SENSING THE SEABED VIBRATIONS – AND SIMULATING THE SEISMIC INTERFACE WAVES

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1 INTRODUCTION

Sound waves from overlying water can affect the seabed, but there are also waves confined to the seabed, with energy from vibratory sources which propagates independently. Measurements and modelling using realistic seabed data show that these modes occur at low frequencies (~20Hz) with low wave speeds (~100m/s). These vibration waveforms do not radiate sound pressure waves into the adjacent bulk media, and can be considered quite separately.

Although their effects can be sensed within both solid and fluid media adjacent to a seabed interface, they show an evanescent decay as the sensors move up or down away from the seabed. In the fluid their water particle motions are almost circular, quite different from the linear motions (to and fro) in plane waves, the simplest configuration of sound pressure waves.

Whilst they can be detected by hydrophones, measuring motion with inertial sensors such as geophones yields more information. It is widely understood that many creatures which occupy this habitat sense such water particle motion, and recent work by Roberts[1] used vibration of the tank wall to study the sensitivities of ground dwelling species such as crabs and mussels. Earlier work by Hawkins & MacLennan[2] used pressure generators to create this motion.

Biological measurements in the laboratory can be improved by an understanding of the seismic wave properties. A small sealed tank acts as a rigid body at low frequencies, with little acoustic pressure created within it as it moves. Geophones can then monitor the motion of the tank and all the water within it. Previous adverse comments by Parvalescu[3] on such a system may have been based on a lack of understanding of the sensitivities to water particle velocity.

The low frequency vibration required can be generated by geophones acting as vibration sources. Geophones have been tested in pairs, with voltages applied to one and output from the other, and with their motion measured by laser vibrometer. Spectral plots of their sensitivity are useful in the design of test systems for bench top biological investigations.

2 MEASUREMENTS OF DREDGING IMPACTS

Seabed vibrations were measured in 2011 by Robinson et al[4] as a subset of a major study of the environmental noise emitted by dredging for offshore aggregates. For one trial a geophone sledge was deployed in ~30m water depth. The dredger "City of Chichester" was operating in the English Channel south of the Needles headland (Isle of Wight). The hydrophone records showed little additional noise below 500Hz compared with other ships of similar size, although increases were seen at frequencies over 1 kHz, due to the operation of the dredging equipment.

In contrast the seabed vibrations during dredging were dominated by an almost sinusoidal narrow band response around 20 Hz. The LGT-20D10 geophones have a primary resonance at 10Hz, but this is damped to give a flat response of ~20 V/(m/s) over the 16 – 300Hz band. Components above 200Hz were filtered to avoid spurious resonances known to exist within the sledge.

