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GUIDANCE NOTES FOR THE APPLICATION OF GEOPHYSICAL AND GEOTECHNICAL TECHNIQUES FOR REDUCING TOPHOLE RISKS IN THE DRILLING OF OFFSHORE WELLS

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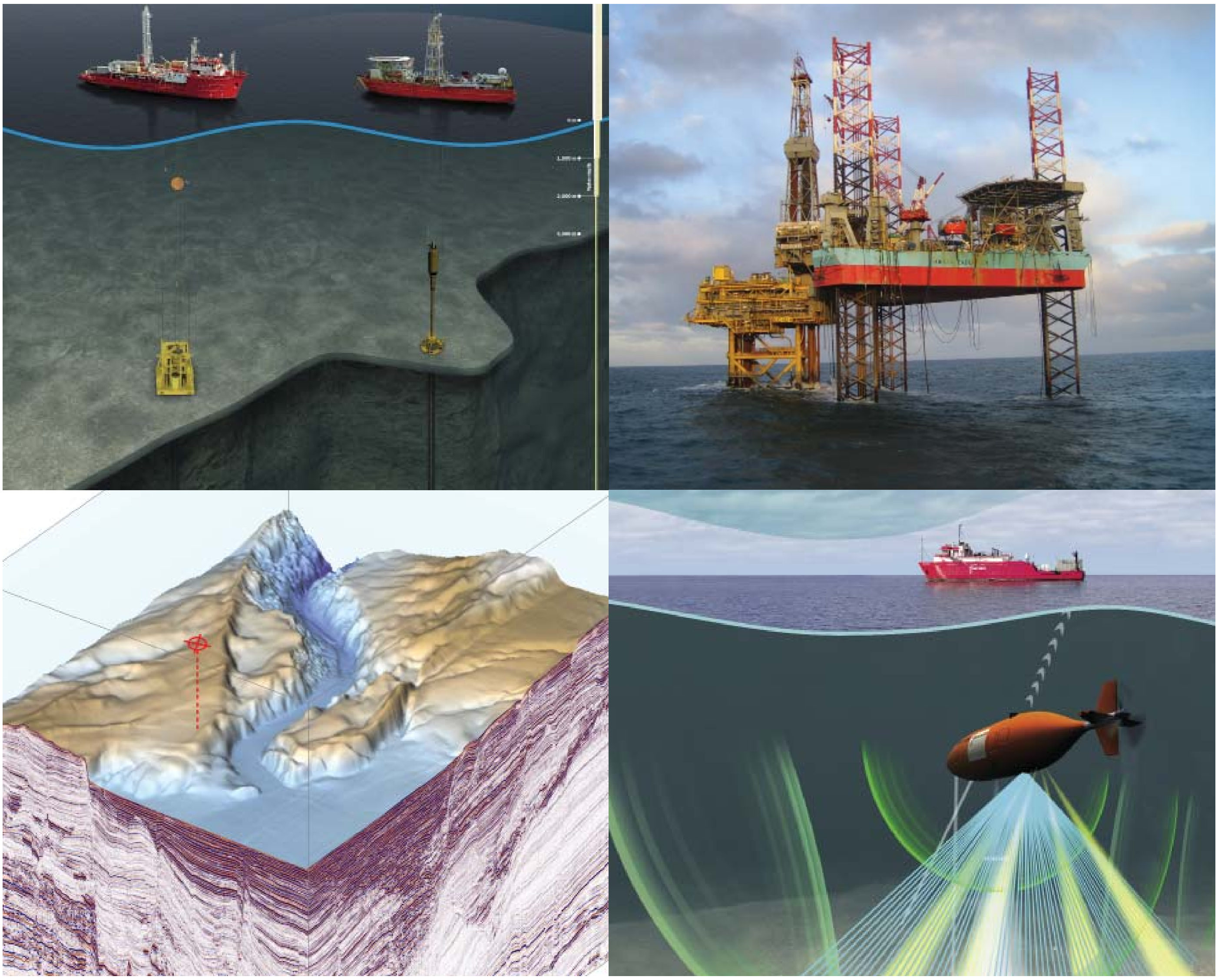

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Guidance Notes for the Application of Geophysical and Geotechnical Techniques for Reducing Tophole Risks in the Drilling of Offshore Wells

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GUIDANCE NOTES FOR THE APPLICATION OF GEOPHYSICAL AND GEOTECHNICAL TECHNIQUES FOR REDUCING TOPHOLE RISKS IN THE DRILLING OF OFFSHORE WELLS

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Definition

In this document the **tophole section** is defined as the depth to the base of the first *pressure containment string*; in other words the *conductor* and the first casing, drilled prior to pressure containment through installation of the *blowout preventer (BOP*). This will normally be a depth of fifty to one hundred metres for the *conductor* and several hundred metres for the *surface casing*.

