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Low frequency ground roll waves created during piling

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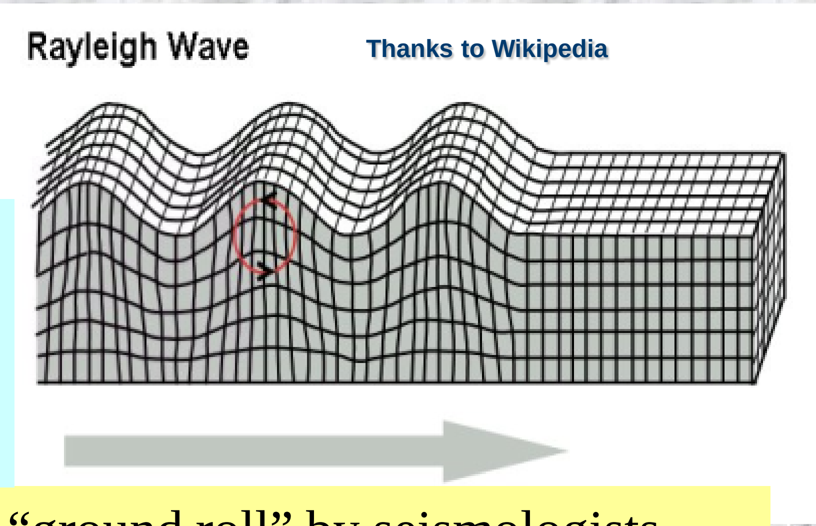
Recent construction of very large monopile windfarm towers has led to further studies of offshore subsea piling mechanics.

In addition to intense impulsive sound in the water, energy will be radiated along the interface at the seabed as **ground roll waves** (mini-earthquakes).

Measurements have been made with geophones and results analysed theoretically. It has become clear that these waves are all pervasive if not widely perceived by humans.

FEA animations show their nature, and their **potential significance to aquatic life**

Piling hammers can deliver over 1 MegaJoule of impact energy



Ground roll waves occur at the interface between water and saturated sediment

- "Rolling" motions of the seabed are termed "ground roll" by seismologists, often concealing energy reflected from lower strata of more interest to them.
- This class of wave includes **Rayleigh, Stonely** and **Scholte** waves, but the elliptical particle motion, shown above, is the key feature
- The peak vertical motion occurs when the horizontal motion is zero
- They are slow, ~ 90% of the shear wave speed, much slower than typical compression wave speeds, including that of sound in water at 1500m/s.
- Measurements in saturated clay show very slow speeds of **only 100m/s**.
- Such low frequency (**~20Hz**) slow wave energy is not well coupled to water
- **This energy is thus trapped at the interface, where flatfish etc may be significantly disturbed**. (Crabs, dabs, plaice and sole, cockles and mussels)

?

In open water, directional sensitivity to low frequency sound (<100Hz) is limited
(wavelength $\lambda \approx$150m at 20Hz in water)

•Whilst LF pressure waves give little directional data, flatfish can get more information from seabed vibration – & water particle velocities – using their otolith sensors.

•Triaxial accelerometer packages record wave directions well - azimuthal directions are given by the x/y amplitude ratio, but there remains an ambiguity for plane waves. These include the P (primary, pressure) and S (secondary, shear) waves within the sediment.

• However, for ground roll, with out-of-plane z axis data, the left/right wave direction **ambiguity is resolved by a phase analysis of the rolling motion**.

• **Many creatures may have evolved to use this vital directional information on the activities of potential predators and prey.**

