

IN12-1140

## NOISE GENERATION FROM GROUND-BORNE VIBRATIONS: BEYOND NOISE NUISANCE TO STRUCTURAL DAMAGE

**Ian Camilleri Cassar**

Dhi Periti,  
Malta  
icc@dhiperiti.com

**Denis H. Camilleri**

Dhi Periti,  
Malta  
dhc@dhiperiti.com

**Vincent Buhagiar**

Environmental Design Unit,  
Faculty for the Built Environment,  
University of Malta,  
vincent.buhagiar@um.edu.mt

### ABSTRACT

In view of the limited land available for new development in Malta, 20-year old, two-storey terraced houses are today making way for apartment blocks, typically 5 floors in height, including a number of basement parking levels. This calls for additional civil works beyond simply building the plot, namely involving demolition and excavation below ground level. The new development is sandwiched between two existing terraced houses or similar blocks, thus any excavations are bound to adversely affect neighbouring property to some magnitude.

Buildings are constructed in load bearing masonry walls with reinforced concrete slabs having a simple bearing on masonry walls. A soft storey is often introduced to satisfy parking or commercial requirements. This heavy form of construction lacking flexibility is prone to cracking. Studies suggest that blasting, piling, pneumatic machinery and heavy vehicles' road traffic cause ground-borne vibrations. These typically translate into intolerable noise levels, even if claimed as only temporary. Tolerance limits vanish when nominal superficial cosmetic cracks develop into structural damage to neighbours' property. These points to the need to assess and regulate the allowable noise and vibration levels in urban areas in order to curtail noise levels, thus preventing unnecessary neighbourhood disturbance, and ultimately structural damage. Through fieldwork on five building sites and empirical studies this paper investigates noise and vibration levels generated from site excavations using standard pneumatic plant. Results already indicate that values obtained are well within established International Standards, however complaints still arise. These stem from cosmetic or serious structural damage to neighbouring property. Currently, in Malta there is no control on the permissible vibration levels or allowable noise levels for

such sites. The paper goes on to recommend the allowable limits for noise levels generated from ground-borne vibrations.

### INTRODUCTION

The level of vibration and noise produced by construction equipment on nearby buildings and its occupants is a complex phenomenon. These levels also depend on the type of equipments used and the distance between the affected areas with construction equipment due to the fact that vibration spreads through the ground and diminishes in strength with distance.

At various levels and frequencies, this vibration or noise level may cause nuisance to the neighbouring occupants, resulting in reduced ability to perform certain tasks and may also cause structural damage to the building. Although there is no relationship between nuisance caused by noise and structural damage, the level of vibration required to cause nuisance to the occupant is much lower than causing structural damage.

Studies suggest that blasting, piling, pneumatic machinery and road traffic cause a certain amount of ground borne vibration. Moreover, such noise annoyance could be a source of major concern to occupants living in nearby residence. This concern leads to a need to assess and regulate the amount of allowable vibration so as to prevent damage to nearby buildings and to avoid unnecessary disturbance to persons living in the vicinity.

As technology evolved the development of buildings changed. Such change is evident in Malta, with demolition construction development increasing at a rapid pace. Many town houses were pulled down to be replaced by six / seven

storey high apartments with basements that are three to five storeys below ground level.

Construction development has changed over time. Advancement in technology and powerful machinery eased the load in workmanship and adopted a more powerful approach. However, despite the change in development, Malta still abides by the 1868 laws.

Due to the lack of strict construction rules, Malta experiences many construction claims associated with structural damage to adjacent buildings caused by vibrations during excavation works. Admittedly, contractors tend to be more careful nowadays, as they are being kept liable for damages caused to neighbouring property.

Apart from recent fatal accidents that unfortunately helped create awareness, contractors and developers are becoming more diligent in their work also due to the fact that building construction is more dangerous, going higher and deeper due to a higher land value.

To what extent is the developer allowed to create inconvenience to neighbouring property and physical/mental strain to residents? For example, neighbouring occupants are sometimes asked to move to alternative residence due to dangerous movements on the party wall resulting from basement excavation works. Admittedly, a third party owner is compensated for damages caused, but can such inconvenience be justified?

This study gathers as much information as possible about the cause of vibrations due to mechanical equipment and blasting, gathered information about the noise levels in this type of excavation work. Vibration and noise levels were recorded in four different site locations in Malta and attempting to come up with a solution that would reduce the amount of damage caused to neighboring building.

## BACKGROUND THEORY

### Vibration Theory

Vibrations are usually recorded in the form of time and particle velocity where the theorem particle velocity was found to coincide with the increase in cracking. Vibration is studied by recording the time history of every vibration from all orthogonal directions. These time histories are then known as the peak particle velocity.

Construction vibrations force the ground to move in 3 dimensions. From these results one can choose how to report readings by either reporting the true vector sum or the peak component.

The comparison of the 3-component time history shows that:

1. Main peaks could be found in all causes
2. the peak component varies
3. the peak amplitude in the longitudinal direction does not occur at the same time of the traverse direction

The peak component is that component which has the largest velocity unit. The true vector sum is the sum of all the components together.

$$\sqrt{\mu^2_L + \mu^2_V + \mu^2_T} = \text{The true vector sum of the p.p.v. from all 3 axis} \quad (i)$$

In most cases the true vector sum will be larger than just taking the maximum of the 3 peak components. It can also be said that by taking the peak component as the main reading is sufficient enough to provide a large safety factor that is not accounted for according to BS 7385-2:1993.

