensity of the vibration generated and its pattern. A general equation has also been defined to determine the vibration propagation along the distance at a construction site, based on the impact generated by all the possible vibration elements, exogenous and endogenous, including machinery working individually or in any possible combination and number. On the other hand, the maximum allowable velocity in the case study is also discussed and compared to international standards, stating some recommendations. It would be very important to have a clear legislation in this regard due to the high density of sensitive constructions in Spain and the economic implications of applying too high or too low standard values.

Keywords: empirical analysis; mechanical excavation; ground vibration; historical construction; wave propagation

1. Introduction

The concern about historical heritage and its conservation has been growing in our society over time, having more and more constructions tagged as architectural heritage. This fact, together with the increase in new infrastructure and population density, makes crucial the determination of potential vibration affections in sensitive constructions generated by new buildings and mechanical surface excavations or blasting operations [1–3], while the opening of underground excavations can also have an important impact [4,5]. Some research has been done to define the impact of using construction equipment on sensitive constructions [6,7] and identify the structural damage caused by vibrations [8], as well as the prediction of the maximum vibration that can be generated [9]. Amick et al. [10] described an interesting investigation regarding the propagation of major vibration sources, such as the movement of heavy vehicles or construction activities, from the ground to more sensitive areas.

Despite the large quantity of studies done over the last decades, due to the logic implications, and case studies in urban areas [11,12], there is still a lack of knowledge of the possible damage in delicate constructions owing to the large variations in rock masses and the proximity and usage of the equipment. Besides, shielding facilities have been verified as non-effective to reduce the propagation of the vibration along the ground in these situations. The technical guideline published by the Department of Environment and Conservation from Australia [13] details some operational mitigation actions, but they are not appropriate in all the possible situations and the degree of attenuation of each measure can vary widely in each case.

There are some national regulations regarding the potential damage of vibrations caused by mechanical excavation and heavy equipment, while international standards are applied in some other countries. However, there is still a legal void in some countries, especially in the case of historical or sensitive constructions [14] that could create situations with too restrictive or permissive legal requirements.

1.1. Objectives of the Study

The aim of the study is to determine the vibration transmissivity to the ground at different distances from distinct heavy equipment in the construction sector, either working individually or simultaneously, defining an attenuation vibration law and a model to predict the potential vibration affection to the surroundings of the infrastructure under construction. The specific legal requirements and the international standards are also discussed, giving some recommendations for future legal thresholds in countries where these standards do not exist, like Spain.

1.2. Literature Review

Vibration issues can be generated by the operation of construction equipment, blasting and traffic traveling. The potential damage to constructions includes superficial and structural damage [15], caused by excavation and demolition activities or earth movement. Besides, it can also affect sensitive equipment, i.e., microelectronic manufacturing equipment, which is very sensitive to ground vibrations and individuals close to the vibration source [16–18]. Usually, the vibration amplitude of traffic is not high enough to cause damage to a construction due to suspension systems and pneumatic tires [19]. On the other hand, railways and trains can also have a significant impact on vibrations, making it necessary to apply countermeasures [20].

The concepts of particle displacement, velocity and acceleration are used to describe ground vibration, being the peak particle velocity the most appropriate variable to assess the potential damage to a construction [14]. Vibration amplitude is described by three components: two horizontal components, transverse and longitudinal, and one vertical component, which generally has the highest amplitude and it is easy to measure [21].

The duration and amplitude of the vibration change depends on the type of operation and equipment, ranging from a high amplitude and short duration to lower and longer characteristics, respectively. The equipment or activities can be classified as continuous, excavation and vibratory compaction equipment, among others, and single impact with or without a high-rate repeated impact vibration, like a jackhammer or other similar breakers.

The maximum velocity component for construction vibration, peak particle velocity (PPV), is used as a descriptor of the wave effect. This preference results from the close association of construction vibration with blast vibration monitoring, where particle velocity correlates with the appearance of cracking [2].

The vibration source creates a disturbance that propagates away, being the R-wave the primary concern for foundations close to the surface [2]. According to Richard [22], R-waves account for 67% of the total energy, S- waves for 26% and P-waves for 7% when the exciting force is applied vertically to the propagation direction. The vibratory excitation propagates radially outward, causing a spreading loss as the wave finds an increasing volume, reducing the amplitude of the displacement. The general expression to model the spreading loss is defined in Section 2.3. When the rock mass is highly fractured and deteriorated, or it is a soil, its behavior is not perfectly elastic, having a damping effect, influenced by multiple variables such as the type of material, moisture or frequency of the vibration source. This behavior was defined by Telford et al. [23], also explained in Section 2.3, having two parameters, γ and α, that represent the geometric attenuation coefficient, depending on the wave type, and the attenuation coefficient of the material. Dowding [2] and Jones and Stokes Associates [24] gathered the typical values of the attenuation coefficient, however, there is a large possible range in each type of material. On the other hand, Sambuelli [25] proposed an interesting approach to forecast the maximum particle velocity on the basis of blasting design and rock parameters, detailing an analytical approach to support the empirical expressions used. The dependence on frequency caused by construction equipment is commonly considered as weak. It is often assumed independent from frequency [26]. Therefore, the greatest concern is related to the distance from the vibration source.

Amick [27] and Hendriks [21] gathered many of the damping coefficients depending on the type of material. Besides, Amick [27] mentions that it is a proper methodology to determine the impact to structures and people. However, most of the information is for soils and not for rocks. Besides, it analyses individual vibration effects, not the global effect of several equipment working at the same time. In this regard, Santamaria et al. [28] suggested different γ coefficients for rock depending on the type of wave, body or surface, and for poor rock mass that still needs blasting operations.

The effect of vibration to constructions has attracted the attention of many researchers over time, focused primarily on the potential damage from mining and blasting [29]. Kadiri et al. [30] gathered an interesting revision of the empirical equations developed in recent decades to improve the vibration prediction caused by blasting.

Currently, there are many different standards used depending on the type of construction, structural conditions and age [24,31], including specific criteria for sensitive and historic buildings [2,32]. There is also an extensive knowledge of vibrations generated in linear constructions such as roads or railways. Crabb and Hiller [33] measured vibrations from several types of construction equipment in a controlled experiment, while Jackson et al. [26] and Hanson et al. [34], provided a national approach to assessing vibrations from construction equipment in the USA.