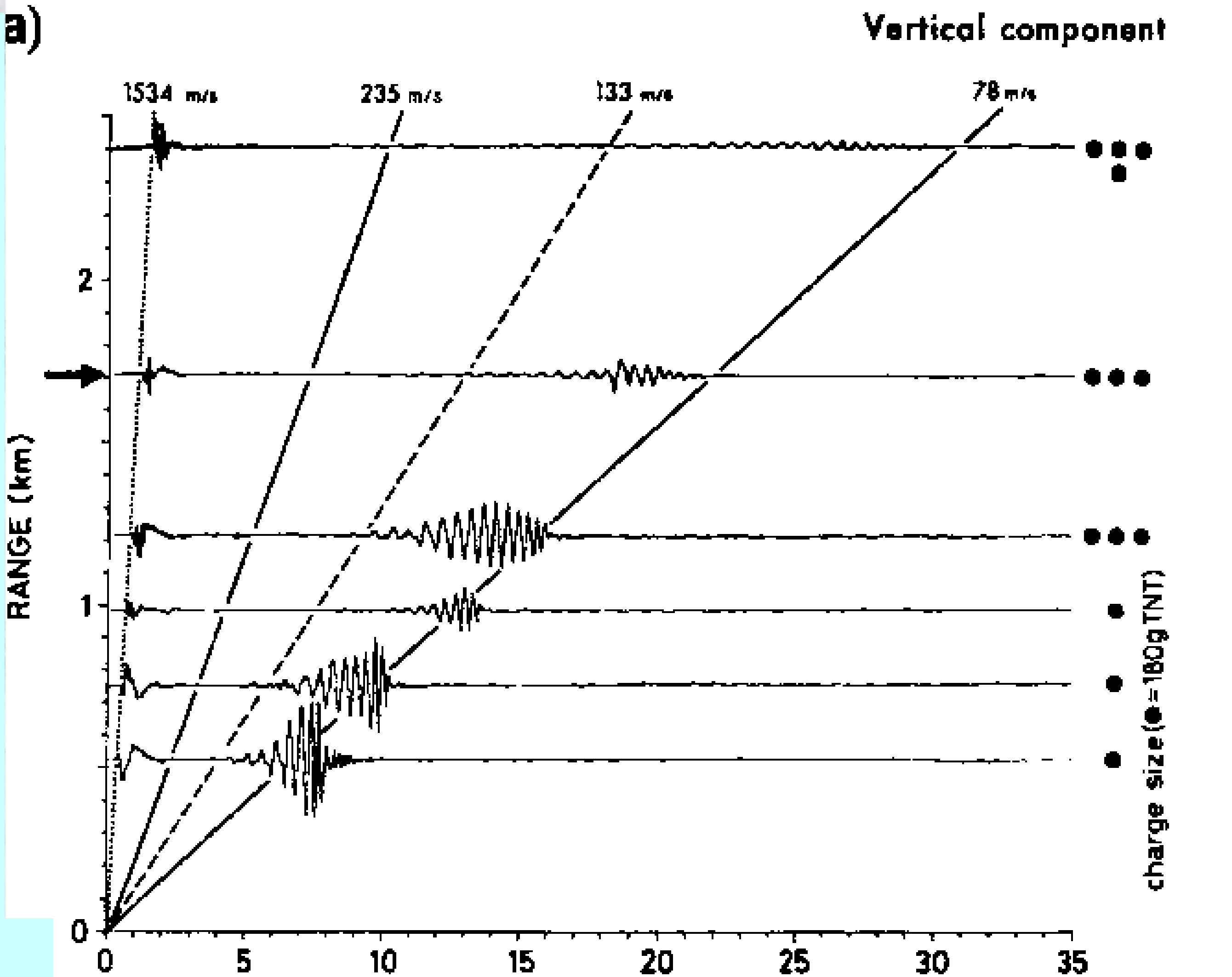
•*Kotas, Rogers, and Yoda (J.A.S.A. 2011) say "….. their ears are too close together for underwater sounds to provide a meaningful time delay"*

•*But also "Detecting the motion of the otolith … and thereby the acoustic particle motion, enables the fish to determine the line of bearing of an incident far-field sound, but not the direction, due to the 180° ambiguity"*

Propagation across the seabed

Ground roll created by TNT explosions

A 10 cycle wavelet is seen at 1200m still visible at over 2km range, using geophones- vertical motion shown here. Propagation is slow and frequency low. Here it is only 2Hz



Time in seconds after the explosion

1983 SACLANT paper SR-71 published in “Computational Ocean Acoustics” Springer 2000

Measurements v models

Understanding the issues needs several parallel approaches –

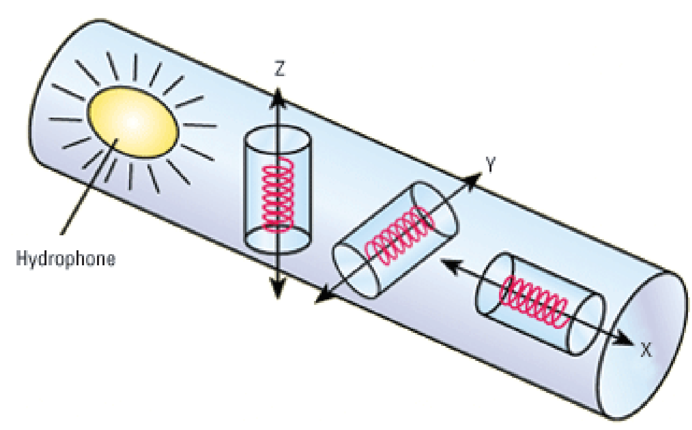
- Measurements of real piling action into the seabed
- Idealised mathematical modelling (analytic, pencil/paper)
- Practical computer modelling (finite element analysis)

A well developed understanding can allow planners to make useful (perhaps even accurate) predictions, if propagation models are available.

Lord Rayleigh provided analytic “half space” equations of motion, but we have some difficulties in finding analytic expressions for the waves seen here

So we use computer based finite element analysis to understand more. This provides some dramatic animations, as well as numeric data.

A simple OBS sledge, seen on test at NPL's Wraysbury reservoir, was designed to be oriented by a short tow across the seabed, using the prow line on the left. It contains 3 geophones and an inclinometer to allow excess tilt to be corrected, if necessary.



