2D UHR seismic survey as a tool for mapping of shallow sub-surface soil stratigraphy at exploratory well locations and for initial assessment of geohazard risk for jack-up platform – A case study

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ABSTRACT: Site characterization relies on geophysical survey followed by geotechnical investigation for calibrating subsurface stratigraphy and to understand soil conditions. Increasingly geophysics, integrated with geotechnics, has been used to deliver 2D/3D sub-surface soil stratigraphy model for the survey area. A cost effective site investigation is one in which the given area is surveyed systematically to identify the uncertainties, to reduce the geohazard risk and to achieve success within short time and limited budget.

In seismic sections we can interpret stratigraphy horizons, small scale sedimentary structures etc. within the soil horizons based on the acoustic characteristics recorded in the data. However, the soil properties are not known, which is required to understand the punch through risk for jack-ups of different capacity. Attempt was made to correlate borehole/Cone Penetration Test (CPT) data available at the punch through locations by carrying out 2D Ultra High Resolution (UHR) seismic survey. The seismic characteristics of soil horizon, when correlated with available geotechnical data, has bought out vital information on the perceived geohazard risk identified during punch through risk analysis for the jack-ups. Mapping of such horizons on seismic data is useful for initial assessment and reporting the occurrence of geohazards within the survey area.

India's western offshore has undergone sea-level fluctuations in the geologic past. The marine transgression and regression processes active over an extended geological time scale, have resulted in complex geology in Mumbai offshore. Due to complex geology noticed in the offshore it is important to know soil distribution pattern and conditions for placement of jack-up at exploratory well locations. Hence, such integrated approach in India's western offshore, which has undergone sea- level fluctuations in the geologic past, has revealed that 2D UHR survey could be a useful tool to identify potential areas having unfavorable soil conditions/geohazard for the emplacement of jack-up platform.

Keywords: Mumbai offshore, 2D UHR seismic, geohazard, site survey, jack-up platform

1. *Introduction*

Several geohazard and site characterization studies have been carried out as part of offshore field development program all over the world. An integrated geophysical and geotechnical approach is required to avoid geohazards, surprises/failures at different stages of the project; which include emplacement of jack-up at exploratory well locations, installation of process platforms/unmanned jackets as part of field development program. Such a standard approach is important so that safety is not compromised and time and investment can be optimized. In the context of this paper, the term 'Site Surveys' refers only to those surveys conducted for the identification of geohazards as carried out for oil and gas projects. It does not refer to other types of site survey operations such as those carried out for wind farms or pipelines. The main purpose of such works is exploring sub-bottom geological section, detection and evaluation of sub-seabed features, which may affect the drilling platform stability (0-50 m below seabed). Neglecting the above type of geohazards may lead to subsidence, loss of stability of the jack-up/platform. The industry sets high standards and has endeavored to raise these standards by issuing up-to-date guidelines for conducting geohazard site surveys. The most recent advances have been data acquisition using 2D UHR data. Seismic interpretation usually means (a) interpretation of exploration seismic where the main purpose is to locate hydrocarbon bearing structures and (b) geohazard interpretation which focuses on interpretation of shallow gas traps and Quaternary geology/most recent soil stratigraphy.

A full understanding of the seabed and sub-seabed conditions is a crucial aspect for the jack-up installation and operation. A punch through is a case of a sudden and rapid penetration into the seabed, usually of one leg due to a reduction of the vertical bearing capacity locally in the seabed layers. Typically, this occurs when a strong layer is overlying a weaker layer. During penetration in the strong layer, the bearing capacity gradually increases, but when penetration comes closer to the weaker layer, the bearing capacity reduces to a level significantly below the current preload at the leg. The leg in that case loses support and penetrates (rapidly), resulting in a (sudden) inclination of the hull. This inclination causes a significant extra overturning moment and base shear which is counteracted by leg bending, leg shear and increasing vertical leg reaction of the punched leg. This situation arises majorly due to non-detailed or absence of a seabed and geophysical survey and the available borehole data is not representative of the ground conditions at the spud-can foundation.

The principal value of 3D exploration data is that they are typically available during early stages of subsea development projects (having already been collected to support exploration work) and cover large areas that will eventually be considered for seafloor development if exploration is successful (at a relatively broad scale and low resolution). Thus, they are useful for obtaining a general understanding of the seafloor geomorphology. Their comparatively low resolution, however, generally makes them secondary rather than primary data for shallow geohazard investigations [1]. One advantage of the lower frequency is that they penetrate much deeper but the vertical resolution is compromised and hence the data is not suitable for shallow geohazard identification. Tools such as SBP, ultra-high resolution 2D multi-channel seismic surveys (2D UHR), and high-resolution 2D seismic surveys (2D HR) may penetrate less than 1000 m and have better vertical resolution and hence shall be able to identify shallow small scale hazard for subsea structures and pipelines [2]. Moore et. al. [3] opined that the ground model can be improved during later stages of the field development, using higher resolution seismic data (2D UHR and AUV) for a specific site.

2. *Geologic setting*

Mumbai High field was discovered in 1965 and started production in the year 1974. Bombay High is an offshore oilfield 165 km off the coast of Mumbai, India, in about 75 m of water. Mumbai offshore basin accounts for nearly two-thirds of the annual petroleum production of India. It produces 14 per cent of India's oil requirements and accounts for 38 per cent of all domestic production.

Mumbai offshore basin, a divergent passive continental margin basin, is located on the continental shelf off the west coast of India. The basin was formed due to extensional tectonics at the time of rifting of the Indian plate from Madagascar during Late Jurassic-Early Cretaceous period. Large-scale volcanic eruptions, which covered most of the basin, followed this episode. Early Eocene marks a widespread transgression. Sedimentation during this period caused some adjustments in the basin. The early Oligocene transgression covered most parts of the basinal area and inundated parts of Mumbai high. A major unconformity is noted at the top of lower Oligocene. Sea-level rise during early Miocene submerged large areas of the basin and terminated the Oligocene delta progradation. The middle Miocene transgression marks the last phase of the widespread carbonate sedimentation in the Mumbai high–DCS area [4, 5].

