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Measurements of underwater noise during piling at the Red Funnel Terminal, Southampton, and observations of its effect on caged fish.

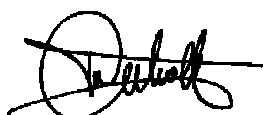
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1. Introduction.

1.1. Background to the work.

This report presents the results of monitoring measurements of waterborne noise taken at Town Quay, Southampton, during piling operations at Red Funnel's Southampton Terminal in September 2003. Simultaneously, observations were made of caged brown trout (*Salmo trutta*) to determine whether there was any observable effect of the piling on their behaviour.

The piling was required as part of a construction project for Red Funnel, installing improved loading facilities at their Southampton Terminal, illustrated in Fig. 1. The project was required to provide infrastructure for improved ferry services, and in particular to allow twin-deck access to ferries. As part of this project piling in the water adjacent to the dock wall was required to provide foundations for the new structure. Existing ferries were also modified during the period of construction to allow twin deck access; during this period a temporary ferry was provided.

Driving of piles in water have been recorded as generating high levels of underwater noise (Abbott & Bing-Sawyer (2002)), and there was consequently concern by the Environment Agency (EA) and English Nature (EN) who have remits to control construction projects so as to mitigate adverse impacts on fish stocks. Their concern related to the possible effects construction noise might have on local fish populations, and in particular on migration of salmon.

A consent had previously been given by the Environment Agency for Red Funnel's contractors to undertake the piling between the 1st December 2003 and the 31st March 2004, during which period no significant impediment to the migration of salmon through the area and into the Test was expected. However, due to significant economic and commercial factors connected with the required timescales for withdrawing the ferries from service, and the need to accomplish the engineering work outside peak travel periods for passengers, a consent was sought from EA and EN to bring forward the piling project to commence on the 1st September.

Permission was subsequently given for the piling to be brought forward to September 2003, subject to two requirements, namely:

1. the mitigation of impact piling noise by use of bubble curtains as required, and
2. the work being monitored by means of measurements of underwater noise.

In addition, Red Funnel provided some funds for direct visual observation of a tethered cage of fish in order to make direct visual observations of any effect. Owing to the problems of obtaining salmon for testing, farmed brown trout (*Salmo trutta*) were used in the tests, being the most closely related species with a similar hearing ability.

These measures were deemed sufficient to ensure there was no increased likelihood of salmon in Southampton Water and the River Test being affected by the piling.

1.2 Piling methods.

Two sorts of piling were undertaken on the site, namely vibropiling and impact piling.

Vibratory pile drivers are machines that install piling into the ground by applying a rapidly alternating force to the pile. This is generally accomplished by rotating eccentric weights about shafts. Each rotating eccentric produces a force acting in a single plane and directed toward the centreline of the shaft. Fig. 2 shows the basic set-up for the rotating eccentric

weights used in most current vibratory pile driving/extracting equipment. The weights are set off-centre of the axis of rotation by the eccentric arm. If only one eccentric is used, in one revolution a force will be exerted in all directions, giving the system a good deal of lateral whip. To avoid this problem the eccentrics are paired so the lateral forces cancel each other, leaving only axial force for the pile. Machines can also have several pairs of smaller, identical eccentrics synchronised to obtain the same effect as one larger pair.

Impact piling is performed using hammers which drive the pile by first inducing downward velocity in a metal ram, as shown in Fig. 3. Upon impact with the pile accessory, the ram creates a force far larger than its weight, which moves the pile an increment into the ground. Most impact hammers have some kind of cushion under the end of the ram which receives the striking energy of the hammer. This cushion is necessary to protect the striking parts from damage; it also modulates the force-time curve of the striking impulse and can be used to match the impedance of the hammer to the pile, increasing the efficiency of the blow.

The sediments at the terminal were found to be relatively soft, such that nearly all the pile driving at the Red Funnel was undertaken using vibropiling. Impact piling was only used at the end of the work, when the final driving of three piles was performed by impact piling for dynamic testing purposes.

2. The Measurements.

2.1. Philosophy of measurements; the dB_{ht} scale.

A brief description of the dB_{ht} scale used in this document, which is a method of rating noise in respect of its potential for behavioural effects and which incorporates species sensitivity to sound, is appropriate.

In man, a commonly used measure of the effect of sound is the Sound Level measured in dB(A) . The human ear is most sensitive to sound at frequencies of the order of 1 to 4 kHz, and hence these frequencies are of greatest importance in determining the physical and psychological effects of sound for humans. At lower or higher frequencies the ear is much less sensitive, and humans are hence more tolerant of these frequencies. To reflect the importance of this effect a scale of sound, the dB(A) , effectively allows for this frequency response of the human ear. The process can be thought of as measuring the level of sound after putting it through a filter which approximates the hearing ability of the human ear. Measurements of sound level in dB(A) have been shown to relate well to the degree of both physical and behavioural effects of sound on humans. This approach has also been successfully extended (Parvin & Nedwell (1995)) to underwater human exposure to sound, despite underwater hearing ability differing greatly from that in air, yielding the dB(UW) , which allows the effects of sound on submerged humans to be estimated.

The response of a living organism to a given sound is dependent on the particular species, since each species has its own range of frequencies over which it can hear and its own hearing sensitivity. Fish typically hear from a few Hz up to 1 kHz and above; marine mammals typically have peak hearing ability from about 1 kHz to 100 kHz. In the $\text{dB}_{\text{ht}}(\text{Species})$, (Nedwell, *et al* (2003)) a similar approach to the dB(A) is used to arrive at a number for the level of a given sound which is indicative of how much that species will be affected by that sound. Similarly to the dB(A) , a frequency dependent filter is used to weight the sound; however the suffix 'ht' relates to the fact that the sound is weighted by the hearing threshold of a given species. The process can be thought of as measuring the level of sound after putting it through a filter which approximates the hearing ability of the species. The level expressed in this scale is different for each species and corresponds to the likely perception of the sound by the species. For instance, the $\text{dB}_{\text{ht}}(\text{Salmo salar})$ level of a sound (i.e. for a salmon) will be different from the $\text{dB}_{\text{ht}}(\text{Phocena phocena})$ level (for a seal). However, the higher the number, irrespective of the species, the more likely it is that it will cause an effect. Initial work on fish indicates that at levels of 90 $\text{dB}_{\text{ht}}(\text{Species})$ or more, significant avoidance reaction occurs.

It may be noted that the effective noise levels of sources measured in $\text{dB}_{\text{ht}}(\text{Species})$ are usually much lower than the unweighted levels, not only because the sound will contain frequency components that the species cannot detect, but also because most marine species have high thresholds of perception of (are insensitive to) sound.

The salmon audiogramme used as the basis of the analysis herein is shown in Fig. 4.

2.2. Location of pile driving and measurement positions.

The piling was carried out at Red Funnel's terminal at Town Quay, at the southern end of Southampton High Street. The location of the site is illustrated in the sketch map in Fig 5. The monitoring measurements were taken at a number of locations, most of them at the far end of Town Quay, in Southampton Water, at the location labelled 'R5' in Fig. 6. In addition

to measurements at this location measurements were also taken at up to 4 other locations (labelled 'R1' to 'R4' in Fig. 6) for research purposes for the EA; the results obtained at these additional locations will be presented in a report in preparation for the EA.

Locations R1 and R2 were at each end of a pontoon which was used for maintenance work on Red Funnels vessels. R3 was from the side of a dolphin, access to which was via a ladder and walkway from the pontoon. R4 was at the 'knee' in Town Quay, and R5 was at the far end of the quay. While the area of the piling looks from the sketch to be relatively confined, in fact since both Town Quay and Royal Pier are open piled structures they did not influence the sound field and hence the propagation conditions approximated to open conditions.

In total 10 piles were driven at the site. Fig. 7 is a sketch giving the locations of the individual piles on the site. It will be seen that two different diameter pile tubes were used, as indicated in the figure; a photograph of the piles is shown in Fig. 8. A general view of the site is given in the photograph of Fig 9.

The vibropiling was undertaken using a PVE 2316 VM driver; a picture of this driver is given in Fig 10. Impact piling was performed using a BSP357/9 hydraulic drop hammer; this is illustrated in Fig. 11.

The distances between the piling and measurement locations were measured using a hand-held GPS receiver and display. The relevant distances (from a point on the quayside adjacent to the ferry's linkspan) are given in Table 2.1.

| Location | Distance (m) |
|-----------------|---------------------|
| R3 | 96.3 |
| R4 | 233.8 |
| R5 | 417.4 |

Table 2.1. Distances of measurement locations from piling site.

For the vibrodriving, a total of nine sets of measurements was taken. Seven of these were at R5, one was between R4 and R5, and another was at R3. For the impact driving measurements were taken at R3. For each measurement a laptop computer running a program which captured the signal from a hydrophone and calculated the dB_{ht} value was used. Table 2.2 lists the driving operations which were captured.

| Pile number | Pile diameter (mm) | Type of driving | Measurement position |
|--------------------|---------------------------|------------------------|-----------------------------|
| 2 | 914 | vibro | R5 |
| 3 | 914 | vibro | R5 |
| 4 | 914 | vibro | R5 |
| 5 | 508 | vibro | R5 |
| 6 | 508 | vibro | R5 |
| 7 | 508 | vibro | R5 |
| 8 | 508 | vibro | R5 |
| 9 | 508 | vibro | between R4 & R5 |
| 10 | 508 | vibro | R3 |
| 1 | 914 | impact | R3 |
| 6 | 508 | impact | R3 |
| 9 | 508 | impact | R3 |

Table 2.2. Details of measurements of pile driving.