The 3 axis geophones are here augmented by a hydrophone, and barrel, not used in the later sea trial. The barrel reduces the penetration into soft silt

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Test pile measurements

- An instrumented test pile belonging to IHC Hydrohammer, Kinderdijk was driven into silt, and the sound in the water measured by TNO Delft. The geophone sledge was added to their suite of six hydrophones to monitor the motion at the water/silt interface at 3 positions and 2 depths.
- The measurements were taken in Dec 2010 (note the frigid conditions) but the analysis is ongoing
- Various measures are being considered for mitigation of the environmental effects for the large number of piles required for offshore windfarms.
- **Such measures are unlikely to confine the ground roll waves**

Test pile (right)
far measurement
position (above)

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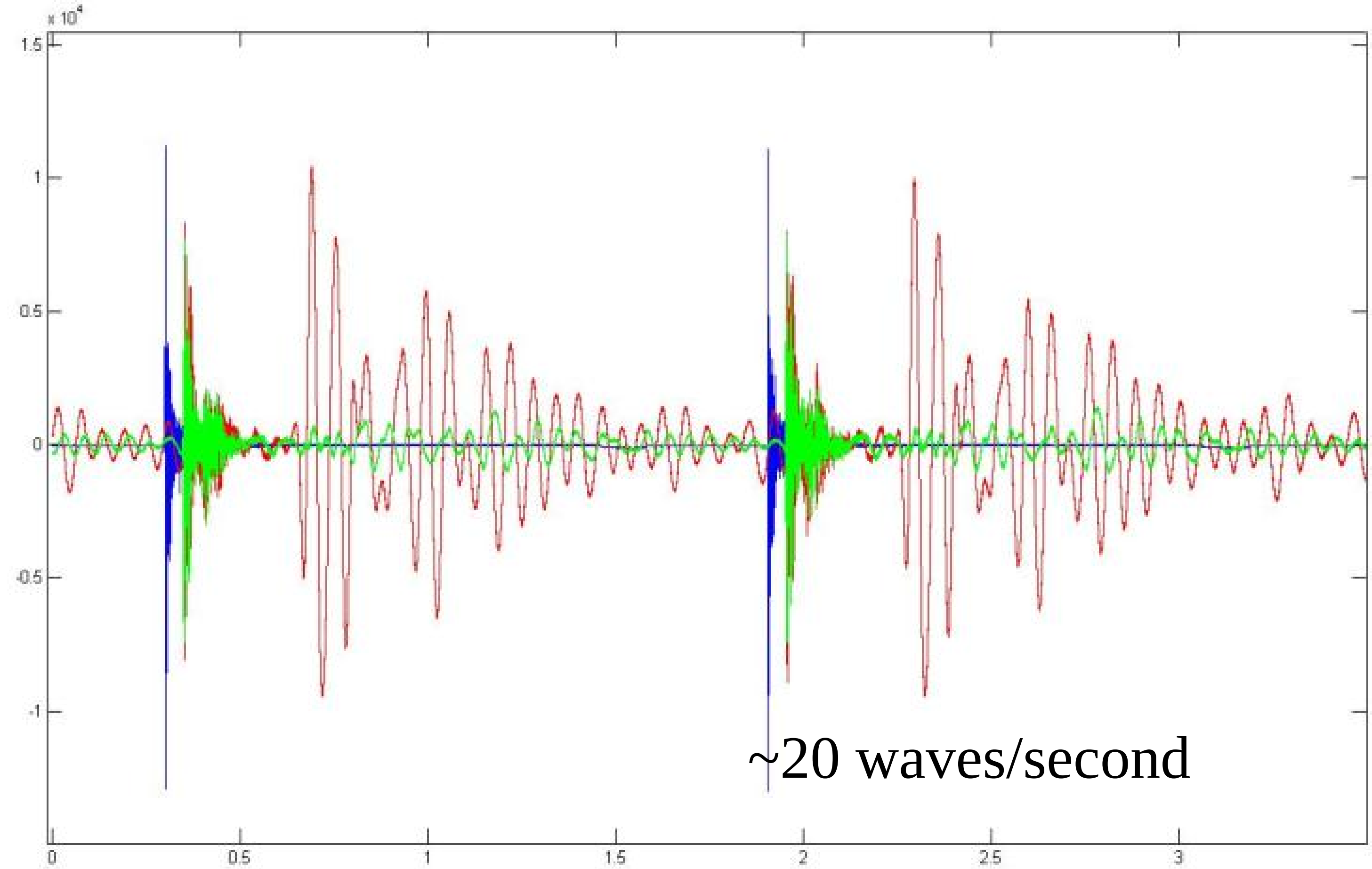
Blue – acceleration of pile – blows every 1600 ms
Green – vertical velocity @ 68m distance
Red – horizontal velocity @68m distance