The Mumbai Offshore Basin is divided into six tectonic blocks (Tapti-Daman, Diu, Heera-Panna-Bassein, Mumbai high-Deep Continental Shelf [DCS], Ratnagiri, and Shelf Margin), and the sedimentary fill ranges from 1100-5000 m. Several large oil and gas fields have been discovered in this basin, and the presence of hydrocarbons has been established in the multiple pay zones belonging to L-III limestone reservoir of Miocene age (only in Mumbai high), Mukta (early Oligocene), Bassein (middle Eocene), Panna (Paleocene to early Eocene) reservoirs, and Daman (early Miocene-late Oligocene) and Mahuva (early Oligocene) formations in Tapti Daman block.

3. *Methodology*

2D multi-channel seismic (2D UHR) site survey was carried out at locations where geotechnical investigation indicated punch through risk for drilling rigs. A 2.5 km x 2 km area was surveyed to understand the shallow stratigraphy around the reported punch through locations. Main survey lines (EW and NS) were run at 100 m spacing and close grid survey lines of 250 m x 250 m area at a line spacing of 25 m and 50 m in perpendicular direction was carried out at the punch through locations reported during geotechnical investigation. In addition, tie-line was run from the borehole location (D – Shifted which is a non-punch through location) to the above punch through location. As part of data acquisition, survey vessel owned and operated by Fugro was deployed with multi-channel survey spread, which consisted of sparker source and the receiver having 24 channel streamer. Table 1 details the multi-channel system and associated equipment's mobilized for the survey.

Table 1. Multi-channel seismic system with data acquisition parameter

Parameter	**Settings**
Source	**Dura-Spark 240**
Power	Field selected for optimum penetration
Recording Length	300 ms
Shot Interval	3.125 m
Sampling interval	0.125 ms
Streamer	**Geometrics Solid MicroEel**
Active Streamer Length	75 m
Number of Channels	24
Group Interval	3.125 m
Data Acquisition/Processing software	Seismic Module Controller/RadExPro
Recording format	Seg-D
Data Interpretation Software	GeoSuite Allworks

Figure 1 below shows the survey corridor (2.5 km x 2 km) and 2D UHR survey lines with all the locations marked in it.

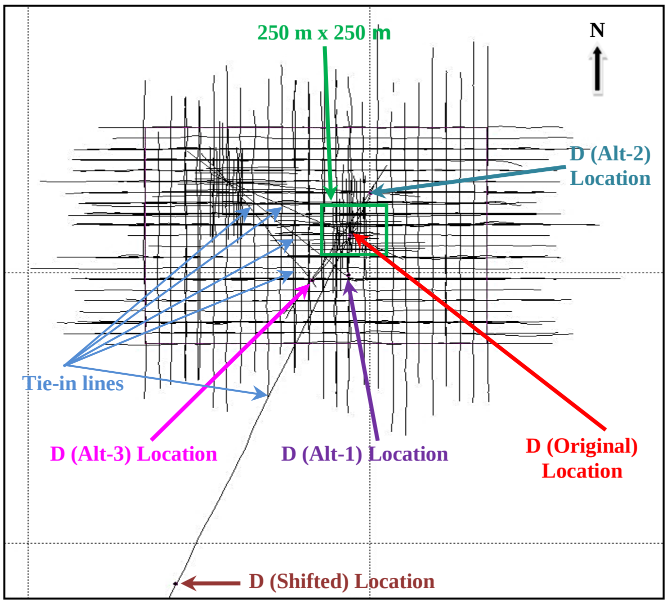

Figure 1. 2D UHR survey lines with the all locations

4. *Results & discussion*

Within the survey area the water depth varies between 76 m and 84 m below chart datum. For ease of understanding the location name has been named as D (Original), D (Alt-1), D (Alt-2), D (Alt-3) and D (Shifted). Results of geotechnical investigation [borehole and Piezocone Penetration Test (PCPT)/CPT or PCPT only] for all the above locations have been summarized in Table 2.

Table 2. Summary of the geotechnical investigation results

Location name	Depth of investigation (m)	Punch through risk	Estimated punch through stratum depth (m)	Remarks as per geotechnical report
D (Alt-1)	29.5 (PCPT) 39.6 (borehole)	Nil for 4 rigs out of 10 rigs	7 to 24	Variable resistance - loose to dense silty fine to medium sand with layers of firm cohesive soil
D (Alt-2)	17 (PCPT)	Punch through risk for all rigs	7 to 12.8	Variable resistance - Very soft to Stiff / Loose to Medium dense Interlayered COHESIVE SOIL /GRANULAR SOIL
D (Alt-3)	26 (PCPT)	Punch through for all rigs	0 to 6.7 12.6 to 13.6 17.4 to 21.5	Variable strength; firm to very stiff cohesive soil layer below a dense granular soil layer
D(Original)	No geotechnical investigation carried out	Punch through risk expected – interpreted from 2D UHR data	5 – 18.2	Inferences purely based on the acoustic characteristics noticed on 2D UHR seismic records
D (Shifted) which is approx. 3.5 km south-west from D(Original)	30 (CPT) 125 (borehole) Platform location	Nil punch through for all rigs	Nil	Max. expected leg penetration – 13 m to 14 m. Between 9 m – 20 m – Dense Silt.

Analysis of geotechnical data has concluded that all the above locations except D (Shifted) has punch through risk for all the rigs or for some of the rigs. Though there is no geotechnical data available for D (Original) location, from the 2D UHR survey (described in below section 4.4) one could deduce similar inferences (geohazard) based on acoustic characteristics noticed in the seismic records. Geotechnical investigation results at the D (Shifted) location has shown no punch through risk for any of the considered jack-up platform.

4.1. D (Alt-1) location

Seismic stratigraphy along EW survey line passing through the D (Alt-1) borehole location is shown in Fig. 2. Unit B shown in the image correlates with the loose to dense silty fine to medium sand with layers of firm cohesive soil as reported in the geotechnical report for this location. The unit B represents variable geotechnical properties and hence it was considered as a punch through location (see table 2, remarks column). In the seismic section, we can see subparallel layering/cross-bedding which indicates a different depositional environment. In addition, the irregular variation in amplitude/chaotic reflection pattern noticed within this sedimentary unit as compared to more or less consistent and uniform amplitude noticed for other units (acoustically transparent soft cohesive sediments, amplitude change with speckled appearance due to granular sediments and closely spaced planar reflections of weak and strong amplitude which are characteristic of interbedded clays and silts) could be associated to the change in soil properties (mixture of dense granular and cohesive soil). Summary of geotechnical investigation and 2D UHR soil stratigraphy at the D (Alt-1) location is given in Table 3.