### Noise (Airborne) Theory

Air-blasts and constructional noise are the common description of air pressure waves generated by explosives or construction machinery. These pressure waves can be described instead of particle velocity as air overpressure

Noise produced by construction equipment does not contain the low frequency pressure wave but it is annoying because it induces vibration sensitivity in residences which lead to the concerns over vibration-induced cracking.

Air blasts and sound can be recorded with two different units of measurement: pressure or decibels although traditionally sound has been reported in decibels because of the wide range of amplitude and frequency that are detectable by the human ear. "Sound pressure is translated into the decibel scale by:"

$$dB = 20 \log_{10} \left( \frac{P}{P_0} \right) \quad (ii)$$

where,  $P$  is the measured peak sound pressure and  $P_0$  is the reference pressure of  $20 \times 10^{-6} \text{ N/m}^2$ " (C.H. Dowding, 2000: 205).

It is true that construction blasting produces an amount of air-blasting pressure but it is very unlikely that it is capable of cracking structures or windows. This is because in construction blasting, too little explosives is used as to damage the building. Thus it is hard for the level of air blast pressure to really exceed the level of 120 dB.

Although the low frequency construction blasting overpressure is normally controlled the audible noise portion of the air blasting may still startle people. These odd air blasts result from detonations with;

1. large quantities of exposed detonating cord
2. little or improper stemming
3. open fractures radiating from blast holes
4. above ground location such as for building demolition.

### Human response to air over pressure

A survey was carried out on human response to eight blasts per day (Borsky, 1965) where 80% to 90 % affected

reported that they reacted to the sound of rattling. In comparison to 15% to 20% who were startled and 3% to 7% reported interference with listening to the radio or television. From this survey a data sheet that indicated that 5% would be more than moderately annoyed at a mean air over pressure of 124dB.

**Demolition by explosion**

Demolition with the use of explosives was first started by military engineers and since then has gained a great amount of popularity. Although explosive demolition has great advantages on the speed of construction, it also includes large risks as demolition can easily get out of control. In Malta, this kind of demolition is not often used for the reason that there usually is not enough distance from the blasting site to the first habitable place. Blasting in Malta is only used in a number of certified quarries and very rarely in a development site.

An exception is the 200 Portomaso Marina complex where controlled blasting occurred to recommended mean-particle velocities. The damage to surrounding old residences was noted as being minimal, except for escape of water to a swimming pool construction.

In the mid-1995 cracking to swimming pool construction in a villa residences residence area had occurred due to quarry blasting occurring on a cliff face located approximately 200m from this residential area. Since then this has been addressed.

**Process**

Blasting is produced by a chemical mixture that reacts rapidly upon burning. In result it releases a large amount of heat and gas. As the burning front advances up a blast hole, as shown in figure 1, the detonation shock pressure is followed by a lower but sustained explosion pressure. The explosive pressure dissipates more slowly than the shock pressure and this supplies most of the energy to move the rock.

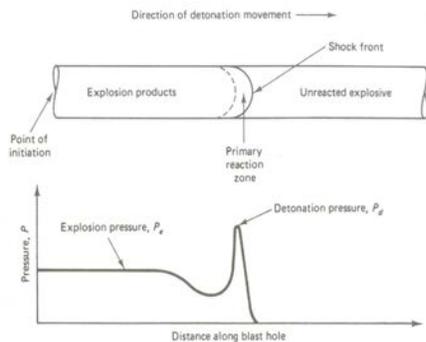


Figure 1: Advancing detonation in blast hole produces short-period detonation and long-period explosion pressure. (Dowding, 2000: 455)

The shock pressure initially fractures the rock adjacent to the blast hole wall, and the sustained explosion extends the blast fracture zone out to as many other holes that would be

produced in the sedimentary rock. The shock wave produced along the explosive column is around the velocity of 2700m/s to 8400m/s.

**CONTROL**

**Air blast control**

The contractor must design the blast rounds to minimize air-blast over pressures. If designed well this must not be a problem.

Also a record for the control of the amount of air blast pressure that is being produced should be recorded. The amount of air blast pressure in Malta must not exceed 120 dB according to Malta Environment & Planning Authority standards.

**Steps to be taken to reduce construction noise**

Construction in itself often generates a lot of noise that cannot be removed. Due to this inconvenience complaints arise due to the interference with people’s lives especially when the community has no clear understanding of the extent of works and duration of the job. This could be reduced if the contractor in charge takes an attitude of concern for nearby residences, even though he may be in compliance with the local ordinance. This situation underscores the need for early identification and assessment of the potential problems of the site.

**Construction noise produced by equipment**

The level of noise produced by the equipment varies greatly and depends on factors such as the type of equipment, the age of equipment, the specific model, and the operation being performed. The equivalent sound level ( $L_{eq}$ ) also depends on the fraction of time that the equipment is used.

Depending on the kind of equipment the dominant noise results from either the engine (bulldozer) or the operation itself (hydraulic hammer). When it comes to assess noise on a construction site, two types of operation must be identified: stationary such as the jackhammer and mobile such as trucks. Stationary equipment operates in the same position for as long as a day, whereas mobile equipment move anywhere around the site. “Standardized procedures for measuring the exterior noise levels for the certification of mobile and stationary construction equipment have been developed by the Society of Automotive Engineers. Typical noise levels from representative pieces of equipment are listed in Table 5.1” (Miller, 2006)

**Construction of noise assessment**

The level of detail of a construction noise assessment depends on the size of the project. In a major project, the construction duration is known to take longer than a small project. Also larger and noisier machinery is usually used in major projects. On the other hand, in minor construction projects, noise assessments are not needed. Nevertheless, it is important, that at an early stage and prior to the commencement of the project, to inform the public of the type of equipment to be used, the level of noise expected, and duration of the project. Mitigations towards construction noise.