2.3. Instrumentation and measurement procedure.

In all three hydrophones, all made by Brüel & Kjær, were used. The first was a Type 8104, serial number 2225716, the second was a Type 8105, serial number 1461320, and the third was a Type 8106, serial number 2256725. Table 2.3 lists the hydrophone that was used for the various piles. Details of the calibrations of these hydrophones and their traceability to International Standards are given in Appendix 1.

| Hydrophone type | Used for piles |
|------------------------|----------------------------|
| 8104 | 2, 3, 4 (vibro) |
| 8105 | 10 (vibro), 1,6,9 (impact) |
| 8106 | 5, 6, 7, 8, 9 (vibro) |

Table 2.3. Listing of hydrophones used for each pile drive.

For the vibrodriving measurements the 8104 and 8105 hydrophones were connected to a Brüel & Kjær Type 2635 Charge Amplifier to condition the signal, and the output from this amplifier was fed to a Kemo filter, set to have a passband of 5 Hz to 20 kHz. The 8106 hydrophone, which has a built-in pre-amplifier adjacent to the pressure sensing element, was connected to a Subacoustech PE6 power supply/amplifier. The output from this was fed to the Kemo filter, set to have a lowpass cutoff frequency of 20 kHz.

Fig. 12 is a block diagram of the instrumentation setup.

The output from the 2635 or PE6 amplifier was fed to a National Instruments 6062E DAQCard, an analogue-to-digital converter card, which was inserted in a PCMCIA slot in a Sony laptop computer. The computer ran a program, written using the National Instruments LabVIEW application, to digitize the signal and calculate a dB_{ht} (*Salmo salar*) value on one second noise segments.

The hydrophone was located at the measurement position by being taped to a rope which had a weight fixed at its end, and the rope and ‘phone were lowered into the water until the hydrophone was 2.5 m below the water surface. The rope was adjusted at regular intervals to keep the hydrophone at a constant depth as the tidal state varied.

After consultation with the Dean & Dyball operatives, and when the pile tube had been readied and it was clear that the driving operation was about to commence, the computer program was started. Data were captured continuously until the pile tube had been driven to depth, or there was a lengthy period when no driving was taking place because difficulties had been encountered.

3. Analysis of measurements and results.

3.1. Vibro driver.

Part of a typical sound pressure level *vs.* time history obtained at position R5 (at the end of Town Quay, at 417.4 m from the piling) on the 18th September 2003 for the vibro driven pile case is shown in Fig. 13. The figure illustrates the level of the sound in dB as a function of the time of day. The upper trace, in blue, indicates the unweighted sound level in dB re 1 μ Pa, and the lower trace the level in dB_{ht} (*Salmo salar*), i.e., as a frequency weighted level above the hearing threshold of salmon. Also marked on the figure are the periods during which vibropiling was undertaken.

First, looking at the unweighted sound pressure levels, it can be seen that there are periodic short but relatively large increases in level up to about 150 dB. These are associated with the passage of vessels along Southampton Water, which is a busy waterway, and the passage of ferries into the Red Funnel terminal. Most of these movements were noted at the time of the measurements, and have been noted on the figure. It is interesting to note that from about 15:00 hrs to the end of the recording at 17:00 hrs there is a significant and continuous increase in level over the earlier part of the recording from 14:00 hrs to 15:00 hrs. This is due to noise from the dredger *Bluefin*, which was removing silt from the waterway by suction dredging. The dredger was at a distance of about 200 m from the measurement position.

In respect of the vibropiling, it may be seen that there is no discernible increase of the signal when the driving is taking place compared to when it is not; in fact the vibropiling could not be discerned in the time history. It was noted when listening to the recordings that the background noise was completely dominated by other man-made noise, and in particular by the movement of vessels.

It is interesting to note that there is little difference in the shape of the time histories (i.e. in the level variations over time between the dB_{ht} (*Salmo salar*) values and the unweighted dB levels), other than the dB_{ht} (*Salmo salar*) values being of much lower level. The lower level results from salmon being relatively insensitive to sound, and to a lesser degree from their limited hearing bandwidth.

Similar results were noted for other recordings made during vibropiling, and in general there was no discernible difference between recordings of sound pressure level *vs.* time history made on days on which vibropiling was being conducted and those on which there was no vibropiling.

In summary, it may be concluded that in respect of the vibropiling, at the range at which monitoring was conducted of 417 m, there was no discernible contribution from the piling above the background noise. It was noted when listening to the recordings that the vibropiling could not be heard above the background noise caused by the movement of vessels.

3.2. Impact driver

Fig. 14 is a plot of a typical pressure time history recorded at location R3; a section of the recording having two pile driver strikes has been illustrated. Fig. 14 (a) illustrates the sound pressure in linear units, and Fig. 14 (b) illustrates the identical recording, but in units of salmon hearing thresholds. First, looking at the unweighted levels, it may be seen that there is a high level of impulsive sound as the pile is struck, having a peak-to-peak pressure of about 200 Pa and a roughly exponential decay, with a time constant of about 0.1 sec. There are two later arrivals, one small arrival occurring at about 0.2 sec after the main arrival, and a further large

arrival about 0.5 sec after the main arrival. These are thought to be seismic arrivals carried in the seabed.

The salmon hearing threshold weighted data of Fig. 14 (b) is generally similar in form to the unweighted data. It is interesting to note, however, that the seismic arrivals, which are at a frequency of about 10 Hz, have disappeared due to the relative insensitivity of salmon to these frequencies of sound.

Fig. 15 illustrates the peak-to-peak Sound Pressure Level of the impact piling as a function of the range from the piling, for all three piles driven. It may be seen that there is a significant scatter in the levels of noise recorded. It may be noted that although overall there was a general fall in noise level with range, there are some points where the noise was significantly higher or lower than the general trend. The reason for these is not known, but it is possible that it results from partial focussing or defocussing of noise during propagation through the water and sediments. There is also a significant variation in overall level between the three different piles driven.

In order to generalise measurements to provide an objective assessment of degree of any environmental effect and the range within which it will occur, it is normal to represent the sound in terms of two parameters. These are:-

1. The Source Level (i.e. level of sound) generated by the source, and the
2. Transmission Loss, i.e. the rate at which sound from the source is attenuated as it propagates.

If a given sound can be represented in terms of these two parameters it allows the sound level at all distances to be specified. Usually the decrease in sound pressure level (SPL) is modelled as being due to geometric losses, i.e. the sound mainly reduces as a result of being spread over an increasing area. Under these circumstances the (SPL) is modelled as

$$\text{SPL} = \text{SL} - N_g \log(R)$$

where SL is the source level of the noise source, N_g is an geometric attenuation constant and R is the range in metres from the source.

However, for the measurements of impact piling at the Red Funnel terminal, the losses in level with range were thought to be mainly due to absorption; consequently a reasonable fit is given by the linear equation

$$\text{SPL} = \text{SL} - N_a (R)$$

where the Source Level is about 194 dB re 1 μPa , and the Transmission Loss rate N_a is about 0.15 dB per metre. At the range at which most of the monitoring was conducted (400 m) the average level from the impact piling would thus be 134 dB re 1 μPa

It is interesting to note that the Source Level of 194 dB is slightly higher than that measured during previous measurements at Littlehampton (Nedwell & Edwards, (2002)) of 192 dB re 1 μPa . These levels are, however, very much lower than others obtained by the authors for underwater piling in deep water, where Source Levels of 246 dB re 1 μPa @ 1 metre have been recorded, associated with propagation to large distances.

4. Observations of fish behaviour.

4.1. Fish monitoring methods.

4.1.1. Source and preparation of fish.

Owing to the problems of obtaining salmon for testing, farmed brown trout (*Salmo trutta*) were used in the tests, being the most closely related species. These were freshwater trout and were obtained from Itchen Valley Trout Farm at Alresford. The average size of fish was 25.4 cm (range 24.0-28.0 cm).

Prior to experimentation the fish were transported to Fawley Aquatic Research Laboratories and acclimated to seawater. This process was carried out gradually over a period of 5 days or more without any apparent adverse effects on the fish. During this time and during the monitoring they were fed pelleted food.

4.1.2. Fish cage design and deployment.

Cages were purpose built for the project and were based on a nominal 1 m cube design. The frames were made from mild steel angle and spray-painted. Plastic mesh of about 25 mm square aperture was fixed to the outside of the frames using plastic-coated wire. A 20 cm-square flap opening was made in the top of the cage, the edges being reinforced with 25 mm plastic pipe attached to both the flap and the outer edges. These were used for introducing the fish and for removing them at the end of the trials. Cable-ties were used to close the openings during the tests. A photograph of a cage is given in Fig. 16.