Table 3. Summary of the geotechnical investigation and 2D UHR seismic stratigraphy results up to punch through depth at D (Alt-1) location

Geotechnical results (based on borehole data		**Interpreted soil stratigraphy from 2D UHR**	
Unit	**Depth to the top and bottom of unit below seabed (m)**	**Unit**	**Depth to the top and bottom of unit below seabed (m)**
Silty sandy Clay	0 – 7	A – Silty /sandy CLAY	0 – 7
loose to dense silty fine to medium sand with layers of firm cohesive soil	7 – 24 (estimated punch through stratum depth)	B & C – Granular soil with pockets of cohesive soil	7 - 25

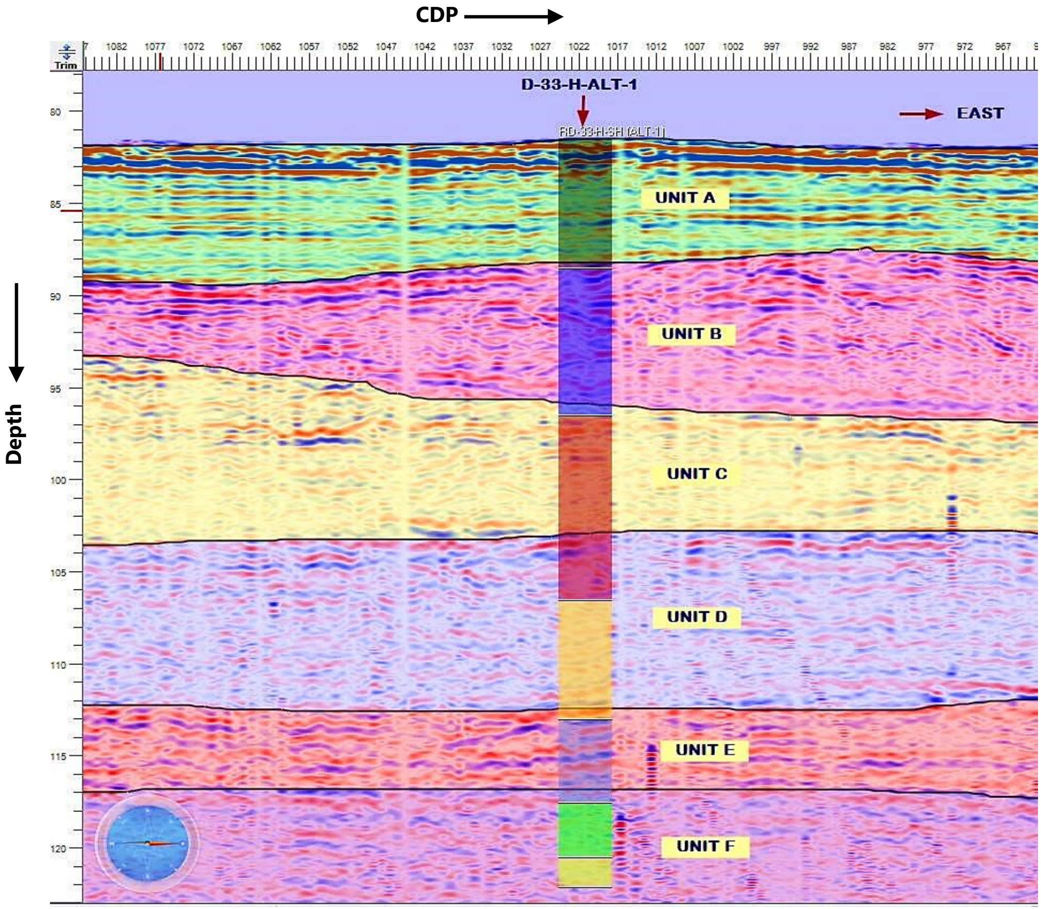

Figure 2. UHR Seismic Profile Section along a survey line passing through the D (Alt-1) borehole location

4.2. D (Alt-2) location

The sub-seabed geology interpreted in the seismic section at the D (Alt-1) location was correlated with the stratigraphy deduced from the PCPT data. Figure 3 represents seismic section along the survey line passing through the D (Alt-2) borehole location.

