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# Measurements of Baseline Underwater Noise and Vibration in Sruwaddacon Bay, Co. Mayo, Eire

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# 1 Introduction

Subacoustech Environmental Ltd were tasked to undertake a series of baseline underwater noise measurements in Sruwaddacon Bay, Co. Mayo, Eire on behalf of RSK Environment Ltd. The measurements were undertaken in support of the latest phase of the development of the Corrib gas pipeline that comes ashore at Broadhaven Bay. It is understood that the pipeline will then be routed further inland by means of a tunnel to be dug using Horizontal Directional Drilling (HDD) techniques underneath Sruwaddacon Bay. The purpose of the measurements is to provide good quality, reliable measurements of baseline underwater noise and vibration to determine the pre-existing acoustic environment in the bay prior to the drilling taking place.

High levels of underwater noise and vibration from anthropogenic sources is known to cause a behavioural avoidance response in fish and marine mammals species and at very high levels can cause physical injury and fatality in some cases. The raw recorded data have been analysed to provide values in terms of unweighted metrics such as Route Mean Square (RMS) Sound Pressure Levels (SPL) in the case of underwater noise and particle velocity in the case of vibration, and also in terms of the hearing abilities of marine mammals using the $dB_{ht}$ metric.

Measurements of underwater noise were undertaken between the 7th – 15th August 2010. Geotechnical ground investigation (GI) works were being undertaken at the site between 9th – 13th August involving the use of 2 jack up rigs at the site. Baseline measurements were undertaken during breaks in the GI works, however, to minimise the interference of noise from the GI works, baseline measurements were concentrated over two periods on the 7th – 8th August and the 14th – 15th August. The rigs were still on site during these periods but were not operational.

Baseline underwater noise measurements were undertaken at 4 predetermined locations over the Sruwaddacon Bay area. These are shown in Figure 1-1 below. Measurements were carried out over as long a period as possible in order to provide an indication of any variation in noise levels over a tidal cycle. This was restricted by both tides, other activities such as boat movements ongoing around the measurement locations or availability of the survey vessel. As the water at locations 1 and 2 is deeper at low tide than at locations 3 and 4 it was possible to obtain data over a longer period at these positions.

The water depth was extremely low at times, and yet it was desired to establish the background noise levels at all states of the tide. This caused problems with the deployment of the hydrophone. For a number of hours either side of high tide it was possible to use an anti-heave buoy to suspend the hydrophone in the water column. The anti-heave buoy is important, in that it is used to reduce hydrostatic pressure changes contaminating the recording as the hydrophone moves up and down in the water column with surface wave motion; these pressure changes tend to generate high levels of low frequency noise which dominate the overall noise levels recorded. In addition, it also removes flow noise contamination from the recordings. Unfortunately, during low water periods it was not possible to use an anti-heave buoy as over 1 m of water depth is required for it to be deployed, and the water was frequently shallower than this. In shallow conditions, a standard pellet buoy was used to suspend the hydrophone. However, although the water was generally calm during the survey, large amounts of hydrostatic pressure changes were sometimes recorded using this method when there were significant waves. . In this case the hydrophone was lowered onto the river bed inside a protective cage and recordings were made as the hydrophone rested in a static location approximately 10 cm above the riverbed. Unfortunately, this method can introduce noise due to the flow of water around the hydrophone.. Of the data presented in this report, where possible they were measured using an anti-heave buoy. In some cases, a pellet buoy or hydrophone deployed on the riverbed were used to suspend the hydrophone. The influence on the overall recorded levels of underwater noise from hydrostatic pressure changes and flow noise around the hydrophone and other extraneous noise sources has therefore been kept to a minimum in the recordings that were made. However, a low level of these may still be present in some of the recordings, and hence they may be considered to be “worst case” indications of noise level..

Details of the tide times in Sruwaddacon Bay are presented in Table 1-1 below and a summary of the weather conditions on each day is presented in Table 1-2.

