OTC 8590

The Integration of Deepwater Geohazard Evaluations and Geotechnical Studies

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Abstract

The integration of high-resolution geophysics, geohazard evaluations and geotechnical engineering has been termed an "integrated geoscience study". This paper focuses on deepwater Gulf of Mexico examples of integrated geoscience studies. Methods to evaluate geohazards and the usefulness of those studies to geotechnical investigations are discussed. Examples illustrate how integrated geoscience studies have been used in the design of offshore foundations.

Introduction

High-resolution geophysical data have been used for many years in geohazard studies to develop an understanding of potential hazards and constraints to offshore operations. Recently, these studies have been extended to the geotechnical engineering community to assist with solutions to problems in several areas. Some of these include the development of sampling and testing plans for soil boring investigations, the interpretation of data from site specific geotechnical investigations, the development of site specific design properties from non-site specific geotechnical investigations, and a better understanding of geological processes which might affect foundation designs. The primary key to the usefulness of high-resolution geophysical data to the geotechnical engineering community depends on the resolution of the data, the development of a geologic model consistent with that data, and an understanding of the geological processes resulting from that model.

The integration of high-resolution geophysics, geohazard evaluations and geotechnical engineering is called an **"integrated geoscience study"**. Its purpose is to develop geotechnical parameters for design and to assess, if necessary, the geological hazards and constraints given that geotechnical knowledge.

Geohazard Evaluations

In US waters, geohazard evaluations are required to meet MMS requirements to assess shallow hazards to ensure that exploratory and development operations are conducted with a minimum risk to human life and the environment[1]. Similar studies are required around the world. While generally prescriptive in their requirements, these studies can serve to guide geotechnical engineering studies related to siting structures on the sea floor. The usefulness of geohazard evaluations to geotechnical engineers depends on obtaining high quality geophysical data and developing an interpretation in which the data fits a geological process.

Geohazard Survey Methodology. While there is a common government requirement, companies have different practices to fulfill the regulations. Shell's present deepwater practice, for example, is not to obtain high-resolution geophysical data unless an evaluation of the 3-D exploration-level geophysical data indicates sufficient complexity to warrant a deep tow or high-resolution 3-D study. The exploration-level 3-D data set is first subset to represent the first two to three seconds of data to reduce the volume of data to be processed. The subsetted seismic data are enhanced using high frequency enhancement and whitening methods that are well known in the industry. Another technique to enhance the data set is termed the Short Offset method. As discussed by Cowlard[2], this method uses near normal incident data volumes and demands that the data position be honored, precise time corrections applied, the absolute true amplitude preserved and the number of near traces reduced to the minimum possible number. By not binning the data and preserving trace location, seismic events are not smeared. The data are migrated using a Kirchhoff migration algorithm.

Given the "re-processed" 3-D exploration data set, two tools are used to evaluate geohazards. The first is a "standard" workstation to map subsurface horizons and amplitude anomalies. Time slices are also used to identify geological processes such as channels. Anomalous amplitudes are usually evaluated by identifying relative signal magnitudes within a mapped set of geophysical horizons and mapped in the usual manner. The ability to show arbitrary lines is particularly useful in illustrating geological features in the context of geological processes and in showing a line directly through the expected well site. The second tool that is used is to develop a three-dimensional image of the water bottom by assigning color to the water depth. We call these images Enhanced Surface Renderings (ESR's)[3]. The positive peak of the water bottom wavelet is also overlaid onto the ESR to create an amplitude-based image. Although displays are created in color to represent either water depth (wavelet amplitude for the Amplitude ESR), a black and white ESR of the water bottom is shown in Fig. 1. (Lease blocks, 5-km square are shown for reference in the figure.) The usefulness of an ESR is similar to side scan sonar in its ability to identify surface features such as faults, fluid expulsion features and slumps. An amplitude ESR is shown in Fig. 2 over a near-surface slump. The slump was originally mapped using data obtained with an EDO deep tow system and is barely visible on the seafloor rendering shown in Fig. 1. The amplitude ESR clearly displays the slump as a higher amplitude region on the ESR. The slump is Recent in age (i.e., last 10,000 years), but is covered by 1-3 meters of hemipelagic material. Since low frequency systems penetrate the sea floor, the slump was picked up within the sea floor seismic trace and can be imaged due to the variation in signal amplitude over the slump region. Thus, high quality geohazard assessments can be made from exploration-level 3-D data if carefully processed and the correct tools are used to evaluate the data. Only when significant geological complexity is seen within this evaluation is a more complex survey warranted to acquire high-resolution geophysical data.