More detailed analysis was made on the logged data



The water pressure wave arrives after 45ms, but the ground roll takes 350ms to arrive

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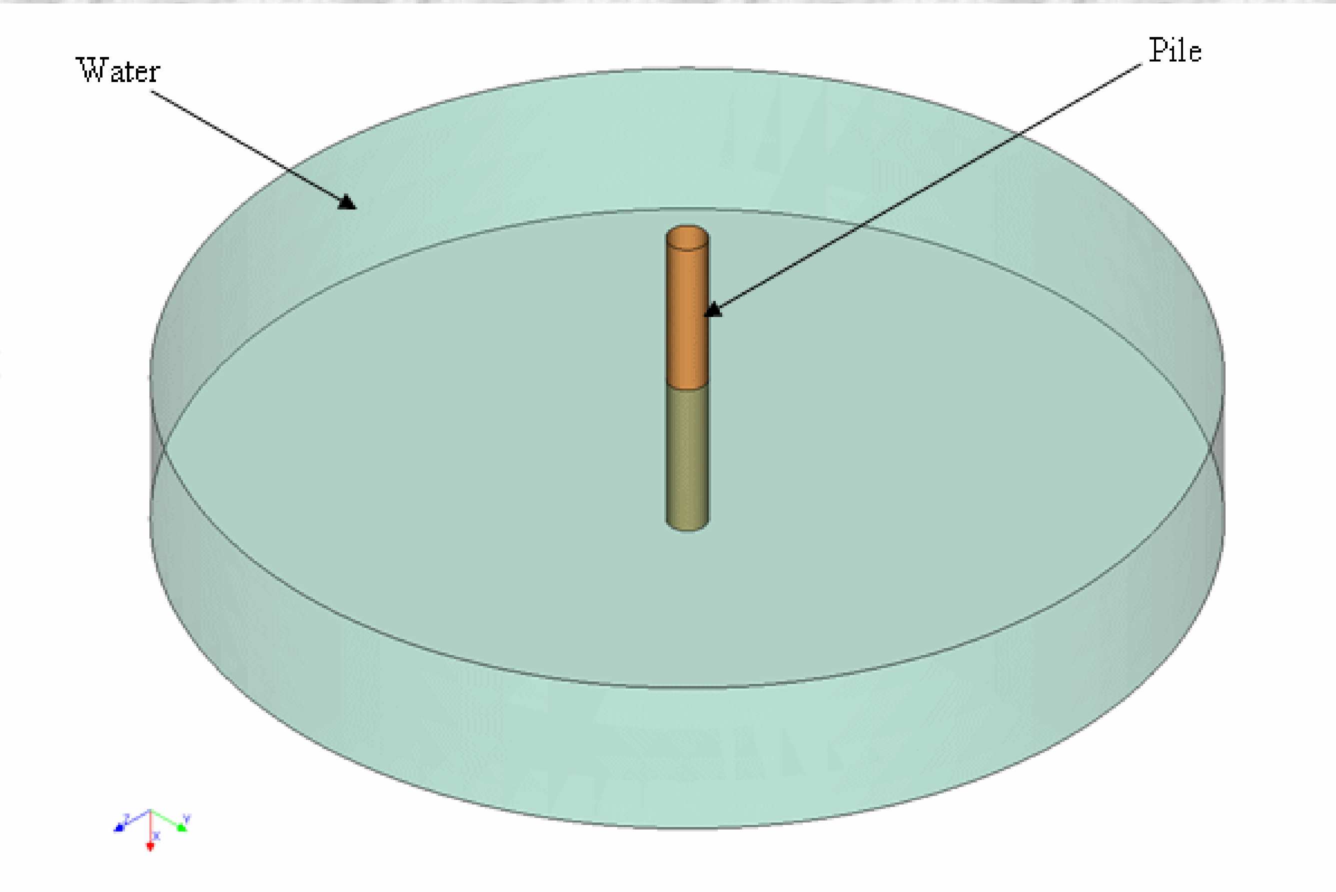
The geophone sledge was deployed using a small boat

- Real time data was viewed by scope
- Two blows are here recorded spaced by 1600ms
- Horizontal motion (bottom trace) is much larger than vertical motion (top trace)
- Seabed motion peaks at over 20mV or 1mm/s (c.f. cod threshold ~0.02mm/s)

Thanks to John King of Pacsys for this explanatory diagram



Piling modelling – axisymmetry

A typical large pile has a 5m diameter. Here water depth is 20m, and the pile top is still 20m above the surface. Whilst many complex vibration modes exist, the real pile needs to be driven vertically, so non symmetric modes are to be avoided. The analysis of symmetric modes can be displayed on a cross-section