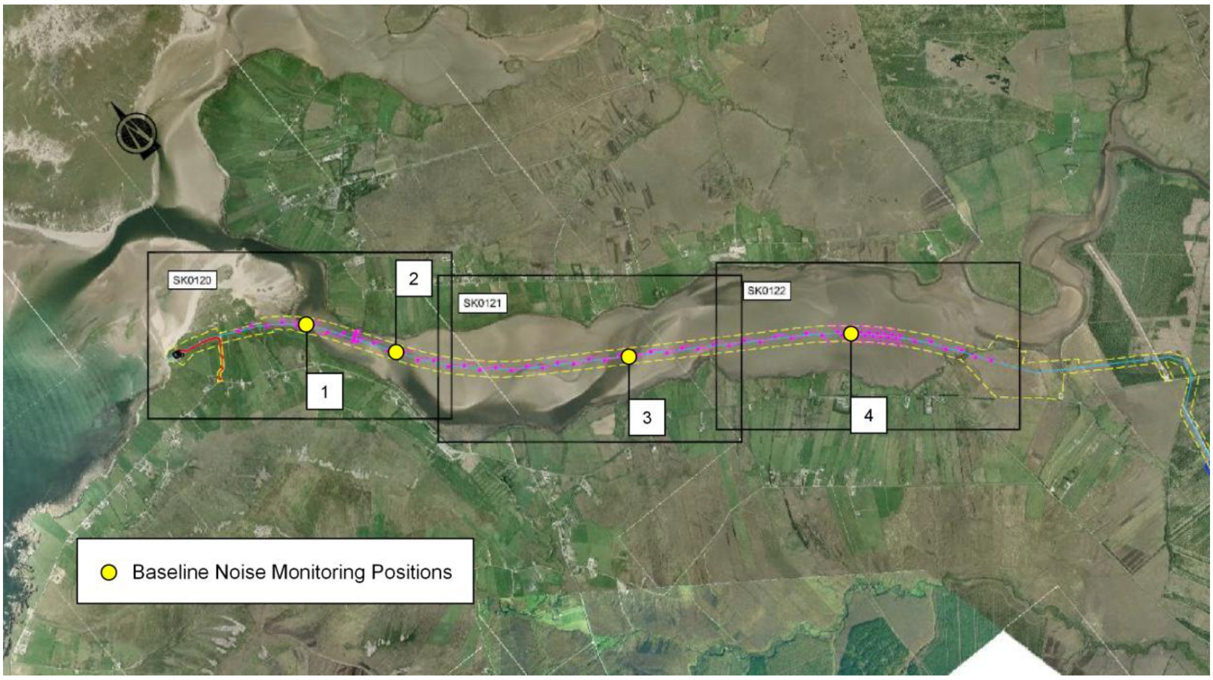

***Figure 1-1 Map showing the proposed pipeline route through Sruwaddacon Bay and the 4 baseline underwater noise monitoring positions***

***Table 1-1 Summary of tide time during the measurement period***

| Date | High Water | Low Water | High Water | Low Water | High Water |
|---|---|---|---|---|---|
| 07/08/2010 | 04:06 | 10:13 | 16:28 | 22:54 | - |
| 08/08/2010 | 05:03 | 11:05 | 17:19 | 23:39 | - |
| 09/08/2010 | 05:51 | 11:49 | 18:03 | - | - |
| 10/08/2010 | - | 02:21 | 06:35 | 12:30 | 18:47 |
| 11/08/2010 | - | 01:00 | 07:18 | 13:52 | 20:16 |
| 12/08/2010 | - | 01:41 | 08:01 | 13:52 | 20:16 |
| 13/08/2010 | - | 02:22 | 08:45 | 14:35 | 21:02 |
| 14/08/2010 | - | 03:05 | 09:31 | 15:20 | 21:50 |
| 15/08/2010 | - | 03:51 | 10:16 | 16:10 | 22:41 |

***Table 1-2 Summary of weather conditions in Sruwaddacon Bay during survey***

| Date | Wind speed (m/s) | Weather | Rain? |
|---|---|---|---|
| 07/08/2010 | 4.5 | light cloud cover | No |
| 08/08/2010 | Very calm | Overcast | No |
| 09/08/2010 | 2.5 – 5 | Bright, clear | No |
| 10/08/2010 | Very calm | Bright, clear | No |
| 11/08/2010 | 2.6 | Overcast | Yes, intermittent |
| 12/08/2010 | 2.5 | Bright | No |
| 13/08/2010 | Calm | Overcast | No |
| 14/08/2010 | 1.2 – calm | Overcast – clear | No |
| 15/08/2010 | 1.5 – calm | Clear | No |

# 2 Measurement and analysis of underwater noise and vibration

## 2.1 Specifying levels of sound using the $dB_{ht}$ metric

The $dB_{ht}$ scale incorporates the concept of “loudness” for a species. The metric incorporates hearing ability by referencing the sound to the species’ hearing threshold, and hence evaluates the level of sound a species can perceive. Experimental evidence indicates that the scale provides an objective rating of the effects of underwater noise on marine animals. It may be considered to be analogous to, or an extension of, the dB(A) scale that is used for human noise exposure.

Since any given sound will be perceived differently by different species (since they have differing hearing abilities) the species name must be appended when specifying a level. For instance the same sound may have a level of 70 $dB_{ht}$(Gadus morhua) for a cod and 110 $dB_{ht}$(*Phoca vitulina*) for a common seal.

The perceived noise levels of sources measured in $dB_{ht}$(Species) are usually much lower than the unweighted levels, both because the sound will contain frequency components that the species cannot detect, and also because most marine species have high thresholds of perception of (i.e. are relatively insensitive to) sound. If the level of sound is sufficiently high on the $dB_{ht}$(Species) scale, then an avoidance reaction or hearing impediment might occur. Linear unweighted SPL data does not allow the underwater sound to be assessed in this biologically significant manner. To determine the $dB_{ht}$(Species) sound level, high quality (1 Hz to 150 kHz) sound recordings are analysed by passing them through a filter that mimics the hearing ability of the animal in question. The output of the filter is therefore a sound level that represents the perceived level of underwater sound by the animal.

Nedwell *et al.,* (2007b) suggests the potential impact of the underwater noise at various $dB_{ht}$ levels on marine species to be;

| **Level in $dB_{ht}$(species)** | **Effect** |
|---|---|
| 0 – 50 | Low likelihood of disturbance |
| 75 and above | Mild avoidance reaction by the majority of individuals but habituation or context may limit effect |
| 90 and above | Strong avoidance reaction by virtually all individuals |
| Above 130 | Possibility of traumatic hearing damage from single event |

***Table 2-1 Assessment criteria used in this study to assess the potential impact of underwater noise on marine species***

## 2.2 Underwater sound and vibration measuring equipment

All of the underwater noise and vibration measurements undertaken as part of this study where sampled, digitised and stored on a laptop computer system as high frequency digital files. This means that the data can be assessed in any of the noise assessment formats described, or in any other future format required by the regulatory authorities.

### 2.2.1 Underwater sound

All underwater sound measurements undertaken as part of this study where undertaken using a Bruel and Kjaer 8106 low noise hydrophone. These sensors are able to measure underwater sound to levels well below sea state zero noise. This is important if the recordings are to be compared with the hearing response of species of marine mammal, many of which have evolved to exploit the efficient propagation of underwater sound for communication, echolocation and detecting prey, and are therefore able to perceive sound to low sea state noise levels.