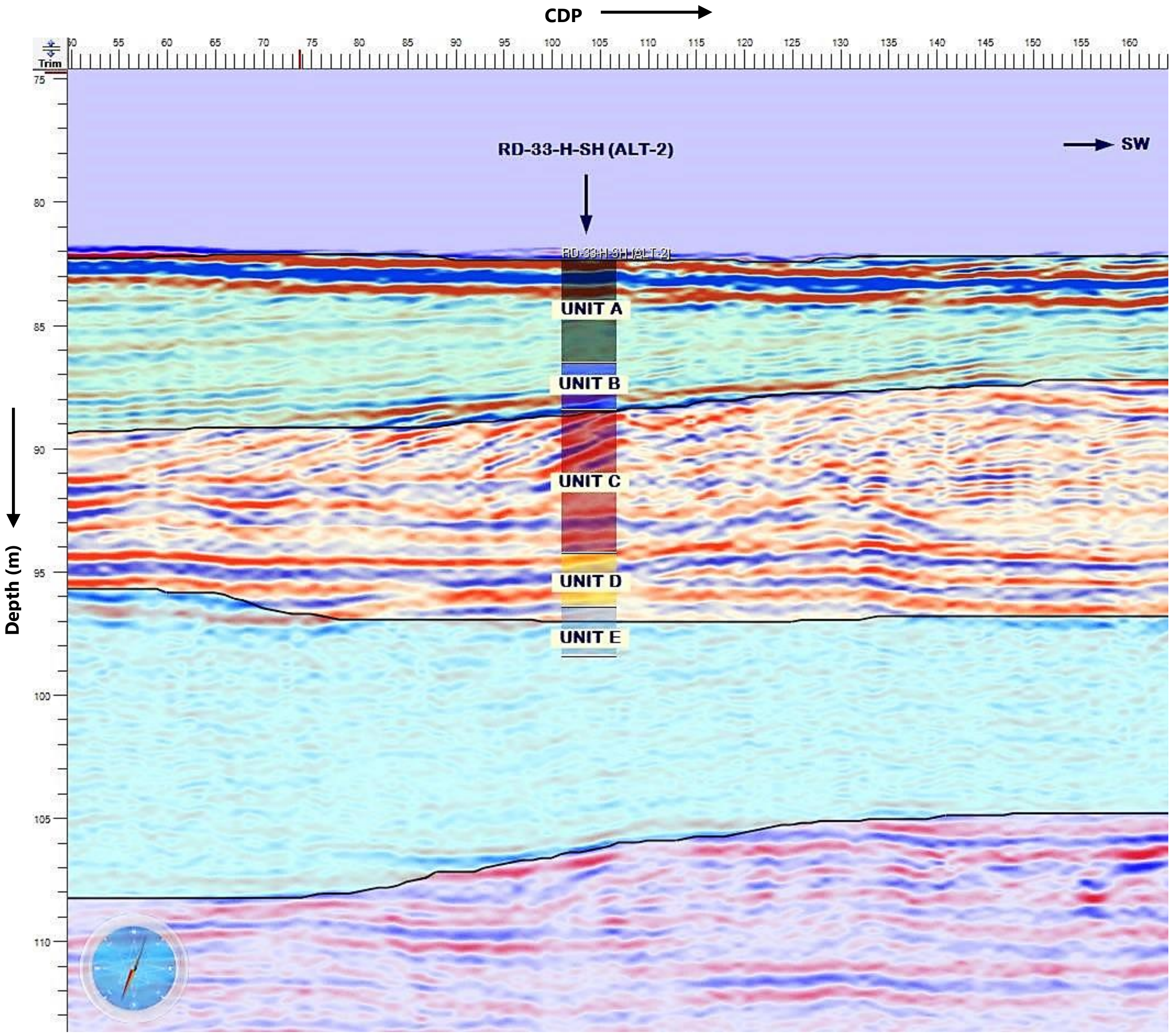

Figure 3. UHR Seismic Profile Section along a survey line passing through the D (Alt-2) borehole location

The UHR seismic section indicates presence of variable resistance strata from 6.0 m to 10.8 m below seabed which is represented by UNIT C. This unit is characterized by distinct cross lamination/bedding of cohesive and granular soils, which correlates with the soil characteristics deduced from PCPT data (refer Table 1). Here, it is evident that the punch through risk for spudded jack-up was mainly due to cross laminated beds which generally show variable geotechnical properties. Local discontinuities of the minor reflectors perhaps indicate small scale lateral facies variation. Another interesting aspect that can be noticed in the above seismic section is the lateral continuity, variations in the thickness, attitude of the soil strata (horizontal, dipping) within those soil units. Moreover, the dipping strata below unit B was underlain by a horizontally layered (interbedded), closely spaced planar reflectors (Unit D – 10.8 m to 14.6 m bsb) which was again underlain by a thick acoustically transparent unit (Unit E – 14.6 m to 23.4 m bsb) and it may suggest relative variation in soil condition. A certain degree of stratification within unit E is indicative of a relatively slow sedimentation rate. The above seismic stratigraphic sequence strongly indicates an unfavorable soil condition for the placement of jack-up. Such acoustic units referred to as seismic stratigraphic units may have significantly different strength and may be characterized by rapid lateral and vertical strength variations which can be mapped using the 2D UHR survey technique. What is also becoming clear is that these interpretations and observations are not confined to one-off conditions, but can be replicated over a number of locations or even under different geological settings.

Thus the 2D UHR system could be considered as a useful mapping tool

- for understanding the lateral and vertical variation in soil stratigraphy,
- for initial assessment and identification of unfavorable soil conditions/geohazard,
- which helps in prioritizing locations for geotechnical investigation based on probability and significance of geohazards,
- for proposing suitable alternate locations to carry out geotechnical investigation for punch through risk analysis for jack-up,
- which will further help in planning and optimizing the deployment of geotechnical vessel and in making informed decisions which in turn will save time and cost for the field owner/operator.

Earlier studies by [6], on the shallow sub-bottom profiles taken from nearshore across the shelf as far as the Bombay High indicates that the sedimentary unit overlying the westward dipping reflector outcrops at outer shelf around 60 – 90 m water depth. These outcrops were identified to be relict carbonate sediments of the late Pleistocene to early Holocene time (recent sediments) of glacially lowered sea-level and was radiocarbon dated to be around 9,000 – 11,000 years old [7, 8]. The erosional truncation of the upper surface of the westward dipping reflectors noticed in shallow seismic record by [9] indicates subaerial erosion which would be possible only during lower seastrand and most likely during a Pleistocene regression.

4.3. D (Alt-3) location

The sub-seabed geology interpreted in the seismic section at the D (Alt-3) location was correlated with the stratigraphy deduced from the PCPT data. Figure 4 represents seismic section along the survey line passing through the D (Alt-3) borehole location.