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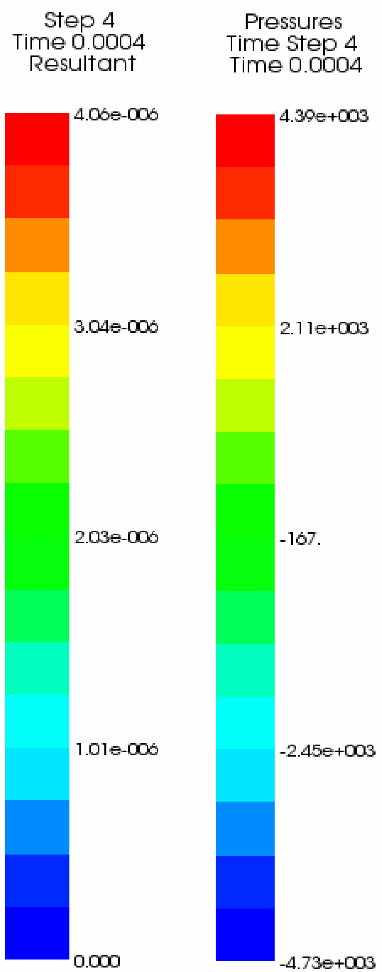
1ms hammer blow, peaking at 1MN, 500 timesteps, each 0.1ms

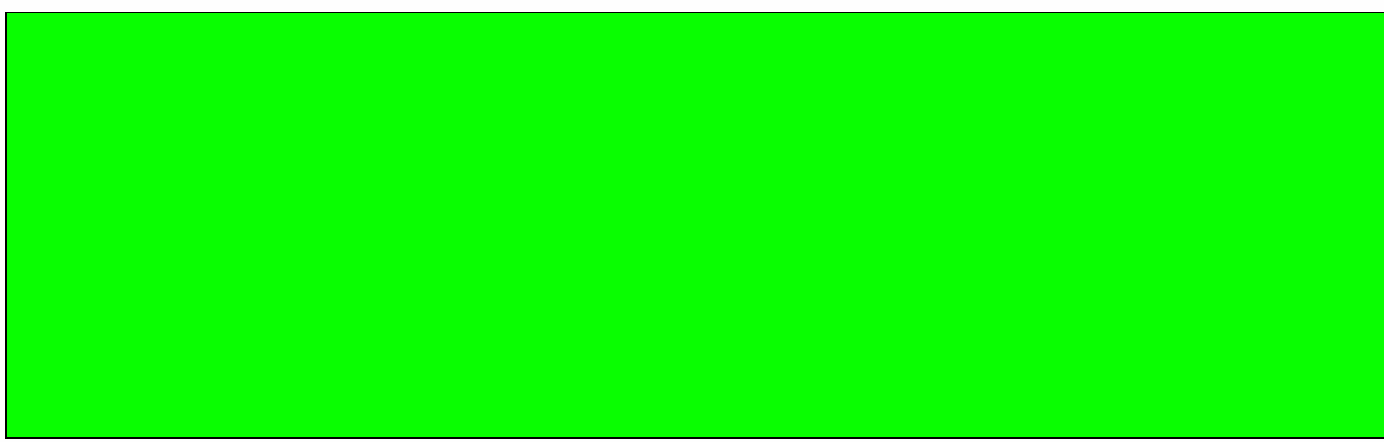


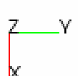
One pile wall is shown with exaggerated animated deformation in 500:1 slow motion (50msec displayed over 25 secs)

– watch the top drop with the impact, and rise again when the pulse returns. Peak displacement colour scale is 0 - 4µm

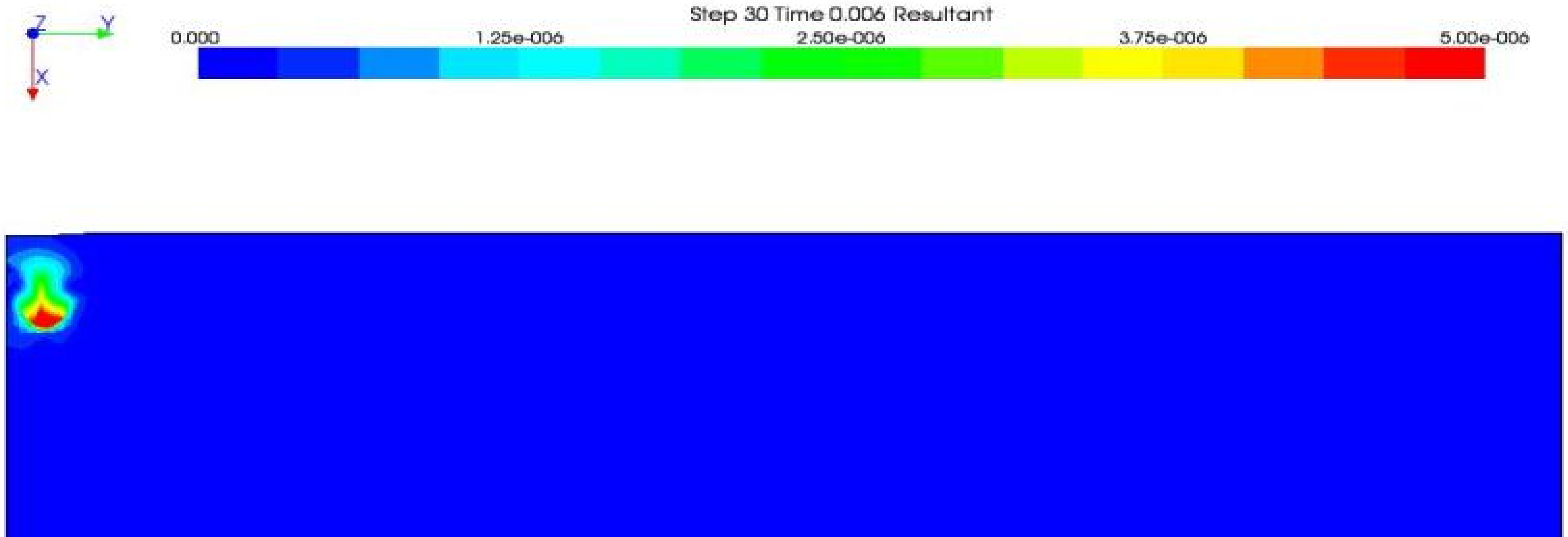
The radial expansion of the pile is the principal means of coupling into the water (colour scale ≈ +/- 4kPa)