After studying the noise levels expected on site during construction works, the level of annoyance may be further reduced by:

- Constructing noise barriers around the area of the site, such as temporary walls, to reduce the noise receiver levels
- Re-route truck traffic from residential streets to areas with less residential homes.
- Keep equipment as far away from the noise sensitive site as possible
- Use of shields can be placed around high level noise equipment when in use
- Combine noise operations to occur at the same time, as these will more or less have the same noise level as when working separately.
- Use special quiet equipment.

**Rating noise levels of human annoyance**

The method used to rate noise levels is divided into two steps. Firstly, a measurement of the noise level from the force must be found, e.g. excavation machinery, then the normal background noise level must be established. These readings help establish whether the noise referred to by the example excavation machinery is likely to give rise to complaints from people residing in the building.

**Methods used to determine specific noise level**

When measuring for specific noise levels, it is important to choose the location as a discrete entity, which is distinct and free of influence from other noises contributing to the ambient noise.

As a rule, ambient noise levels are made up of residual noise and specific noise when present. To be able to distinguish between both levels of noise, readings must be taken at two time intervals. One reading is taken when both noise levels are present, and another when only the residual noise is present, for example at night. When the residual noise is impossible to measure, such as factory machinery that is used twenty-four hours a day, it is possible to measure the residual level in an ambient similar to that to be tested.

Difference between noise level readings with specific noise present and absent dB	Correction to be subtracted from noise level reading with specific noise present dB
> 9	0
6 to 9	1
4 to 5	2
3	3
< 3	estimate of the residual noise level

Table 1; Correction to noise level readings (BS 4142: 1997: 3) Compensation for the effect of the residual noise is noted in Table 1.

**Assessment method of noise level**

To assess whether the noise level is of significance or not, the difference between the two measured background noise levels must be found. The greater the difference between levels, the higher the risk of complaints.

- A difference of around +10dB or more indicates that the complaints are likely
- A difference of around + 5 dB is a marginal significance
- If the rating level is more than 10 db below the measured background then complaints are unlikely.

Example of obtaining noise level rating (BS 4142: 1997)  
 A factory that has recently become operational and works only during the day produces a continuous steady hum that can be heard at the measurement position.

*Results:*

Measured noise level;  $L_{Aeq(7min)} = 51$  dB  
 Residual noise level;  $L_{Aeq(7min)} = 36$  dB  
 Background level;  $L_{Aeq(7min)} = 35$  dB  
 Time period of 1hr  
 Correction from Table 5: 0 dB  
 Specific noise level;  $L_{Aeq(60min)} = (51 - 0) = 51$  dB  
 Acoustic feature corrected; +5 dB  
 Rating level  $(51 + 5) = 56$  dB  
 Background level;  $L_{Aeq(15min)} = 35$  dB  
 Excess of rating over background level;  $(56 - 35)$  dB = 21 dB  
 Assessment indicates that complaints are likely

**HUMAN RESPONSE TO CONSTRUCTION**

Studies suggest that humans are more sensitive to vibrations and noise than the structure itself. Example, cosmetic cracking is unlikely to occur if the peak particle velocity does not exceed 25mm/s but humans are affected by this level of vibration that may affect both their quality of life as well as their working efficiency. The level of annoyance is also related to the time interval of vibrations. If the vibration is felt for just 10 minutes, it is unlikely that people raise complaints, but if vibrations go on for a whole day, then complaints are much more likely due to inconvenience and reduction in quality of life.

It is also important to note the type of complaints. People usually complain against vibration movement, but in reality, such vibrations are not caused by ground movement but to the air blast pressure caused by the air-over pressure.

A typical first-time construction vibration complaint might sound similar:

*“I was sitting on my kitchen stool when I heard this loud noise and felt the entire house shake. Even the pictures on the wall rattled, so I knew something was going to happen to the house. I looked up and saw this crack in my ceiling that had never been there before.”*

(C.H. Dowding, 2000: 366).

If one were to consider the crack mentioned above it is likely that the crack has been there for months before and the owner never noticed. An interpretation of the quote is that the person on the kitchen stool was alerted to look for cracks after the ground movement was felt, and then decided to complain.

The relationship between ground motion and air overpressure differ in time difference. Persons notice and react to blast-produced vibrations at levels that are lower than the damage threshold. Persons inside buildings will hear and feel the 5 – 25 Hz structure mid-wall and mid-floor vibrations. Ground vibrations are normally blamed for the house vibration when long range air blasts found under perfect weathering conditions will be one cause responsible.

Vibrations enter the human body along either axis. The level of tolerance of vibration is made up due to comments of the occupants of the building. These comments usually arise when the threshold of perception is slightly higher than normal. So in general satisfactory magnitudes are related to the complaints of residents rather than due to health hazards or lack of working efficiency.

That is why to reduce complaints and annoyance it is important to respect the surrounding residents. As an example, there exist cases where the level of threshold of vibration was higher than normal as, for instance, in excavation works, and the startled factor was reduced by using warning signals, announcements, regularity of occurrence, and an effective program of public relations.

*Comment probability:*

Comment probability can be estimated by finding the vibration dose value (eVDV)

$$eVDV = 1.4 \times a \times (r.m.s.) \times t^{0.25} \quad (iv)$$

where, a(r.m.s.) is acceleration frequency, t is the number of occurrences multiplied by the time duration.