Some literature is focused on defining the peak particle velocity (PPV) depending on the type of equipment [35,36]. For instance, Hiller and Crabb [37] and Jackson et al. [38] developed an expression to determine the vibration generated by a roller drum at a short distance, taking into account the length of the roller drum. Moreover, Hanson et al. [34] proposed an empirical equation to predict vibration from pile driving. Dowding [2] also proposed an expression for the impact hammer based on experimental data. However, several machines work at the same time usually, which is necessary to analyze the overall vibration impact.

All this knowledge has fostered the development of international standards to provide guidance for building damage from mechanized construction, as well as blasting. The most common are the following: German Standard DIN 4150-3:1999, British Standard BS 7385-2:1993 and Swiss Standard VSS-SN640-312a:1992, all taking into account the effect on sensitive or historical constructions in all of them, but with different approaches. Additional research has been done regarding the maximum allowable vibration velocity, such as the American Association of State Highway and Transportation Officials [39], that defines different allowable velocities for transient sources and continuous or frequent intermittent sources. On the other hand, Schiappa de Azevedo and Patricio [40] considered that the maximum velocity permitted depends on the type of ground where the historical building is placed.

Several methods to reduce the vibration are proposed. One of the most common among them is a wave barrier, which cut the wave transmission from the source to the receiver. Wave barriers must be very deep and long to be effective, and they are not cost-effective for temporary applications such as pile driving vibration mitigation [15]. Other measures or elements, like crushing equipment when working in concrete or hard rock can be used to reduce the vibration from a hydraulic breaker, however, it cannot always be applied [15]. Other more general measures such as maintenance of the machines, reducing the time that different equipment are working simultaneously or their size can also be evaluated, but it is impossible to avoid the whole problem, and it is often not feasible [14].

2. Materials and Methods

2.1. Case Study

A cut and cover tunnel was planned to be constructed parallel to a heritage construction site, around 100 m away, in northwest of Asturias, Spain (Figure 1). The excavation was done by a mechanical method, using different excavators equipped with a V-type bucket, a ripper and a hydraulic hammer as well as a bulldozer and a vibrating roller for the management of the backfill material. The hydraulic hammer was subsequently replaced by a vibration ripper due to operational considerations, such as the weakness of the rock mass, during the excavation process.

Figure 1. Case study. (**a**) Cut and cover tunnel under construction. (**b**) Historical site where the field instrumentation was placed.

The rock mass of the case study site is composed of Ordovician shale materials (dark shale from the Luarca Formation) which are found in a massive scale and with an 80° dip. Several uniaxial compression strength tests were done, obtaining a value between 12.5 and 23 MPa. Besides, the rock mass is highly fractured with several joint directions, having a medium to low rock mass rating (RMR), between 21 and 40, classified as poor-quality rock mass.

The rock mass excavatability can be classified as diggable and/or rippable under the criterion of Tsiambaos y Saroglou [41]. These authors define, on the Hoek-Brown abacus, the zones in which different excavation methods can be used: digging, ripping, breaker hammer and blasting. The GSI index and the point-load strength I_s are the representative parameters of the rock mass.

In this case, the rock mass can be considered blocky/disturbed, with a GSI between 20 and 40. On the other hand, an I_s value between 0.5 and 1 can be deduced from the rock compressive strength. Consequently, the rock mass can be classified as diggable and/or rippable (Figure 2). These assumptions were verified during the field work, where the excavation was carried out almost totally with excavators and rippers.

On the other hand, the backfill material was spread and compacted in different layers as the base and sub-base for the infrastructure. It is a material with a granulometry that ranges between 80 and 0.08 mm, mainly composed of sand and gravel, with less than 2.4% of fine elements. The density during the test was around 1.8 tn/m^3.

