Seabed Seismic Coupling – Testing and Evaluation

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Abstract: *Measurement of the effectiveness with which seabed seismic sensors record ground motion, particularly shear waves giving rise to horizontal motions, has proved difficult. This paper looks the problems of field trials, lab based test facilities and alternative strategies to evaluate coupling. Lab based test facilities give rise to problems because of the bounded space, and because the resulting motions are complex and involve rotational components. Complete understanding of the behaviour of the test volume and the sensor under test require full six-component measurement of motion and multiple measurement channels. All motions must be converted to displacement to avoid confusion. Rotations also have unexpected effects upon Galperin configuration sensors. Shaking geophones yield some useful information, but large scale field trials remain the only reliable test.*

Coupling of gravity deployed Ocean Bottom Seismometer multicomponent sensors has been an issue for at least 30 years, and remains largely an empirical art rather than a science. There are a number of reasons why it retains it elusive nature ;- the environment is generally hostile and all operations have to be conducted remotely, the nature of the seabed is highly variable from place to place, so that it is impossible to directly compare results from different sites, but largely because making detailed in-situ comparisons of a number of sensors accurately deployed in controlled deep sea conditions adjacent to each other is extremely costly. This paper considers some of these problems, and ways in which coupling can be evaluated in the laboratory, and the limitations that result. Variations of the internal sensor geometry also affect the sensor response in deployed sensors.

The history of multicomponent sensor packages for Seabed seismics has been marked by many designs that can now be seen on a cursory inspection to offer poor coupling fidelity, and rather few designs that inspire much confidence. The basic reason for this poor design lies in a failure of designers to understand intuititively the properties of the seabed. This can largely be traced to the difference between the properties of seabed materials we observe when we handle them in the lab or in shallow water muds, and the mud properties as they affect seismic waves. Put simply, all our physical experience of mud is related to its plastic properties ABOVE the yield point, whereas seismic signals received are invariably in the elastic range well below these levels. Because of this, designers have failed to take account of the seabed as a very springy underdamped material. Once one accepts the intuitive idea that seabed mud behaves like a sheet of foam rubber, the true nature of the problem becomes evident.

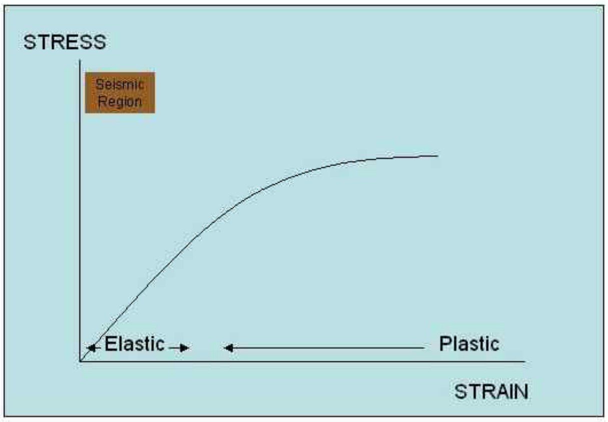

Fig 1. Cartoon of physical properties of mud – all our physical experience relates to the plastic region!

I first became aware of the complexity of seabed coupling in 1984 through an unplanned comparison of two cylindrical 3 component seismometers – one deployed on end and one on its side. Since the sensor geometry was so difference and there were several sensors of each type, it was clear that the fundamental difference in received shear wave signals was due directly to the sensor geometry. I was able to reproduce the effect on board ship only by modelling the seabed with a very elastic material –soft foam sheet – much to my surprise. I guess there are still too many people around in the business who haven't taken this on board yet!