Place	Low probability of adverse Comment	Adverse comment possible	Adverse comment probable
Residential Day Time	0.2 to 0.4	0.4 to 0.8	0.8 to 1.6
Residential Building night	0.13	0.26	0.51

Table 2: Vibration dose values ( $m/s^{1.75}$ ) above which various degree of adverse comment may be expected in residential buildings (BS 6472:1992:13)

**Example:**

Take the vibration occurrence to be 10 times, with an interval of 25s each, having a frequency of r.m.s. acceleration of  $0.1m/s^2$  r.m.s., during a 16hr day.

$$\begin{aligned}
 eVDV &= 1.4 \times a \times (r.m.s.) \times t^{0.25} \\
 &= 1.4 \times 0.1 \times (10 \times 25)^{0.25} \\
 &= 0.557m/s^{1.75}
 \end{aligned}$$

If compared to Table 4 above, it can be concluded that there will be a possibility of complaints.

**CONSTRUCTION EQUIPMENT**

Construction equipment such as rock excavating trenchers, hydraulic hammers, vibratory rollers and so on, also tend to cause some source of vibration which is usually taken for granted. Such equipment can cause four energy transformations which are impacting, vibrating, rotating and rolling. These sources of energy could be transformed to cause ground vibrations.

**Mechanical equipment used in Maltese construction**

In Maltese construction, apart from the traditional mechanical equipment such as trucks, bulldozers, hydraulic hammers and shovels, recent years have seen the use of rippers, trenchers and hydraulic milling cutters. Their introduction to Maltese construction was important as these mechanical constructional equipments all used for excavation are known to have a lower vibration level when compared to the hydraulic hammers.

In Maltese construction, it has become common practice that when excavating in line with a neighboring party property, the contractor does not excavate to the edge of the adjacent property with the use of a hydraulic hammer but arrives to 0.75m from the party wall which is the present rock excavation being the legal outstanding limitation which has to be observed in force. This measurement is created by producing a trencher cut into the existing rock. The rest of the 0.75m excavation work is completed with the use of hydraulic milling cutters which create low vibrations properties. This does not only help to reduce but also creates a rock separation will reduce the travel of the produced vibration velocity.

Also with regards to the noise levels, the equipment has reached a certain level of noise reduction due to the improvement of technology and the new European Union legal specification on “environmentally damaging noise emissions from equipment and machinery intended for outdoors.” (Bautechnik, 2002).The formula underlying this new 200/14 EC noise directive is as follows:

$$L_{wA,g} = L_p - k_1 - k_2 + 10 \times \log(s/s_0) + K$$

- Where:  $L_{wA,g}$ : is the guaranteed noise level
- $L_p$ : Measured sound pressure
- $k_1$ : Correction for excavator noise
- $k_2$ : Correction for noise reflection in the area
- log: Recalculation of measured distance
- K: Safety margin

It was also stated that all equipment designed in the EU cannot have a  $L_{wA}$  greater than 108dB at a distance of 40cm away from the hammer. Thus, for the production of hydraulic hammers inside the EU this law is valid. However, this does not mean that all the equipment used by contractors in European

countries must abide by this law. In Malta the use of older machinery, creates a noise level greater than the one mentioned above can still be used. On the other hand, Maltese contractors are aware of the noise annoyance and the European laws so the new equipment which is being purchased all abides by this EU law.

The new hydraulic hammers are being designed with noise silencers that reduce the noise to ¼ of that produced by the open hydraulic hammer (older type hydraulic hammers).

‘As to compare hydraulic hammers the distance is as follows:

- Pre-1985            70m
- Silent                31m
- Extra silent        10m

Type	1	2	3	4	5
Weight max, kg	1330	1710	2350	3800	4120
Impact energy, J	2600	4000	5700	900	
Impact rate, Hz	7.5 - 13.5	5.5-9.5	5-10.5	6-9	4.5-9
Carrier minimum pressure, bar	200	190	210	205	180
85 dB(A) level, distance from hammer, m	N/A	14-38	17-25	18-42	
Carrier weight limits, tonnes	18-26	21-32	27-40	40-70	42-75
Tool Diameter	120	140	150	165	180
Length of tool	580	625	605	750	780

Table 3: Some of the Hydraulic hammers used in Maltese construction (Bautechnik, 2000 & Rammer 2004)

## GUIDE FOR MEASUREMENT OF VIBRATION IN BUILDINGS

The British standard guide BS 7385-1 shows the basic principles for carrying out vibration measurement and processing data with the right system to reduce inaccuracy as far as possible.

The evaluation of the effects of building vibration is firstly directed at the structural response of the building, including sufficient methods where frequency, duration and amplitude can be identified.

### Definitions

*Peak particle velocity (ppv):* is the maximum instantaneous velocity of a particle at a point during a given time interval

*Peak component particle velocity:* the maximum value of any one of the three orthogonal component particle velocities measured during a given time

## Quantities of vibration excitation to be measured.

The peak particle velocity was measured, being found to be the best single descriptor for correlating vibration.

The preferred method of measuring the particle peak velocity is to record simultaneously three orthogonal components of particle peak velocities. The peak component is that component which has the largest velocity unit. The true vector sum is the sum of all the components together.

B.S. 7385-2:1993 states that “the maximum of the three orthogonal components should be used for the assessment”. As for the Malta Environment and Planning Authority it is important that the peak particle velocity is stated as a vector value.

## Ideal position of the transducer

To establish a proper characterization for the vibration of a building, the size and complexity of the building must be noted. Measurements should be taken, if possible, at the base of the building facing the source of the vibration. If this is not possible, the measurements should be taken on the ground outside the building.

Where the purpose of monitoring is to establish the vibration level of traffic, pile-driving or blasting it is ideal to carry out simultaneous measurements from the inside of a distant building, as this will achieve the highest level of amplitude.