High-resolution Data Acquisition. Deepwater provides its own unique requirements to acquiring high-resolution geophysical data. Surface towed high-resolution systems adequate for shallow water will usually not provide sufficient resolution in deepwater. A good example is side scan sonar which is most effective when the height of the fish above the sea floor is about 10% to 20% of the range (i.e., the distance from the center line of the fish to the outside edge of the sonar image). This physical requirement requires that the fish be "flown" relatively close to the sea floor for high-resolution systems such as the commonly used 100 kHz sonar's whose ranges are typically set at 200 meters. In the early 1980's, several types of deepwater side scan sonar systems were deployed and tested by Shell on the US East Coast[4,5] in water depths from 100 meters to 2,450 meters. The system producing the most stable high-resolution data used a positively buoyant fish kept a constant height off the sea floor. This was achieved by attaching a chain to a fairlead clamped to the tow cable some 33 meters from the fish (Fig. 3). Thus, the tow vehicle remains at a constant height off the sea floor during the survey. Experience with this EDO deep tow system has been favorable. The fish has never been lost due to the chain catching on a bottom object. Since its deployment, the most significant improvement has been the addition of bottom-mounted computing and telemetering transponders anchored 25 to 30 meters above the sea floor[6,7]. One of the features of the deep tow system is that the 3-1/2 kHz subbottom profiler in the tow vehicle produces subbottom images of extremely high resolution since the profiler acts as if it was in only 25 to 30 meters of water. High resolution penetrations to more than 60 meters are common in the deepwater Gulf of Mexico clays using this system. The deep tow system was used on nearly all deepwater exploration prospects as the primary means of geohazard surveying in the late 1980's. From 1985 to 1990, the system was used on an average of six prospects per year. During that time period, significant understandings of recent deepwater geological processes were developed. Some of the more interesting were reported in the literature[8,9,10,11]. To date, about fifty deep tow investigations have been conducted by Shell in the deep water Gulf of Mexico and Atlantic East Coast.

Deep penetration systems have evolved from the single channel analog sparker and mini-sparker systems of the 1970's and 1980's to complex 2-D and 3-D high-resolution, multi-fold acquisition systems. The best 2-D data are acquired with systems using multiple sleeve gun sources with anywhere from 24 to 96 channels. Common sampling rates vary between 0.25 ms to 0.5 ms. For the US Gulf of Mexico, MMS requirements usually dictate that the line spacing of 2-D systems be 300 meters by 900 meters[1]. Early in Shell's deepwater geohazard surveys, single channel sparker and mini-sparker surveys were conducted as separate surveys from the deep tow survey. These systems were marginal in assessing deeper penetration geohazards. Special methods were later employed to put as many shots into the water column as possible to increase resolution. Multi-fold 2-D surveys gradually were used starting in the late 1980's – especially for TLP related projects.

Deep penetration, high-resolution, multi-fold 3-D systems are now being deployed in the US Gulf of Mexico. For example, a system deployed for Shell this past summer employed four streamers set 30 meters apart (Fig. 4). The cmp bin size is 6.25 meters in-line by 15 meters cross-line as the natural acquisition bin dimensions. The source is a multi-sleeve gun array called the TriCluster 80©. Each streamer uses only a single active section of eight geophones each. The methodology for processing short offset data has been discussed by Cowlard[1]. Theoretically, only one hydrophone per cable is required using this method although it is common to use two to three channels per streamer. Compared to single streamer 3-D systems, costs and time to conduct a survey are typically reduced by a factor of at least three. High-resolution 3-D systems have been found to be especially useful for characterizing the upper 150 meters of sediment for TLP related design issues and also to produce high-resolution imagery for shallow water flow stratigraphic mapping of sediments to penetrations greater than 750 meters. Another potential use of the system is to assess shallow reservoirs as the time and cost to acquire data is about one-tenth that of traditional 3-D acquisition. The data resolution improvement is marked. Shown in Fig. 5 is an exploration-level 3-D section. When compared to the short offset derived 3-D data section shown in Fig. 6, it is very obvious that a significant improvement in resolution has been achieved.