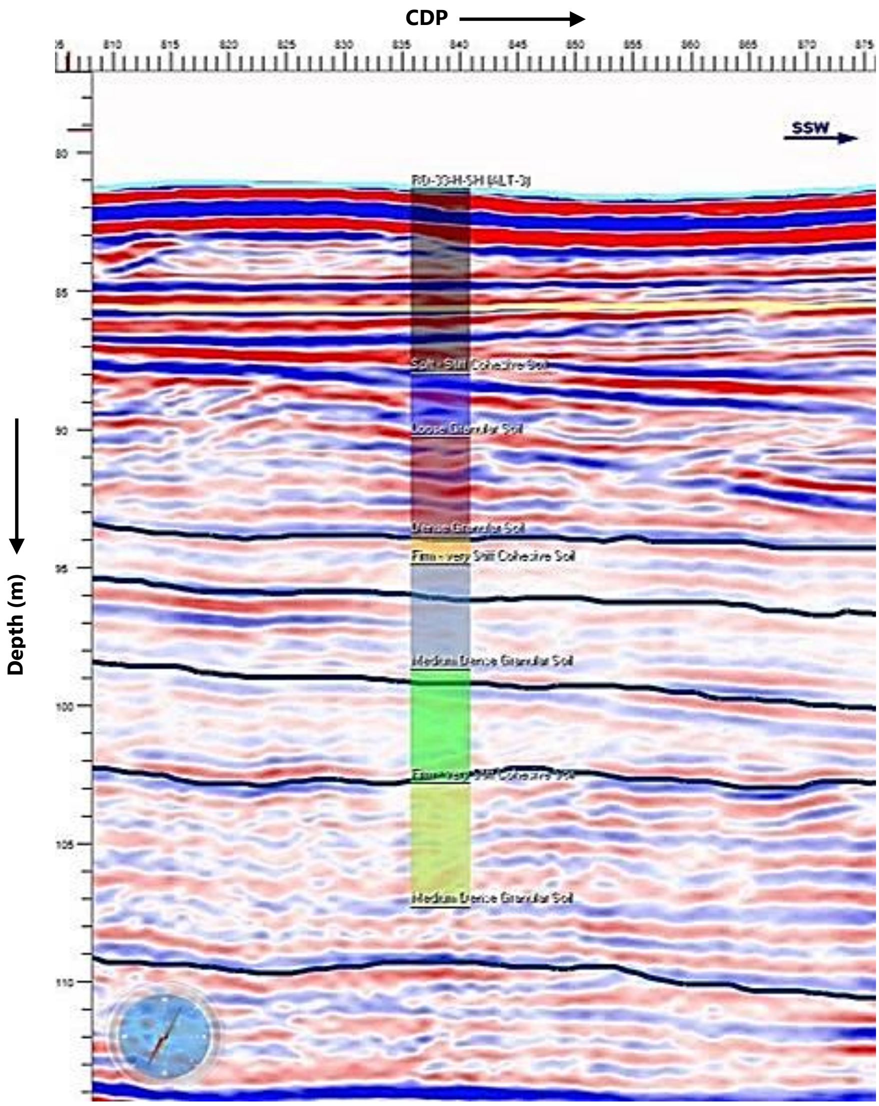

Figure 4. UHR Seismic Profile Section along a survey line passing through the D (Alt-3) borehole location

The UHR seismic section invariably shows alternate units of acoustically transparent cohesive and alternate banding of weak and strong seismic reflection signals, indicating vertical variation in the sedimentary facies and this shows a certain cyclicity which appears to be significant. The strong reflectors represent the coarse grained materials and the intervening acoustically transparent layers are fine grained sediments. The cyclic nature of the stratigraphy seen at this location will result in variation in the soil strength characteristics and hence it may be a geohazard for the spudded jackup because of punch through risk. The seismic stratigraphy interpreted in 2D UHR record and the stratigraphy deduced from the PCPT data is in good agreement (see Table 4).

Table 4. Summary of the geotechnical investigation and 2D UHR seismic stratigraphy results up to punch through depth at D (Alt-3) location

Geotechnical results (based on PCPT data)		**Interpreted soil stratigraphy from 2D UHR**	
Unit	**Depth to the top and bottom of unit below seabed (m)**	**Unit**	**Depth to the top and bottom of unit below seabed (m)**
Very soft to stiff cohesive soil	0 – 6.7	A – Cohesive soil with traces of granular soil	0 - 4.5
Loose Granular Soil	6.7 – 9.0	B – Predominantly Granular soil	4.5 – 12.6
Dense Granular Soil	9.0 – 12.6		
Firm to very stiff Cohesive Soil	12.6 – 13.6	C – Cohesive soil	12.6 – 14.8
Medium dense Granular Soil	13.6 – 17.4	D – Granular soil	14.8 – 18.0
Firm to Very Stiff Cohesive Soil	17.4 – 21.5	E – Cohesive soil	18.0 – 21.0
Medium Dense Granular Soil	21.5 – 26.0 (end of PCPT)	F – Granular soil	21.0 – 28.0

Examination of similar shallow seismic records in the western continental shelf indicated the presence of layered sequence underlying the acoustically transparent modern Clay [10]. Therefore it appears that this layered sequence is a regional depositional unit, which possibly reflects the prevailing climatic condition.

4.4. D (Original)

The D (Original) location is approx. 425 m south west of D (Alt-2) location. The sub-seabed geology interpreted in the seismic section along the survey line passing through the D (Original) location is shown in Figure 5. The seismic stratigraphy interpreted in 2D UHR records is given in Table 5. A tie-in survey line was run connecting these two location to correlate the sub seabed stratigraphy.

Table 5. Seismic stratigraphy results along a survey line that is passing through at D (Original) location

Seismic stratigraphy interpreted from 2D UHR records			
Unit Description	**Depth to the top and bottom of unit below seabed (m)**	**Thickness in m**	**Interpreted soil stratigraphy from 2D UHR**
Unit A	0.0 – 5	5	Acoustically transparent Cohesive soil
Unit B	5 – 15.6	10.6	Cross-bedding / lamination of cohesive and granular soils (as per geotechnical investigation results the punch through risk for jack-up was reported at D (Alt-2) due to presence of variable resistance of strata between 7 m and 12. 8 m below seabed)
Unit C	15.6 – 18.2	2.6	Cohesive soil and the unit seems to be pinching out close to the D (original) location
Unit D and below	> 18.2 m up to limit of interpretable data	--	Alternate units of granular (with occasional pockets/thin layers of cohesive soil) and cohesive soil