## Instrument used

The instruments used to make this study possible was a Bruel & Kjaer being the Modular Precision Sound Level Meter, Type 2231 product which was used to measure the vibration and sound levels of the case studies listed in the following chapter.



Figure 2: the Modular Precision Sound Meter, Type 2231 attached to the tri-axial accelerometer,

## Case Studies

In this study four different site were visited in different locations of Malta. Readings of vibration and noise levels were taken from different distances and height levels around the sites between the tri-axial accelerometer and the construction equipment. The ground material found in all three sites was found to be in globigerina limestone (k/a tal-franka) being a soft easy worked limestone with a crusing strength of

20N/mm<sup>2</sup>. This is used extensively as a load bearing material and easily worked into mouldings and balasters although being highly porous, whilst the quarry in Rabat was in lower coralline (k/a *tal-qawwi*) having a crushing strength of 75N/mm<sup>2</sup>, used extensively for concrete aggregate.

The tri-axial accelerometer was placed flat on the ground giving 3 reading for x, y, z directions. Readings were measured on each axis and the square root of all the max. P of the 3 axis was found in that time period and taken as the maximum peak particle velocity.

From each position on site, ten readings were taken and each reading had a duration time of 1 minute.

These sites were visited on different occasions so as to get readings from different levels of excavation. Most of the time, readings were taken from the same position so as to compare readings between one visit and another. The difference in readings was often due to the different positions of the construction equipment, the difference in depth of excavation level and also because visits were interspersed by approximately two weeks.

**Site 1: Marsascala – South of Malta**

The size of the site is around 4500msq and different positions were chosen around the site to take vibration and noise readings. This site was visited on four different occasions.



Figure 3: Hydraulic hammers in operation at Marsascala site

**Findings**

If site visit 1 were to be compared with site visit 2, it could be concluded that the difference in height and distance from the hydraulic hammer does affect the level of the peak particle velocity. This could be noted by studying the results of position 1 and position 2 in site visit 1 and 2. In site visit 1, the average reading was 1.6mm/s and the average reading in site visit 2 had an average reading of 1.13mm/s. This difference in vibration levels could be caused by the difference in height and distance from the hydraulic hammer. As in site visit 1 the height from the hydraulic hammer to the tri-axial accelerometer

was 5m whilst in site visit 2 the height was of 10m. There was also a difference in distance between the hydraulic hammer and the tri-axial accelerometer of 15m.

These same findings could also be noted on other occasions.

Position	max P(mm/s)	Avg. max p(mm/s)	Description
1	2.16	1.6	25m away and 5 m above hydraulic hammer.
2	1.3	0.97	37m away and 15m above hydraulic hammer.
3	4.29	3.33	12m away and level with hydraulic hammer
4	4.75	4	2m away and level with hydraulic hammer.
1	1.39	1.13	40m away and 10 m above hydraulic hammer.
2	1.46	1	70m away and 20m above hydraulic hammer.
5	1.25	1.07	work was not in process
1	1.6	1.34	30m away and 10 m above hydraulic hammer.
5	2.27	1.66	work not in progress
1	1.89	1.165	10m away and 20 m above hydraulic hammer.
6	1.42	1.08	10m away and 2m below the hydraulic hammer.
7	1.74	1.68	6m away and level with the hydraulic hammer

Table 4: Balluta, St Julian’s, Site visit 3, Max. and average value of PPV readings (mm/s)

It was also found in this dissertation that the difference between readings of position 1 and position 2 in site visit 1 was approximately 1mm/s and the difference between readings of position 1 and 2 in site visit 2 was only of 0.2mm/s. Why are the differences not the same? The reason is that at a certain level, the peak particle velocity cannot decrease further as this would be the natural peak particle velocity of the ground. This peak particle velocity varies according to the site. For example, if there is heavy traffic in the area, the peak particle velocity would be higher than that in a quiet country lane. So it could be concluded that the results recorded from position 2 on site visit 2 are probably the readings of the natural vibration for that particular area of the site.

From site visit 4 it can be concluded that the largest factor that affects the peak particle velocity when comparing one site visit to the other is the difference in height from the hydraulic hammer to the tri-axial accelerometer rather than the distance between them. This can be clearly observed when comparing position 1 with all site visits. In site visit 4, although the distance from the hydraulic hammer to the tri-axial accelerometer was the least when compared to those recorded in other site visits, it still had a very low particle peak velocity and was nearly equal with the result of the particle peak

velocity of site visit 3 having a distance of 40 m from the hydraulic hammer and the tri-axial accelerometer. The reason for these 2 results that were nearly equal to each other was that in site visit 2 the distance between the hydraulic hammer and the tri-axial accelerometer was of 40 m while when compared to site visit 4 the distance was only 10m but the depth between the tri-axial accelerator and the hydraulic hammer in site visit 2 was of 10m and in site visit 4 the depth was of 20m.

These findings suggest that the depth between the 2 sources is more effective to reduce the peak particle velocity than the distance between them.

**Comparing site visit sound results**

When comparing sound results obtained in site visit 3 with site visit 5, the results obtained for the common distances are more or less the same. In site visit 3 the sound level with no machinery in operation was taken so as to achieve the background noise level of that area. The readings were taken close to the residential area having an average reading of 58.3 dB. This distance from the residential area to the site was approximately 25m. The readings recorded in site visit 5 show that the noise level recorded for a distance of 25m when the machinery is in operation was of 67.5 dB. These results could well establish whether the noise would cause annoyance by using the analysis found in BS.4142: 1997.