The Bruel and Kjaer 8106 hydrophone has a linear sensitivity to underwater sound over the frequency range from 7 Hz to 80 kHz. The calibration chart for the sensor, traceable to international standards, is provided at Appendix A. However, Bruel and Kjaer also provide sensitivity data outside of the linear range, from 0.25 Hz to 150 kHz, so that the acoustic data can be extended well beyond the linear frequency range specified above. A benefit of this broad, well specified frequency calibration is that an inverse filter can be applied to flatten the response of the hydrophone..

All underwater sound recordings undertaken in the course of this study were digitised and stored on a portable laptop computer system at a sample rate of 350, 000 samples per second. In theory this provides acoustic data to a frequency of 175 kHz. Subsequent analysis of the acoustic data was conducted over the frequency range from 1 Hz to 120 kHz. Spectral levels of noise in this report are presented over the frequency range from 1 Hz to 100 kHz.

### 2.2.2 Ground vibration

Riverbed vibration measurements were made with a V901 calibrated low frequency geophone, supplied by Vibrock Ltd. To allow baseline ground vibration measurements at the low levels expected in the Sruwaddacon Bay area, the analogue signal from the geophone was amplified by a Subacoustech calibrated 68IA0201 voltage amplifier prior to digitisation and storage. Vibration data was captured at a sample rate of 10,000 bits per second.

# 3 Results of baseline underwater noise and vibration monitoring

Table 3-1 below presents a brief summary of the levels of underwater noise measured at the 4 locations in Sruwaddacon Bay. The data are presented in terms of unweighted RMS Sound Pressure Levels analysed over an interval of one second and RMS dBht levels for various species of marine mammal also analysed over a period of one second. Also shown is the number of samples, n, recorded at each location. From this it can be seen that a considerably wider sample of data was recorded at locations 1 and 2 than at locations 3 and 4.

The raw data files were checked and any recordings contaminated with apparent large amounts of wave or flow noise related to the hydrophone deployment method were removed from further analysis. Where there was a degree of uncertainty the files were left in for further analysis. The unweighted data indicate relatively high levels of underwater noise, with maximum levels of over 130 dB re. 1 μPa recorded. It is possible that some of the higher levels of recorded noise may be related to either hydrostatic pressure changes due to surface waves moving the hydrophone vertically in the water column, or flow noise around the hydrophone when it was deployed in a static location on the riverbed. Since these are periodic phenomena, the mean levels of underwater noise for each location may be a better indicator of the true levels of baseline underwater noise in Sruwaddacon Bay.

The maximum $dB_{ht}$ levels (perceived loudness) for the marine mammal species bottlenose dolphin, harbour porpoise, harbour seal and striped dolphin indicate high maximum levels of background underwater noise. In other words, the Sruwaddacon Bay may be considered to be a “noisy” location for these species. In the case of the harbour porpoise the perceived levels of baseline underwater noise for this species is above 90 $dB_{ht}$. As Table 2-3 in the previous section indicates, a strong avoidance reaction would be expected in marine mammals as a result of exposure to these levels of underwater noise. While these levels of baseline underwater noise have been recorded by the authors before, they are typically found in areas of extremely high tidal flow which generates high levels of underwater noise. While there was relatively first flowing water on the flood and ebb of the tides in Sruwaddacon Bay, close analysis of the data indicate that these highest levels of noise were recorded during periods when the hydrophone was in a static position on the riverbed. It is possible, therefore that these apparently high levels of noise are a result of flow noise over the hydrophone during some recording periods. Again, it is likely that the mean levels presented in Table 3-1 may be a better indicator of the true perceived background noise levels on the bay for marine mammals. Nevertheless, the levels of perceived background noise for the species considered are fairly high.

Figure 3-1 presents a summary of the data as a distribution of the measured levels of the background noise. The data show that the distribution is centred around RMS Sound Pressure Levels of about 110 dB re. 1 μPa or below, with levels higher and lower than this recorded less frequently. The data for locations 1, 2 and 3 indicate that the levels of baseline underwater noise are broadly similar for each location while the data for location 4 shows that generally lower levels were recorded.

Figure 3-2 presents a plot of Power Spectral Density (PSD) data for typical recordings taken at location 1. The plot shows a variation of about 20 dB can be seen over most of the frequency range from about 100 Hz up to 100 kHz. A slightly wider range of spectral levels is evident at frequencies below about 100 Hz, likely to be due to the varying levels of surface wave noise recorded depending on the method of deployment of the hydrophone. It is interesting to note that in the frequency band from about 50 Hz to 1 kHz, there is evidence of machinery noise, perhaps from distant shipping. It should be noted that due to the high tide coinciding well with the measurements presented in Figure 3-2 and the relatively deep water at location 1, all measurements after approximately 13:00 were undertaken using the anti-heave buoy. Any flow noise around the hydrophone would therefore have been kept to a minimum during these measurements, so the relatively high levels of high frequency noise presented are likely to be actual background noise at location 1 in Sruwaddaccon Bay. The steep rise in spectral levels at higher frequencies above about 10 kHz is typical of the noise induced by fine scale turbulent flow over rough surfaces. It is notable that the lowest spectral levels of noise in the frequency band from 10 kHz and above were recorded just after 16:00 which was approximately slack water in the bay according to local tide tables.

Figure 3-3 presents a summary of typical spectral levels of underwater noise measured at location 2. In general, the spectral levels are slightly lower than those measured at location 1. Slightly higher levels of noise at frequencies above about 30 kHz were recorded for measurements between 09:00 and 10:00..