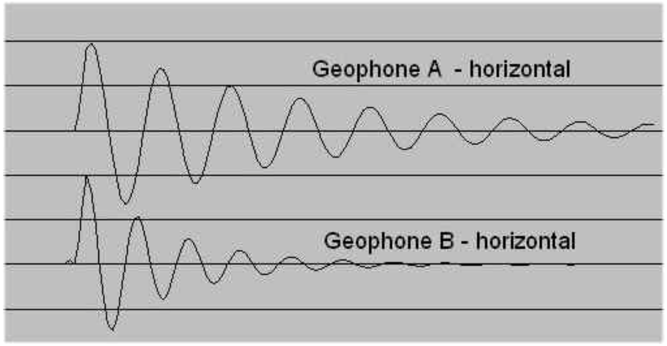

Fig 2. Differences in shear arrival due entirely to sensor geometry

The starting point for any discussion of sensor coupling fidelity is to define what we mean by fidelity and how do we know when we have achieved it. Our requirement for fidelity depends on what we intend to use the data for , and how far we can compensate for poor data by processing or other means. Since we are principally concerned here with multicomponent sensors, we can assume that we are interested in both p and s waves, and therefore in recording the true vector directions of the incident wave motion so that we can separate arrivals by motion direction. This is known as vector fidelity. In addition, of course, we also want our sensors to respond linearly to all signal frequencies and amplitudes present in the incident waves. Thus our perfect sensor would output signals corresponding exactly to the hypothetical motion of a point within the seabed at the sensor position, but in the absence of the disturbance caused by the sensor itself. In the absence of infinitesimally small sensors placed without disturbing the seabed, this ideal must remain a fantasy.

In practical terms we need our sensors to respond to as much of the range of incident seismic frequencies as possible since this maximises the information content of the signals. We need to ensure that the upward travelling s waves can reliably be distinguished from upward travelling p waves, i.e. that horizontal and vertical seabed motions are not confused by spurious motions of the sensor itself in response to ground motion. We also expect azimuthal uniformity so that the response to horizontal motions does not vary with source direction. In general we can be somewhat relaxed about having different coupling frequency responses to horizontal and vertical motion provided that there is a reasonable range of overlap, since we can post process quite simply if required. These practical fidelity requirements are therefore the basis for both good sensor design and the design of evaluation methods.

Ideally it would be possible to measure the response of any given seabed sensor package in calibrated and repeatable tests and assign a set of coupling parameters that would completely characterise its performance under all circumstances. Any design could then be rated against the required fidelity criteria for a particular application. In practice we are a very long way from this ideal. Our current understanding of the problems of design and coupling is at the level of intuition supported by some fairly basic physics, and our attempts to use complex mathematical analysis has yet to yield meaningful practical improvements. Against this background, assessments of vector and response fidelity remains strictly empirical and the only reliable way to make judgements between different seabed sensors is through direct comparison tests.

Even a direct comparison test between a number of possible sensor designs is far from straightforward. Sensors will couple differently to different seabed materials – stiff mud may , for instance, favour heavier sensors, so that a comparison is valid only for that particular seabed type. There may be local inhomogeneties in the seabed so that not all the sensors in the test are in similar material. The deployment method may not place all sensors uniformly on the seabed – the surface strength gradient in many seabeds means that the coupling may depend on how hard the sensor is pushed , and thus variations in placement can contaminate the results. In order to get representative data to give a meaningful comparison, a large number of shots must be fired at a different ranges and azimuths. A meaningful comparison therefore needs a significant number of each type of sensor, a reliable and repeatable deployment system, preferably with subsea photography, and extensive shooting of real seismic sources. In short a R.O.V and a full seismic shoot at a very substantial cost in time and resources.

Fig 3. ROV deployment of seismic node in deep water

One alternative to such ‘real world’ testing is to reproduce a piece of seabed in the laboratory and use this for tests. The first complication is that we are moving from a real environment where the seismic wavelength is small compared to the physical dimensions of our ‘laboratory’ to a situation where the test facility is a very small fraction of a seismic wavelength. We have thus moved from a world of waves to a world of particle motion. This inevitably means that the interaction of our model seabed with its boundaries is of comparable complexity to the interactions of the sensor with the ‘seabed’. We must then consider how we are to generate and apply our test excitation to simulate the seismic arrivals. This is not as easy as it might seem:- in the real world seismic signals of interest consist of ‘pressure’ (p) waves and ‘shear’ (s) waves that both arrive substantially vertically. In the laboratory model we have to substitute a simple, direct physical vibration in such a way so that we can control or compensate for spurious motions introduced by our simulated seismic wave. Assuming that we can impart a controlled, known motion to some external boundary of the ‘seabed’, we have to be able to measure the actual motion of the material surrounding the sensor. Some idea of the complexity of this problem can be gained by thinking of the complexity of the motion of a bowl of jelly (American: jello) when the bowl is shaken! Add a layer of water on top of the jelly and the complexity rises further.