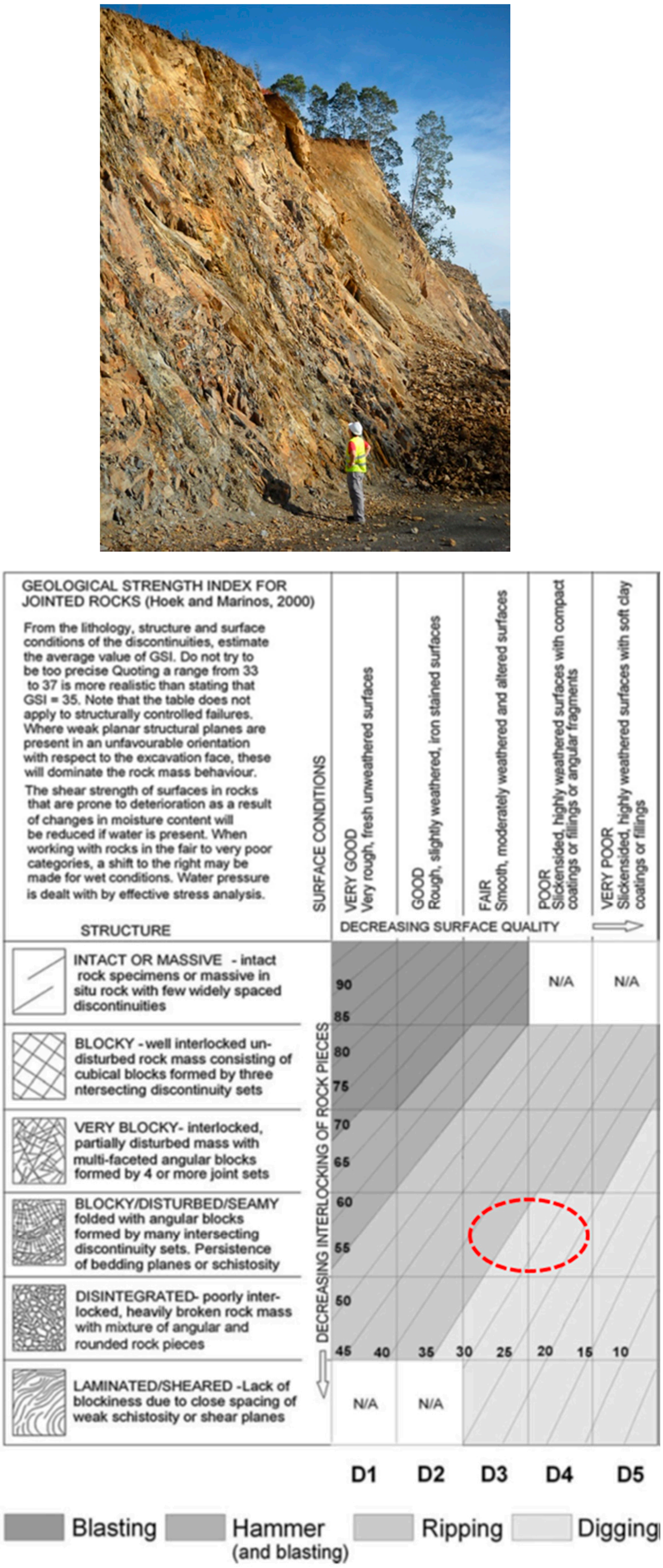

Figure 2. Excavatability of the shale rock mass for $I_s < 3$ according to Tsiambaos and Saroglou [41].

2.2. Equipment for Data Adquisition

The equipment used for the data obtaining were three seismographs of the Vibracord type, one seismograph of the Instantel Blastmate II type and two seismic stations of the MarSlite type. In the case of the seismographs, they have three seismic channels (vertical, longitudinal and transversal) and the following operational range of velocity, 0–150 mm/s, and frequency, 2–250 Hz. The attachment of the equipment to the ground was done following the criteria stablished by the UNE 22-381. The detection limit of the seismographs and seismic stations are 0.01 and 0.001 mm/s, respectively. The procedure followed was similar to the one explained by Lane and Pelham [11] and Andrews et al. [15], having two main stages to determine the vibration behavior in this case:

1. Several tests were done in situ to determine the attenuation vibration law for the specific ground of the case study and for each piece of equipment, described in Section 2, in the real location and carrying out a regular operation;
2. Recording of the vibration transmission in the historical site foundations during 48 work days, 24 h a day.

2.3. Vibration Fundamentals

The vibration propagation to the ground depends on many different factors, such as the rock mass anisotropy, its heterogeneity and the degree of fracturing, among other elements [42].

The vibration behavior along the distance, from a certain source, can be analyzed taking into account, or not, a damped response from the rock mass. Its simplest way is the attenuation vibration law without a damped effect, as it is seen in Equation (1).

$$v_{max} = v_0 \left(\frac{r_0}{r}\right)^{\gamma} \tag{1}$$

where v_{max} (mm/s) is the peak particle velocity (PPV) or maximum velocity at a distance r from the source; it is assumed that the initial velocity v_0 (mm/s) at a certain distance r_0 (m) is known. The γ coefficient (dimensionless) is an empirical value that depends on the characteristics of the ground and the wave frequency, usually between 1.4 and 1.7 [43], obtaining the value by in situ measurements or using bibliographical values. Equation (1) can be applied when the rock mass has very good quality and for short distances, assuming that the vibration amplitude waves diminish with distance due to the expansion of the wave front [44].

On the other hand, the attenuation vibration with the damped effect occurs when we have soil or poor-quality rock masses and long distances, having an inelastic attenuation due to heat losses and yielding of the ground. Therefore, the vibration amplitude decreases because of the expansion of the wave front and the inelastic behavior, as in Equation (2).

$$v_{max} = v_0 \left(\frac{r_0}{r}\right)^{\gamma} e^{\alpha\ (r_0 - r)} \tag{2}$$

where α (m^{-1}) is an empirical coefficient based on the damping characteristics of the material [44]. Depending on the case, both methods could be used successfully, obtaining even similar results at short or middle distances. Nevertheless, in some cases, such as the one studied here, the first method cannot be used to properly predict the peak particle velocity over all the range of distances. Therefore, it is assumed that Equation (2) is the most adequate expression in this case study.

Parameters α and γ have been adjusted to the case study from the point cloud of the measurements done in situ analyzing the different types of equipment. The envelope curve defines the maximum potential vibration based on the data measured.

The great advantages of empirical formulas, such as Equations (1) and (2), are their simplicity and easy understanding. They are widely accepted in real projects [27,33–38], achieving very good correlations with in situ measurements if they are applied under the proper conditions. However, further developments are necessary to cover as many conditions as possible in future situations.

The procedure to fit Equations (1) and (2) to observed data from different soils or rock masses is extensively explained by Amick and Gendreau [17], obtaining the γ coefficient from each specific case study. This approach has been successfully used in many previous studies [21,24,37].

2.4. Set Up

The installation of the seismic stations and seismographs to determine the vibration created by each type of equipment is displayed in Figure 3, having the characteristics detailed below.

Figure 3. Layout of the equipment for monitoring the work of: (**a**) V-type bucket, (**b**) ripper (**c**) hydraulic hammer and (**d**) bulldozer and a vibrating roller.

(a) Mechanical excavation using a Hitachi 500 with a V-type bucket for rock. Installation of 4 seismographs and 2 seismic stations;

(b) Ripping operation using a Komatsu PC 450 LC6K equipped with a ripper. Installation of 3 seismographs and 2 seismic stations;

(c) Fragmentation using a Hitachi ZX240 equipped with a hydraulic breaker hammer Furukawa F45. Installation of 4 seismographs and 2 seismic stations;

(d) Earth moving and compacting roller. The first operation was done with a Bulldozer Cat D6N, while the second one using a Bomag BD211D. In both cases 4 seismographs and 2 seismic stations were used.

The seismic stations not seen in Figure 3 were placed between 30 and 40 m far from the operation in the direction of the historical site. All measurements were done while the equipment was performing the operations.

2.5. Maximum Allowable Velocity

The competent authority established a maximum value of 0.1 mm/s for this particular case study. However, there is not a clear legal value in Spain for this type of vibration source. Table 1 gathers the main international values in this regard.

Table 1. Values stablished by different sources/authors.