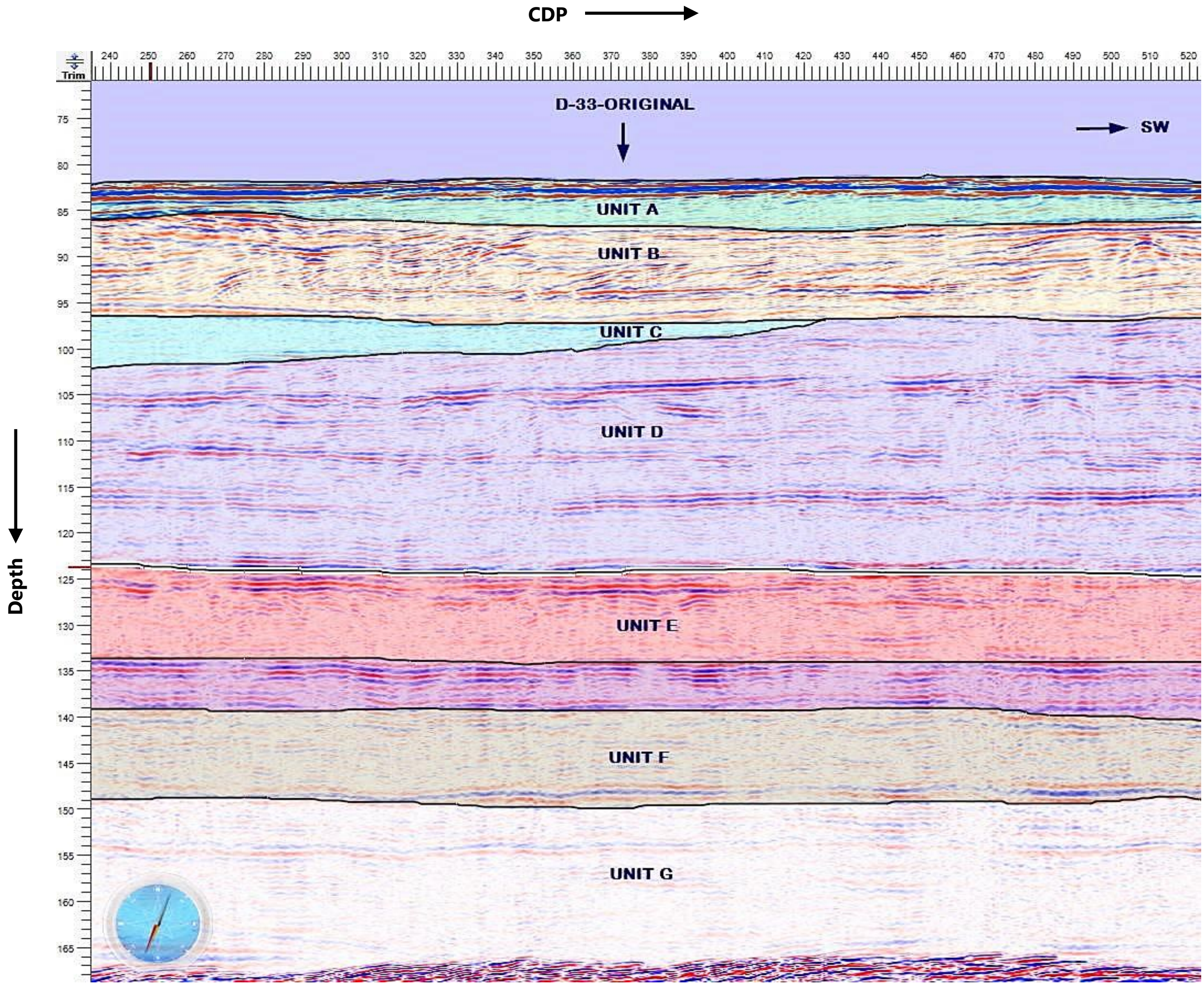

Figure 5. UHR Seismic Profile Section along a survey line passing through the D (Original) location

Presence of cross-bedding/lamination of cohesive and granular soils along with amplitude variation between 5 m and 15.6 m below seabed (Unit B) can be interpreted in 2D UHR seismic record at the D (Original) location. Moreover, a relatively acoustics transparent cohesive strata (Unit C) is seen pinging out at the D (Original location) which again may not be conducive for jack-up placement. The above results from UHR survey shows close similarities to D (Alt-2) location, with a difference in thickness for different stratigraphic units. Thus it implies that the D (Original) location is not suitable for placement of spudded jack-up for drilling exploratory wells or in other words, the distinctive acoustic characteristics noticed within Unit B indicate that soil properties may not be conducive and punch through risk can be expected for jack-up and hence carrying out geotechnical investigation will be a futile exercise. It can be concluded that one can often predict the general soil stratigraphy and may be able to estimate the geotechnical properties by inference based partly on the character of acoustic units displayed on seismic data and correlating it with the nearby geotechnical borehole data.

4.5. D (Shifted)

D (Shifted) is approximately 3.5 km south-west of D (Original) location. A tie-line was run between these two locations (refer figure 1) to understand the variation/change in the soil stratigraphy. The sub-seabed geology interpreted in the seismic section along the survey line passing through the D (Shifted) location is shown in Figure 6. The seismic stratigraphy interpreted in 2D UHR records is given in Table 6. Geotechnical borehole data has been correlated with the seismic stratigraphy interpreted from 2D UHR records.