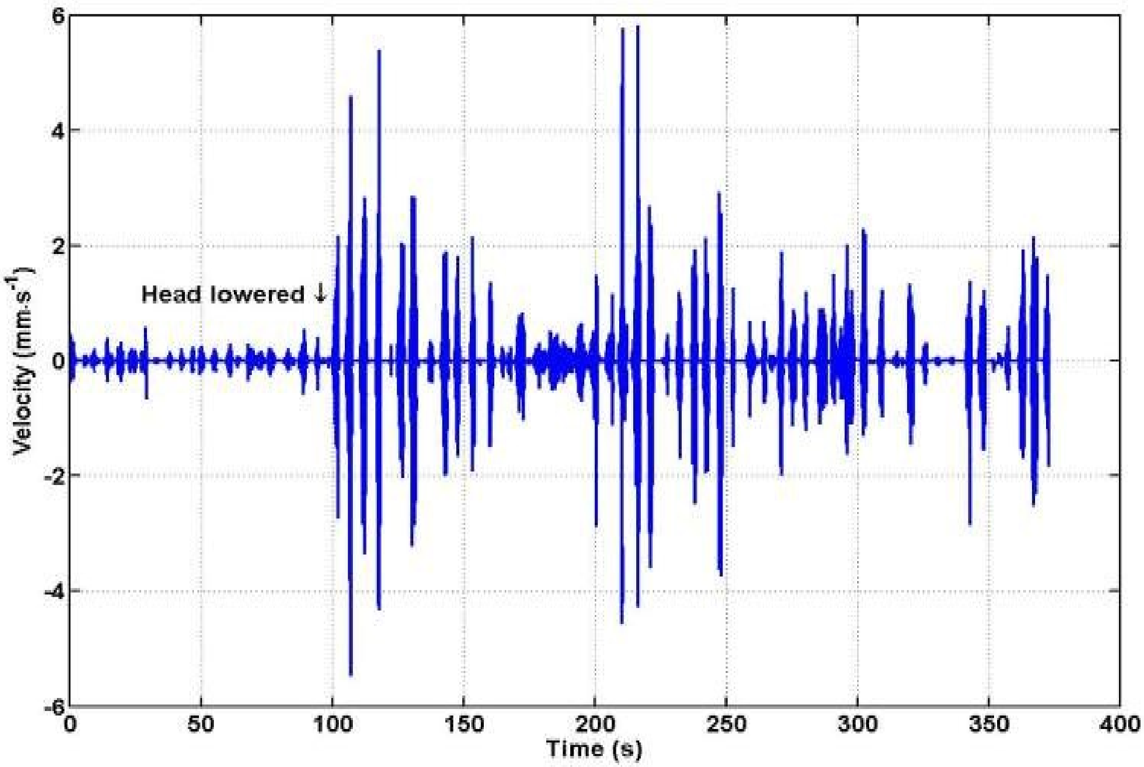


Fig1. The recorded vibration increased sharply when the dredge head was lowered into contact

The response grew when the dredge head was lowered to the seabed, (Fig 1 at 100s) when operating about 100m away from the sledge. Each peak shown consists of a seismic wavelet, a packet of narrow band energy. In the report the dominance of the ~23 Hz signals (Fig 2) was tentatively assigned to a resonance on the dredger. However, this is more credibly explained by the response of the seabed.

3 ANALYSIS OF THE VECTOR COMPONENTS

Further analysis of a selected wavelet was made using all three geophones, arranged to sense three velocity vectors labelled “Heave”, “Surge” and “Sway”, terms used for ship motion. Heave is vertical motion, whilst surge is in the direction of the “prow”, the tow point by which the sledge was aligned and bedded in. A separate tow line was used, alongside the deployment line and signal cable, all of which were slack whilst the monitoring vessel “George D” was at anchor.

The plot of surge against sway (the lateral motion) forms a transverse plane hodogram (Fig2) which indicates a bearing for the source ~ 15° off the prow. The surge waveform is the largest, peaking at almost 5 mm/s. Other records had peaks up to 6mm/s. The sagittal plane hodogram (heave v surge) shows ellipsoidal figures which become nearly circular in the coronal plane (heave v sway). A circular plot indicates a 90° phase difference between the vertical and horizontal motion. This pattern is the signature of ground roll, the seismic “Rayleigh” waves which share their elliptical motion with the analysis made by Lord Rayleigh.[5]

His equations are for waves on an interface between an infinite isotropic solid and a vacuum, two adjacent “half-spaces” with no dimensions specified. True Rayleigh waves in half-space models show no dispersion. Waveforms are transmitted without distortion, in contrast to what is seen here. Subsequent half-space models changed the vacuum to another isotropic solid (Stoneley[6]) or a fluid (Scholte[7]) and these also show no dispersion. But computer modelling to replicate the narrow band response and the seismic wavelet structure needed a layered seabed.

All these interface waves share the rolling motion indicated by the elliptical hodograms, with local evanescent energy storage, recovered as the waves pass. No energy is radiated into the spaces above and below. If the internal losses are ignored, this cylindrical energy spreading from a seabed impact source propagates better than sound in open water (spherical spreading). More realistic waves as discussed by Strick et al[8] have other losses.