Peak sound pressures form cone waves seen moving outwards from the pile wall (shown separated from the water for clarity)





Seabed excitation. In this model the pile tip has penetrated to 4m and the impact is simulated at that point. The cross-section extends from the symmetry axis out to a 100m radius, with the excitation at 2.5m radius.

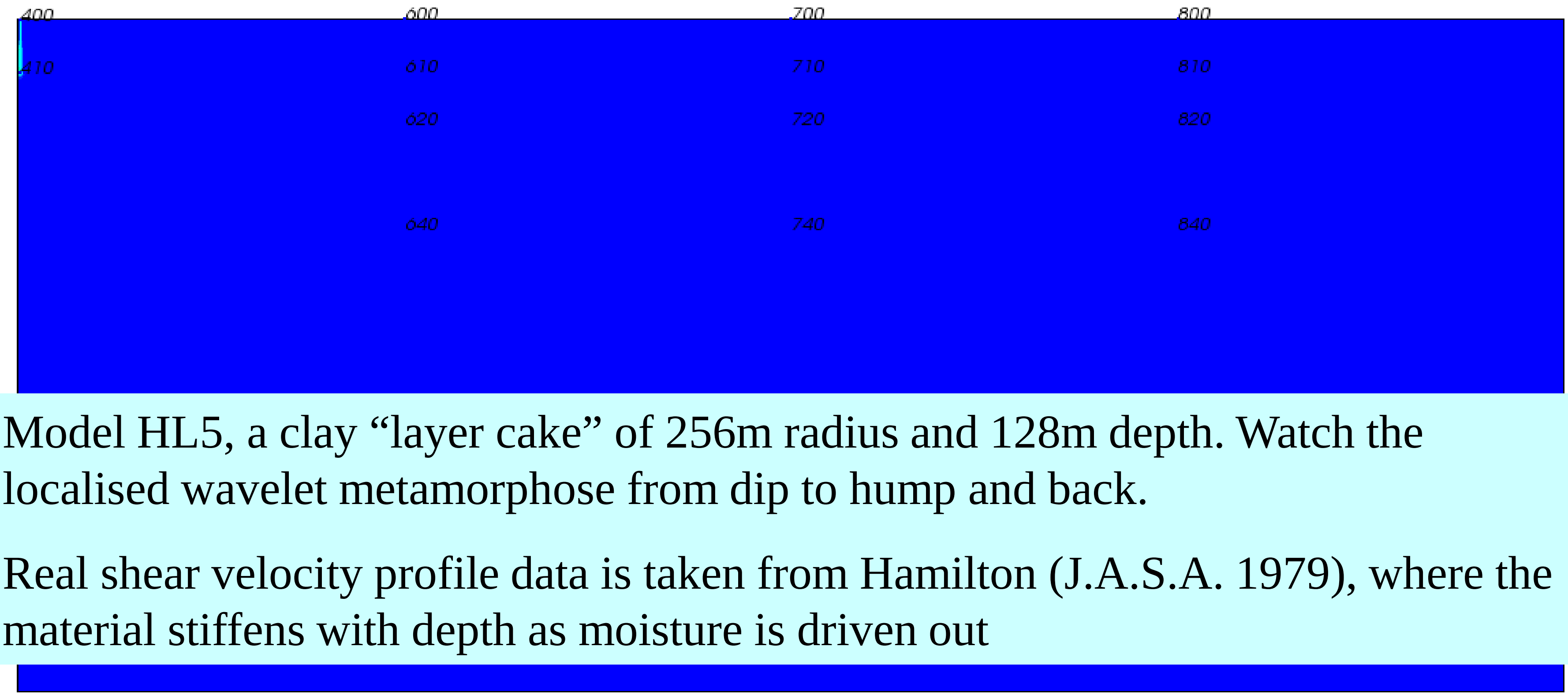


In all these models the simulated piling pulse is idealised. Real piling data is complex with significant higher frequency vibration. This model forces the clay directly. The response shown is linear, whereas of necessity the real clay is deformed as the pile is driven in

The magnitude is also arbitrary, set at 1MN peak force, with around 1kJ energy input (c.f. MJ piling hammers). There is no absorption.