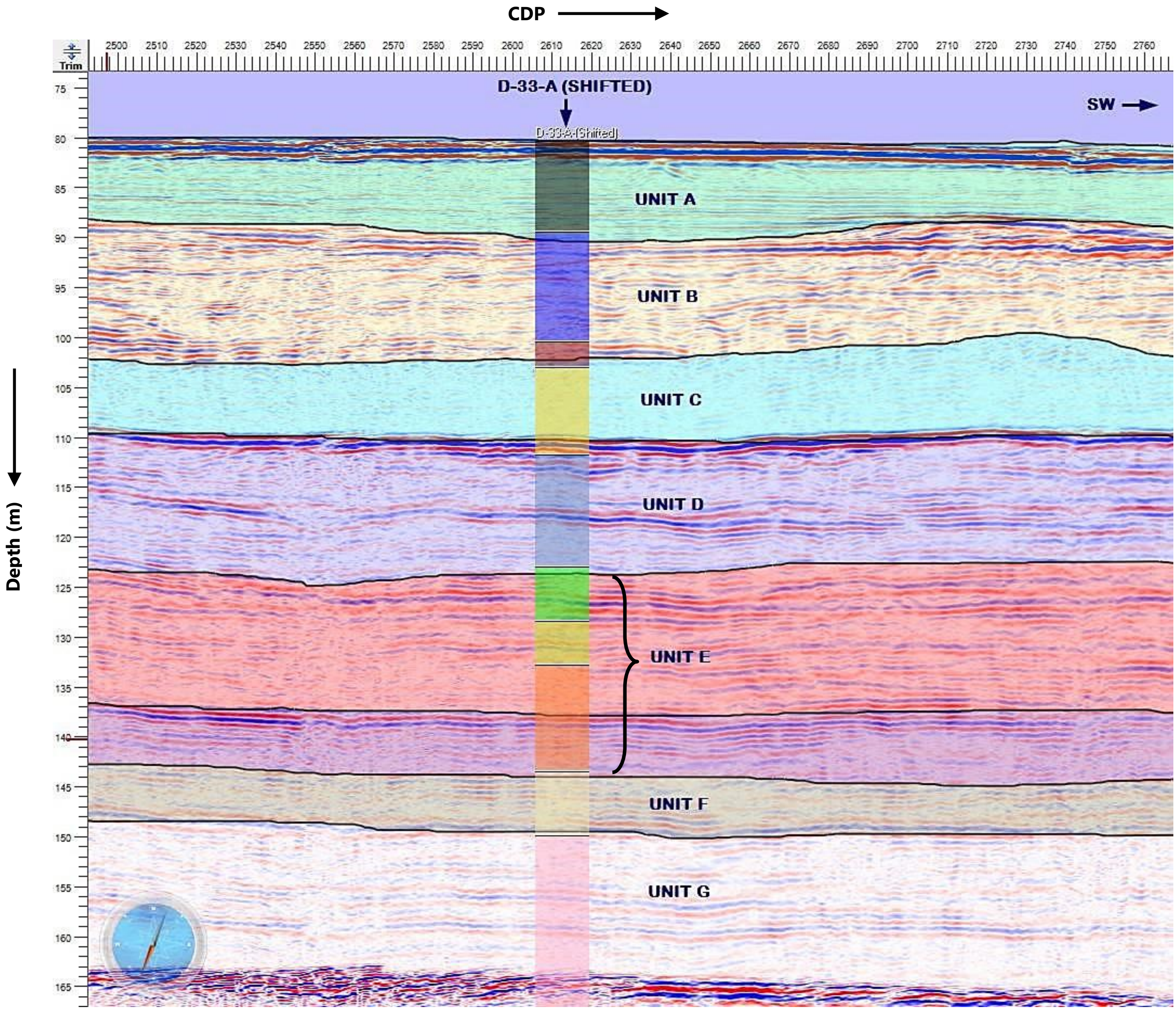

Figure 6. UHR Seismic Profile Section along a survey line passing through the D (Shifted) borehole location

The acoustics characteristics observed in the 2D UHR data for soil units (granular unit underlain by cohesive unit), lateral continuity and variation in thickness among soil units, chaotic reflection pattern and attitude of soil strata (sub-parallel, discontinuous, dipping/cross laminated) that is recorded at punch through locations, which has been explained in previous sections above, is relatively absent at the D (Shifted) location. Each unit shows characteristic reflection pattern/amplitude implying that the soil properties remain more or less homogeneous and consistent within the individual soil units at the D (Shifted) location which is contrary to the non-uniform, rapidly changing soil conditions noticed at punch through locations explained in above sections. In addition, the absence of relatively high amplitude strongly reflective units at the top, which is underlain by relatively weaker acoustically transparent soil unit, indicates that the location might be favorable for spudding of jack-up. Thus the uncertainties/unfavorable soil conditions interpreted in the 2D UHR seismic record at D (Alt-1), D (Alt-2), D (Alt-3) and D (Original) locations could be considered as a useful tool and the method/technique can be applied elsewhere in the world for the initial assessment of geohazard.

The geotechnical borehole drilled prior to the seismic survey show close correlation with the 2D UHR interpretation results. Depth to the top and bottom of Unit B as interpreted in seismic record is 9.7 m to 21.7 m below seabed and it consists of a series of closely spaced planar reflectors that are commonly characteristic of interbedded clay and silt with traces of sand and shell fragments. Table 6 summarizes the correlation between 2D UHR interpretation results and geotechnical borehole data. Based on the jack-up leg penetration analysis carried out at this location, maximum expected leg penetration would be 13 m to 14 m below seabed (i.e. within Unit B).

Table 6. Summary of the geotechnical investigation and 2D UHR seismic stratigraphy results at D (Shifted) location

Geotechnical borehole results		**Interpreted soil stratigraphy from 2D UHR**	
Unit	**Depth to the top and bottom of unit below seabed (m)**	**Unit**	**Depth to the top and bottom of unit below seabed (m)**
Very soft silty CLAY	0 – 9	A – Silty CLAY	0-1.42
Dense Clayey SILT with traces of sand & shell fragments	9 - 20	B - Clayey Silt with fine Sand	9.7-21.7
Medium Dense silty SAND	20 – 22.5		
Medium Dense Clayey SILT with traces of Sand and shell fragments	22.5 – 31.3	C – Clayey SILT with fine Sand	21.7 – 29.7
Silty CLAY with traces of fine sand pockets & shell fragments	31.3 – 42.5	D – Dense SILT with fine Sand & Shell Fragments	29.7 – 42.7
Stiff CLAY*	42.5 – 48.0	E - Silty/Clayey SAND	42.7 – 63.0
Very Dense SAND*	48.0 – 52.4		
Very Stiff SILT*	52.4 – 63.0		
Very Dense SAND	63.0 – 69.4	F – Dense SAND	63.0 – 69.0
Very Stiff CLAY	69.4 – 99.6	G – Silty CLAY with fine	69.0 – 83.3
Very Dense SILT	99.6 – 104.3	Limit of UHR Data	
Medium Dense SILT	104.3 – 108.0		
Very Dense SAND	108.0 – 124.0		
Hard CLAY	124.0 – 125.0		

(*) The clear demarcation of these units in the 2D UHR seismic records could not be made, as the sand laminations are noticed in all the three units.

4.6. Discussion

While going through the available literature, majority of the geohazard studies/research all over the world were focused on the identification of shallow gas hazard and its depth of occurrence (since it is considered as a major hazard/risk for exploratory drilling work due to blowout conditions) in the 3D exploration/2D HR seismic records. Earlier research carried out by [6, 8, 9] in the Mumbai offshore region were mainly focused on understanding the transgressive/regressive cycles from the seismic records; and their inferences were based on the single channel shallow seismic data. Analysis of high resolution seismic profiles by [11] on the inner continental shelf (< 60 m water depth) off India from 10 degrees N to 22 degrees N show 5- 35 m of weakly stratified acoustically transparent clays. At water depth of 15-50 m, the sub-bottom profiles are characterized by anomalous seismic signatures in the form of acoustic masking. These extend from the underlying Late Pleistocene unconformity, often stretching along the bedding planes, and occasionally surfacing on the sea bed. These acoustic masking could be due to shallow hydrocarbon gases (mainly methane) which might have been derived from biogenic sources or geothermal processes, or both. Thus, very limited studies/literature is available which focuses on geohazard risk for jack-up platform (punch through risk) caused by the unpredictable soil condition.

The above examples discussed in this paper demonstrate the apparent advantages of 2D UHR survey for initial assessment of geohazard within the survey area. For example, carrying out geotechnical investigation without proper understanding of the sub-seabed geology might result in unsuccessful site investigation and will result in lost time and money. The decision on carrying out 2D UHR survey heavily depends on the geological complexity of the study area, or in other words, lesser geological complexity of the study area will result in a consequent decrease in the number of unsuccessful geotechnical investigations. Inevitably, the selection of multi-channel seismic (2D UHR) survey for such application must take account of significant consequences arising out of it and the choice of this method will eventually be weighed against a number of factors, including cost, time, risk involved, and fitness-for-purpose in terms of data quality, resolution and identifying suitable location for geotechnical investigation for punch through analysis.