This complexity when using a simulated soft deep sea mud highlights one of the limitations of conventional geophones:- To describe completely the motion of a rigid body in 3 dimensional space requires 6 independent components – conventionally we use the set of 3 orthogonal translations (x,y,z) and 3 rotations about orthogonal axes (rx,ry,rz). A conventional seabed geophone has only 3 components, orthogonal horizontal components x and y and vertical component z. While it does not respond to rotations about the axes through its individual sensor elements, rotations about any other axes cannot be distinguished from translations. This means that if the seabed sensor body rotates as a result of horizontal motion of the seabed – i.e. it rocks – the measured horizontal components are contaminated by the rotations signals, depending upon the position of the axis of rotation. Given only 3 measured signals it is theoretically and practically impossible to know the full motion of the seabed geophone. While this ***may*** not be a major error in a well designed sensor package on the seabed, the exaggerated rocking motion of simulated seabed mud in any small test volume subjected to linear motion, with possibly complex axes of rotation makes this a potentially major source of error.

A number of industry seismic geophones use a Galperin configuration rather than a conventional orthogonal arrangement of sensors. A Galperin geophone consists of a set of 3 orthogonal sensors oriented symmetrically about a vertical axis so that each inclines at 37.3 degrees to the horizontal. In this configuration the sensors respond to both xyz translations AND rotations about x and y axes but not about z. (To be strictly accurate, they don't respond to rotations about any axis that intersects the convergence of the 3 sensor axes). Furthermore the response to sensor body rotations depends upon whether the sensors in the Galperin configuration converge upward or downward. This difference may be significant in real seabed conditions where modelling shows it can make a 10 to 20% difference. In a restricted lab based test it could have an even more significant effect.

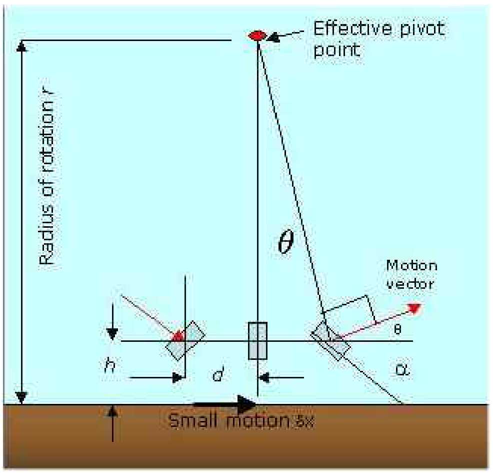

Fig 4. Galperin response to rotations

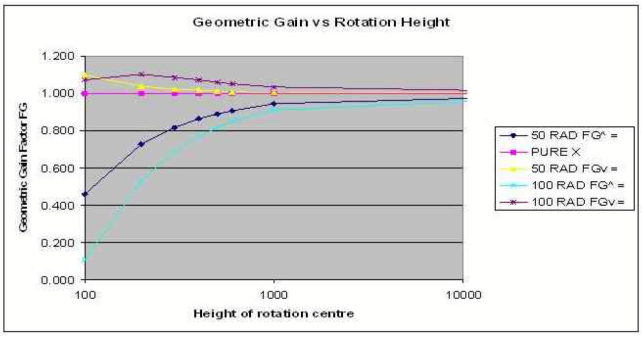

Fig 5. Error in horizontal response due to rotations in Galperin sensors with normal and inverted configuration.

These differences between sensor configurations, combined with the complexity of the expected motion within the test volume mean that we have to measure and record all 6 components of motion for as much of the system as we can – at least for the simulated seabed in the region in which the sensor is sited, and preferably also of the sensor itself, if necessary by adding small external sensors. We should also record at least 3 if not 6 components of external box motion. When all channels are taken into consideration, any recording system monitoring the experiment will need a minimum of 12 channels and probably 18 to 24 to stand a chance of capturing the expected motion. Analysis of the resulting data is made more difficult because the normal sensors are acceleration or velocity sensors, and data needs to be filtered to remove offsets and integrated to give displacement data in order to understand the actual motions, as this example shows:

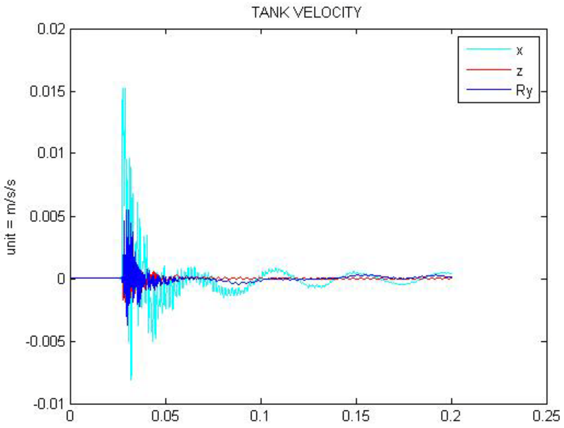

Fig 6. Test Tank body motion – raw velocity data from impulse

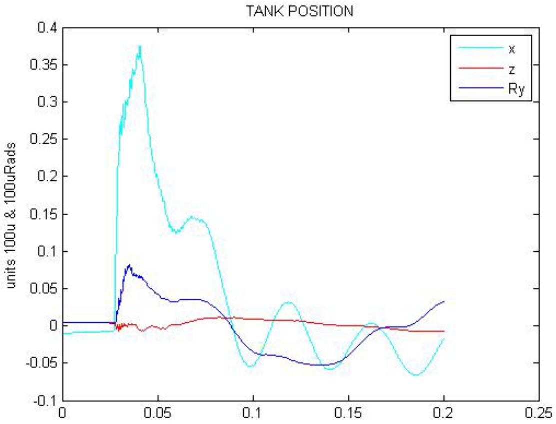

Fig 7. Test Tank motion – data integrated to displacement – now you can see what is happening with an impulsive input along x!

There have been a number of designs for laboratory coupling test rigs, but so far they do not offer a predictable way of comparing sensors. Part of the problem has been a failure to account satisfactorily for rotations through the lack of 6 component monitoring. This is a problem Carrack is currently addressing with a new design of reference geophone.

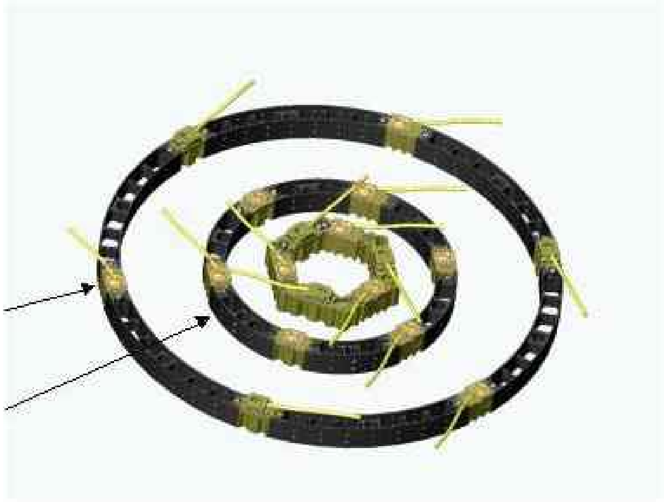

Fig 8. Three possible configurations of the CARRACK 6 component Reference Geophone for different applications

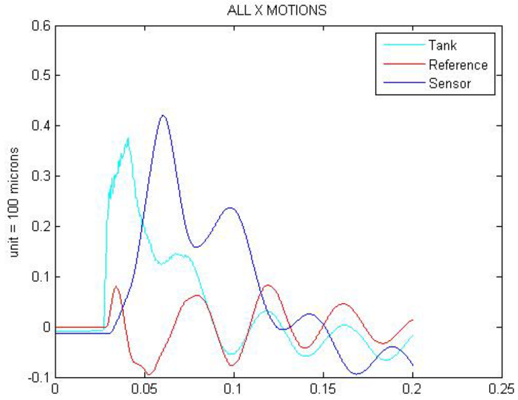

Fig 9 Tank, Reference and Sensor x-motion showing complex response to impulse.

An alternative to shaking the whole test volume is to put small shakers within the sensors and effectively measure the inverse coupling of the sensors. This approach reduces but doesn't eliminate the boundary problems, and introduces its own rotational modes that need to be taken into account. It also requires that a sensor housing is suitable for modified to house a shaker in addition to its normal sensors. In one example tested by CARRACK, a motor with a vertical shaft has a flywheel with eccentric mass unbalanced by 5 gm at radius of 4mm near the base of the geophone. The motor is logarithmically ramped down in speed from 100 Hz to 10 Hz over a minute and the output of the sensors is recorded.

