SEABED STABILITY EVALUATION STUDIES USING SHEAR WAVE PROPAGATION PHENOMENA

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Abstract:- The seismic shear wave velocity is the geophysical parameter which is widely used by engineers to predict the stability of sediments under dynamic load conditions. In particular, in earthquake engineering studies it is used to estimate ground motion amplification and the liquefaction potential of unconsolidated sediments in response to earthquake vibrations. In the marine environment, assessment of the *in situ* shear wave velocity structure of sea floor sediment layers is far from straightforward. There are major logistical problems associated with deploying and operating sources and receivers on the sea floor, and marine shear wave surveying is yet to become a routine technique.

Recognising the potential of shear waves for characterising seabed stability, the University College of North Wales (UCNW) have put considerable effort in recent years into the development of hardware and methodologies for quantifying the *in situ* velocity structure, and are now able to map the surface sediment velocity distribution in a pseudo-underway routine fashion, and to define the gradient structure of the subsurface layers to a few tens of metres below the seabed.

As part of a joint project between UCNW and the Geological Survey of Canada, the methodology is currently being applied in studies of the stability of sediments in areas of potential hydrocarbon development, and in areas prone to earthquake induced failures. In terms of the latter, the intention is to test the viability of the methodology as a tool for use in the regional assessment of sediment liquefaction potential.

1. INTRODUCTION

The stability of sea floor sediments is dependent on a number of factors which include its physical state, its behaviour in response to external loading, and the stress history. In terms of sediment properties, the depositional environment and sediment supply initially control the texture, sediment grade and sedimentation rate, and these in turn influence variables such as porosity, packing etc. A sea floor sediment may ultimately fail for a number of reasons such as oversteepening, build-up of gas pressure, generation of excess pore water pressure, ground shaking, or possibly a combination of the above.

Sea floor stability evaluation is a particularly important aspect of seabed classification so far as engineering applications are concerned. This paper provides a background to the use of shear waves in stability evaluation studies (with particular reference to their use in predictions of the liquefaction potential of sediments under earthquake loading), includes an outline description of hardware and methodologies developed by UCNW for shear wave data acquisition, and presents preliminary results from an on-going research exercise designed to investigate the stability of the delta front sediments accumulating at the mouth of the Fraser River, British Columbia.

2.SHEAR WAVES IN STABILITY EVALUATION STUDIES

Over the past decade, the seismic shear wave velocity has been gradually gaining acceptance as a parameter which can be used for engineering site investigation and structural design. Through elastic theory it is possible to develop relations between the seismic wave velocities and dynamic elastic moduli (and more particularly so far as this paper is concerned, between the shear wave velocity and the sediment rigidity), and, via an empirical approach, the shear wave velocity has also been shown to be extremely useful for predicting other physical properties/responses. To reach this point of practical commercial application has required the concerted efforts of a number of researchers and practictioners as geophysical methodologies are by no means automatically accepted by the engineering community. The reader is therefore directed towards the geophysical and geotechnical literature for further relevant details of the more fundamental aspects of shear wave propagation phenomena e.g. Richart *et al* [1], Stoll [2].

In the marine environment the seismic approach to quantifying physical properties may be particularly appropriate as many of the engineering problems are of a dynamic nature; also, the only viable means of obtaining representative information may be geophysical because physical sampling inevitably disturbs the sediment and *in situ* geotechnical testing is often prohibitively expensive.

So far as earthquake engineering is concerned, the initial goal might be the regional assessment of sediment liquefaction potential, and it is in this particular field of study that shear waves offer the greatest potential in terms of the classification and mapping of the seabed. According to Stokoe and Nazarian [3], and based essentially on empirical evidence (pre and post-shock studies of sediments which were affected by recent earthquakes), the limiting criterion for liquefaction for earthquakes to magnitudes 6.5 causing peak accelerations of about 0.17 g or greater, is a shear wave velocity of 140m/s, Finn *et al* [4]. This threshold velocity relates to the possibility of seismic porewater pressures being developed but does not conclusively indicate whether or not the excess porewater pressure will cause liquefaction. However, the authors consider the relations sufficiently significant to justify the use of shear waves in hazard evaluation studies, and the methodology particularly attractive because it can readily be extended to cover other peak accelerations for a range of differing magnitude earthquakes.