Source	Threshold Value (mm/s)
Studer and Suesstrunk [45]	1.8–3
Forsblad [46]	2
Swiss Standard	3
Standard DIN 4150	2.5–10
Schiappa de Azevedo and Patricio [37]	1.75–10

The German standard DIN 4150 gives a range of maximum values for historical sites depending on the frequency and type of vibration, short- or long-term exposure, while the Swiss Standard VSS SN640 is commonly considered as very conservative [34]. However, this last one has been widely used by many different public administrations [31]. Another widespread reference, the British Standard BS 7385 from 1993, does not include a threshold for sensitive or historical constructions, but it depends on the type of construction. On the other hand, the Spanish maximum legal value regarding blasting operations close to old or historical buildings is 4 mm/s, UNE 22381-93.

3. Results and Discussion

3.1. Anlalysis of the Equipment

The vibration level is characterized by the maximum velocity or peak particle velocity (PPV) in the vertical direction because it is less influenced by the alignment of the geophone than the longitudinal or transversal components. Table 2, Table 3, Table 4, gather the peak particle velocities at different distances, recorded in situ for the equipment working directly in shale rock mass and backfill material.

Table 2. Velocities at different distances for the excavation equipment.

V Bucket		Ripper	
Distance (m)	Velocity (mm/s)	Distance (m)	Velocity (mm/s)
2.5	1.36	4	1.36
5	1.33	10	0.38
6	0.66	10	0.25
6.6	0.38	11	0.095
6.6	0.51	11	0.183
9.5	0.23	30	0.009
10	0.215	30	0.019
40	0.008		
40	0.009		

Table 3. Velocities at different distances for the excavation/fragmentation equipment.

Vibrating Ripper		Hydraulic Hammer	
Distance (m)	**Velocity (mm/s)**	**Distance (m)**	**Velocity (mm/s)**
2	4.31	2	3.33
2	3.63	3.5	1.99
10	1.85	3.5	2.72
15	1.39	5	1.36
18	1.16	8	0.88
18	1.39	8.5	0.90
27	1.38	9.5	0.51
27	0.46	10	0.40
35	0.92	10	0.119
35	0.69	10	0.137
35	0.62	30	0.012
		30	0.006

Table 4. Backfill operations with different equipment.

Bulldozer		Vibrating Roller	
Distance (m)	**Velocity (mm/s)**	**Distance (m)**	**Velocity (mm/s)**
1	5.1	1.5	3.33
3	2.5	3	15.76
3	1.14	3.5	4.99
4.5	2.5	5	4.54
5	1.77	5	6.12
7	1.58	5	3.99
7	0.51	6.5	3.85
8.5	0.45	7	5.44
9	1.33	7	5.33
11	1.4	8.5	4.31
11	1.36	9	6.6
12.5	0.66	10.5	1.27
30	0.044	30	0.27
30	0.035	30	0.27
30	0.039	30	0.27

It can be seen that the behavior of three types of equipment (excavator, ripper and breaker hammer) working on the shale bed rock is quite similar, achieving very low velocity values from 30 m and further, being much lower than the threshold values established by the legal requirements and international standards. The rock mass behavior to the vibration transmission is almost the same in the three types of equipment, varying only in the vibration intensity, especially in the case of the hydraulic hammer.

On the other hand, a few differences have also been detected. The excavation using the bucket has a more uniform evolution regarding the distance of measurement, while the ripper operation has a higher value close to the source and, then, the velocity decreases faster. A plot of the actual data, taking into account the distance from the vibration source, is included in Figure 4, showing an almost linear trend with a negative slope.

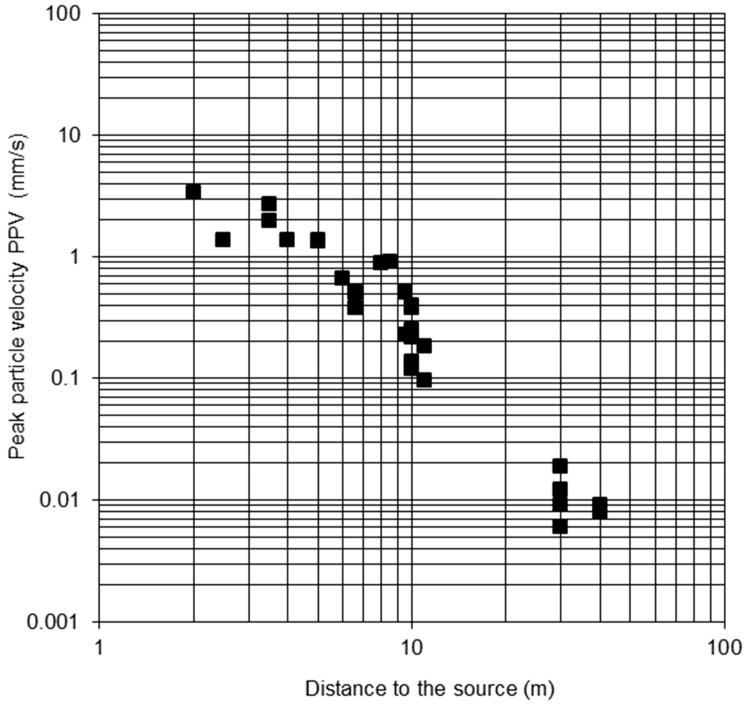

Figure 4. Logarithmic graph of the excavation, ripping and fragmentation equipment (without vibration).

It has to be pointed out that the vibrating ripper generates vibration levels of about one order of magnitude bigger than the other equipment (Figure 5). This vibrating ripper will be considered, from a ground vibration point of view, equivalent to the vibrating roller which is analyzed henceforward.