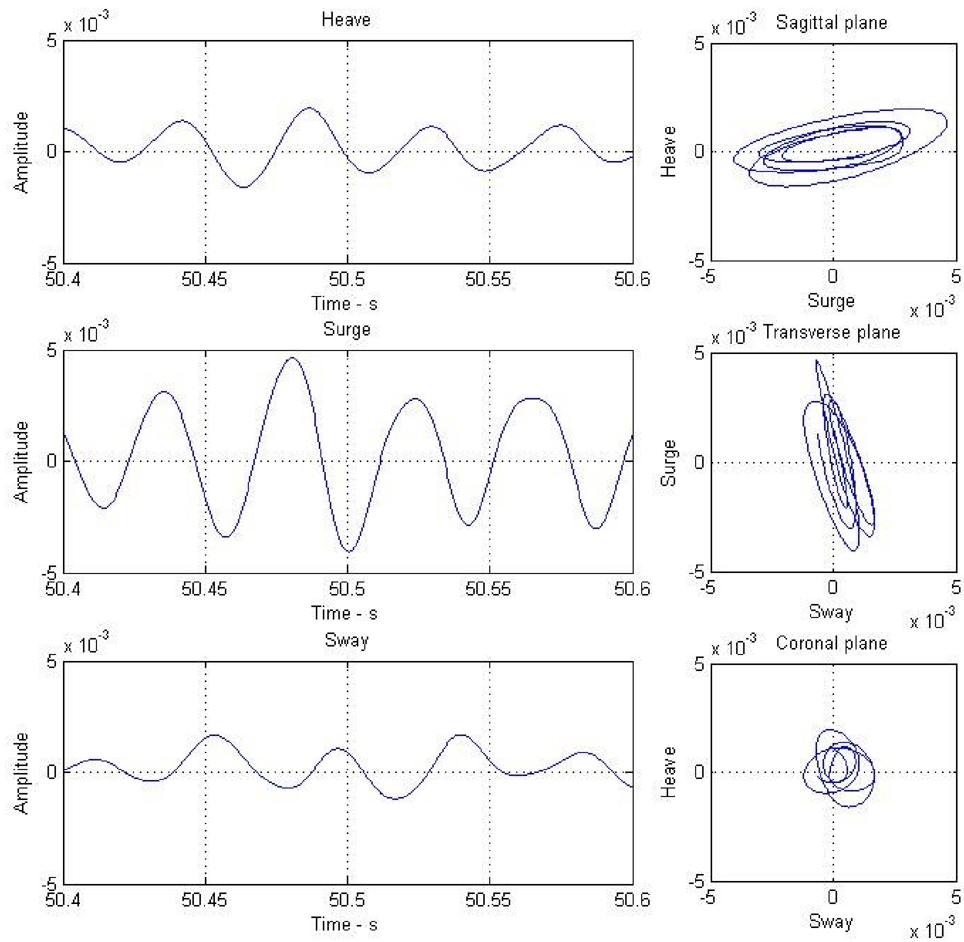


Fig2. A selected wavelet is shown expanded with three signals plotted against each other

4 MEASUREMENTS OF PILING IMPACTS

The sledge developed for the dredging trial was later deployed in a dock at Kinderdijk NL[9], in which an experimental pile was being driven. The instrumentation was on the adjacent quayside, and the data thus includes some reverberation and alignment uncertainty.

However, the timing of the blow is recorded by an accelerometer on the pile and this allows the wave speeds to be assessed. The 45ms delay before the first geophone peaks occur is the time for the pressure wave to reach the sledge at 65m range, whilst the 350ms delay before the onset of the seismic wave corresponds to a ~200m/s transfer of the initial energy.