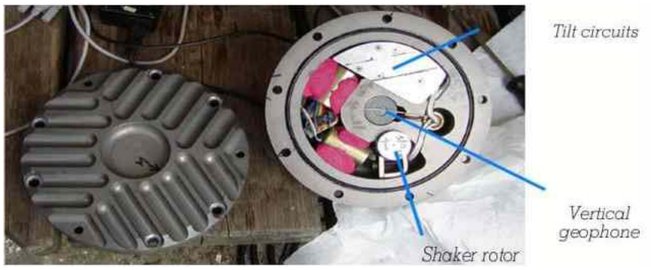

Fig 10. Internal arrangement of CARRACK geophone modified with shaker motor (base view shown).

The circular amplitude of the freely suspended geophone is calculated from the mass ratio of sensor to flywheel and checked by suspending the geophone in air. Suspending the geophone in water gives an indication of the mass of sensor plus entrained water. When the sensor is placed on a surface, the amplitude of its motion will be reduced depending upon the degree of coupling to the surface, or put another way, to the effective mass of the sensor and its mud roots. This yields some interesting results – in general the 'coupling' is good on all surfaces at low frequencies, i.e. below 20 Hz, but in clays the coupling is dramatically reduced at higher frequencies. In sand the amplitude of motion was sufficient to cause the sand to fluidise at higher frequencies and the sensor housing sinks into the sand.

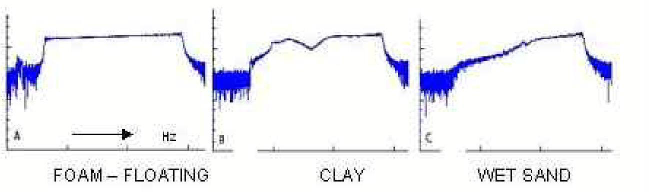

Fig 11. Response of shaking geophone 10 Hz to 100 Hz Vertical axis is seismometer x output (velocity).

So far we have assumed that we can find a material that will simulate deep sea mud for lab studies. Conventionally it has been assumed that pure china clay can be mixed with water and settled and possibly subsequently de-watered to give the required strength to accurately simulate a particular seabed mud. This give a repeatable material with measurable and consistent properties. However, there is increasing evidence that first few metres of the seafloor owe their physical properties more to biological activity than to the inert materials it mostly consists of. Recent analysis of mud from offshore Angola, for instance, suggests that the top few meters of mud have all passed through the digestive tracts of seabed worms, and been packaged into protein wrapped bundles that retain their effective low strength properties until the gravitational load a few meters down overcomes the strength of the bundles *(Prof Andrew Bolton, Schofield Centre, University of Cambridge pers. com.)*. It is therefore doubtful whether lab tests can ever be reliable indicators of deep sea performance for more than a subset of environments. While the importing of actual seabed mud seems a reasonable option, it is difficult to recover large enough quantities of deep sea mud, and any biologically produced structure is unlikely to survive the transfer. The resulting biological decay is probably a sufficient disincentive in itself.

One possible solution is currently being investigated by Carrack Measurement Technology – a seismic test range on inter-tidal mud where a small source and reference geophones can be used to generate and monitor a simulated shear wave. A number of sensors can be compared against a known geophone, for instance the annular Carrack Reference Geophone. Access to the mud near low tide will enable geophones to be planted accurately and the position checked at low water. The limited source possibilities and the difficulty of working in tidal estuaries will complicate the comparisons, but it does seem to offer a reasonable compromise between real world and lab based trials, and has the advantage that the same site can be used many times for non simultaneous comparisons.

Conclusion: Taken together this represents formidable challenges to any attempt to quantify the coupling of a seabed sensor package. Field tests are inevitably of limited validity, complex and expensive. Lab tests result in extremely complex motions and the complex analysis of large volumes of data, and are unlikely to yield definitive results that translate to the real environment. At present the best hope for advancing the performance of multicomponent seabed geophones would seem to be through careful attention to good design principles, and a long term monitoring of the effects of changes in design and of new configurations. Our understanding of seabed coupling would be advanced significantly if we had data from sensors with 6 components (5 would be enough if we can ignore rotations about a vertical axis of symmetry) and I hope that na opportunity to make that experiment will arise soon.