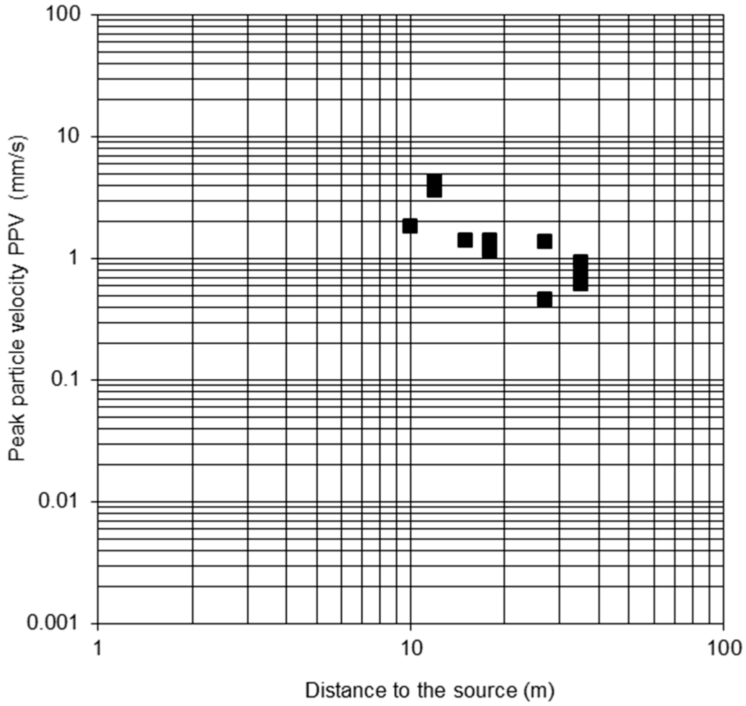

Figure 5. Logarithmic graph of the ripping with vibration.

In the case of compacted granular material, the velocity achieves a value lower than 0.1 mm/s at a distance around 25 m for the bulldozer and 50 m for the vibrating roller, with the usage of the last one having a much higher impact (Table 4). The actual data plotted in Figures 6 and 7 also display an almost linear trend with a negative slope, but with a higher dispersion of the measurements at a short distance from the source in the case of the vibrating roller (Figure 7).

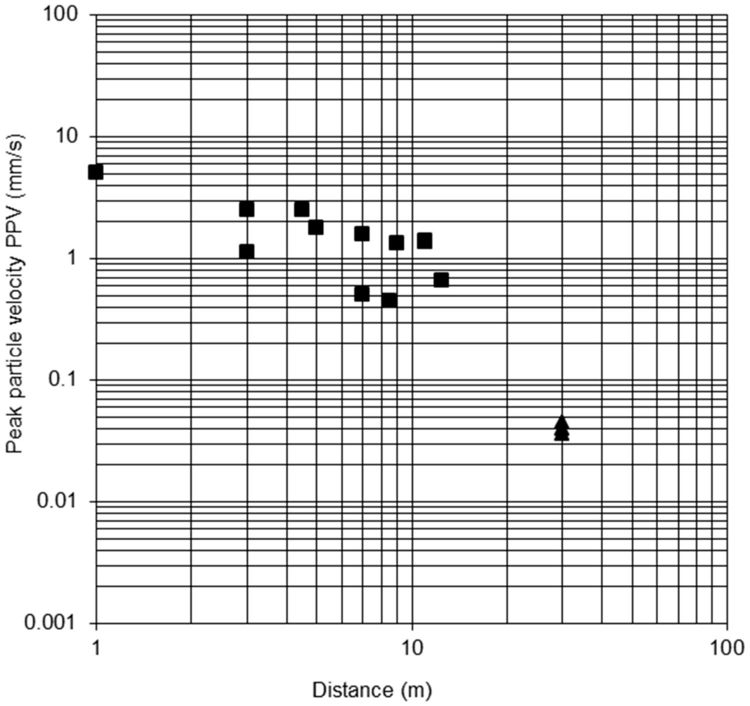

Figure 6. Logarithmic graph of the bulldozer.

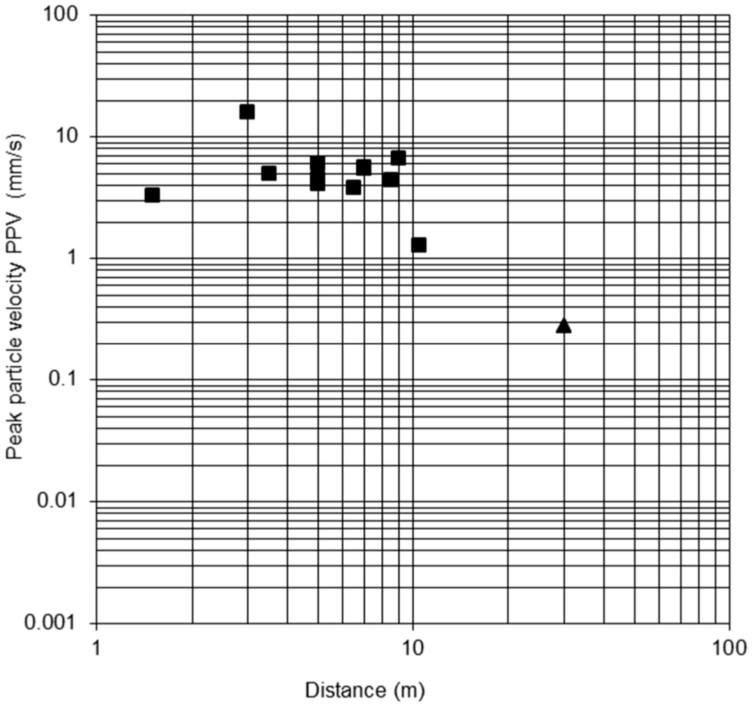

Figure 7. Logarithmic graph of the vibrating roller.

The values from Tables 2–4 give slightly different results, for the same type of equipment, to previous research for a similar case study [47]. In this regard, an adjustment of the α coefficient is done based on the characteristics of each equipment. The following expressions, Equations (3)–(5), define the representative vibration attenuation law for the use of each type of equipment, obtained from

Equation (2) and actual data. The actual data show that the same expression can be used for the vibrating roller and the vibrating ripper, either at short or long distances.