During the trials the cages were taken to their respective positions suspended from 25 litre surface buoys by four ropes fixed to the top corners of the cage. The rope lengths were adjusted to put the centre of the cage 2.5 m below the water surface. Although the monitoring for Red Funnel Ltd required only a cage at 400 m (nominal), cages were also positioned at nominal distances of 25 m (cage 1), 50 m (cage 2), 100 m (cage 3), and 200 m (cage 4) as part of the EA-funded research project; these were as close as possible to the acoustic monitoring positions, without the hydrophones being able to touch the cages. A further 'control' cage was located in the dock of Fawley Power Station, approximately 10 km from the piling site; this dock was not subject to boat traffic or other significant disturbance during the period when fish were held there.

4.1.3. Closed-circuit television monitoring.

The behaviour of the fish was monitored via underwater closed-circuit television (CCTV) cameras fitted inside each of the fish cages. Aquacam® monochrome underwater cameras were used, these being waterproof to 10 m depth. Mountings for the cameras were fixed close to the top corner of the inside of the cage. The cameras were introduced via the openings and attached to the mountings. This allowed the cameras to be aimed across the long diagonal of the cage for maximum field of view.

Signals from the cameras were fed into multiplexers and thence into time lapse video cassette recorders (VCRs) and video monitors. The longest cable run was 180 m and a line amplifier was used to boost the signal and improve picture quality. The VCRs were run in 3-hour mode (i.e. non-time-lapse) and tapes were changed every 3 hours during the working day. This meant that a considerable number of hours of 'control' (background) records were made when there were numerous disturbances from boat traffic, including the regular arrivals and departures of the Red Funnel Isle of Wight ferries, small craft movements and the occasional ocean liner passing. A typical frame from the video recording is shown in Fig. 17.

On completion of the field work sequences of images were digitized and transferred to CD-ROMs using a WinTV® digital interface.

4.1.4. Assessing fish reactions to noise.

Video tapes were reviewed after the event to identify any changes in behaviour that might have resulted from the piling noise or other local underwater noise events associated with ship movements in the locality. All reviewing was undertaken 'blind' by the operators, i.e. they were unaware of what sequences correlated with particular events and this information was only later added by another operator.

Two types of behaviour were investigated:

Startle reactions: A startle reaction here was defined as the 'C-start' behaviour described by Blaxter and Hoss (1981) in response to an underwater sound stimulus, i.e. a sudden C-shaped flexure of the fish's body, which is quite clearly different from routine swimming activity.

Fish activity level: The second type of behaviour considered was a simple change in activity level of the fish. Captive fish that are exposed to irritating stimuli commonly show 'milling behaviour', in which the fish swim faster and make random turns. This type of behaviour is believed to provide a strategy for sampling the environment to expedite the fish's escape from potentially harmful conditions.

Activity level was measured by counting the number of times a fish entered the camera's field of view within a two-minute observation period. This was possible because the field of view was limited by water clarity, so that the fish moved frequently in and out of vision. For each type of event investigated, a two-minute 'control' period preceded each two-minute 'event' period. The control and event activity levels were compared using the non-parametric Mann-Whitney U-test (Campbell (1974)) with the null hypothesis that activity levels were not significantly different at a specified probability level.

4.1.5. Post-trial treatment of fish.

Fish were removed from the cages at the end of the trials and returned to the laboratory for further analysis. The fish were examined for signs of pressure-related injury (Turnpenny (1998)), e.g. externally for haemorrhaging of the eyes or gas embolisms in the eyes, and internally for swimbladder rupture.

4.2. Fish behavioural reactions.

4.2.1. Behavioural reactions during vibro-piling

The initial cage placed at Location 5 (end of Town Quay, 400 m) to fulfil the Red Funnel monitoring obligations was put in position 24 h prior to the start of vibropiling but was raided overnight and the fish stolen. Since cages were in place at the other locations and fish in these showed no reaction to vibropiling, the cage at Location 5 was not replenished until 24 h before the start of impact piling. Observations are presented here for the cages at Locations 1 and 2.

Analysis of startle reactions was based on review of the VCR images at the start-up instant of each vibropiling session and for the next 5 seconds. No startle response was seen in any of the vibropiling sequences for any of the piles driven by this method.

Table 4.1 and Fig. 18 show the activity level observations (number of movements per 2-minute period) for the 2-minute period prior to piling and then for the first 2 minutes during vibropiling. Activity levels are seen to remain similar before and after the start of piling. The

data shown combine the observations for all of the vibropiling operations. The Mann-Whitney U-test shows that there was no significant difference in activity level following the commencement of vibropiling ($P=0.001$).

| No. of movements per 2 min period | | | Mann-Whitney U test | | |
|-----------------------------------|--------|--------|---------------------|--------|--------|
| Location | Before | During | U | Z | P |
| 1 | 147.5 | 152.5 | 69.5 | 0.1443 | 0.8852 |
| 2 | 150.5 | 149.5 | 71.5 | -0.028 | 0.9769 |

Table 4.1. Fish activity statistics for vibration piling.

4.2.2. Behavioural reactions during impact piling

Impact piling was carried out on 24th September and data are reported here only for Location 5. Table 4.2 shows that no startle reaction was recorded for the start of each of the three piling sessions that took place.

| Pile | Start Time | Startle Reaction ? |
|------------|------------|--------------------|
| 1 (914 mm) | 08.41 | no |
| 2 (508 mm) | 11.11 | no |
| 3 (505 mm) | 11.54 | no |

Table 4.2. Fish startle reactions.

Activity levels recorded before and during the impact piling sessions are shown in Table 4.3 and Fig. 19. These again show no significant difference ($P=0.001$) between activity levels before and during testing.

| No. of movements per 2 min period | | | Mann-Whitney U test | | |
|-----------------------------------|--------|--------|---------------------|-------|-------|
| Location | Before | During | U | Z | P |
| 5 | 12 | 9 | 3 | 0.654 | 0.512 |

Table 4.3. Fish activity statistics for impact piling.

4.3. Fish injuries

Table 4.4 records fish injuries investigated. No evidence of fish injuries was seen in either the fish held at Location 5 or in the Fawley controls.

| Type of Injury | Frequency (sample size 10 fish per cage) | |
|---------------------|--|-----------------------|
| | Location 5 (Town Quay) | Control (Fawley Dock) |
| Swimbladder rupture | 0 | 0 |
| Eye haemorrhage | 0 | 0 |
| Eye embolisms | 0 | 0 |

Table 4.4. Fish injury records.

4.4. Summary of observations on fish.

The caged trout monitoring revealed:

1. No evidence that trout reacted to impact piling at the regulatory stand-off range of 400 m;
2. No evidence that trout reacted to vibropiling even at close range (<50 m);
3. No evidence of gross physical injury to trout at the monitoring range of 400 m.

5. Conclusions

1. Monitoring measurements of the waterborne noise resulting from impact piling and vibropiling were taken at Town Quay, Southampton, during construction operations at Red Funnel's Southampton Terminal in September 2003. At the same time, the reactions of caged farmed brown trout (*Salmo trutta*) was observed on CCTV equipment to determine whether there was any observable effect of the piling on the their behaviour.
2. In respect of the vibropiling, at the range at which monitoring was conducted of 417 metres, the noise could not be detected above background noise, with any noise from the vibropiling being drowned by noise from the movement of vessels.
3. The caged trout monitoring revealed no evidence that trout reacted to vibropiling at even a close range of less than 50 m.
4. The Source Level of the impact piling was about 194 dB re 1 μ Pa, and the Transmission Loss rate N_a is about 0.15 dB per metre.
5. There was no evidence of gross physical injury or that trout reacted to the impact piling at the monitoring range of 400 m, at which range the sound level would have been about 134 dB re 1 μ Pa.

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Figures



Fig. 1. Photograph taken from quayside with ferry docked at terminal, and vehicles disembarking along linkspan. Structure on left of photograph is covered walkway for pedestrian passengers, and the dolphin on which it rests can be seen.

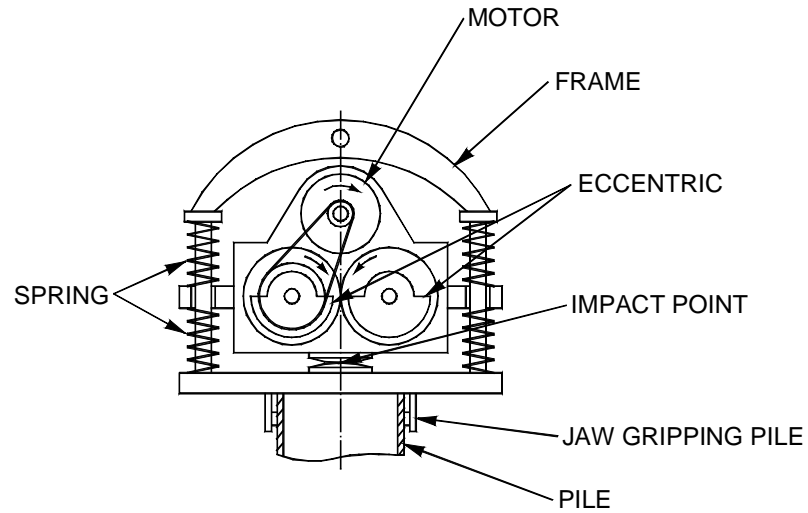


Fig. 2. Sketch to illustrate principle of vibro pile driving.