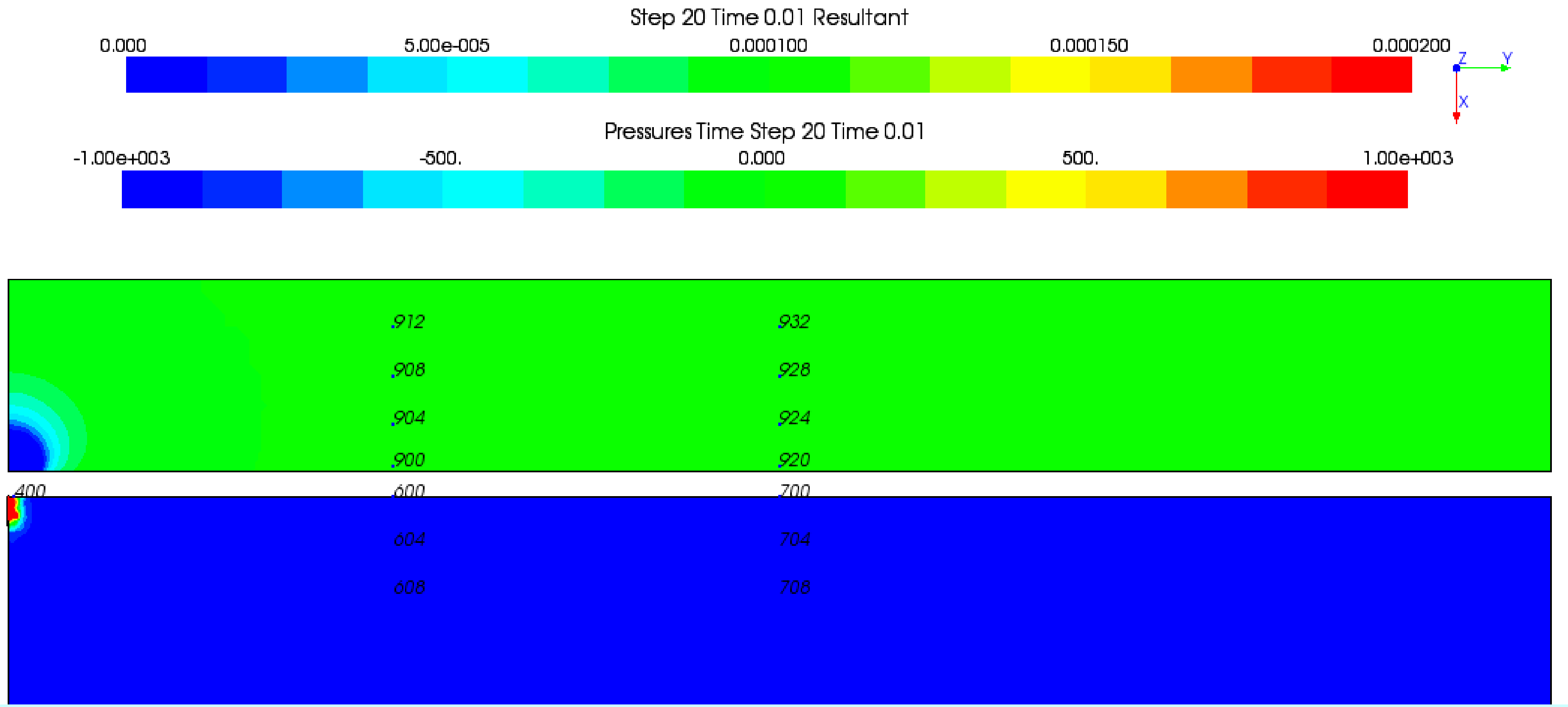
GROUND ROLL SOLITON IN SATURATED CLAY

This model is “tuned” to show the ground roll, but these waves usually dominate at a distance as they propagate well



Model HL5, a clay “layer cake” of 256m radius and 128m depth. Watch the localised wavelet metamorphose from dip to hump and back.