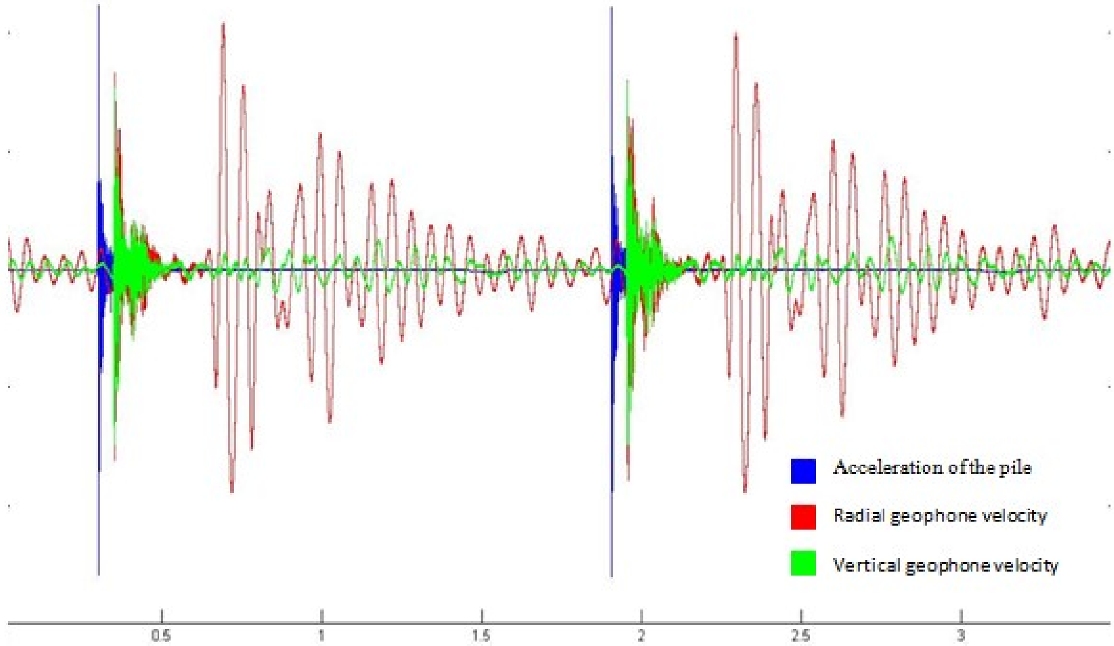


Fig 3 shows two geophone signals (vertical and radial) plus a signal from a pile accelerometer

The impulsive nature of the impact is replicated by the pressure waves, but the seabed vibrations have a greatly extended period of excitation at ~18 Hz. The early signals are due to a sensitivity of the geophone housing to pressure waves, but the later signals are due to the vibration of the sediment in the dock. Energy from the impact is stored and radiated slowly as ground roll waves. The ground roll form is confirmed by the 90° phase shift between the two velocity components.

6 THE USE OF FEA TO STUDY FURTHER DETAILS

The contrast between the nature of the sound pressure waves and the ground roll observed has been studied using Pafec finite element analysis (FEA) by Hazelwood & Macey[10]. Theoretical half space models were amenable to analytic mathematics, but study of the water particle motions associated with the ground roll waves across the seabed needed computer modelling. Various models have been tried, but results here are for a layered seabed structure with mechanical properties which vary from a soft, almost fluid mud at the interface to stiffer clays at depth. The data is from a review of measured seabed structures by Hamilton[11], and extends down to 128m below the interface, well below the penetration of any significant wave energy,

Note that these layer thicknesses now specify dimensions which, in conjunction with the wave speeds, define timescales. This changes the propagation from a dispersion free “hi-fi” system into a strongly modal system, where the seabed properties determine the nature of the wavelets. This was analysed by a transient model using 0.5ms time steps rather than a sinusoidal drive. The piling action is simulated by a 40 ms long force pulse, applied vertically to the seabed, at the origin of an axisymmetric model where waves propagate radially, The details are then displayed on a 2D plot. Fig 3 shows the wavelet in a solid only model after 0.54s.