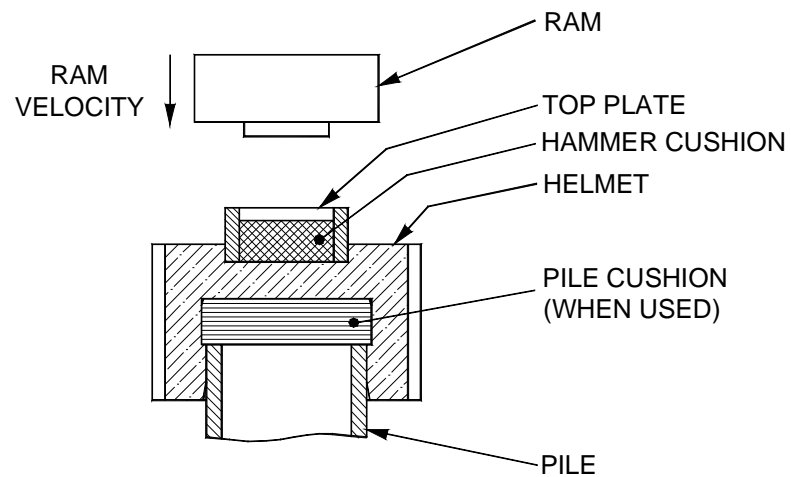


Fig. 3. Sketch to illustrate principle of impact piling.

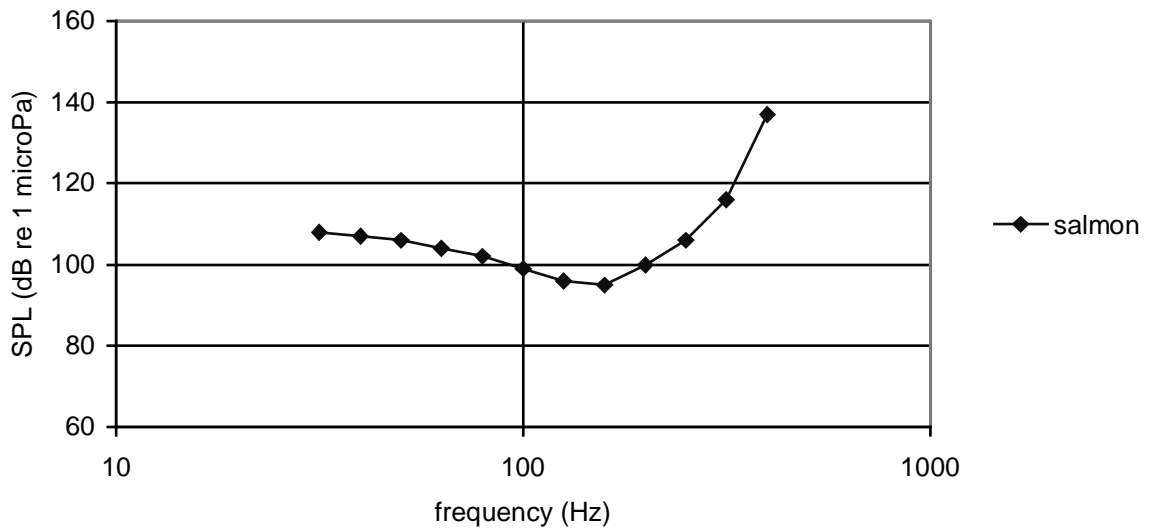


Fig. 4. An audiogramme of salmon hearing.

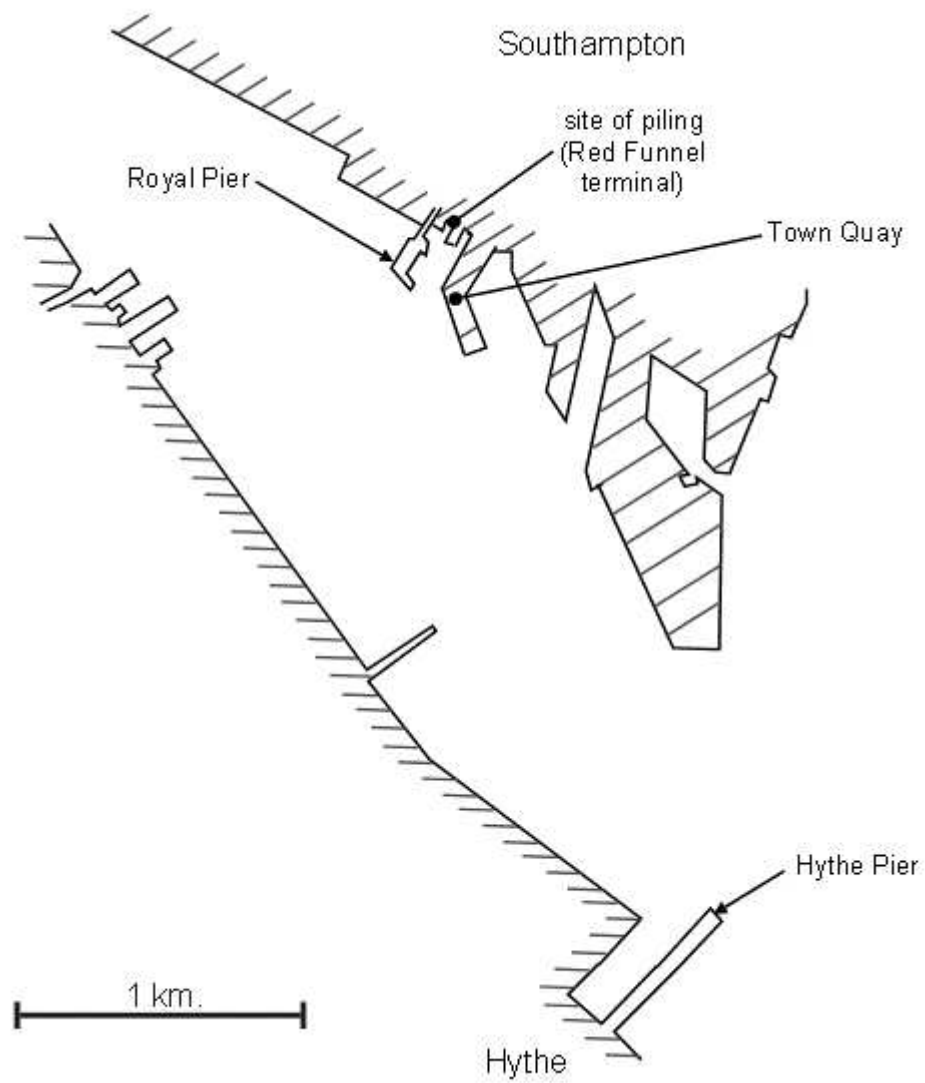


Fig. 5. Sketch map showing location of site in Southampton

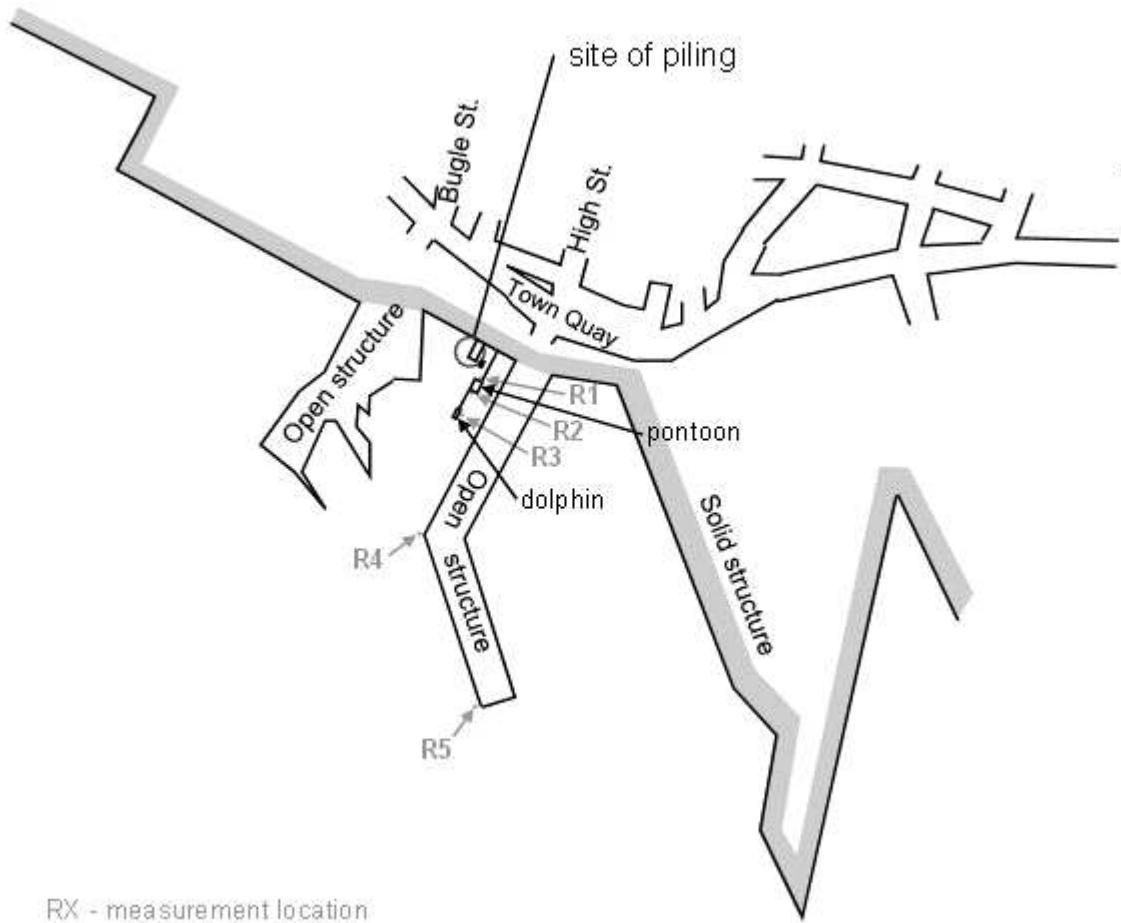


Fig. 6. Sketch map showing piling and measurement locations.