Throughout the document, items that appear in the glossary (Section 7), are shown in italics.

1 Introduction

The offshore oil and gas industry spends around [1]$60bn per year on oil and gas wells. Investment on this scale comes with risks, and although the offshore industry leads the way in industrial HSSE standards, it is estimated that around 10% of this expenditure, or $6bn, can be attributed to ground related issues such as ***stuck pipe***, ***lost circulation***, ***wellbore instability*** **and shallow water flows**. On top of this are **environmental costs** of the oil spills that can result from loss of well control, and most importantly the **human costs** in terms of injuries and loss of life resulting from some of the worst incidents. Given the appropriate data, analysis, engineering and application these risks and costs can be foreseen, mitigated and ultimately reduced.

Tophole integrity and risk reduction depends on understanding the soils and rocks throughout this section of the well. The primary sources of information are complementary **geophysical (remote sensing) and geotechnical (intrusive) methods**. In the top few tens of metres reliable geotechnical data may be available, but deeper than this information is often limited to what can be inferred from *logging while drilling* and is far from precise. Geophysical data are normally available throughout the tophole section, although their *resolution* will always decrease with depth, and their value is limited without proper correlation to soils data.

In this document the **risks and problems** within and around the well are described. Information and advice in the use and application of geotechnical and geophysical *site investigation* techniques for the planning of offshore wells are provided. Finally, a **systematic approach** to assessing and mitigating top-hole geo-risks is suggested.

The document is aimed at:

- Geoscientists and engineers involved in data collection and analysis;
- Survey or *site investigation* project managers;
- Drilling engineers;
- Foundation engineers;
- Operators;
- Well planners;
- Operations geologists;
- Well operations managers;
- Surveyors.

The first two groups in the above list are already involved in *site investigation* and will be aware of the reasons for gathering good quality data to mitigate the risks associated with topholes. The other groups represent those focused on well design, construction and operation and have most control over good drilling practice and well performance. These groups may not be as closely involved in *site investigation*.

An important conclusion of the industry specialists who contributed to this document is that there should be effective dialogue between the geoscience community involved in *site investigation* and the engineering community involved in drilling. This is the essential message of the document. Existing techniques and knowledge are sufficient to address all tophole associated risks and problems, provided they are applied effectively by all parties working together.

It is the aim of this document to reach out to both practitioners and end users; to provide a reference that describes best practice in the use and application of *site investigation* techniques for the planning and execution of offshore wells. By this means it is hoped that common global standards will be promoted, leading to improvements in safety, efficiency and reduced environmental impact.

These guidance notes are not intended to be prescriptive, nor detailed in relation to specific aspects of well design, such as fatigue life design. It should be noted that offshore wells are structures and therefore should be designed and built in accordance with the general requirements of ISO 19900.

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[1] From a review of industry financial reports.

2 Shallow Geohazards –
Typical Problems and Failures

Shallow *geohazards* can pose significant threats to well *spudding* and drilling operations as illustrated in Figure 1. Insufficient consideration of the issues can result in severe consequences ranging from avoidable non-productive time to catastrophic events. Responsibility for assessing project risk, and reducing this to acceptable levels, ultimately rests with the operator or exploration company. However, geoscientists specialising in *geohazards* and understanding shallow section geology have an essential part to play in identifying and characterising the hazards, the risks they pose, and in helping to deliver safe, predictable and cost-effective wells with no surprises. Such specialists exist within many operating companies, exploration companies, contracting companies and consultants.