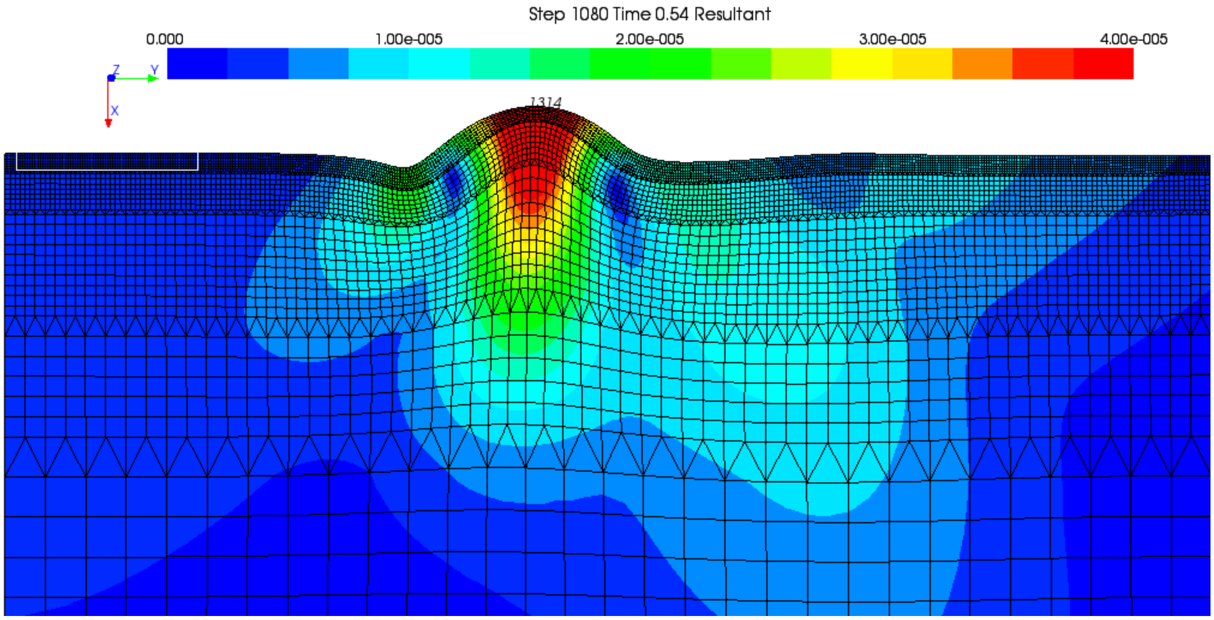


Fig 3 The seabed is divided into smaller elements near the interface. Node 1314 is at 52m radius

This compact wavelet shows the concentration of energy at a single peak, which moves outward (travelling to the right) from the origin. The colour scale shows the displacement vector magnitude displayed as an exaggerated deformation. The largest elements shown here are 2mx2m. The evanescent decay with depth has reduced the deformation to less than 20% of the peak (<10% of the energy density) by 20m depth. The wavelet has been tracked for over 1sec (> 100m from the source), remaining compact, but with metamorphosis from a single hump to a single dip and back again. .This remarkable property appears to be due to the layered seabed structure.

When a 16m water layer is added, the data can be used to determine the water particle velocities, accelerations and the corresponding acoustic pressures. Fig 4 is for model PWB26, where two co-located interface nodes at 64m radius are used to compute both fluid acoustic pressures and solid acceleration. Unlike a plane wave, whose velocity is in phase with the pressure, the acceleration is now in phase with the pressure, to give an “imaginary” fluid acoustic impedance.

The dominant frequency is ~40 Hz so an angular frequency ($\omega = 2\pi f$) of 251 s^{-1} is used to convert the peak acceleration of 5.5 m/s^2 to a velocity of 22 mm/s. With a peak pressure of 3300 Pa the impedance magnitude is ~0.15 MPa/(m/s). For this pressure the water particle velocity is 10 times larger than would be expected using a plane wave “real” impedance of ~ 1.5 MPa/(m/s). The horizontal water motion is also found to exceed that of the ground by a factor ~3. This slippage will tend to rip apart any creature which spans the interface.

Other data provided by the FEA in Hazelwood & Macey[10] may explain the resolution of the 180° ambiguity by small aquatic species. This uncertainty in travel direction is hard to resolve for continuous low frequency plane waves, even using vector sensors such as fish otoliths. But a travel direction reversal changes the progression within a sagittal hodogram from clockwise to anticlockwise. Sensing this change will require the creature to perform a phase analysis.