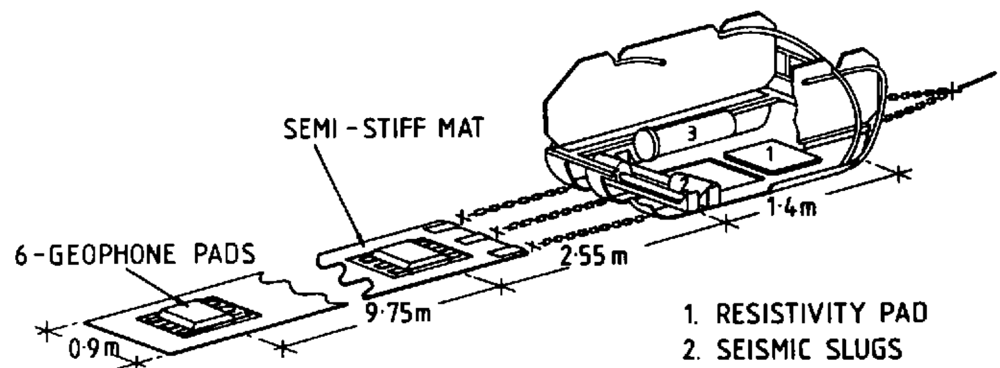
Finn et al [4] have carried out a series of land-based seismic and geotechnical tests (using a seismic cone penetrometer) in the Fraser Delta, BC, to compare various procedures for the *in situ* assessment of liquefaction potential. They conclude that predictions using shear wave velocity measurements compare favourably with other methods (such as through analysis of basic cone data), particularly in terms of cost effectiveness. Further, Hunter *et al* [5] for the same sites, reinforce the case for shear wave methodologies by comparing interpreted surface refraction profiles with downhole seismic data, and recommend that surface refraction shooting be given serious consideration as a reconnaissance method for the regional assessment of liquefaction potential, provided the limitations of the technique are recognised (see later - summary and conclusions).

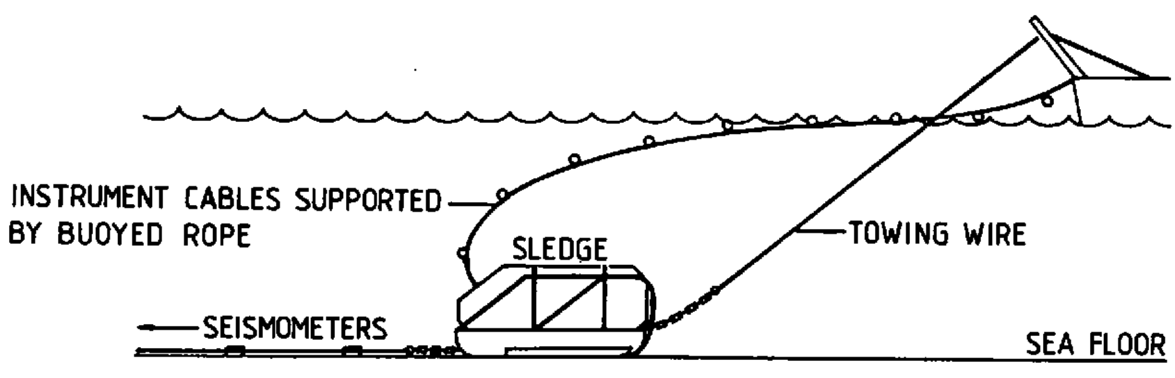
3. THE UCNW SHEAR WAVE ACQUISITION SYSTEM

Non-invasive methods for the acquisition of shear wave velocity data on land are well established and either make use of the seismic refraction principle (where the essential measurement is the travel-time of the seismic body wave propagating over a known surface distance), or the analysis of the surface wave component of the seismic wavetrain. Data acquisition and analysis using the former approach are relatively straight-forward provided that the field procedures and systems hardware are purpose designed to match the requirements of the survey. Thus, the UCNW approach to marine measurement has been to adapt land-based methodologies for offshore application. A series of papers have already been published covering development of the hardware and reporting results from initial sea trials, Davis *et al* [6 & 7] and Huws *et al* [8], and it remains here merely to present the current state of the art.