Geotechnical Evaluations

The usefulness of a geohazard evaluation for geotechnical purposes is totally dependent on the geophysical data quality and the geological model interpreted from the data. While the 3-D exploration-level data serves as a guide to the scope of a geotechnical evaluation, a more complex geophysical survey is usually warranted. If near-surface (*i.e.*, upper 75 meters) is to be imaged, Shell uses the EDO deep tow system. The subbottom data are especially useful in assessing the soils for skirted foundations (*i.e.*, suction piles), anchors, jet pipes and the upper sections of TLP piling. For deeper penetration studies, the system of choice is the 3-D short offset system. This system is useful to correlate deeper geotechnical horizons of interest to TLP foundations.

A geohazard which has been a constraint to Gulf of Mexico (US) deepwater drilling operations is shallow water flow. Unconsolidated sands some 325 to 900 meters below the sea floor can be encountered which contain water pressures above hydrostatic. The overlying clays are often soft such that there is limited room between the pressure required to cause formation fracture and the pressure required to control flow from the sands due to the excess hydrostatic pressures. If the well flows due to this phenomenon, it is called a shallow water flow. The identification of potential shallow water flow zones through geophysical data is enhanced with high resolution data and a knowledge of the stratigraphic conditions that cause shallow water flow. Casing set above the shallow flow zone is one of the methods used to mitigate shallow water flows. Often 3-D high-resolution systems such as described earlier are required to better define the stratigraphy associated with shallow water flows.

Geotechnical Investigations

A geotechnical investigation is required to design the foundation for most offshore structures. The **integrated geoscience study** forms the basis for the geotechnical evaluations. It combines the geophysical data, a model for the geological processes used to explain the geophysical data and the geotechnical data itself to develop the soil properties required for the foundation design. If potential geohazards were identified in the initial geohazard study, additional geophysical and geotechnical work may be required to specifically address potential constraints for field development. One example was to assess shallow slumps through the use of deep tow data and strategically placed shallow cores obtained with a submersible[9].

Fast tracking developments often require that a geotechnical investigation be performed without a precise location for the structure. One product of an integrated geoscience study allows soil properties to be projected from the soil boring site to the actual site of the foundation. The geohazard study and additional high-resolution geophysical data are also used to plan the geotechnical investigation.

Planning The Investigation. An integrated geoscience study begins with the planning for the geotechnical investigation. The high-resolution geophysical data are reviewed and horizons mapped which may be significant to determining geotechnical properties. An example of a 3-1/2 kHz subbottom profiler line where several horizons are mapped is shown in Fig. 7. For mooring studies, more than one boring is usually planned to characterize soil horizons. For TLP investigations, a single boring is the objective with the site chosen in consultation with the subsurface evaluation team to pick a TLP site suitable for both production and geotechnical siting purposes.

If a geologic process is suspected to be active within the context of the engineering life of the facilities to be installed, then a part of the geotechnical investigation should be focused toward determining the affect of the process on the design of the facilities. Often, as many geophysical horizons are mapped as reasonably possible. Penetrations are assigned to the horizons and the sampling and *in situ* program developed to characterize the horizons. For example, if slumps were seen in the high-resolution geophysical data, then geotechnical samples might be obtained and tested such that slope stability studies might be performed. The more common integrated geoscience study is to use the results of the high resolution study to determine boring locations and sampling intervals. Often a boring site is picked which shows similar lithology to the planned site of the facility in order to provide some flexibility to move the facility. This flexibility is particularly important for fast tracking developments. Most geotechnical investigations also require that an advanced test program consisting of both static and cyclic tests be conducted. As such, closely spaced sample tubes are obtained in order to ensure that soil properties are similar within the zone sampled.

In planning a sampling program, *in situ* tests and retrieved samples must be obtained to characterize the major geologic horizons. Advanced test sample intervals are selected so that the samples are representative of each significant geological horizon and to allow for missed or short recoveries during tube sampling. The "saved" tubes are usually nickel plated to prevent corrosion, capped tightly and refrigerated to inhibit post-sampling effects which might effect soil properties. The scope of typical deepwater Gulf of Mexico investigations has recently been discussed by Dutt, *et al*[12] and Pelletier *et al*[13].