Real shear velocity profile data is taken from Hamilton (J.A.S.A. 1979), where the material stiffens with depth as moisture is driven out



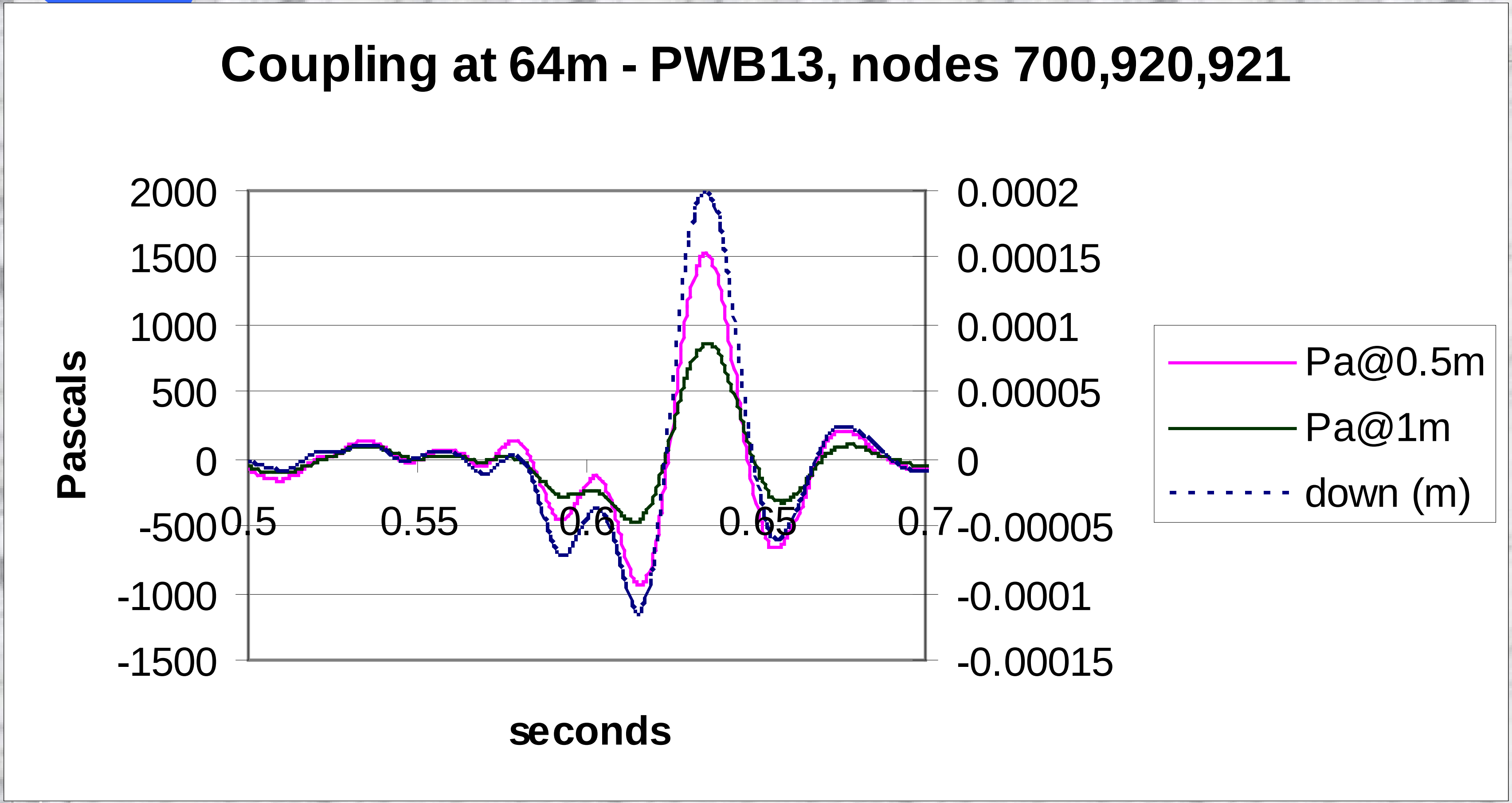
PWB13 has 16m water overlying the clay. The ground roll wavelet properties are little changed, but evanescent waves are seen in the water.

The waves are analysed at various nodal points such as #700, #920. The white gap is for clarity. Node 924 is 4m above the seabed at 64m range.

Solid displacements are vector magnitudes (0- 0.2mm colour scale)

Water pressures are bipolar scalars (+/- 1kPa colours).

The data is stored for different time steps



The water pressures show a similar shape to the sediment motion
Note that a positive water pressure overlies a dip in the sediment.

Conclusions

- This study has explained how ground roll wavelets are created, by matching theory and measurements for wave speeds (~100m/s) and dominant frequencies (~20Hz) in saturated sediments.
- Further work on biological impacts is much needed. Do these waves provide a window on the world for flatfish & crabs? Can they sense direction by these means to hunt or hide?
- More modelling should allow the prediction of such impacts using data such as the pile dimensions and hammer energy.
- More measurements on piling and dredging effects are required
- Thanks to Patrick Macey of Pacsys (PAFEC finite element software) for help in constructing models and making animations.
- Thanks to TNO Delft and NPL Teddington for the opportunity to take part in their collaborative trials.