Baseline riverbed vibration was also measured during the survey. Figure 3-4 presents a typical time history of the measured data from the geophone in terms of particle velocity (mm/s). It can be seen that the file is heavily quantised, indicating that it was not possible to resolve the analogue input into a digital signal due to the extremely low levels of vibration, which were below the floor of the very sensitive equipment used.

For comparison, Figure 3-5 presents a riverbed vibration recording measured approximately 23 m from GI works involving both rotary drilling, which was continuously operational throughout the recording, and cable percussive borehole drilling, which commences approximately 17 seconds into the recording. These data indicate that both these operations generated a low level of ground borne vibration which was recorded by the geophone.

***Table 3-1 Summary of one second RMS Sound Pressure Levels and RMS dBht levels of baseline underwater noise recorded in Sruwaddacon Bay***

| Location | One Second RMS Sound Pressure Levels | | | One second RMS dBht Levels | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Bottlenose dolphin | | | Harbour porpoise | | | Harbour seal | | | Striped dolphin | | |
| | Max | Min | Mean | Max | Min | Mean | Max | Min | Mean | Max | Min | Mean | Max | Min | Mean |
| 1 (n=3774) | 136 | 92 | 110 | 83 | 35 | 57 | 92 | 45 | 67 | 57 | 16 | 32 | 85 | 36 | 59 |
| 2 (n=2399) | 131 | 99 | 112 | 67 | 36 | 49 | 76 | 46 | 58 | 53 | 17 | 53 | 69 | 38 | 51 |
| 3 (n=756) | 125 | 88 | 107 | 54 | 30 | 37 | 63 | 42 | 47 | 34 | 9 | 18 | 56 | 32 | 38 |
| 4 (n=246) | 112 | 87 | 98 | 48 | 23 | 33 | 56 | 34 | 44 | 30 | 0 | 13 | 49 | 25 | 35 |

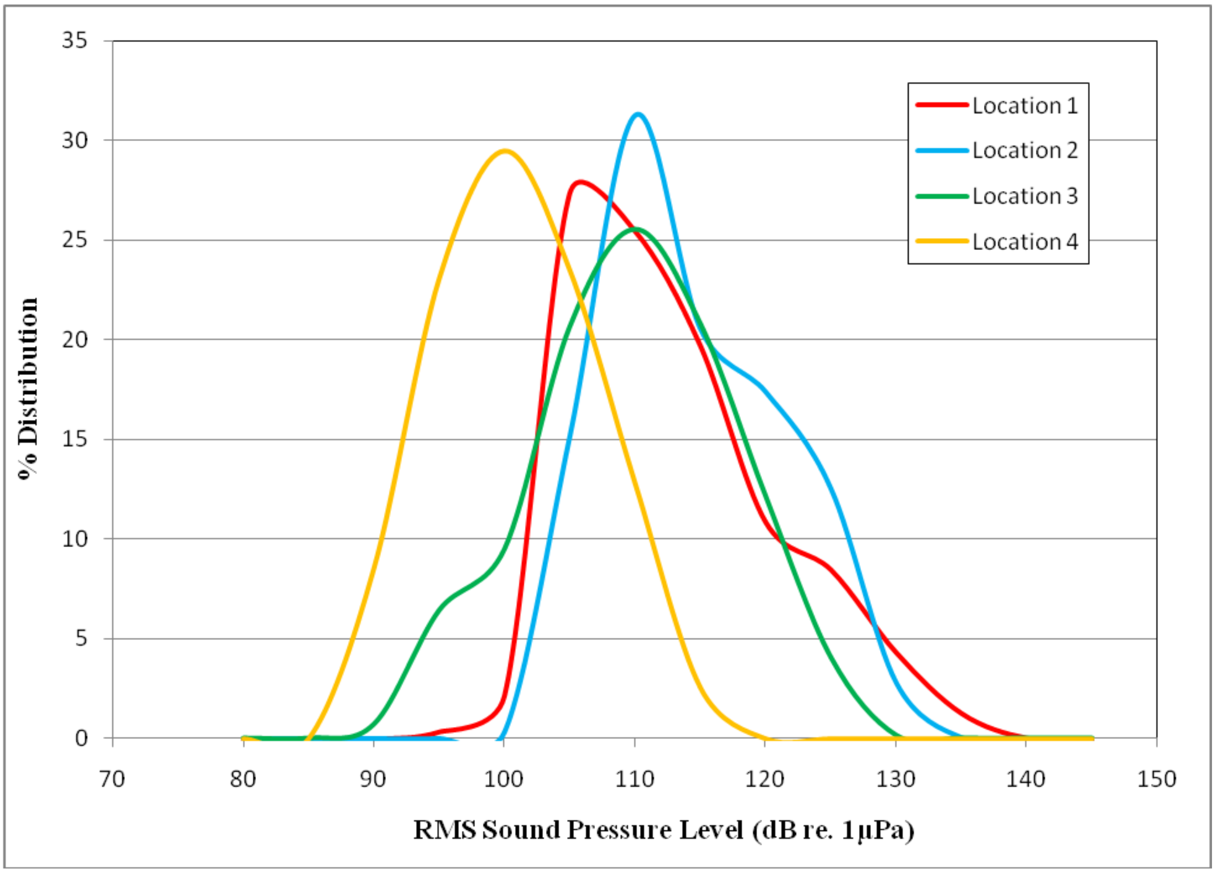

***Figure 3-1 Summary of one RMS Sound Pressure Levels of underwater noise measured at each location in Sruwaddacon Bay in August 2010. The data are presented as a distribution of measured noise levels***