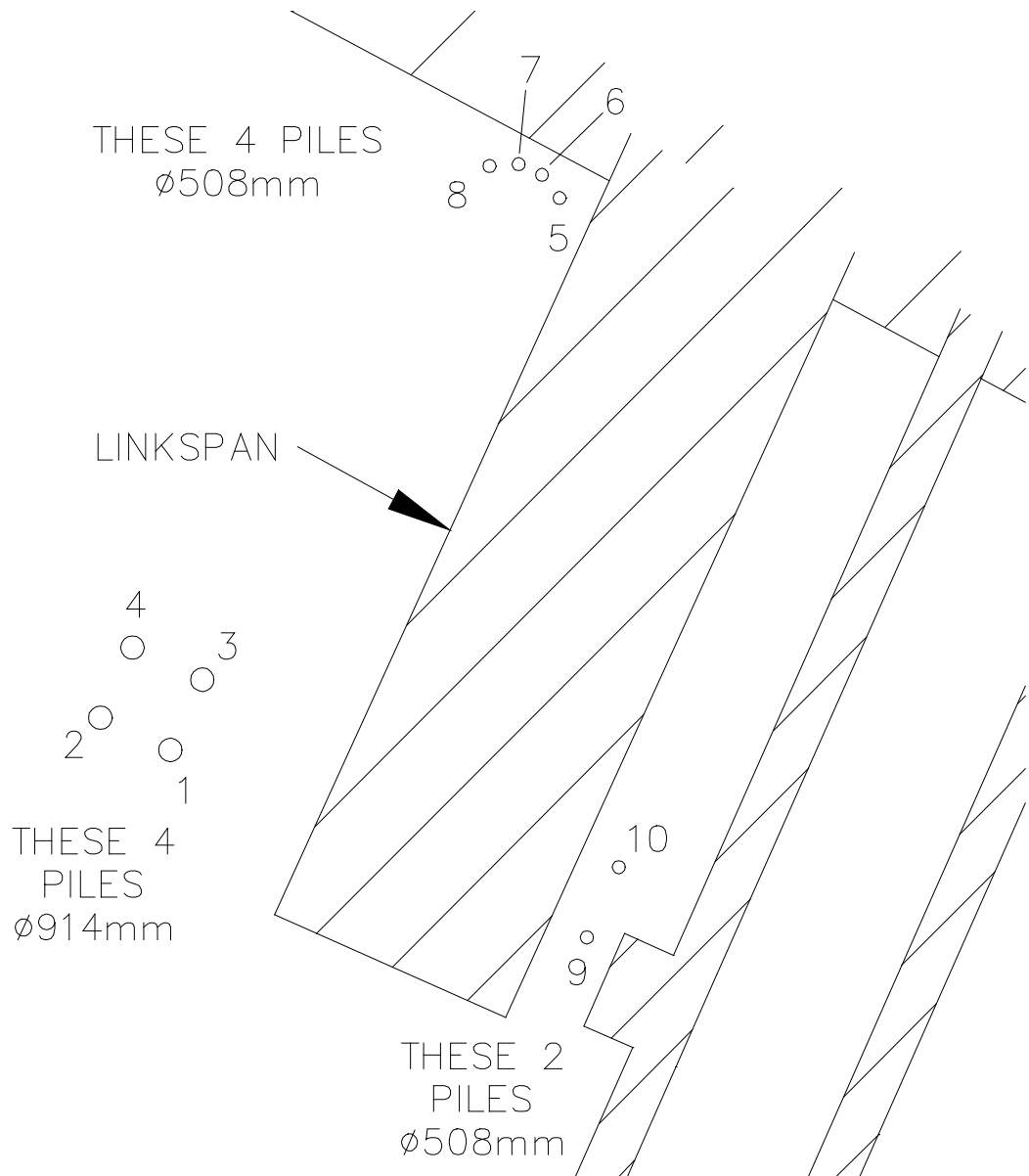


Fig. 7. Details of pile locations.



Fig. 8. Photograph of pile tubes being unloaded from lorry.



Fig. 9. Photograph of site during piling operations. The two groups of four piles to one side of the linkspan can be seen. The other two piles (numbers 9 and 10) are obscured by the structure (pedestrian walkway) on the right of the photograph. One pile in each of the groups was left standing proud, for later dynamic testing purposes using the impact driver.



Fig. 10. A PVE 2316 VM vibropiling driver. It is shown resting in a cradle made of I-section beams.

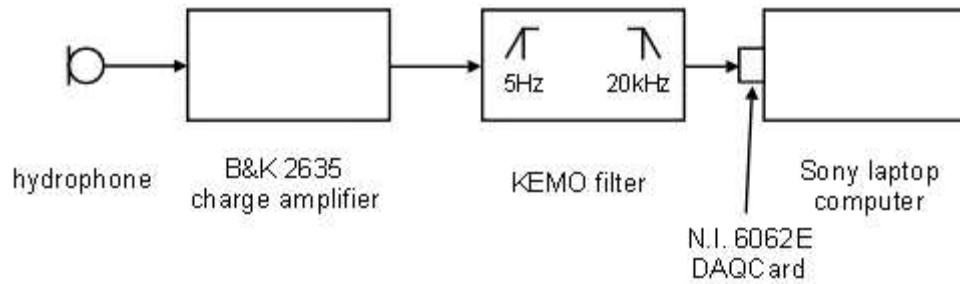


(a). A view of the lower end of the impact driver, while it was lying on a lorry.

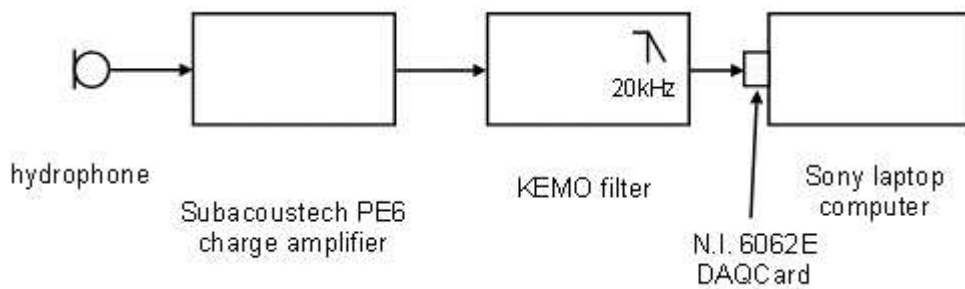


(b). The impact driver being held on the top of a pile for driving purposes.

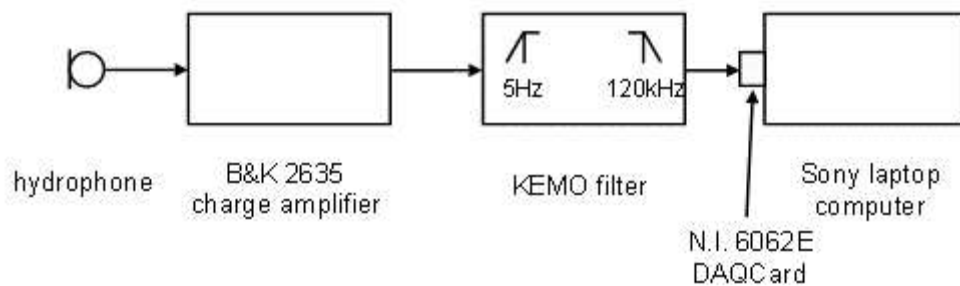
Fig. 11. The BSP 357/9 Hydraulic Drop Hammer used for impact driving.



(a). set-up for 8104 and 8105 hydrophones, for vibrodriving.



(b). set-up for 8106 hydrophone, for vibrodriving.



(c). set-up for 8105 hydrophone, for impact driving.

Fig. 12. Block diagram of instrumentation.