Interpreting The Data. In addition to serving as an aid in the planning of sampling intervals, high-resolution geophysical data are useful in the interpretation of geotechnical properties. Important to this process is developing a geological model which integrates both the geophysical and geotechnical data into a coherent interpretation. Slump units, geological unconformities and varying depositional processes are expected to have an effect on interpreted geotechnical properties.

Once the geotechnical investigation is completed, the data from each boring is segregated into its respective horizon and interpreted within each like-horizon. If more than one boring was obtained, the test data within each like-horizon is combined for all borings. Disturbance does not affect index properties such as water content and Atterberg Limits. Thus, these data are compared to determine if the same soil has been sampled within like-horizons. If successful, the next comparison should be between soil density, remolded shear strengths and finally static shear strengths. A truer shear strength profile results when like-horizons between one or more borings are interpreted together. Spurious shear strength values can more easily be eliminated by this methodology. The interpretation of the shear strength profile is based on the like-horizon results and adjusted for individual horizon differences in thickness.

An example of using the high-resolution data to understand the geotechnical behavior was the boring obtained at the site of the Mars TLP[14]. Shown in Fig. 8 is a portion of a high-resolution geophysical line, with the log of the soil boring and test results shown at the point in the record where the boring was drilled. The geological model developed for this deepwater site indicated that the clay horizons should be composed of layered deposits of hemipelagic clays with interbedded slump units. Based on the regional geophysical data, the slump units did not appear to have traveled great distances, and were expected to contain locally slumped and rotated deposits of clay. In fact, the samples retrieved from the slump units showed mostly layered sediments, some of which showed inclined bedding. Thus, the soil properties were expected to be more variable within the slump units than in the adjacent layered deposits. The sampling and testing program consisted of a series of regularly spaced tube samples and in situ tests, as well as closely spaced tube samples in those units where advanced tests were conducted. Several geotechnical horizons could be correlated to those horizons. Each geotechnical parameter was then interpreted based on the data within the horizon, its geological origin, and the implication of the geological origin on the data. One example of the usefulness of the integrated study was the interpretation of the Direct Simple Shear (DSS) data. Shown in Fig. 9 are the S_u/σ'_{vc} ratios from the DSS tests. The S_u/σ'_{vc} ratios outside of the slump unit (labeled as Landslide Unit B in Fig. 8) were reasonably constant, while the S_u/σ'_{vc} ratios within the slump unit showed considerable variability. We interpreted the variability of the soil layers being at varying inclinations to the direction of shearing. Two additional DSS tests were run where inclined layered soils were sheared perpendicular to the layers. In one case, the layers were "down slope" to the shear direction and "up slope" to the shearing direction in the other test. As observed in similar tests (Sobotka, 1979), the "down slope" S_u/σ'_{vc} values were higher than the "up slope" tests. As shown in Fig. 9, the "up slope" - "down slope" tests encompassed the range of S_u/σ'_{vc} values measured. Thus, the slump unit's S_u/σ'_{vc} ratio was interpreted to be the average of the "up slope" - "down slope" tests, and the variability observed was due to the rotation of the bedding during the slumping process.

Laterally Projecting Geotechnical Data. Another application of deepwater integrated studies is to use the geological model and geophysical data to laterally project soil properties from the site of a geotechnical investigation to the nearby site of the structure. This technique may avoid the need for multiple borings at the same site, or the need for a new investigation for "minor" changes in location. Few studies have been done in the deepwater Gulf of Mexico to show the extent of the possible variability of soil properties. One obvious reason for this is that additional geotechnical investigations are conducted only when the engineer expects to see a change rather than do another boring where the site appears similar. In general, where the geophysics indicate similar geology and relatively constant unit thicknesses, a change in location less than a few hundred meters probably does not warrant another geotechnical investigation. Significant location changes may warrant a limited-in-scope geotechnical investigation or a confirming CPT investigation at the new location.