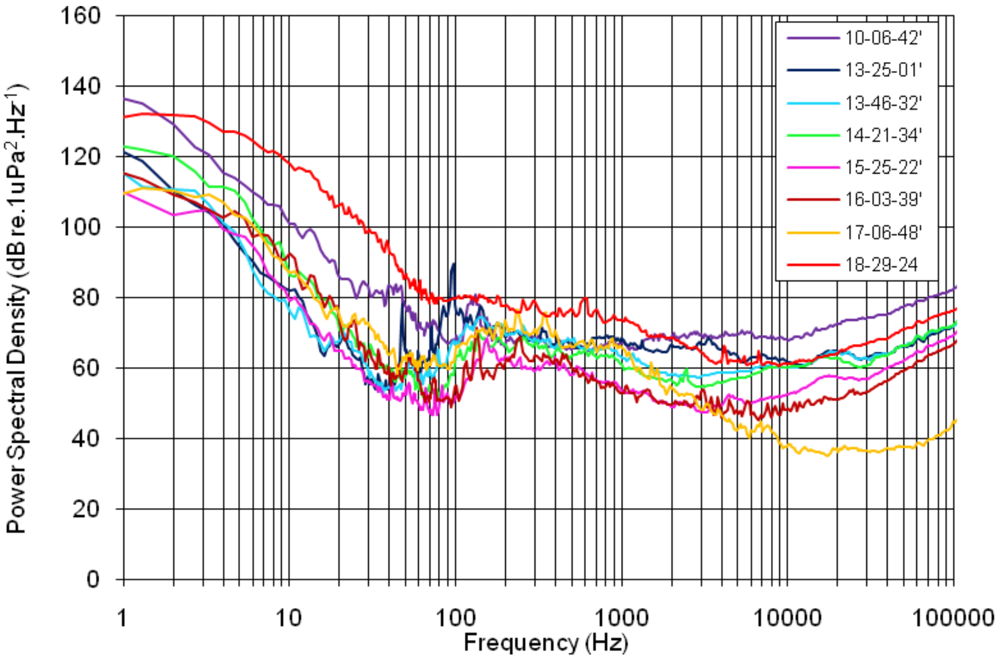

***Figure 3-2 Typical spectral levels of baseline underwater noise recorded at location 1 in Sruwaddacon Bay in August 2010***

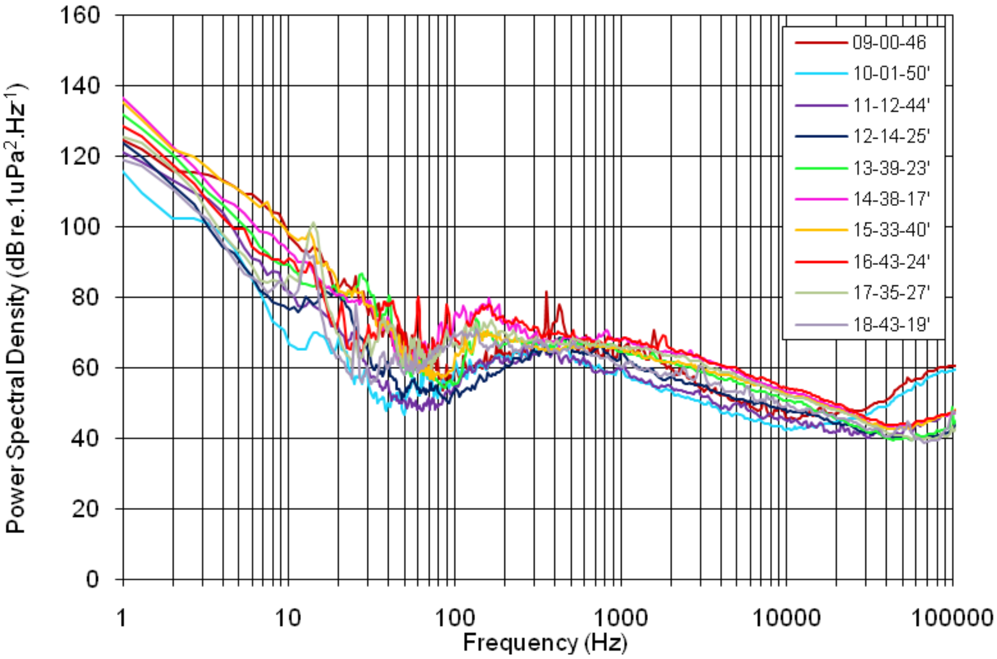

***Figure 3-3 Typical spectral levels of baseline underwater noise recorded at location 2 in Sruwaddacon Bay in August 2010***