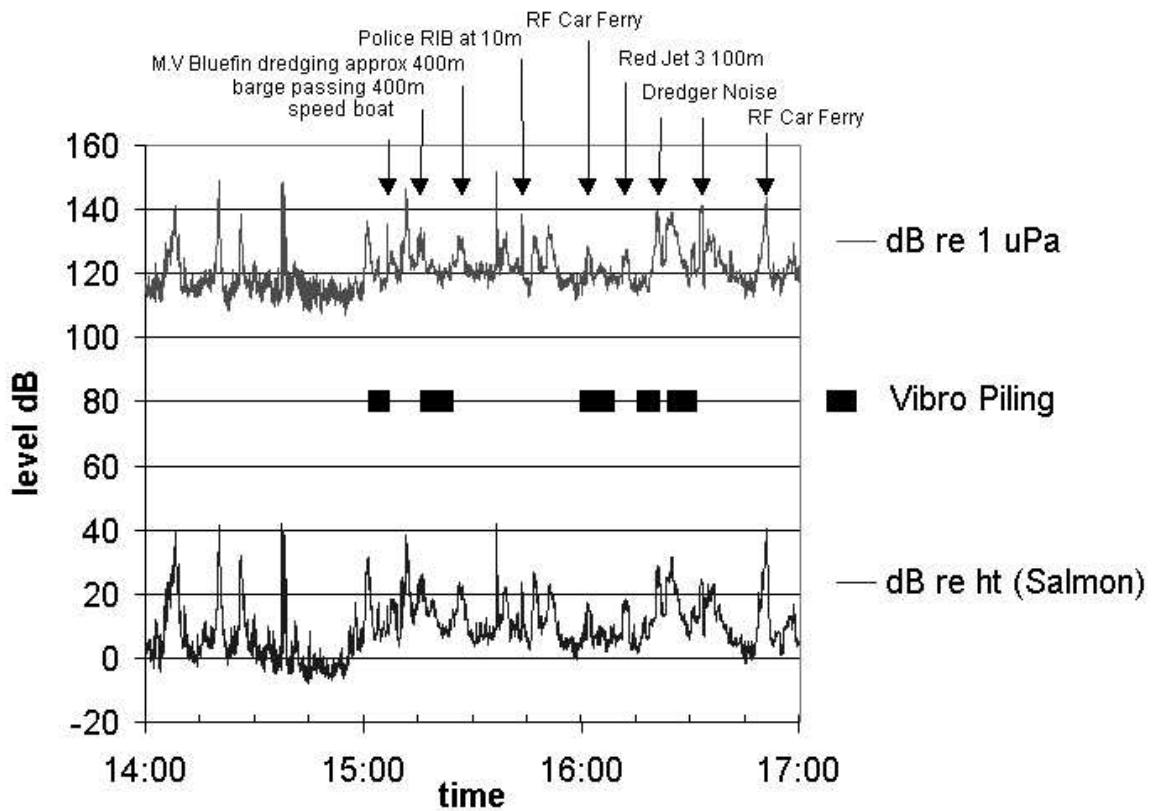
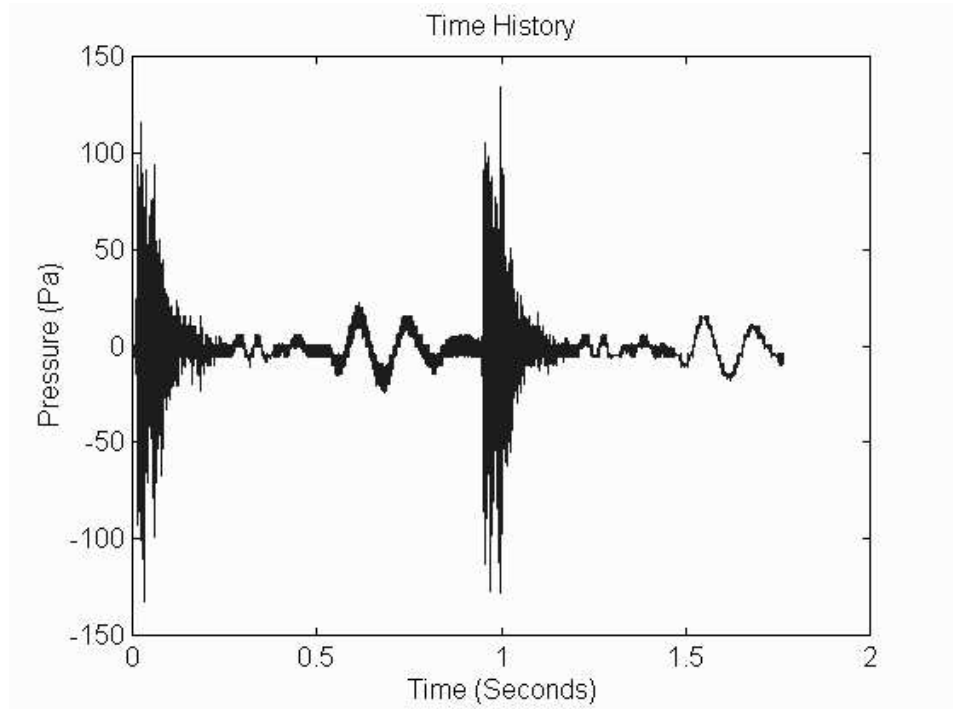
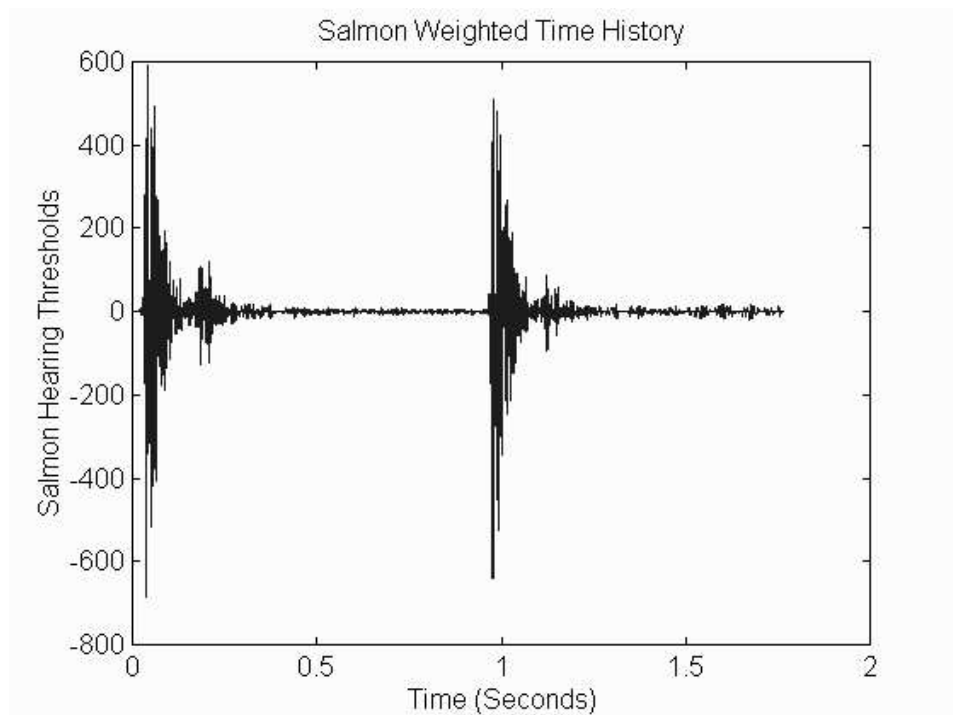


Fig. 13. A typical sound pressure level vs. time history obtained at the end of Town Quay (location R5) for a vibro-driving case.



(a). An unweighted time history.



(b). Time history using the salmon weighting curve.

Fig. 14. A pressure vs. time history for impact driving, obtained from measurements at location R3.

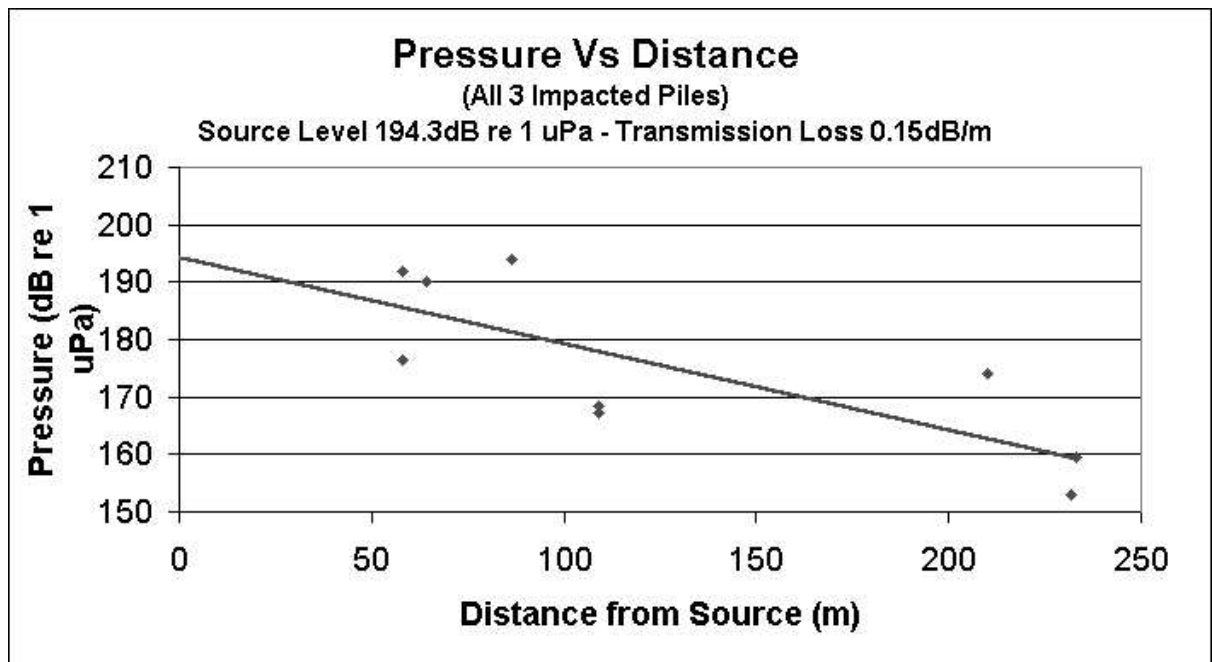


Fig. 15. Variation of peak-to-peak pressure with distance for impact driving.