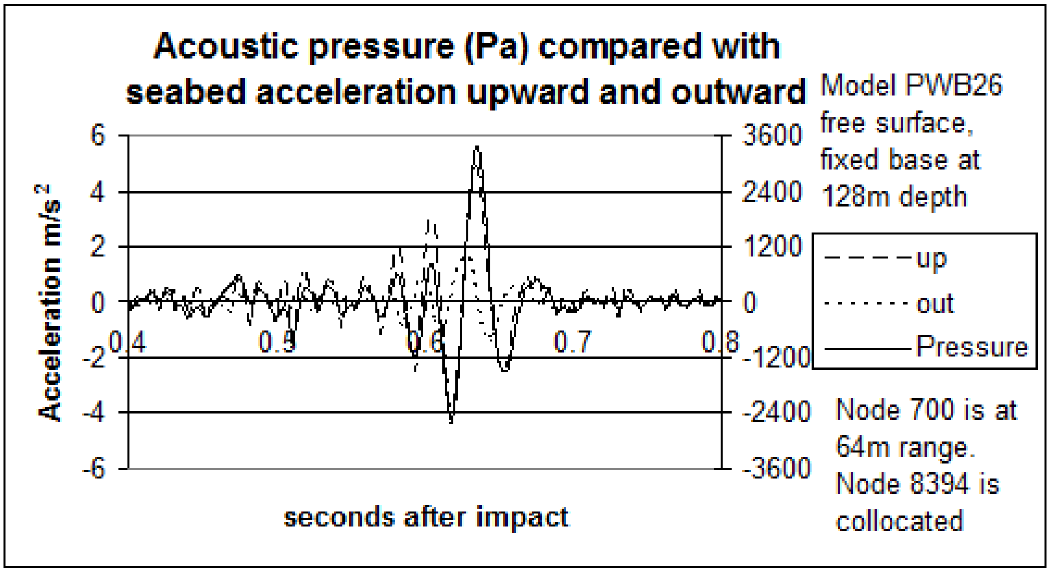


Fig 4 With a covering of water this model PWB26 computes the fluid coupling details.

7 SIMULATING THE VIBRATION IN BIO-SENSITIVITY TESTS

It is recognised that whilst mammals and some fish have excellent hearing, using sound pressure waves for many life functions, other aquatic species are more sensitive to vibration and the water particle velocity[2]. A water particle was defined by Kinsler & Frey[12] as a volume large enough to approximate to a continuous medium but with almost uniform motion and pressure.

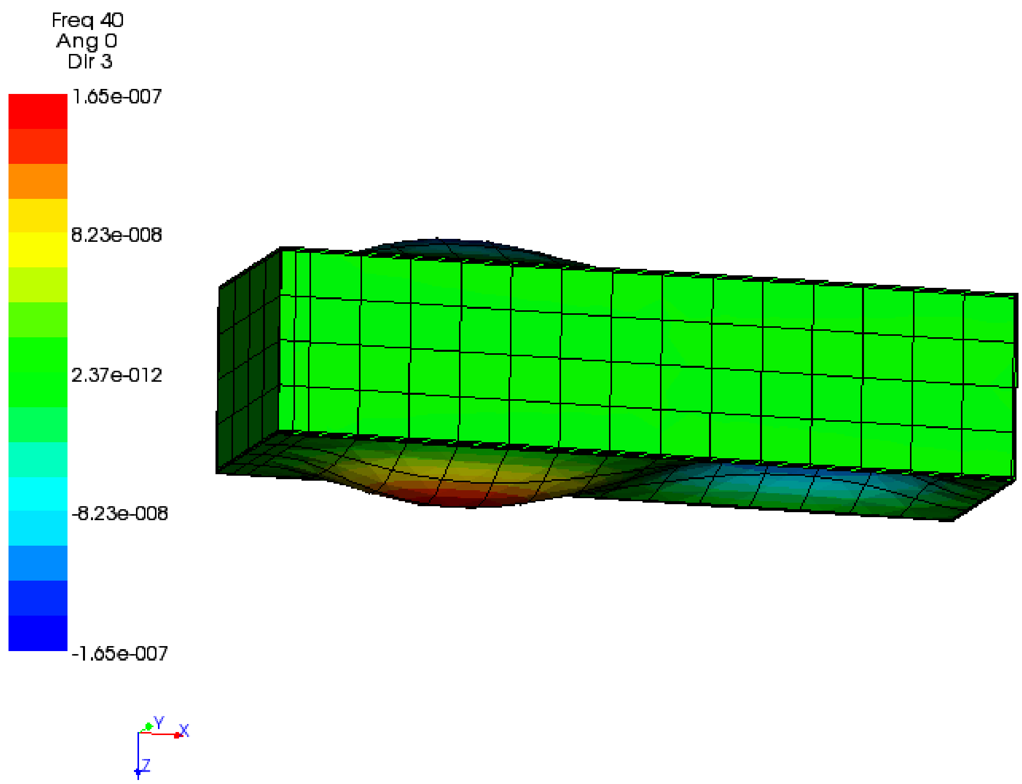


Fig 5 Deformation of a glass tank, filled with water, vibrated in the X direction via the left end wall