Excavator equipped with a V bucket or a ripper:

$$v_{max} = 4.5\ r^{-0.5}\ e^{0.060\ (1-r)} \tag{3}$$

Bulldozer:

$$v_{max} = 10\ r^{-0.5}\ e^{0.055\ (1-r)} \tag{4}$$

Vibrating roller or excavator equipped with a vibrating ripper:

$$v_{max} = 35\ r^{-0.5}\ e^{0.055\ (1-r)} \tag{5}$$

The α values obtained range from 0.055 to 0.060 m^{-1} for a poor rock mass and a frequency between 50 and 100 Hz, while α is 0.055 m^{-1} for backfill materials with a frequency between 30 and 40 Hz. The results are consistent with previous publications on rock masses ranging from very poor to very good [2]. Besides, if Equations (4) and (5) are applied, i.e., r = 7.6 m, the PPV obtained for the bulldozer and the vibrating roller are 2.5 and 8.8 mm/s, respectively, which are very similar to the results obtained by Hanson et al. [34].

Figure 8 gathers the vibration behavior generated by each type of equipment in a highly fractured shale rock mass and backfill material. Taking into account the legal requirement established by the administration, the minimum safety distance to the historical site is 35 m for the excavation operations, 50 m for the bulldozer and 80 m for the vibrating roller. The huge impact, in terms of the vibration generated, by the vibrating roller has also been mentioned in previous research [48]. During the excavation process, the hydraulic breaker hammer practically was not used, while the vibration ripper worked most of the excavation time.

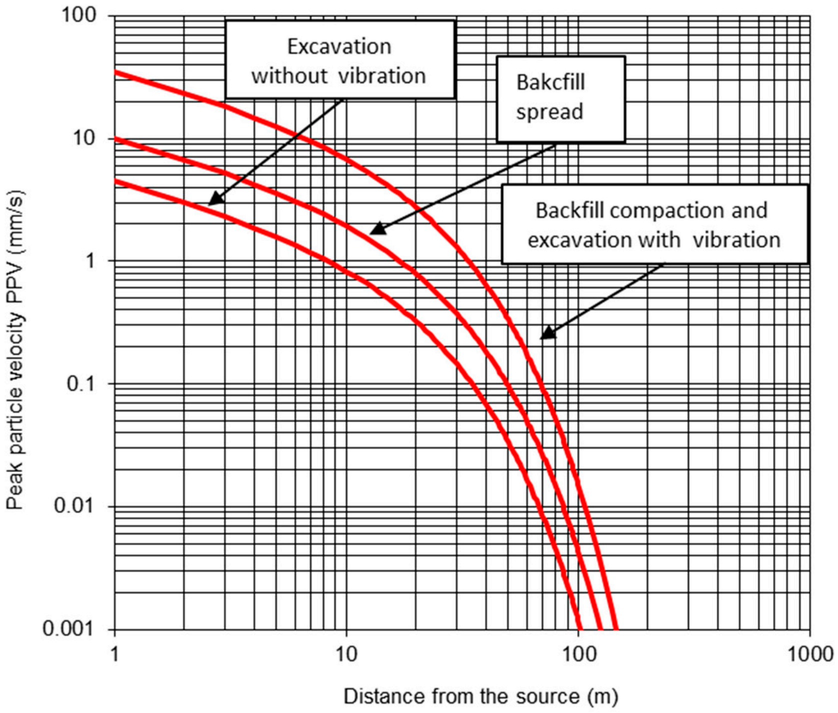

Figure 8. Vibration behavior of the equipment, based on the distance.

3.2. Historical Site Analysis

Figure 9 shows different machinery working in the initial trench for the cut and cover tunnel. The ground vibrations were recorded with a seismic station located close to the foundation of the historical building while machinery was working.

Figure 9. Machinery working in the trench.

The measurements were carried out when the machinery was working on the side nearest to the building to control vibrations under the most unfavorable conditions, having a practically constant distance to the building. On the other hand, the excavation depth did not vary too much during the whole monitoring period. The whole data set from the historical site foundation is included in Figure 10 regarding the maximum velocity. The distance during the recording period is around 100 m, which is the minimum distance during the excavation period.

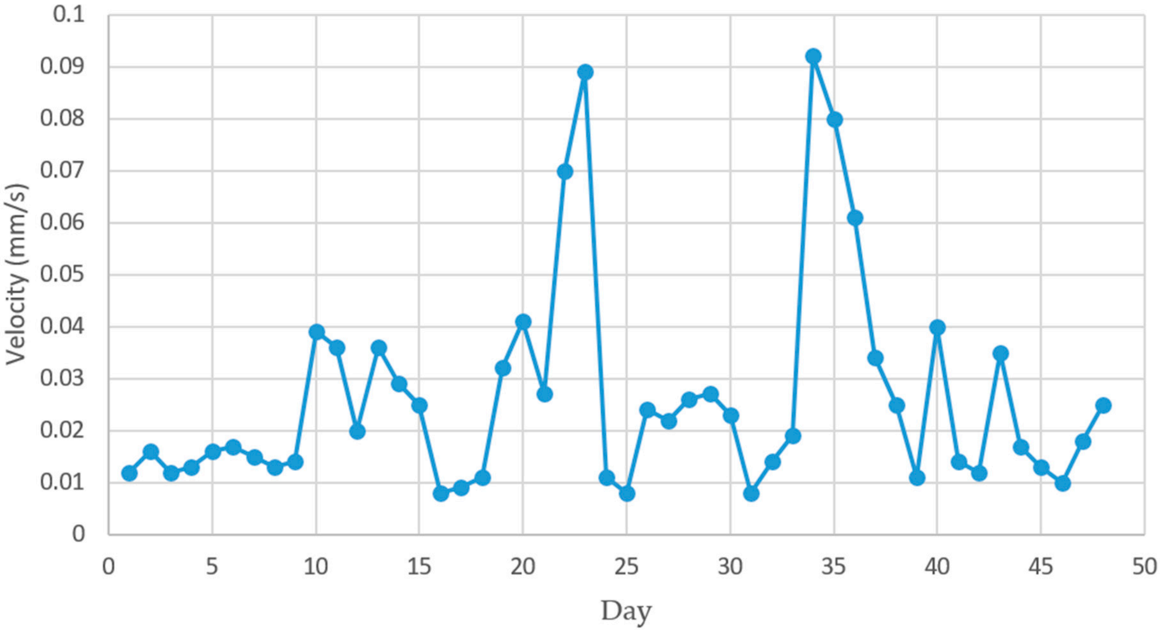

Figure 10. Maximum daily velocities recorded in the foundations of the historical site.