At one deepwater Gulf of Mexico TLP location, lateral projection of soil properties was done for two borings some 485 meters apart to another site some 700 meters away. This procedure was accepted by the approving authorities. The interpretation of the two borings was done as described earlier and projected to the new site using high quality deep tow 3-1/2 kHz subbottom profiler data and 3-D high-resolution data. The geotechnical properties of the two borings correlated well between like-horizons. A log of the two borings and the arbitrary 3-D high-resolution line between the two sites is shown in Fig. 10. Projections like this absolutely require very high-resolution geophysical data. However, the procedure has limits. These same two borings were projected to a third boring site some 2,100 meters from the other two borings. While the water contents and Atterberg Limits correlated to like-horizons, the remolded and static shear strengths did not.

The same two borings discussed above also illustrate the possible magnitude of the variability of geotechnical parameters over large lateral distances. As previously discussed, the units were picked on the basis of high-resolution geophysical data and confirmed by geotechnical properties such as water content, Atterberg Limits, and soil density measurements. The site-to-site integration of two landslide (or slump) zones is as an example of the integration process. The units are designated as Unit V and Unit VII in Fig. 10. These units were expected to show considerable shear strength variability within each unit due to the lateral translation and rotation of the clay beds which occurred during the slumping process. Remote Vane shear strengths from the borings are shown in Fig. 11 for both units. The upper landslide unit shows intra-site scatter in the Remote Vane values, while the lower landslide unit shows both sets of RemoteVane values to be similar. Thus, it could be inferred that the upper units are different and should be treated as a two distinct geotechnical units, while the lower landslide unit could be interpreted as having the same shear strength profile at both locations. Additionally, other measures of shear strength such as miniature vane and unconsolidated-undrained (UU) strengths should also be evaluated to make a final interpretation of the shear strength variability between sites.

Summary

With the high cost of deepwater developments it is important to obtain high quality geophysical and geotechnical data and to use it in such a way that the field development has flexibility such that the facilities can be moved without requiring new geotechnical data. High-resolution data are an important part of this process. The systems most critical to this are 3-1/2 kHz subbottom data and 3-D high-resolution, multi-fold geophysical data. Planning for these surveys should take advantage of the standard 3-D geophysical data obtained for exploration purposes. Workstations and renderings of the water bottom aid in evaluating a site. These data are used to plan the geotechnical program location and sampling program. Upon completion of the program, the soil data should be interpreted within each geotechnical horizon. For multiple investigations, data should be combined within geological horizons to increase the reliability of the interpretation. Laterally projecting soil properties is possible with this technique.

Future Trends

In the area of geophysics, 3-D high-resolution, multi-fold geophysical systems will become a standard tool for evaluating shallow water flow sites and for development projects so that integrated geoscience studies can be better used. Rendering subbottom horizons will also become possible with this type of data. Swath bathymetry will be collected and water bottom amplitude renderings (*i.e.*, using backscatter data) will be produced which are similar to the process described by Doyle, *et al*[3].

Geotechnical investigations are now possible in water depths more than 3,000 meters. Extremely stable vessels such as the semi-submersible Uncle John and bottom founded reaction systems are keys to obtaining better geotechnical data in deepwater. We have seen differences between deepwater borings obtained at different times in near-by locations and can attribute the differences to vessel stability. Future developments will certainly see more use of the piezo-CPT and the piezocone to determine *in situ* pore pressures. Better understanding between sampled and *in situ* data (shear strength and permeability in particular) will eventually happen as more data are collected in the very soft clays of the Gulf of Mexico. Some additional research is required in soft, underconsolidated clays to better correlate Normalized Soil Behavior and SHANSEP[16] methodologies. Research will also be required to understand why some sites have different ratios between sampled and *in situ* shear strengths. There are indications that these differences may be caused by differences in *in situ* stress conditions due to salt movements.