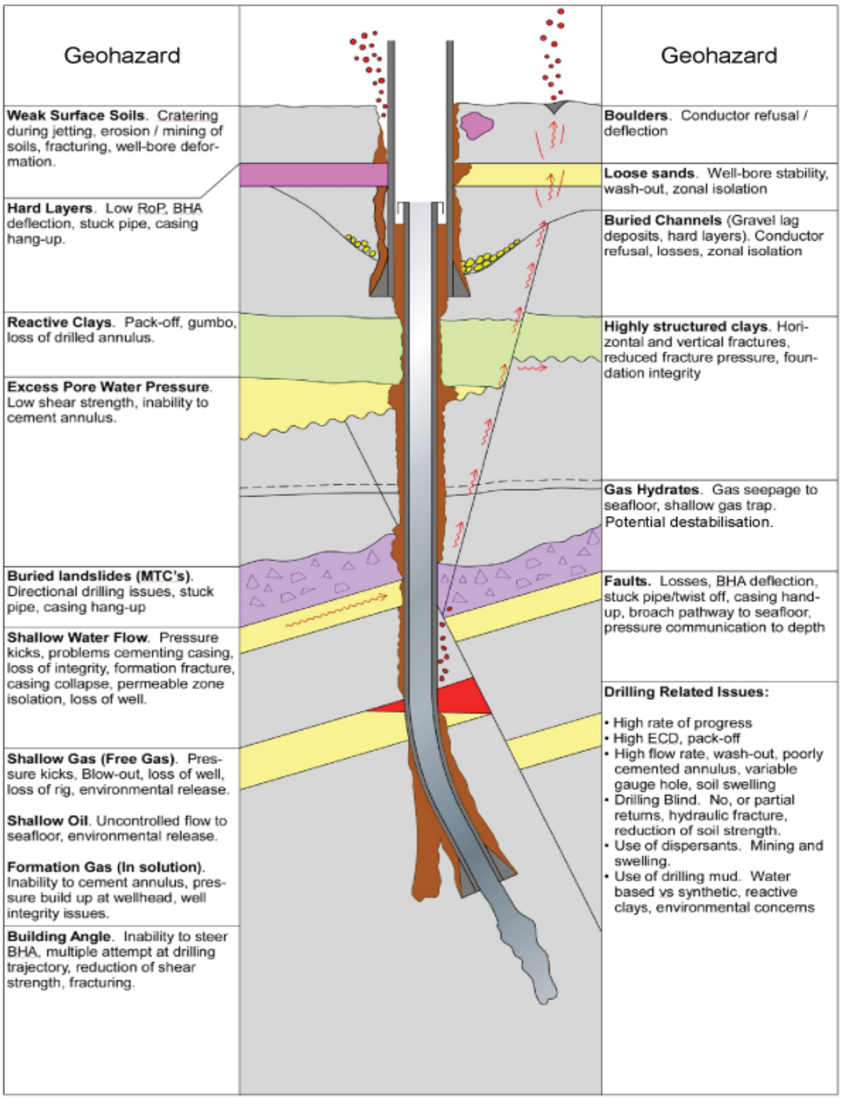

Figure 1: What Can Go Wrong When Drilling the Tophole Section

The risks that *geohazards* pose to *spudding* and drilling activities depend on many variables. Some of the most important are listed below:

- Ground conditions;
- *Conductor* installation methodology;
- Type of drilling platform;
- Quality of the tophole soils data and ground model;
- Availability of offset data;
- Remoteness of the operations.

An integrated multi-disciplinary project approach to the identification, characterisation and assessment of hazards and risks is essential for an optimised outcome.

The purpose of Table 2.1 is to provide an aide memoire of the typical *geohazards* that can be encountered in the shallow section, and some of the potential impacts their presence may have on drilling operations in the tophole section. The table also offers some guidance on the data and tools that may be suitable for identifying and characterising *geohazards* so that they can be assessed, and measures considered to manage effectively the risks they pose.