Calculation

Measured noise level;  $L_{Aeq(1min)} = 67.8$  dB  
 Background level;  $L_{Aeq(7min)} = 58.2$  dB  
 Specific noise level;  $L_{Aeq(1min)} = (67.8 - 0) = 67.8$  dB  
 Acoustic feature corrected; +5 dB  
 Rating level  $(67.8 + 5) = 72.8$  dB  
 Background level;  $L_{Aeq(15min)} = 58.2$  dB  
 Excess of rating over background level;  $(72.8 - 58.2)$  dB = 14.6 dB

Assessment indicates that complaints were likely to occur as the difference between the noise level produced while construction and the background noise was larger than 10 dB.

**Site 2 – Balluta, St Julian’s**

The site is approximately 300sqm and surrounded on 3 sides with party walls. The vibrations and noise level readings were always taken from the exposed side of the site. The site was visited on two occasions: one time when work was in progress and another time when there was no work. On both occasions the vibration readings were taken so as to compare between the vibrations when excavation works are underway to the vibrations of normal traffic levels.

On one occasion, the sound level was also recorded. The reading results turned out to be adequate and not of much annoyance to nearby residents. As this is a sensitive site in terms of its surroundings, in this case with a hotel in the background, the necessary precautions were taken well ahead of commencement of project works. The type of equipment

used on this site provides enough evidence of caution. It was of type 1 seen in Table 3 which is one of the smaller sizes.

**Findings**

The three sets of readings show that vibrations caused by the hydraulic hammer were not felt. This was noted when comparing the reading taken in the second visit when the hydraulic hammer was not in use There was no increase in peak particle velocity. The 0.87mm/s average obtained from all sets of readings indicate the vibration level produced by the heavy traffic from the Sliema front.

The hydraulic hammer chosen for the excavation works on this site produced a very low peak particle velocity that was probably even lower than the natural ground vibration: there was no difference between the results taken when construction was in operation and when the machinery was still, as shown in Table 5 below.

Site Visit 2			
Position	max P(mm/s)	Avg. max p(mm/s)	Description
1	0.92	0.87	work not in progress
Site Visit 3			
2	0.95	0.85	Tri - axial accelerometer placed on soft ground
2	0.97	0.87	Tri - axial accelerometer placed on solid concrete ground

Table 5: Balluta, St Julian’s, Site visit3, Max. and average value of PPV readings (mm/s)

The equipment used for this construction site did not only suit the surroundings in terms of vibrations but also suited the noise levels so as to disturb the neighbourhood as little as possible. The noise level in the area did not increase. In fact, the hydraulic hammer during operation could hardly be heard. This was also due to the fact that the site is located in a busy area and the background noise level was already high. During construction works the average noise level was of 60dB(A).

**7.3 - Haz-Zebbug**

This site is located on a main road.. This plot is surrounded on its 3 sides with party walls. The size of the plot is around 200sqm.

The system used for excavation works was different from that in the other case studies. Here the contractor-in-charge took extra precautions on the excavation works so as to avoid damage to any party wall or building. In this case, the excavation work was undertaken by first slicing 0.75m away from the party wall as stipulated in the law. This operation was done with a trencher. The rest of the rock that comes in the

middle was excavated normally with a hydraulic hammer. In this case, a hydraulic hammer type 2 in Table 3 was used for the excavation of this site. The cut rock done with the trencher also acts as a marker. Thus, the excavation work done by the hydraulic hammer continues only until it reaches the line of the sliced rock. The rock is also sliced so as to avoid continuity of the rock under the private dwelling. The rest of the rock i.e. the 75cm of rock to the party wall is then excavated by the use of a hydraulic milling cutter. This is used to prevent the party walls and dwelling being effected in any way by the vibration of the hydraulic hammer.

The accelerometer was first placed on the same side of the excavation work, just 2 m away, and a set of readings was taken. The other reading position was across the road 10m away from the construction site and another set of vibration readings was taken. This was done so as to study the difference between particle peak velocities with the increase in distance from the vibration source.

- Position 1; 2 m away and 2 m above the hydraulic hammer
- Position 2: 10m away and 2 m above the hydraulic hammer

**Findings**

From the 2 sets of vibration readings recorded, the difference between the 2 positions was the distance between the tri-axial accelerometer and the hydraulic hammer. Between position 1 and position 2 there was a difference of 2.3 mm/s which is clear that this difference is due to the difference in distance between the position 1 and 2 because the depth between the tri-axial accelerometer and the hydraulic hammer was kept equal. In fact, the position 2 was only across the road from position 1.

Quarry, Rabat - Gebla tal-qawwi			
Position	max P(mm/s)	Avg. max p(mm/s)	Description
1	4.77	3.415	5m away and 2m above hydraulic hammer
2	6.86	6.05	3m away and same level as hydraulic hammer
3	1.7	1.48	25m away and same level as hydraulic hammer

Table 6: Haz - Zebbug, Max. and average value of PPV readings (mm/s)

**7.4 Site 4 – Ta’ Zuta hard stone quarry in Rabat**

A hard stone quarry was chosen as one of the case studies to compare the difference in the results of peak particle velocity between the vibrations induced through soft stone i.e. the other three case studies, and the peak particle velocity with the vibrations induced through hard stone.

In this case, readings were taken at various different distances and levels with the hydraulic hammer. The hydraulic hammer used was of the type 5 mentioned in Table 3 which is the most powerful hydraulic hammer types used in Malta. The reason that this type of machinery was used on this site is because there are no habitable areas in the vicinity and therefore no risk of damage.

Readings were taken from 3 different positions:

- Position 1: 5m away and 2m above hydraulic hammer
- Position 2: 3m away and same level as hydraulic hammer
- Position 3 : 25m away and same level as hydraulic hammer

**Findings**

From these readings it was noted that again the distance and height level between the hydraulic hammer and the tri-axial accelerometer make the most difference.