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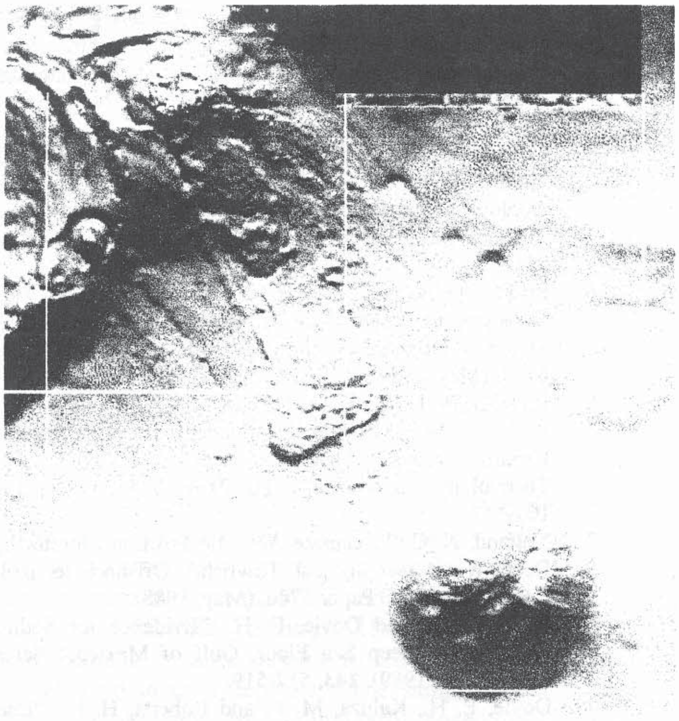


Fig. 1-Seafloor rendering based on 3-D exploration-level data.

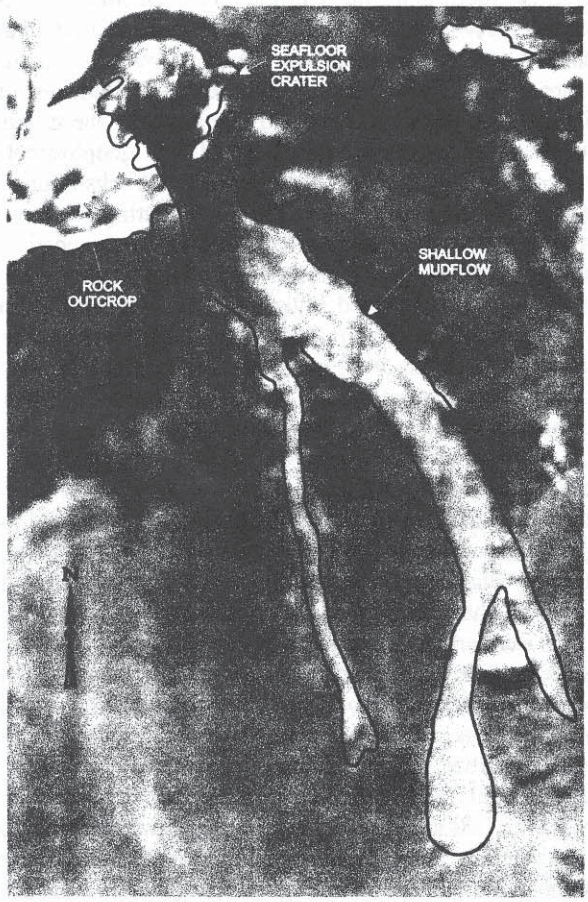


Fig. 2-Seafloor amplitude rendering over expulsion crater and subsequent mudflow.

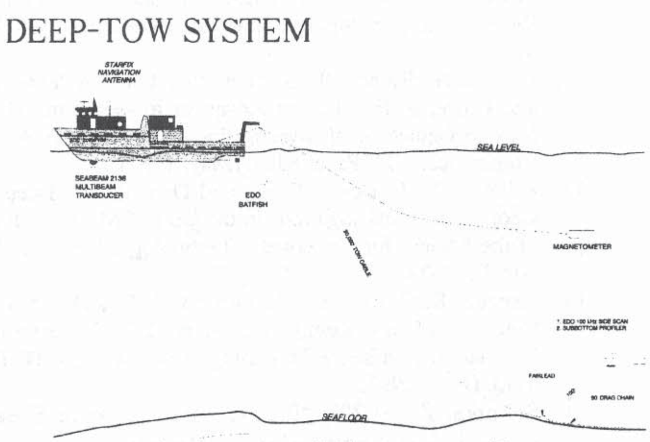


Fig. 3-Schematic of EDO deep tow system.