(a). A general view.



(b). View showing flap opening for introducing and removing the fish.

Fig. 16. A cage used for the fish monitoring.

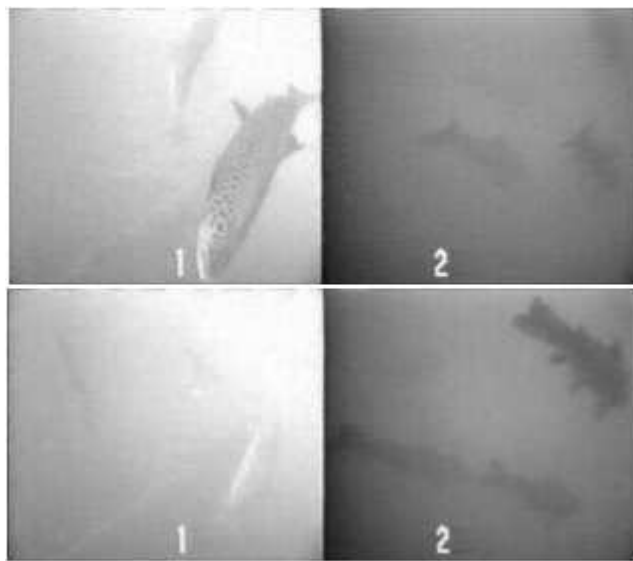


Fig. 17. A clip from the fish monitoring video.

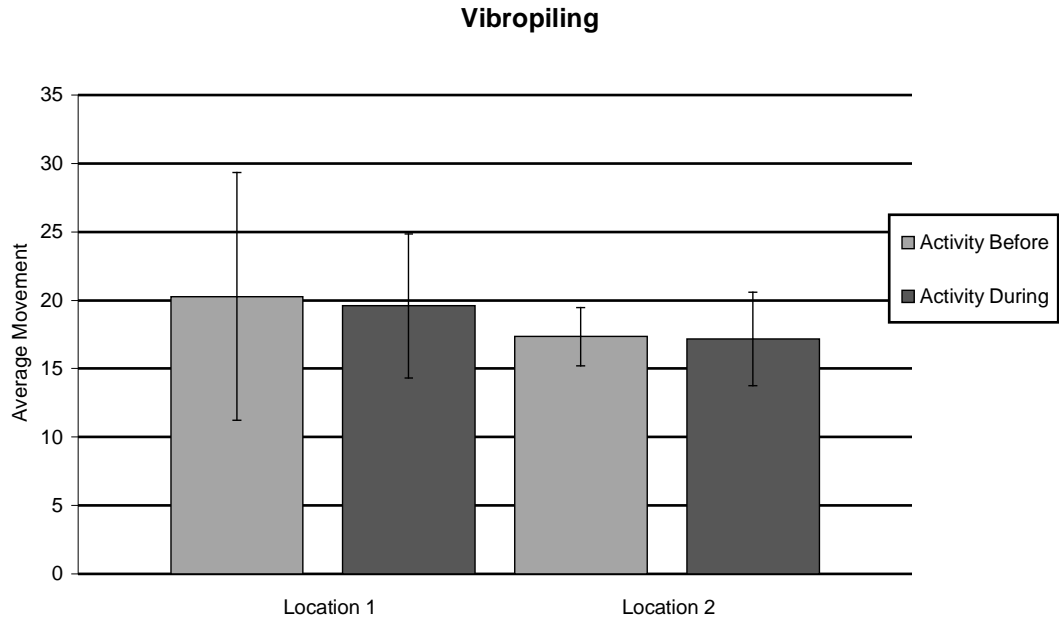


Fig. 18. Comparison of fish activity levels before and during vibropiling (all data collected between 15-23 September), based on observed fish movements over 2 minutes before the start of piling and for 2 minutes from the start of driving each pile (mean & 95% confidence interval).

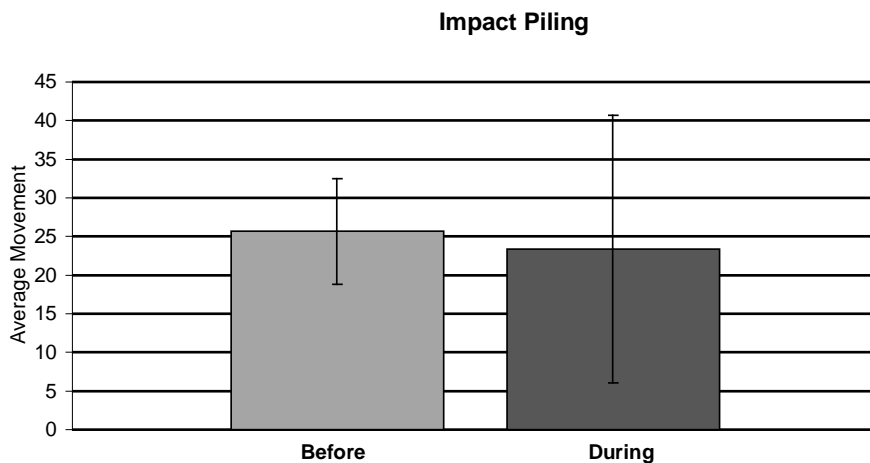


Fig. 19. Comparison of fish activity levels before and during impact piling (piling on 24th September), based on observed fish movements over 2 minutes before the start of piling and for 2 minutes from the start of driving each pile (mean & 95% confidence interval).

Appendix 1: Hydrophone calibration certificates

Calibration Chart for Hydrophone Type 8104 Serial No.:2225716



Calibration Chart for Hydrophone Type 8104

Serial No.: 2225716

Reference Sensitivity at 250 Hz ± 2% at 23 °C
Including integral cable 10 m

Voltage Sensitivity (Open Circuit Sensitivity):
206 dB ± 0.25 dB re 1 V/μPa** or 495 μV/Pa

Charge Sensitivity: 422 · 10⁻³ pC/Pa

Capacitance (including integral cable): 8520 pF

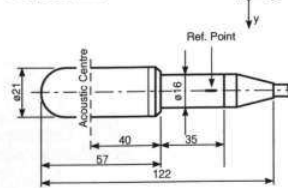
Cable Capacitance: 150 pF/m

Leakage Resistance: 2800 MΩ at 23 °C

Frequency Response (at ref. pos.):
Individual Free Field Frequency Response Curve attached

Measuring Uncertainty (re 10 kHz):
10 to 80 kHz ± 1.5 dB
80 to 100 kHz ± 1.8 dB
100 to 200 kHz ± 1.5 dB, -3.5 dB

Physical (mm)



Cable: Shielded low noise with two conductors, waterblocked to MIL - C - 915

Weight (including 10 m cable): 1.6 kg

Environmental

Operating Temperature Range:
Short term -40° C to +120° C
Continuous -40° C to +80° C

Change of Sensitivity with Temperature:
Charge 0 to 0.03 dB/°C
Voltage 0 to -0.04 dB/°C

Change of Sensitivity with Static Pressure:
0 to -3x10¹ dB/Pa
(0 to -0.03 dB/atm)

Temperature Transient Sensitivity: ≤ 70 Pa/°C
(ANSI S2.11-1969); measured with Brüel & Kjær Charge Preampifier Type 2626, LLF 3 Hz

Allowable Total Radiation Dose: 5 x 10⁷ Rad

Maximum Operating Static Pressure: 4 x 10⁶ Pa (40 atm)

Summarized Specifications (re 250 Hz)

Frequency Response (tolerance field excluding measurement uncertainty):
0.1 Hz to 10 kHz ± 1.5 dB
0.1 Hz to 80 kHz ± 4 dB
0.1 Hz. to 120 kHz +4 dB, 12 dB