Table 2.1: Summary of Geohazards, their Potential Impact on Drilling Operations and Identification and Characterisation Techniques

Geohazard	Potential impact(s) on drilling operations	Identification and characterisation techniques						
		HR	OFF	SBP	3D	GEO	SSS	MBE
Shallow gas (free gas)	Pressure / gas kick Blowout Loss of well Loss of vessel buoyancy Uncontrolled environmental emissions Inability to cement *annulus* Pressure build-up at wellhead Well integrity issues	•	•	•	•			
Gassy soils (gas in solution)			•			•		
Shallow water flow	Pressure kicks Uncontrolled flows to *seafloor* Problems cementing *surface casing* string Loss of integrity of *surface casing* string Formation fracture and flows to surface outside *conductor* Loss of foundation support - subsidence Loss of well Permeable zone isolation Hole expansion / washout	•	•		•			
Shallow oil / hydrocarbons	Uncontrolled flow of fluids to *seafloor* Inability to cement *annulus* Uncontrolled environmental release	•	•	•	•	•		
Gas hydrates	Disassociated gas seepage to *seafloor* and consequent geotechnical uncertainty Possible link to chemosynthetic communities *Shallow gas* trap	•	•	•	•	•	•	
Buried relict landslide (mass transport complex, *MTC*)	Directional drilling issues *Stuck pipe / BHA* Casing hang-up *Jetted conductor* problems	•	•	•	•	•		
Faults	Losses Broach pathway to *seafloor* in event of underground blowout leading to *seabed* cratering Directional drilling difficulties *Stuck pipe* Casing hang-up Pressure communication to depth	•	•	•	•	•	•	•

Geohazard	Potential impact(s) on drilling operations	Identification and characterisation techniques						
		HR	OFF	SBP	3D	GEO	SSS	MBE
Soft soils	Cratering during jetting operations Wellbore stability and verticality Mining / erosion of soils Fracturing Wellbore deformation Excessive jack-up rig leg penetration Insufficient rig anchor capacity	●	●	●		●		
Hard soils	Low Rates of Progress (*RoP*) Jetting resistance Directional drilling issues *Stuck pipe / BHA* Casing hang-up Challenging anchoring operations	●	●	●		●		
Swelling clays (gumbo)	Pack-off Loss of drilled *annulus* Plugging and fouling of tools and pipe		●			●		
Boulders and gravels	*Conductor* drivability problems (possible refusal) *Conductor* deflection / verticality issues Reduced rates of progress *Stuck pipe* Heavy vibrations during drilling and bit damage	●	●	●		●		
Unconsolidated sands	Wellbore stability Wash-out Inability to cement *annulus* Permeable zone isolation	●	●	●		●		
High salinity	Swelling Reduction in shear strength		●			●		
Excess pore water pressure	Lower shear strength – reduced *conductor* axial and lateral capacity Inability to cement *annulus* Drilling-induced *seabed* instability		●			●		
Highly structured clays	Reduced fracture pressure – formation damage Heterogeneous soil properties – *conductor* resistance design considerations		●			●		
Seafloor features – e.g. steep gradients, channels, bedforms					●		●	●
Fluid expulsion features – e.g. pockmarks, fluid chimneys		●		●	●		●	●

Key

HR	*Multichannel high resolution seismic reflection* data
OFF	*Offset well* data
SBP	*Sub-bottom profiler* data
3D	3D seismic reflection data (water depth and data quality are significant considerations)
GEO	Geotechnical data (various techniques available for different applications)
SSS	*Sidescan sonar* data
MBE	*Multibeam echo sounder*

3 Approaches to Adopt

3.1 THE GROUND MODEL

3.1.1 What is a Ground Model?

A ground model is a 3-dimensional representation of the Earth constructed from a database of any valid input data. A ground model may take one of a number of different forms. For example, when based on bathymetric data in the marine environment it may take the form of a terrain or geomorphological model, or when based on seismic reflection data it may take the form of a structural model. It is typically created in the very first geoscience activity of a project and remains in place as a constant reference, available to be enlarged, added to, updated and refined as the needs of the project develop.

Geographical Information Systems (*GIS*) offer a number of advantages for the construction, compilation and delivery of a ground model. All types of data from multiple sources can be loaded into a *GIS* project, including maps and cross sections of differing scales together with point source ground truth data with associated attributes. *GIS* allows data to be viewed and compared during the process of integration, and specialist tools can be made available for detailed analysis as required. The same *GIS* project can be used to deliver products at any stage in the development of the ground model, whilst retaining the database for future development and refinement. *GIS* also allows rapid archiving and retrieval.