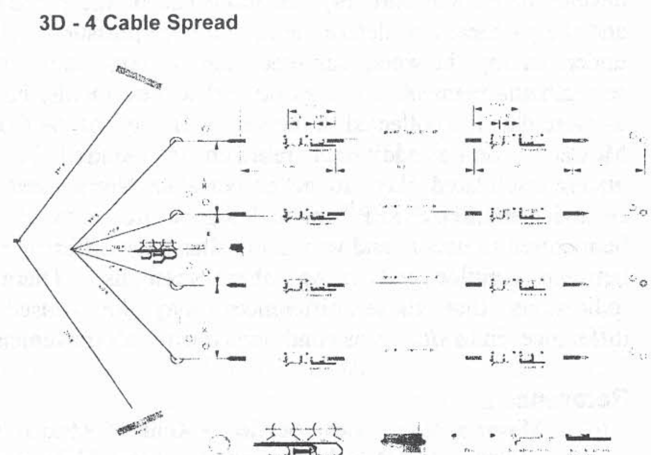


Fig. 4-Schematic of short-offset, high-resolution, multi-fold 3-D acquisition system.

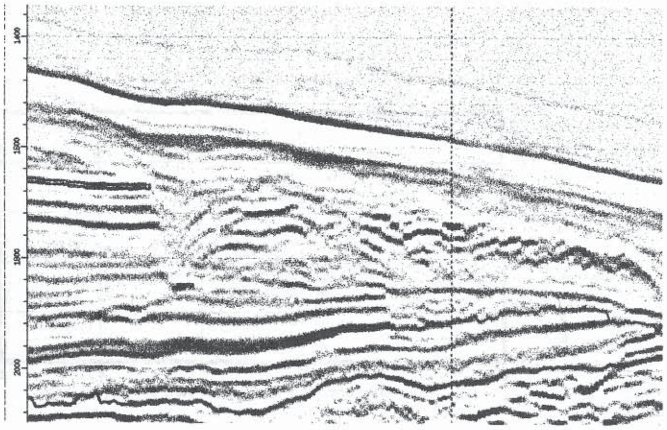


Fig. 5-Example cross-section of exploration-level 3-D data.

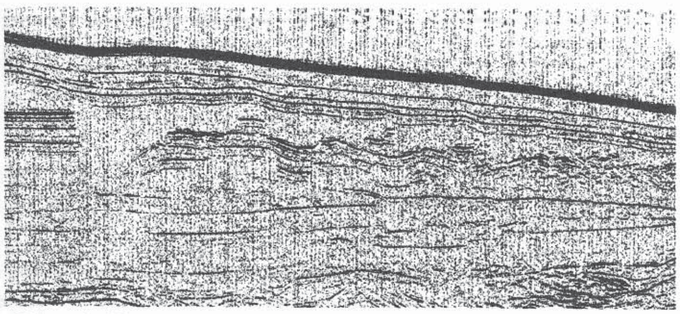


Fig. 6-Example cross-section of short-offset, high-resolution 3-D data.

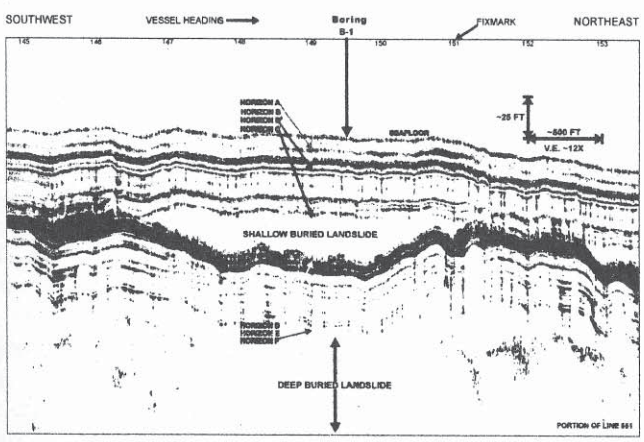


Fig. 7-Subbottom profiler record showing stratigraphic conditions below boring B-1.