The maximum velocities only exceed 0.04 mm/s on five days. These days with the higher values correspond to the usage of, at least, the vibrating ripper and vibrating roller simultaneously, working the two types of equipment with the higher potential of vibration. Values are especially high when the vibrating roller is working. The excavation equipment was used on all the operating days, while the bulldozer was used on all the days with a registration of 0.03 mm/s or higher. When the vibrating roller is added, the maximum vibration is doubled.

On the other hand, days with a value around 0.01 mm/s coincide with the weekend or situations with no simultaneous activities and without the usage of the bulldozer and/or the vibrating roller. Besides, some abnormal situations have also been detected: measurement 23 corresponds to an earthquake more than 100 km away, while measurement 34 is related to a landslide close to the construction site.

A completely vibration-free excavation is unachievable [48], therefore background vibration will be always present, varying from the area of study. In this case, it reached around 0.005 mm/s. Moreover, what also have to be considered are other elements influencing the background that can increase it to around 0.01 mm/s. In this regard, the location of the historical site, close to the Cantabrian Sea, can suffer strong wind and high tidal conditions that increase the background values. Other elements, like agricultural activity around the area, were also identified, reaching occasional values around 0.066 mm/s.

A specific analysis of the equipment, either individual or combined, was also done to know the maximum potential vibration. The data collected in the historical site were correlated with the type and number of machines working, taking into account the time. Table 5 gathers different combinations of the maximum vertical vibration velocity associated with the usage of equipment at the same time, which was daily known. The abnormal values obtained due to the specific conditions detailed in the previous paragraphs have been filtered. These abnormal peaks were easily identified, being isolated maximums, while peaks related to the machine's activity are repeated many times along the day or working period.

Table 5. Vibration velocity and type and number of machines working.

V Bucket	Ripper	Vibration Ripper	Bulldozer	Vibrating Roller	Velocity
1	0	0	1	0	0.006
1	1	0	1	0	0.008
0	0	0	0	0	0.005
0	0	0	0	0	0.005
1	1	0	1	0	0.006
1	1	0	1	0	0.006
1	1	0	1	0	0.006
1	1	0	1	0	0.006
1	1	0	1	0	0.007
0	0	0	0	0	0.005
0	0	0	0	0	0.005
1	1	0	1	0	0.006
1	1	1	1	0	0.030
1	1	1	1	0	0.025
1	0	1	1	0	0.020
0	0	0	0	0	0.005
0	0	0	0	0	0.005
0	0	0	0	0	0.005
1	1	1	1	0	0.020
1	1	1	1	0	0.020
1	1	1	1	0	0.015
1	0	1	1	1	0.030
1	0	1	1	1	0.040
0	0	0	0	0	0.003
0	0	0	0	0	0.003
1	0	1	1	0	0.015

Table 5. *Cont.*

V Bucket	Ripper	Vibration Ripper	Bulldozer	Vibrating Roller	Velocity
1	0	1	1	0	0.015
1	0	1	1	0	0.015
1	0	1	1	0	0.015
0	0	0	0	0	0.008
0	0	0	0	0	0.005
0	0	0	0	0	0.005
1	0	1	1	0	0.015
1	0	1	1	1	0.050
1	0	1	1	1	0.040
1	0	1	0	0	0.020
1	0	1	0	0	0.015
0	0	0	0	0	0.005
0	0	0	0	0	0.005
1	1	0	0	0	0.005
1	1	0	0	0	0.005
1	1	0	0	0	0.005
1	1	0	0	0	0.005
1	1	0	0	0	0.005
0	0	0	0	0	0.005
0	0	0	0	0	0.005
1	1	0	0	0	0.005
1	1	0	0	0	0.005

Assuming the superimposition principle, the maximum vibration of the day can be expressed by Equation (6). This approach is considered acceptable because the vibration periods are for an order of magnitude of milliseconds, compared with the daily measurements. In short, if two machines work the same day, their vibrations coincide many times along the day.

$$v_{max}(100) = v_{Bmax} + n_{Ex}v_{Exmax} + n_R v_{Rmax} + n_{VR}v_{VRmax} + n_{BD}V_{BDmax} + n_{CR}V_{CRmax} \tag{6}$$

V_{Bmax}: background maximum velocity;
V_{Exmax}: excavator maximum velocity;
V_{Rmax}: ripper maximum velocity;
V_{VRmax}: vibrating ripper maximum velocity;
V_{BDmax}: bulldozer maximum velocity;
V_{CRmax}: vibrating roller maximum velocity;
n: number of equipment.

If Equations (3)–(5) are applied for a distance r = 100 m from the vibration source, the maximum velocities are: excavator V_{Exmax} = 0.0012 mm/s, ripper V_{Rmax} = 0.0012 mm/s, vibrating ripper V_{VRmax} = 0.015 mm/s, bulldozer V_{BDmax} = 0.0043 mm/s and vibrating roller V_{CRmax} = 0.015 mm/s. These values, multiplied by the type and number of machines working each day and the background constant velocity V_{Bmax} = 0.005 mm/s give the potential velocity estimated, as in Figure 11, validating the accuracy of the equations proposed for the purpose of the study.

Figure 12 displays the comparison between the actual values and values using Equation (6). As it can be seen, the equipment with the highest influence are the vibration ripper and vibrating roller, while the other type of machine has an impact between 10 and 15 times lower.