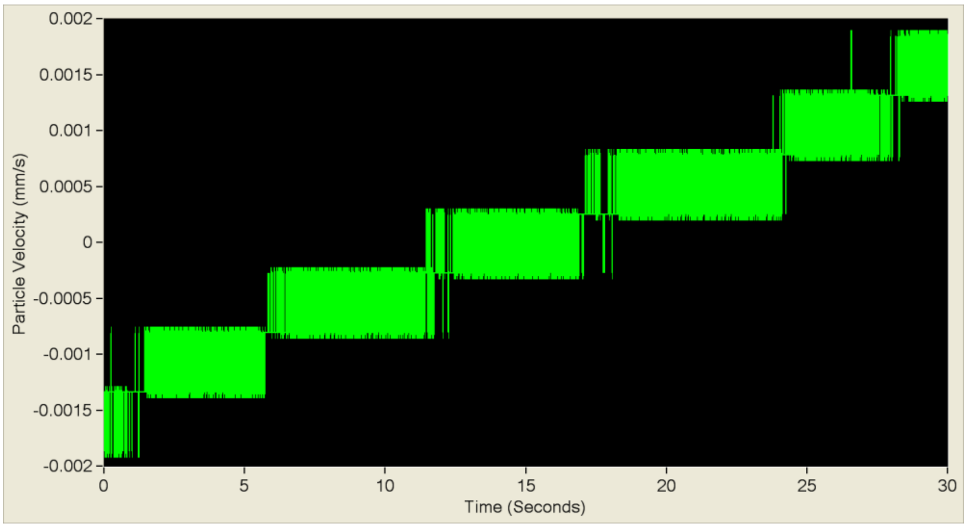

***Figure 3-4 Typical time history of baseline river bed vibration measurements in Sruwaddacon Bay***

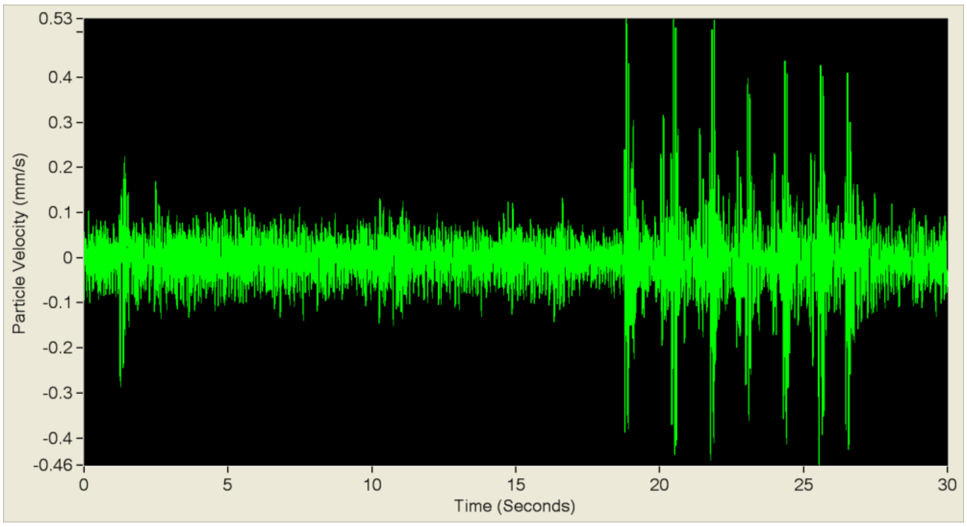

***Figure 3-5 Typical time history of riverbed vibration measured approximately 23 m from geotechnical GI works***

# 4 Summary and Conclusions

A series of baseline underwater noise and vibration measurements were undertaken in Sruwaddacon May, Co. Mayo, Eire in August 2010. The data will be used to inform an assessment of the potential impact on marine mammal species that tunnelling operations as part of the Corrib pipeline installation may have. The data have been analysed to provide the data in terms of unweighted levels of underwater noise (such as RMS Sound Pressure Level) and vibration (as particle velocity) and also in terms of the hearing abilities of marine mammals using the $dB_{ht}$ metric.

1. The background noise levels in Sruwaddacon Bay were found to be centred around RMS levels of about 110 dB re. 1 μPa, with levels higher and lower than this recorded less frequently. The data for the three locations nearest to the sea (locations 1, 2 and 3) indicated slightly higher levels of noise than for location 4, which was the most inland position.
2. The data analysed to obtain $dB_{ht}$ levels (perceived loudness) of baseline underwater noise for bottlenose dolphin, harbour porpoise, harbour seal and striped dolphin also indicate that the Sruwaddacon Bay may be considered to be a “noisy” location for these species, with the maximum $dB_{ht}$ levels of baseline underwater noise being in some cases above 90 $dB_{ht}$. This probably results from a high level of high frequency noise (above about 30 kHz) being caused by fine scale turbulent flow over surface roughness, although in some cases there may be an apparent contribution caused by flow noise around the measurement hydrophone.
3. Riverbed vibration measurements indicated that there are extremely low baseline vibration levels in the river. These levels were so low that it was not possible to resolve them. However, a riverbed vibration recording at 23 m from rotary drilling and cable percussive borehole drilling indicated a low level of ground borne vibration.

# Appendix A Measurement of underwater noise

## A.1 Introduction

Sound travels much faster in water (approximately 1,500 m/s) than in air (340 m/s). Since water is a relatively incompressible, dense medium, the pressures associated with underwater sound tend to be much higher than in air. As an example, background levels of sea noise of approximately 130 dB re 1 µPa for UK coastal waters are not uncommon (Nedwell *et al,* 2003 and 2007a). This level equates to about 100 dB re 20 µPa in the units that would be used to describe a sound level in air. Such levels in air would be considered to be hazardous. However, marine mammals and fish have evolved to live in this environment and are thus relatively insensitive to sound pressure compared with terrestrial mammals. The most sensitive thresholds are often not below 100 dB re 1 µPa and typically not below 70 dB re 1 µPa (44 dB re 20 µPa using the reference unit that would conventionally be used in air).

## A.2 Units of measurement

Sound measurements underwater are usually expressed using the decibel (dB) scale, which is a logarithmic measure of sound. A logarithmic scale is used because rather than equal increments of sound having an equal increase in effect, typically a constant ratio is required for this to be the case, that is, each *doubling* of sound level will cause a roughly equal increase in “loudness”.

Any quantity expressed in this scale is termed a “level”. If the unit is sound pressure, expressed on the dB scale, it will be termed a “Sound Pressure Level”. The fundamental definition of the dB scale is given by:

$$\text{Level} = 10 \times \log_{10}(Q/Q_{ref}) \qquad \textbf{\textit{eqn. A-1}}$$

Where $Q$ is the quantity being expressed on the scale, and $Q_{ref}$ is the reference quantity.