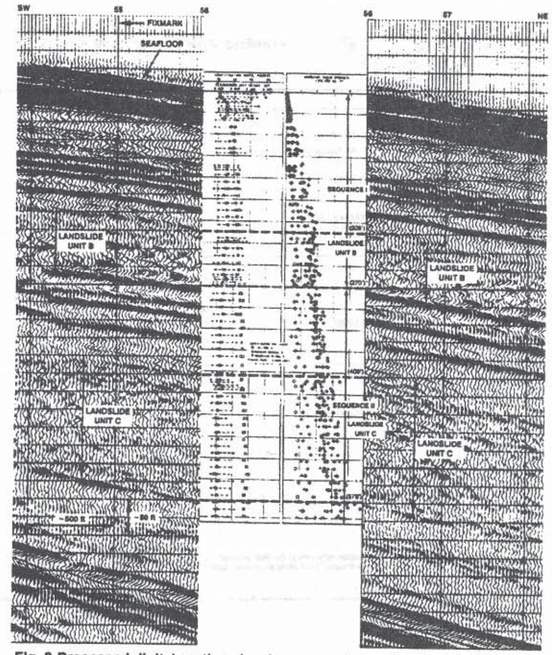


Fig. 8-Processed digital section showing comparison with soil boring.

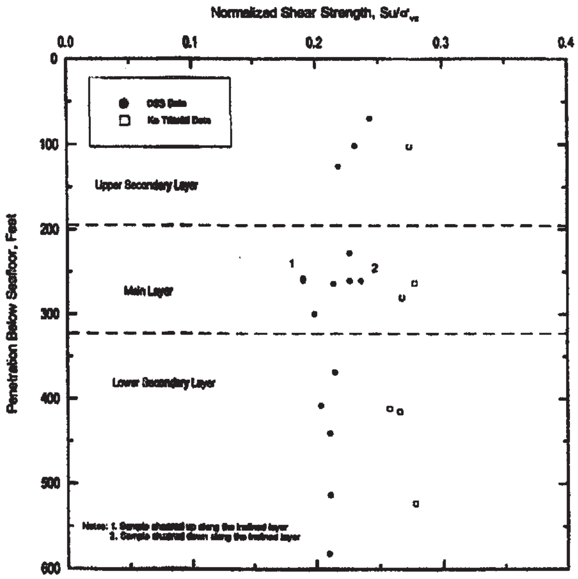
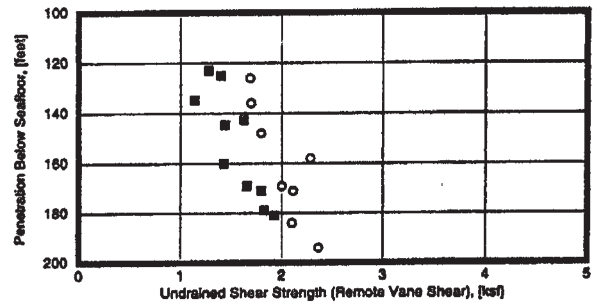
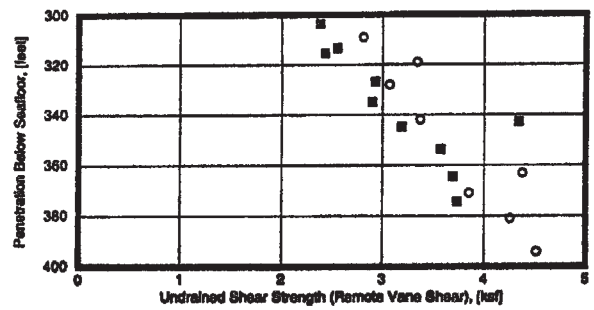


Fig. 9-Normalized direct simple shear strength versus penetration.



a. - Upper Landslide



b. - Lower Landslide

Fig. 11-Comparison of remote vane strength for two landslide units.

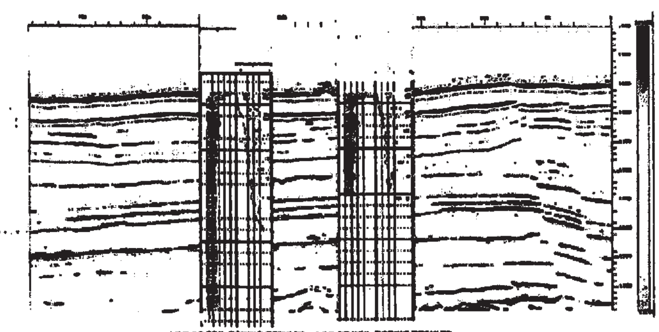


Fig. 10-Correlation between two borings with an arbitrary high-resolution 3-D line.