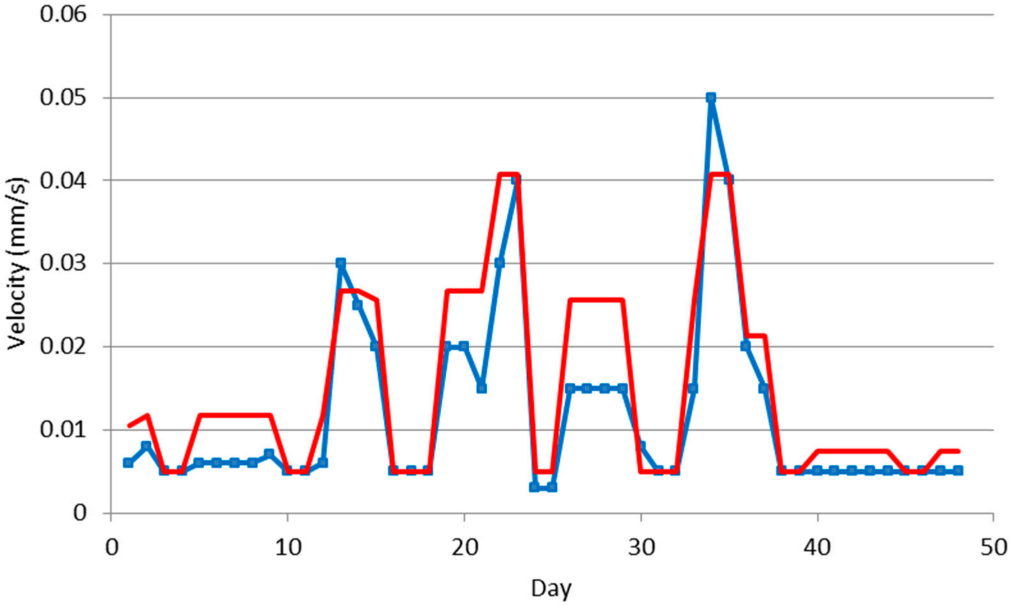

Figure 11. Maximum filtered daily velocities, in blue, and estimated values using Equations (3)–(5), in red.

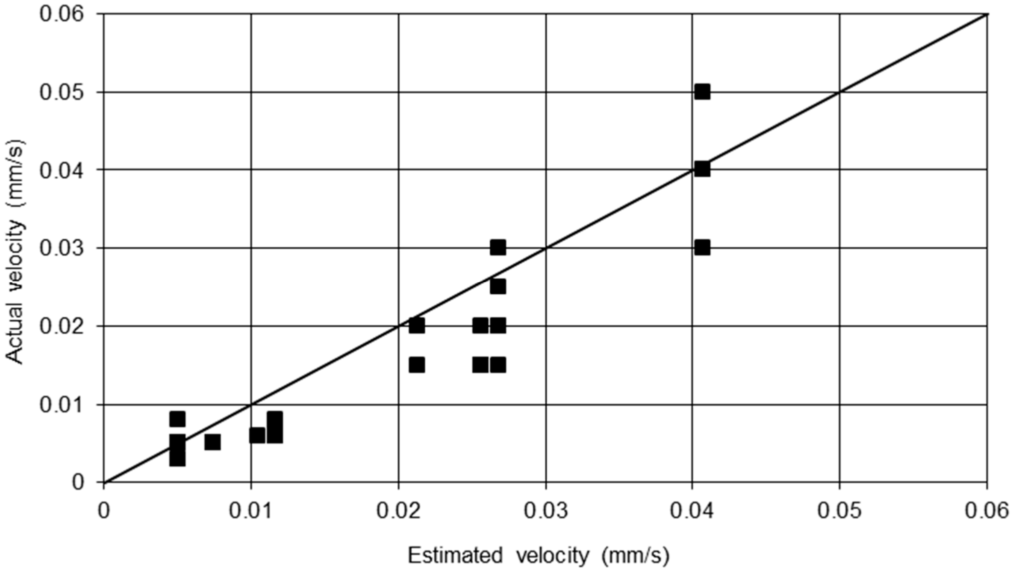

Figure 12. Correlation between actual velocities and velocities estimated by Equation (6).

It can be observed from the previous figure that the values obtained by Equation (6) slightly overestimate the velocity, allowing a certain safety factor in real situations and ensuring no affectation to the infrastructure or construction.

The empirical laws proposed in this section can be used to assess the ground vibration level and solve complex problems in a practical way. Moreover, the influential variables are easy to understand and measure in real situations. Equations (3)–(6) are also useful in many different scenarios in construction works. However, their applicability should be limited to similar conditions to those found in the case study, either rock mass or machinery.

4. Conclusions

The coefficients α and γ for a poor-quality shale rock mass and backfilled material have been determined for the different mechanical excavation equipment (excavator equipped with a V bucket, a ripper, a vibration ripper and a breaker hammer) and the backfill equipment (bulldozer and vibrating roller). The vibration propagation at different distances has been defined for any type of equipment, obtaining three expressions, Equations (3)–(5), and validating their accuracy. In addition, a two-step procedure has been defined to determine the real ground vibration attenuation law: (1) monitoring the vibration emitted by each source and (2) monitoring the whole excavation taking into account the multiple sources. The method proposed allows to define the attenuation law at short and long distances.

The vibration pattern is similar within the two groups of activities, excavation and backfill, but it has different intensities. The vibration ripper and the vibrating roller display the highest values. Besides, a general expression considering the different type of equipment and number, working simultaneously, has been proposed, as in Equation (6), including the background vibration of the area.

The results from the case study show a condition with lower velocities than the maximum established by the public administration of 0.1 mm/s. However, the conditions imposed were too restrictive compared with the international legislation and vibration caused by other methods, such as blasting, as it has been stated in this research. It would be advisable to define a threshold similar to the international standards, which range between 18 and 30 times higher than the restriction established in the case study, as well as in the same order of magnitude as the Spanish limit value for blasting operations. The outcomes also give a wider range of operational conditions for poor rock masses that can be mechanically excavated.

Author Contributions: Conceptualization: R.R.; methodology: R.R., M.B.; validation: R.R.; formal analysis: R.R., M.B.; investigation: R.R., M.B.; writing—original draft preparation: R.R.; writing—review and editing: R.R., M.B. All authors have read and agreed to the published version of the manuscript.

Funding: The present work was funded by the company Via Tramo 2 UTE in the frame of the University-Company collaboration projects FUO-EM-188-11 and FUO-EM-256-12.

Acknowledgments: The authors would like to thank to the personnel of the Department of Geology—Area of Internal Geodynamics (University of Oviedo) for their collaboration in field data acquisition.

Conflicts of Interest: The authors declare no conflict of interest.

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