Horizontal Directivity 100 kHz:
(XY-plane) ±2 dB

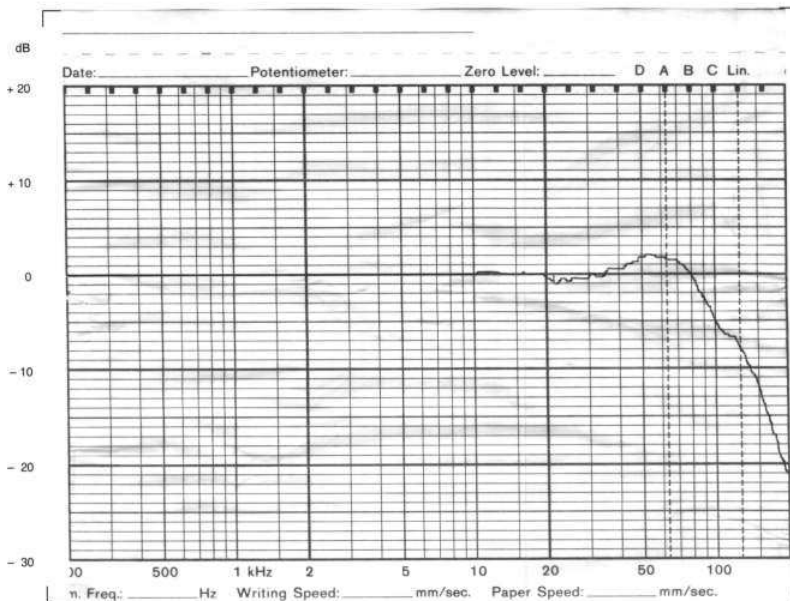
Vertical Directivity 50 kHz:
(XZ-plane) ±2 dB

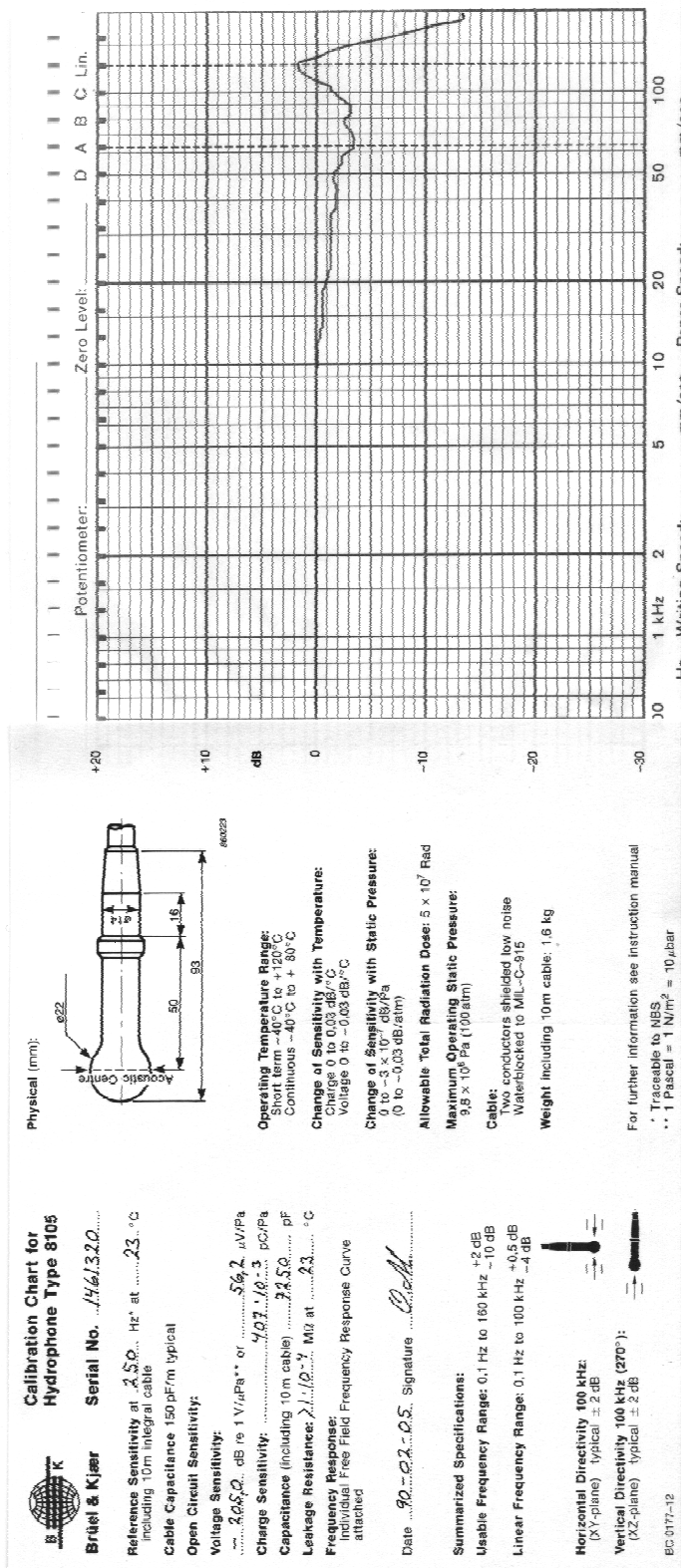
Note: All values are typical at 25° C (77° F), unless measurement uncertainty or tolerance limit is specified. All uncertainty values are specified at 2 σ (i.e. expanded uncertainty using a coverage factor of 2).

For further information see User Manual

* Sensitivity Traceable to:
DPLA: Danish Primary Laboratory of Acoustics
NIST: National Institute of Standards and Technology, USA
** 1 Pascal = 1Nm⁻² = 10 μbar

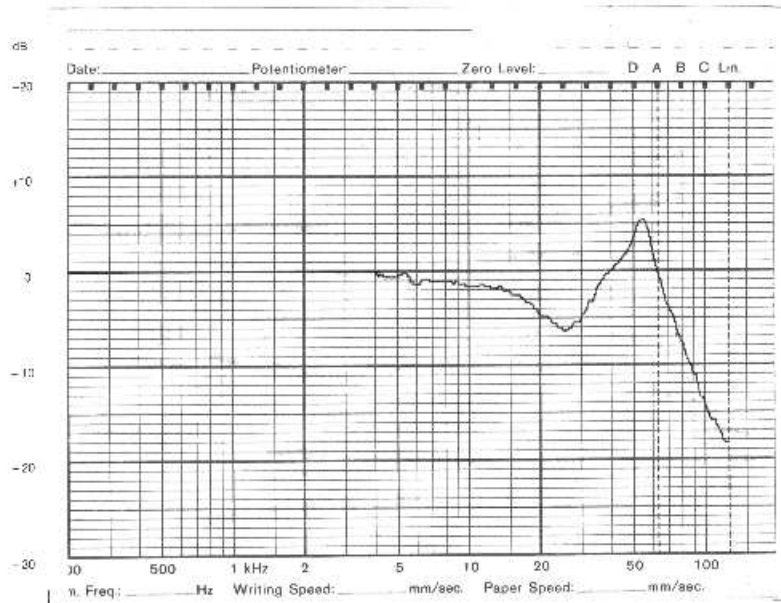
Date 6 Dec 00 Signature PTO





Calibration Chart for Hydrophone Type 8106

Serial No.: 2256725



Physical Unit
 Weight (including cable): 305 g
Preamplifier
 Gain: 11 dB
 Maximum Output Signal: 3.5 V or 28 mA for a 12 V supply; 7.0 V or 28 mA for a 24 V supply
 High-pass Filter: 3 dB at 7 Hz, 1.2 Hz
 Maximum Output Effect: 50 mV
 Output Impedance: < 30 Ω
 Caution: Do not exceed 15 V insert voltage calibration signal
Environmental
 Operating Temperature Range: 10°C to +80°C
 Storage Temperature Range: -40°C to +80°C
 Change of Voltage Sensitivity with Temperature: 1 Hz, 0.1% / °C
 Change of Sensitivity with Static Pressure: 1 Hz, 1% / 10⁵ Pa (0.75 - 3.0 bar) (dB/m)
 Maximum Operating Static Pressure: 3.8 x 10⁷ Pa (300 atm)

Allowable Total Radiation Dose: 5 x 10⁷ Rad
 For further information see User Manual
 * Sensitivity (available)
 Briel-Kjaer A/S, Department of Acoustics
 P.O. Box 105, DK-2600 Lyngby, Denmark
 Tel: +45 44 45 88 00, Fax: +45 44 45 88 01

Calibration Chart for Hydrophone Type 8106

Serial No.: 2256725
 Reference Sensitivity at 25°C: 2.3 mV/μPa
 Voltage Sensitivity (open circuit) at 25°C: 2.3 mV/μPa
 Frequency Response (at 25°C): 1 Hz to 100 kHz
 Frequency Response (at 25°C): 1 Hz to 100 kHz
 Frequency Response (at 25°C): 1 Hz to 100 kHz
 Measurement Uncertainty: 10% (1 Hz)

Summarized Specifications (at 25°C)
 Frequency Response: 1 Hz to 100 kHz
 Sensitivity: 2.3 mV/μPa
 Measurement Uncertainty: 10%
 Horizontal Directivity: 20 kHz: ±2 dB
 Vertical Directivity: 20 kHz: ±3 dB

Notes: All values are typical at 25°C (V_{eff}) unless measurement uncertainty or tolerance limit is specified. All uncertainty values are specified at 25°C. The indicated uncertainty using a coverage factor of 2.
 CE
 Date: 08 Feb 2007
 Signature: [Handwritten Signature]