The hardware consists of a seismic source designed to preferentially generate horizontally polarised shear waves (an electro-magnetic hammer device), a series of horizontally-sensitive, gimbally-mounted geophones, a multi-channel engineering seismograph, and appropriate firing and interfacing electronics. The source is sledge mounted to allow it to be towed along the seabed while remaining coupled to the sediment surface. For short range measurements (shallow depth investigation), the geophones are attached to the sledge to allow the entire array (source and receivers) to be towed as a single entity. The geophone coupling is ensured by mounting individual units in stainless steel sledges which are attached to a heavy rubber mat. Figures 1a and b illustrate the basic system components (underwater part) and towing configuration. Measurements can be made in a pseudo-underway fashion as the sledge and receivers are towed along a pre-determined survey line. Individual point measurements are made by paying-out slack on the towing cable, this causing the sledge to go stationary for a few seconds whilst a shot is fired (to enhance the signal-to-noise level and ensure adequate seabed coupling).

Figure 2 shows an example record collected with the system described above. Data are analysed using a conventional travel-time/ distance approach and, for the array currently used by UCNW (and illustrated in Figure 1), velocities relate to the upper few metres of sea floor sediment (sampling depth being controlled by the velocity structure and length of spread).





Figs.1a & b The UCNW pseudo-underway sea floor shear wave system.

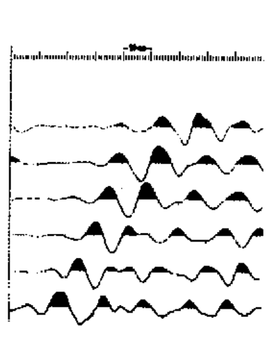


Fig.2 An example shear wave record collected in the Fraser delta with the above system.

The UCNW sledge has also been instrumented for electrical resistivity measurements and, since the horizontal source also generates a small amount of compressional energy, it is possible to make simultaneous measurements of apparent formation factor (AFF) and the two seismic wave velocities. Data sets for profiles shot in two different areas (one off the N.Wales coast and one in the Firth of Clyde) have been published in references 7 & 8 respectively, and these illustrate the potential of the method for defining subtle variations in the physical properties of the surface sediment layer.

For measurements to greater depths within the sediment column a slightly different approach to data acquisition is required. In order to investigate the velocity gradient to a few ten's of metres below the seabed surface, it is necessary to utilise a surface spread of some 100-200 metres; thus a separate geophone cable is needed. The UCNW approach is to use two detector units (each unit consisting of gimballed horizontal and vertical geophones and a single element hydrophone) at a fixed spacing of 10 metres, and initially deploy these on the seabed with the furthest unit at the chosen maximum receiver offset. A seismogram is then compiled using data recorded from a single shot point as the detecting units are progressively moved towards the stationary source.

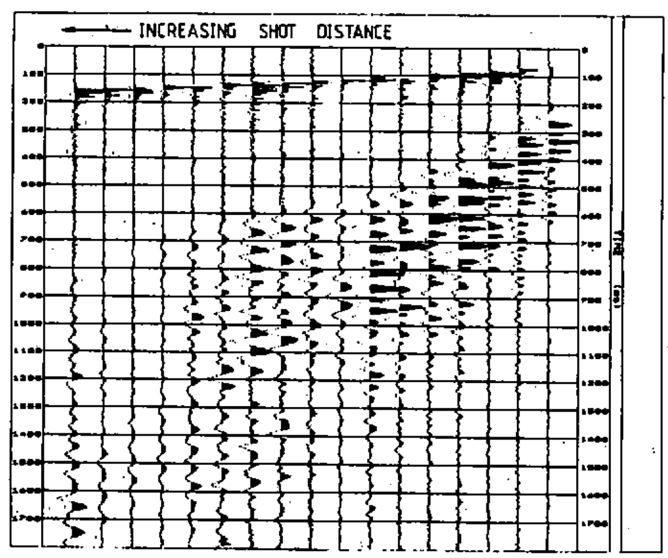


Fig.3 An example multi-channel refraction record (compilation).

Figure 3 above is an example of a multi-channel seismic record compiled from data collected in the Menai Strait, and one where the maximum receiver offset was 180 metres. The early high frequency arrival on each channel is the compressional wave, the shear wave being the lower frequency later event.

Since its development the UCNW hardware has been used to investigate a number of sites in UK and Belgian waters in relation to hydrocarbon development and defence applications. Currently efforts are being directed towards stability evaluation assessment on the Canadian Continental Shelf.