It was also noted that there was a difference of approximately 2mm/s between these readings obtained from the quarry and the reading obtained in Marsascala on the first visit position 4 both having the same distance between the tri-axial accelerometer and the hydraulic hammer. This was due to the fact that in this quarry the stone is coralline limestone “tal-qawwi” while the rock found at Marsascala was of globigerina limestone “tal-franka”. Also the difference was in the hydraulic hammer used. In Marsascala a hydraulic hammer was of type 2 and in the quarry hydraulic hammer type 5 from Table 3 was used.

Haz-Zebbug			
Position	max P(mm/s)	Avg. max p(mm/s)	Description
1	4.35	3.31	2 m away and 2 m above the hydraulic hammer
2	1.23	1.02	10m away and 2 m above the hydraulic hammer

Table 7: Ta’ Zuta quarry at outskirts of Rabat, Max. and average values of PPV readings (mm/s)

**CONCLUSIONS**

From the recorded readings of vibration and noise levels as taken from the 4 sites used in this study, result conclusions could be established for good practice related to site excavation regarding the vibration limit, values, and also noise annoyance limit values

**Conclusion regarding vibration levels**

As from the information recorded for the maximum peak particle velocity allowed in construction vibration in different countries, the vibrations levels established from the site visits where well below the (BS 7385-2:1993) value of 12.5mm/s. So why do accidents and damage still happen in surrounding buildings?

The reason for this is that the value stated to be 12.5mm/s adequate for sites where the surrounding buildings have good foundations on solid rock. The reason that adjacent buildings in Malta could have some damage, which in some cases may be severe, is because the building was not built well enough at the outset of construction. Alternatively, the rock that lies beneath the building might be highly fissured.

An example of a building which was not built well originally would be a house constructed directly on soil, a very common occurrence in old parts of villages in Malta i.e. the ground slab is placed on the soil surface. In such instances, as soon as excavation works in the vicinity commence, the ground slab suffers movement.

More recent constructions could be even more unstable as a soft storey may have been introduced at the lower levels, opening up spans with rigid overlying floor plans to cater for the provision of the car-parking or commercial use at ground level.

A worst case scenario would be, if the excavation work is happening adjacent to the building and excavation is downwards, the ground slab which is supporting the walls might have some slippage causing the walls to move or even buckle outwards.

The example mentioned above is a common source of damage in Malta today. The reason being that most new developments have basements that go beyond one storey added to the project. On the other hand, the building standing exactly next door to the new development site was never meant to withstand such a drop exactly on the other side of the party wall. Thus, as the excavation works go deeper than the foundation level of the old building, movements occur and building movement crack patterns start to appear.

Another reason why buildings movement occurs is again the fault of the new construction style. Most of the new developments currently built have one or two and sometimes up to 5 storey basement included in the project. The adjacent building to the excavation site might end up moving slightly due to the fact that Maltese rock consists of a lot of fissures. So when excavation goes beyond the existing foundations, and bad fissures are encountered, these fissures might end up sliding or falling off, leaving the existing building with a gap underneath. This might result in movement to the building or even worse collapse of the slab as this is not designed to take a cantilever moment.

These risks due to fissures could be reduced by taking core tests on site before excavation commences, in order to get an idea of the texture of the existing rock underneath. This practice is gaining popularity with big developments in Malta, however, core tests are still considered an unnecessary expense to the owner of small scale developments. Even not

undertaking larger scale excavation works during the rainy season will help mitigate damage as water integrating with fissures may increase the incidence of sliding due to lubricating effects.

The examples mentioned above suggest that the 12.5 mm/s cannot be adopted for construction works in Malta. Damage to buildings is not only caused by vibrations produced by the construction machinery but a combination of vibrations, a weak fissured rock and poor adjacent construction.

Noting the above on existing weak building constructions, should not it be considered that lower PPV values are adopted. Over these past two to three years, contractors have become more cautious during excavation as accidents are becoming more frequent due to projects that involve deep basements.

Today, in many of the construction sites where excavation work is being done adjacent to party walls, contractors are to observe the legal rule of 75cm away from the party wall when it comes to using the hydraulic hammer, and the rest of the 75cm is then removed by using the hydraulic milling cutter. This reduces the amount of vibration that reacts on the wall, and under the adjacent dwelling. This system helps reduce the damage to adjacent dwellings but is only effective up to a certain depth. This system is effective when excavating up to 2 - 2.5m for a sub-basement but does not make any difference when used in excavation works which go nearly 2 storeys down in line with an adjacent building. In such case, if the rock is weak and fissured in that area or the building was built on weak foundations, rock slippage and movement of the building are possible.

The findings also suggest that the difference in vibration levels between coralline limestone "hard stone" which was the rock found at ta' Zuta quarry and globigerina limestone "soft stone" found at Marsascala site had a difference in PPV of 2 mm/s.

### **Conclusion regarding Sound results**

From the results gathered for this study it can be concluded that the noise nuisance level varies depending on the type and location of the site. Excavation equipment suitable for that particular site may be determined by the location type of the site.

For example in site which is usually considered as a busy and noisy area, one may afford to use large equipment producing reasonably high levels of sound. However, in quiet areas such as residential area, one must be more careful on the type of equipment chosen so as to respect the surrounding community. As stated in the BS 4142:1997 reduction in complaints and annoyance to the surrounding community is achieved if the sound level produced does not exceed 10dB above the level of the back ground noise in that particular location when construction equipment is not in use.