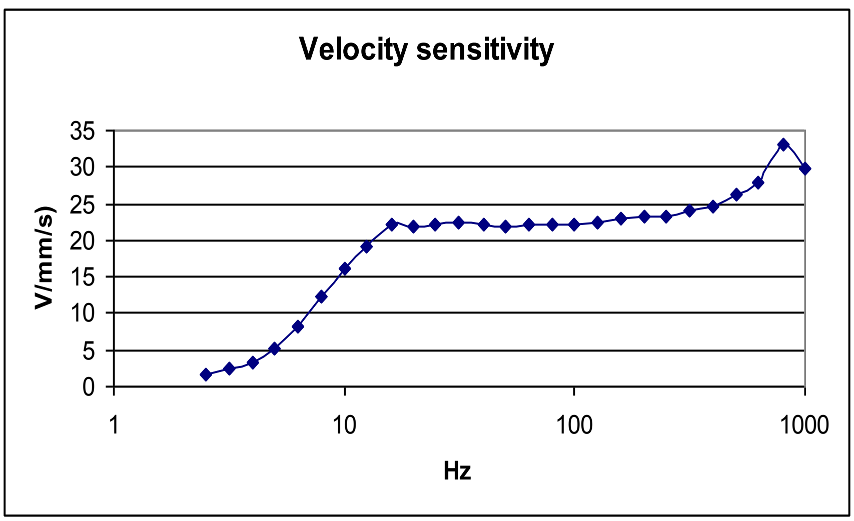
The particle size should be much less than a wavelength so larger volumes are permitted at lower frequencies. For FE analysis the element size must also be small compared to a wavelength.

2015 collaborative work with the University of Exeter has used a small sealed tank, shaken to observe the effects on creatures within. It was decided to use a succession of synthetic 20 Hz wavelets, each 1 sec long, based on the data from piling and dredging..

Since this work is unusual, a discussion of the adverse comments made by Parvalescu[3] is needed. His concerns were for the simulation of sound pressures in small test tanks. Indeed, little sound pressure is then developed in proportion to the motion, much as within evanescent waves. The small tank simulates a single water particle, with minimal error.

However the wavelength used is not that of plane pressure waves. For solid bars, Poisson contraction reduces the wave speed to the "rod wave" speed, and with a soft fluid centre this effect is even greater. More FE analysis has been conducted to check this. Fig 5 shows a 1.2m long rectangular tank driven in the X direction, with the Z axis deformation plotted. The glass walls bow, showing that the motion is not uniform. If the glass were rigid, the vibration of the end wall would launch a plane pressure wave, but this model shows how it yields, and reduces the pressure to 4.5 Pa. For this 40 Hz sinusoidal motion the peak deformation of 165 nm corresponds to 41.5.µm/s velocity. This impedance of 0.108 MPa/(m/s) is much less than the 1.5 MPa/(m/s) of a plane wave. The current trials used a smaller (< 0.2m) stiffer glass jar, chosen to provide even better support, and uniformity of motion.

8 USING GEOPHONES AS MONITORS AND DRIVERS



Two geophones were clamped in a light stiff tube hung on thin elastic. One geophone drove the vibration which was monitored with a laser vibrometer at the National Physical Laboratory. Fig 6 shows the 22V/(m/s) response of the other from 16 Hz to 200Hz. As additional mass (such as a shaken jar) is added, the motion reduces but this result for velocity sensitivity is unchanged.

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Fig 6 The response of a LGT 20-DT10 geophone to vertical vibration (NPL July 2015)

When available a shaker table is best to achieve the desired vibration. Soft support bench top rigs are less expensive, although the rig response can be complicated. However, provided the tank is adequately stiff the motion is that of a rigid body, which can be monitored by geophones.

9 CONCLUSIONS

The application of seismic interface wave data to biological tests has been discussed, showing how ground roll waves differ from plane waves and are significant for seabed dwelling species. Further details may prove important if the work can be extended to more complex shaking test rigs which drive motion in both axes.

Improved FEA should also allow further testing of the physical properties of these waves and their propagation.

9 ACKNOWLEDGEMENTS AND REFERENCES

The development of the shaker rig was much assisted by Steve Simpson and Rick Bruintjes of Exeter University. The geophone measurements depended on help from colleagues at the National Physical Laboratory, especially Steve Robinson, Pete Theobald and Michael Wood. Helpful contributions from Tony Hawkins and from Patrick Macey of Pacsys Ltd were appreciated

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