The dB scale represents a ratio and, for instance, 6dB really means “twice as much as …”. It is, therefore, used with a reference unit, which expresses the base from which the ratio is expressed. The reference quantity is conventionally smaller than the smallest value to be expressed on the scale, so that any level quoted is positive. For instance, a reference quantity of 20 µPa is usually used for sound in air, since this is the threshold of human hearing.

A refinement is that the scale, when used with sound pressure, is applied to the pressure squared rather than the pressure. If this were not the case, if the acoustic power level of a source rose by 10 dB the Sound Pressure Level would rise by 20 dB. So that variations in the units agree, the sound pressure must be specified in units of RMS pressure *squared*. This is equivalent to expressing the sound as:

$$\text{Sound Pressure Level} = 20 \times \log_{10}(P_{RMS}/P_{ref}) \qquad \textbf{\textit{eqn. A-2}}$$

For underwater sound, typically a unit of one microPascal (µPa) is used as the reference unit; a Pascal is equal to the pressure exerted by one Newton over one square metre. One microPascal equals one millionth of this.

## A.3 Quantities of measurement

Sound may be expressed in many different ways depending upon the particular type of noise, and the parameters of the noise that allow it to be evaluated in terms of a biological effect. These are described in more detail below.

### A.3.1 Peak level

The peak level is the maximum level of the acoustic pressure, usually a positive pressure, or level of the sound pressure above the local ambient pressure. This form of measurement is often used to characterise underwater blasts where there is a clear positive peak following the detonation of explosives. Examples of this type of measurement used to define underwater blast waves can be found in Bebb and Wright (1953 to 1955), Richmond *et al* (1973), Yelverton *et al* (1973) and Yelverton (1981). The data from these studies have been widely interpreted in a number of reviews on the impact of high level underwater noise causing fatality and injury in human divers, marine mammals and fish (see for example Rawlins, 1974; Hill, 1978; Goertner, 1982; Richardson *et al,* 1995; Cudahy and Parvin, 2001; Hastings and Popper, 2005). The peak sound level of a freely suspended charge of Tri-Nitro-Toluene (TNT) in water can be estimated from Arons (1954), as summarised by Urick (1983). For offshore operations such as well head severance, typical charge weights of 40 kg may be used, giving a source peak pressure of 195 MPa or 285 dB re 1 µPa @ 1m (Parvin *et al,* 2007).

### A.3.2 Peak to peak level

The peak to peak level is usually calculated using the maximum variation of the pressure from positive to negative within the wave. This represents the maximum change in pressure (differential pressure from positive to negative) as the transient pressure wave propagates. Where the wave is symmetrically distributed in positive and negative pressure, the peak to peak level will be twice the peak level, and hence 6 dB higher.

Peak to peak levels of noise are often used to characterise sound transients from impulsive sources such as percussive impact piling and seismic airgun sources. As an example, measurements during offshore impact piling operations to secure tubular steel piles into the seabed have indicated peak to peak source level noise from 244 to 252dB re 1µPa @ 1m for piles from 4.0 to 4.7 m diameter (Parvin *et al,* 2006; Nedwell *et al,* 2007a).

### A.3.3 Sound pressure level (SPL)

The Sound Pressure Level is normally used to characterise noise and vibration of a continuous nature such as drilling, boring, continuous wave sonar, or background sea and river noise levels. To calculate the SPL, the variation in sound pressure is measured over a specific time period to determine the Root Mean Square (RMS) level of the time varying sound. The SPL can therefore be considered to be a measure of the average unweighted level of the sound over the measurement period.

As an example, small sea going vessels typically produce broadband noise at source SPLs from 170 – 180 dB re 1 µPa @ 1 m (Richardson *et al,* 1995), whereas a supertanker generates source SPLs of typically 198 dB re 1 µPa @ 1 m (Hildebrand, 2004).

Where an SPL is used to characterise transient pressure waves such as that from seismic airguns, underwater blasting or piling, it is critical that the time period over which the RMS level is calculated is quoted. For instance, in the case of a pile strike lasting say a tenth of a second, the mean taken over a tenth of a second will be ten times higher than the mean taken over one second.

### A.3.4 Sound Exposure Level

When assessing the noise from transient sources such as blast waves, impact piling or seismic airgun noise, the issue of the time period of the pressure wave (highlighted above) is often addressed by measuring the total acoustic energy (energy flux density) of the wave. This form of analysis was used by Bebb and Wright (1951 to 1955), and later by Rawlins (1987) to explain the apparent discrepancies in the biological effect of short and long range blast waves on human divers. More recently, this form of analysis has been used to develop an interim exposure criterion for assessing the injury range for fish from impact piling operations (Hastings and Popper, 2005; Popper *et al*, 2006).

The Sound Exposure Level (SEL) sums the acoustic energy over a measurement period, and effectively takes account of both the SPL of the sound source and the duration the sound is present in the acoustic environment. Sound Exposure (SE) is defined by the equation:

$$SE = \int_0^T p^2(t)dt$$ ***eqn. A-3***

where p is the acoustic pressure in Pascals, T is the duration of the sound in seconds and t is time in seconds.

The Sound Exposure is a measure of the acoustic energy and, therefore, has units of Pascal squared seconds ($Pa^2s$).

To express the Sound Exposure on a logarithmic scale by means of a dB, it is compared with a reference acoustic energy level of 1 $\mu Pa^2$ ($P^2_{ref}$) and a reference time ($T_{ref}$).