The examples presented in section 4 were ideally suited for the application of 2D UHR survey technique. The method is ideally suited for areas which have undergone sea-level changes in the past resulting in complex geology and formation of meso and micro scale sedimentary structures noticed within 100 m below seabed which might be a geohazard for jack-up platforms.

5. Conclusions

In order to understand the shallow geology and the punch through risk for jack-up platform identified during geotechnical investigation in the Mumbai High offshore, a 2D UHR dataset was acquired for the area and the results of the 2D UHR survey has provided a lot more information about the study area than had been expected and the same could be used as a tool for mapping the potential areas showing unfavorable soil conditions and for initial geohazard assessment within the survey area. The inhomogeneities in soil horizon in terms of reflection amplitude, layering pattern were interpreted in seismic records and it has revealed the distinct advantage in using 2D UHR data for identification of shallow sub-surface and stratigraphic evidences of sub-bottom geohazards, which may help to reduce the possible risks in the placement of jack-up platform. The imaging of very fine-scale subsurface structures such as sub-parallel layering, cross-bedding/lamination, denser and stronger layer underlain by softer and weaker units, illustrates the advantage of ultra-high-resolution nature of these data.

The marine transgression and regression processes that were active in the geologic past have resulted in complex geology in Mumbai offshore basin. Due to complex geology noticed in the Mumbai offshore it is important to know soil conditions for placement of jack-up platform of different capacity at exploratory well locations. Currently, the practice is to deploy geotechnical survey vessel at exploratory well locations for carrying out soil investigation (borehole/CPT/borehole and CPT) for punch through risk analysis for jack-up platform of different capacity. Sometimes such soil investigation has been met with some success but in some cases without, due to punch through risk encountered for all jack-up /some of the jack-up. To overcome this problem, it will be prudent to carry out seismic survey first for initial assessment of geohazards in the specified area and identify suitable location/s based on 2D UHR seismic survey results followed by soil investigation for the punch through risk for jack-up platform. Further it will help in planning and deployment of geotechnical vessel and in making informed decisions which in turn will save time and cost. Hence, the above practice of 2D UHR survey for initial geohazard assessment followed by soil investigation could be considered as a suitable work flow in such regions where complex geological process were active in the past and punch through risk for jack-up platform has been controlled by soil stratigraphy and small scale sub-seabed sedimentary structures. Multi-channel continuous seismo-acoustic profiling data collected in the process of site survey and the interpretation of high resolution seismic data allows reducing the risks of unsuccessful geotechnical investigation. This study highlights the potential benefits that 2D UHR data bring in terms of sub-seabed anomaly identification and improved quality of data, along with the added freedom of being able to select suitable and safer locations within the entire survey grid for undertaking geotechnical investigation for punch through risk analysis.

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References

[1] Federico D. Martin., Luis F. Batalla., Rafaela L. De Oliveira Pinheiro., Luis G. Escalona., Seif El Mistikawi., Justin Tiffany, Daniel E. Pryne, William C. Haneberg, Kerry J. Campbell. "The integration of 3DX seismic, high-resolution geophysical, and geotechnical data to recognize and mitigate against potential geohazards to subsea installation designs in the Campos Basin, offshore Brazil", In: Ocean Technology Conference (OTC Paper-25938-MS), Houston, Texas, USA, 2015. https://www.researchgate.net/publication/282130585

[2] Nadim, F., Kvalstard, T.J. "Risk Assessment and Management for Offshore Geohazards", In: First International Symposium on Geotechnical Safety & Risk, Shanghai, Tongji University, China, 2007. https://www.researchgate.net/publication/266867436 .

[3] Moore, R., Usher, N., Evans, T. "Integrated Multidisciplinary Assessment And Mitigation of West Nile Delta Geohazards", In: Proceedings of the 6th International Offshore Site Investigation and Geotechnics Conference: Confronting New Challenges and Sharing Knowledge, London, UK, 2007. https://www.researchgate.net/publication/254549104

[4] Basu, D.N., Banerjee, A., Tamhane, D.M. "Facies distribution and petroleum geology of Bombay offshore basin, India", Journal of Petroleum Geology, 5, pp. 57-75, 1982. https://doi.org/10.1111/j.1747-5457.1982.tb00560.x

[5] Zutshi, P.L., Sood, A., Mohapatra, P., Ramani, K.K.V., Dwivedi, A.K., Srivastava, H.C. "Bombay offshore basin-lithostratigraphy of Indian petroliferous basins", Unpublished document (document V), Keshava Deva Malaviya Institute of Petroleum Exploration (KDMIPE), ONGC Dehradun, India, 1993.

[6] Siddiquie, H.N., Rao, D.G., Veerayya, M., Wagle, B.G., Almeida, F., Bhattacharya, G.C. "Surficial Geology of Bombay-Bombay High region and its implications in offshore engineering problems", In: Seminar on Coastal Engineering, National Institute of Oceanography, Goa, India, 1977.

[7] Hashimi, N.H., Guptha, M.V.S., Kidwai, R.M.S., Nair, R.R. "Sediments and sedimentary processes on the continental shelf of Bombay", Mahasagar, 11(3 and 4), pp. 155-161, 1978.

[8] Nair, R.R., Hashimi, N.H. "Holocene climatic inferences from the sediments of the western continental shelf", Proceedings of Indian Academy of Sciences (Earth and Planetary Sciences), 89(3), pp. 299-315, 1980. http://drs.nio.org/drs/handle/2264/6834

[9] Bhattacharya, G.C., Almeida, F., Vora, K.H., Siddiquie, H.N. "Subsurface geology off Bombay

with Paleoclimatic inferences interpreted from shallow seismic profiles", Journal of Coastal Research, 3(4), pp. 521-530, 1987. http://drs.nio.org/drs/handle/2264/6118

[10] NIO. "Surveys of the proposed submarine pipeline routes from Bassein to Gujarat", Unpublished Report, Goa, India, 126 p, 1978.

[11] Karisiddaiah, S.M., Veerayya, M., Vora, K.H., Wagle, B.G. "Gas-charged sediments on the inner continental shelf off western India", Marine Geology, 110, pp. 143-152, 1993. http://drs.nio.org/drs/handle/2264/2872