4.THE FRASER DELTA PROBLEM

4.1 Continental Margin of Western Canada - Tectonic setting

The tectonic setting of the continental margin of western Canada is a complex one. The subduction zone underlying Vancouver Island and lying some marks the convergent boundary between the North America Plate, the Explorer and the Juan de Fuca Plates. This NW to SE trending zone of active convergence ultimately gives way to transform faulting in the northeasterly direction at the point where the Explorer Ridge spreading centre confronts the Pacific, America and Explorer Plates to create a ridge-trench-transform triple junction. Estimates of rates of movement along the plate boundaries range from 10-60 mm per year and large magnitude earthquakes are a frequent occurrence, Riddihough [9].

4.2 Surficial Geology

The Fraser River flows down from the Rocky Mountains of British Columbia and ultimately drains into the Strait of Georgia. The Strait is essentially a series of structural depressions which act as sediment traps for virtually all material eroding off the southern part of the western Canadian landmass. Sediment from the Fraser River has been continuously accumulating in the southeastern part of the Strait throughout the Holocene resulting in the development of a major delta feature. Some parts of the delta continue to prograde at rates estimated to be between 3 and 9 metres per year, others are actively eroding due to a cessation of sedimentation locally, coupled with rising sea level, Bornhold and Barrie [10]. The sediments making up the delta are typically a mixture of prodeltaic silts and clays, and sandier foreset and topset beds. Due to the loose nature of the material and the depositional environment, it is likely that a large proportion of the delta front may prove to be unstable in the event of a large magnitude earthquake.

4.3 The Research Programme

The Geological Survey of Canada have completed two stages of a multi-stage research programme of the Fraser River Delta, and have now entered into a third stage in which the geotechnical component is of paramount importance. Offshore geophysical surveys have already generated a significant amount of data (seismic reflection profiles and sidescan sonargrams) which continue to be used to construct gross models of the delta front and provide an insight into potential sediment failure mechanisms. Land-based data (such as that described in 2 above - references 5 & 6), are being used to construct similar models for the on-shore portion of the delta, and have provided the major justification for using shear wave techniques offshore. Stage 3 of the research programme aims to take a more integrated approach to the offshore investigation of the stability of the delta front, and to this end, one of the final objectives is to produce a liquefaction assessment based on *in situ* shear wave velocity data.

During a recent cruise on the Canadian Scientific Ship 'John P. Tully' (November 1992) it was demonstrated that the UCNW sledge could be used to collect shear wave velocity data for the near surface sediment routinely while underway. During the cruise, an 8 km coast-parallel profile along the delta front was surveyed in water depths ranging from 25-50m using the short-range system. At the peak rate of sampling, point measurements were being made at approx. 20m intervals along the line thus allowing a detailed interpretation of the spatial variability in surface sediment properties.

The record presented as figure 2 was collected during the recent Fraser cruise. Individual records such as these can be analysed either to provide velocity information for the immediate surface layer or to provide detail on the near surface velocity gradient (if appropriate). It would appear from a preliminary investigation of the recently acquired data that shear wave velocities near the seabed surface are of the order of a few ten's of m/s (typically 40-60 rising to around 100m/s a few metres below the surface). It can therefore be concluded that the sediments under investigation would be prone to liquefy under the influence of large-amplitude earthquake waves.

Although during this initial research cruise the emphasis was placed on the assessment of the stability of the near surface sediment layer, some preliminary measurements made using the long-range geophone cable deployed some 100 to 150 metres beyond the source did indicate that the potential existed to produce the information required to provide a tentative assessment of the depth-dependent variation of liquefaction potential (to a few ten's of metres below seabed surface) based on shear wave velocity data.

5.SUMMARY AND CONCLUSIONS

The Fraser Delta problem is not a unique one. There are several areas around the world where rapidly accumulating sediments have been subjected to earthquake loading, and there is significant evidence suggesting liquefaction induced sediment failure. In other seismically active areas failures have been attributed to internal amplification of earthquake waves, with the gross sediment layering or individual 'sensitive' horizons controlling the amplification effects. Whatever the cause or combination of causes, analysis of shear wave propagation phenomena can provide an indication of the failure potential of the sediments.

In terms of the methodology, the major limitation of the seismic refraction approach is that it relies on an increase in velocity with depth thus making it impossible to resolve zones of velocity inversions. While the general trend for marine sediments may be for this type of increase (due to the overburden effect), increasingly, researchers are seeking ways of obtaining more detailed information for more complex and variable sequences. At present the most viable approach would appear to be through the spectral analysis of surface waves (SASW), Addo and Robertson [11], and it is likely that, given the appropriate software development, this type of analysis could also be applied to the sledge data.

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