The Sound Exposure Level (SEL) is then defined by:

$$SEL = 10\log_{10}\left(\frac{\int_0^T p^2(t)dt}{P_{ref}^2 T_{ref}}\right)$$ ***eqn. A-4***

By selecting a common reference pressure $P_{ref}$ of 1µPa for assessments of underwater noise, the SEL and SPL can be compared using the expression:

$SEL = \mathrm{SPL} + 10\log_{10}\mathrm{T}$ ***eqn. A-5***

where the SPL is a measure of the average level of the broadband noise, and the SEL sums the cumulative broadband noise energy.

Therefore, for continuous sounds of duration less than one second, the SEL will be lower than the SPL. For periods of greater than one second the SEL will be numerically greater than the SPL (i.e. for a sound of ten seconds duration the SEL will be 10dB higher than the SPL, for a sound of 100 seconds duration the SEL will be 20dB higher than the SPL and so on).

## A.4 Source level and transmission loss

Sound levels underwater are usually quantified in terms of the source level, which is a measure of the sound energy released by the source, and the transmission loss, which is a measure of the rate at which that energy is lost. Sound propagation is thus described by the simple equation:

$L(r) = SL - TL$ ***eqn. A-6***

where *L(r)* is the Sound Pressure Level at distance *r* from a source in metres, and *SL* is the source level, which may be thought of as the “effective” level of sound at one metre from the source. *TL* is the transmission loss (Kinsler *et al,* 1982).Transmission Loss (TL), is defined as:

$$TL = 20\log\left(\frac{P_0}{P_R}\right)$$ ***eqn. A-7***

where $P_o$ is the effective acoustic pressure at a point at 1m from the source, as per the Source Level above, and $P_R$ is the acoustic pressure at range R away from it. The Transmission Loss is therefore a measure of the rate at which the sound energy decreases with increasing range.

Frequently a simplification is made by assuming that the Transmission Loss may be approximated due to spreading and absorption losses, such that:

$TL = N\log(r) + \alpha r$ ***eqn. A-8***

where *r* is the distance from the source in metres, *N* is the constant factor for attenuation due to geometric spreading, and $\alpha$ is a factor for the absorption of sound in water and boundaries in dB/m (Urick, 1983; Kinsler *et al,* 1982).

For instance, spherical spreading gives a value of $N$=20. By combining equations A-6 and A-8, the level of sound at any point in the water space can be estimated from the expression:

$$L(r) = SL - N\log_{10}(r) - \alpha r \qquad \textbf{eqn. A-9}$$

Over short distances, absorption effects have little influence on the Transmission Loss and can often be ignored. The Source Level itself may be quoted in any physical quantity, for instance, a piling source may be expressed as having a "peak to peak Source Level of 200 dB re 1 µPa @ 1m".

This simple but convenient formulation ignores the practical difficulty of estimating the Source Level. Since the measurements are usually made at some distance from the source (in the acoustic far field), and extrapolated back to the source, the true level at one metre may actually be very different from the Source Level used in these equations.

It is often not realised that, since the value of Source Level quoted for a particular source is obtained by extrapolation; the value will depend on the model that is used to perform the extrapolation. Figure A-1 illustrates this point. The diagram illustrates a set of measurements made of the noise from piling. In the simplest case, in order to draw conclusions about the data, it may be fitted to a straight-line model; this is shown in the figure by the green line. Such a model effectively assumes that the noise level, NL, behaves as $L(r) = SL - N\log_{10}(r)$. This however will generally over-estimate the level for low and high ranges, since it ignores the effects of absorption of the noise. The improved model including absorption, $L(r) = SL - N\log_{10}(r) - \alpha r$, gives a better fit to the data, and indeed this simple form is usually adequate for modelling sound propagation from a source in deep water of roughly constant depth. However, in the case of the shallow coastal waters where wind farms are typically situated, the depth may rapidly fluctuate between shallow water of a few metres and deep water of tens of metres or more. In these circumstances, the Transmission Loss becomes a more complex function of depth that depends heavily on the local bathymetry and hence must be calculated using a more sophisticated model, such as *INSPIRE*. Where these effects are included, as illustrated by the blue line, yet another value of Source Level may result; typically lower levels of noise may be predicted near to the piling.

The variation in estimates of Source Level for the same data set, when analysed in different ways, indicates how Source Level will in general be a function of the model that is used to express the noise levels.

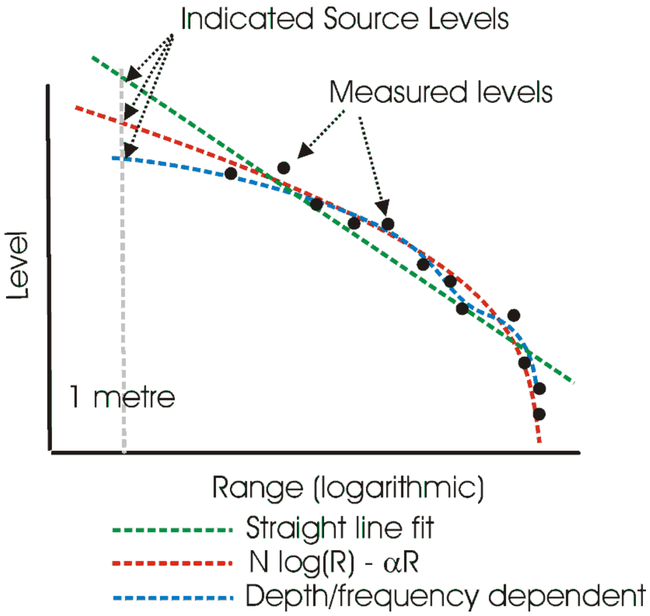

***Figure A-1 Differences in source level estimation based on various models***

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