### Conclusion regarding blasting results

Findings suggest that blasting seems to be under control. with stated PPV limit of 8mm/s and the study results show that there never seemed to be explosions that went higher than 8mm/s. The highest reading was 6.86 mm/s.

As for the air-over pressure, the limit stated for blasting in Malta must not exceed 120 dB(A) where in some cases this limit was exceeded. Although this limit was exceeded, there seems to be no problem in Malta as this is hardly ever the case. Although these results seem to be satisfactory, there still are many complaints reported to MEPA and on print media. These complaints are due to human reaction to sudden movement and large noise. Vibration is felt much more when inside a dwelling as a result of the air-over pressure created. That is why it is very important for contractors to inform the surrounding community about the time, date and duration of blasting as this would reduce shock to persons inside the dwelling.

### OPPORTUNITIES FOR FUTURE RESEARCH

In terms of future research, several areas seem to be most promising. The control of noise levels caused by excavation works in different areas is an issue that can be easily controlled and can start being implemented in the construction of Malta as this is not a very complicated issue. The outstanding area appears to be insufficient legislative control locally.

As for vibration control more detail must be undertaken in the study of rock types in Malta as the problem of damage seems to occur due to the weak rock formation encountered in Malta, which is excited due to the forcing vibration of the mechanical equipment used on site for excavation works. In parallel with amendments to Maltese legislation should be undertaken.

The fundamental natural frequency vibration characteristics of typical Maltese constructions referred to casually in text requires further in-depth study, as these require consideration with the forcing vibration of the excavating equipment, for the multiplying effect of resonance to be mitigated.

Blasting measures appear to be working satisfactorily with a PPV value adopted of 8mm/s. However, in the case where water retaining structures or historical sites are in the immediate vicinity, further studies ought to be undertaken to evaluate the lower PPV value necessary for these site conditions.

### REFERENCES

1. Bautechnik Report (2000), Krupp Berco Bautechnik GmbH, Essen, Germany.
2. Bier, David A. & Hansen. Colin H. (1996) *Engineering Noise Control: Theory and Practice*, 2<sup>nd</sup> Edition – Spon Press.
3. BICC (2001) *Excavation and Party Walls*, Malta.
4. British Standard, *Evaluation of Human Exposure to Vibrations in Buildings ( 1Hz to 80 Hz)*, British Standard BS 6472 – 1992, London, England.
5. British Standard, *Evaluation of Human Exposure to Vibrations in Buildings – Part 1 : Guide for Measurement of vibration and Evaluation of their Effects on Buildings*, British Standard BS 7385/1 – 1990, London, England.
6. British Standard, *Evaluation of Human Exposure to Vibrations in Buildings – Part 2 : Guide to Damage Level from Groundborne Vibration*, British Standard BS 7385/2 – 1993, London, England.
7. British Standard, *Method for Rating Industrial Noise Affecting Mixed Residential and Industrial Areas*, British Standard BS 7385/2 – 1993, London, England.
8. Bruel and Kjaer (1987) *User's Manual: Systems engineered products*, Denmark: Naerum Offset.
9. Dowding,C.H. (2000) *Construction vibration*, McCormick School of Engineering and Applied Science, Northwestern University, United States of America.
10. European Standard (1994) *Euro code 8: Design Provision for Earthquake Resistance of Structures Part 1-1: General rules – Seismic actions and general Requirements for structures*, European Committee for Standardization (CEN)
11. Freeman. T.J., Littlejohn, G.S., Driscoll, R.M. - Institution of Civil Engineers (1999), *Has your House got Cracks*, Cromwell Press
12. Faky, Frank & Walker, John.(eds.) (2004) *Advanced Applications in Acoustic, Noise and Vibrations*, Spon Press.
13. Gaar, Micheal and Fulber, Anja, Bautechnik Report (2002), Krupp Berco Bautechnik GmbH, Essen, Germany.
14. *Handbook of Noise and Vibration Control*, 4<sup>th</sup> Edition – Trade and Technical Press (1979)

15. Harrison. David A. (1997) *Noise Control Manuel for Residential Buildings*, McGraw Hill. Companies.
16. Harris Miller & Hanson, Vanessa Hangen Brustlin (2006), 'Noise and Vibration During Construction'; In Transit Noise and Vibration Impact Assessment.
17. Irwin. J.D. & Graf. E.R. (1979) *Industrial Noise and Vibration Control*, Prentice Hall
18. The institution of Structural Engineers (1995) 'The Structural Engineer's Response to Explosion Damage', SETO Ltd, London.
19. The Institution of Structural Engineers (1989) 'Soil-Structure Interaction: The Real Behavior of Structures', London.
20. Lipsconb, David M. & Taylor. Arthur C. (eds.)(1978), *Noise Control; Handbook of Principles and practices*, Van Nostrand Reinhold.
21. Moore, J.E. (1966) *Design for Noise reduction*, Architecural Press.
22. Norton, M.P. (1989) *Fundamentals of Noise and Vibration Analysis for Engineering*, Cambridge University Press.
23. Roshams. Steve (2001), *Excavation*, Cambridge University Press.
24. Smith, J.W. (1988) *Vibration of Structures – Applications in civil engineering design*, J.W. Arrowsmith Ltd., Briston.
25. Steidel, Robert F. (1971) *An introduction to Machanical Vibrations*, John Wiley and Sons, Inc.
26. Vander Zid, Aldert (1976) *Noise in Measurement*, Wiley Press Ltd.
27. Yang. S.J. & Ellison A.J. (1985) *Machinery Noise Measurement*, Clarendon Press, Oxford.
28. Yerges, Lyle F. (1978) *Sound, Noise and Vibration Control*, 2<sup>nd</sup> Edition – Nostrand Reinhold