3.1.2 Application of the Ground Model to Well Site Investigation

A well *site investigation* requires a ground model extending from the *seafloor* to a depth of several hundred metres that characterises the geological succession from an engineering perspective and identifies *geohazards*. The prime dataset will usually be seismic reflection data, and constructing the ground model starts with mapping key seismic horizons and noting stratigraphic variations. This produces a structural framework into which ground truth information, that may come from *offset wells*, geotechnical sampling or the overall well prognosis, can be integrated. This may be an iterative process, whereby insight into the relative significance of seismic horizons is gained by comparing geophysical with geotechnical and geological data, which thereby leads to re-interpretation and refinement of the seismic analysis.

It is the aim of a successful well *site investigation* to produce a ground model that contains the information required for a thorough understanding of the *seafloor* and *seabed* conditions relevant to drilling the tophole section.

The available data needs to be analysed for all *geohazards* contained in Table 2.1, and the potential for hazardous conditions evaluated and assessed. This may include:

- The probability of *shallow gas* being present;
- The potential for shallow and deep seated slope instabilities;
- The potential for debris / turbidity flows;
- The potential for variable soil conditions, including strength *inversions*, uncemented soils, boulders;
- The probability of high pressure sand layers capable of producing shallow water flow.

The end result is a series of *structure maps* and geological cross sections showing seismic horizons, geological and geotechnical units, *soil provinces* and geological features that might influence well planning, engineering and rig installation, and from which the risk posed by each geo-constraint to the well may be evaluated.

The ground model produced for an exploration well site will often be the first detailed study made of the shallow geological section. In cases where this is followed by appraisal drilling and then field development and production, the exploration ground model will form the first stage in a single, wider process of understanding the *seabed* and shallow geological conditions that will be updated and refined through subsequent stages. For example, detailed soil zonation will be required when planning the foundations of development structures, and slope stability risks will need to be thoroughly understood when placing structures for the life of the field. At each stage, the existing ground model should be reviewed to identify any data gaps for the next phase and plan new data acquisition, the output of which is an updated ground model. This ensures that existing knowledge is captured and maintained, so that data collection programs are efficiently planned and kept to an appropriate level.

3.2 DESK STUDY

The first stage in understanding geological conditions in an area where offshore drilling is planned is to conduct a desk study using any existing relevant data. *Exploration 3D seismic reflection data* will often form the prime dataset for the purposes of deriving an initial image of the *seafloor* topography. Consideration should be given to using near offset subsets or undertaking *short offset processing* to improve shallow section *resolution*. Other types of data to include are the following:

- Regional geological and geophysical information;
- Geophysical data from nearby *site investigations*;
- Geotechnical data from nearby *site investigation*s;
- *Offset well* information including logging while drilling data and all log data;
- Installation records for piled structures and jack-ups near the location;
- Information in the public domain;
- Academic and research papers with original data if available.

The objective of a pre-drilling desk study in a new exploration area is to initiate the process of characterising the *seafloor* and shallow geological conditions. The initial ground model will normally be a geological model designed to enable a preliminary, regional view to be taken concerning any *geohazards* that may impact on drilling operations and to plan future *site investigations.*

A crucial decision to be made from the results of the desk study is whether new geophysical and geotechnical data is needed. This will also depend on the type of rig, the type of well and the water depth. In many cases good quality *exploration 3D seismic reflection data* can provide useful geophysical information, but these data are not a substitute for *sub-bottom profiler* data for the identification and mapping of shallow geology and *geohazards* in the top 100 m of the *seabed*. The value of *exploration 3D seismic reflection data* will depend upon its quality and frequency content, the nature of the *seafloor* and *seabed* conditions and the planned drilling programme. For deep water wells, *exploration 3D seismic reflection data* can form a suitable replacement for HR seismic reflection data in the evaluation of well site *geohazards* and thus may replace the need for new HR seismic reflection data collection in a geophysical *site investigation*. This is a generally acceptable practice providing the minimum quality criteria for *exploration 3D seismic reflection data* are met. These criteria are contained in IOGP Report No, 373-18-1 (Ref. 1). *Exploration 3D seismic reflection data* is not a replacement for a geophysical *site investigation* when a bottom founded drilling rig, such as a jack-up rig, is to be used.

Where there are significant *geohazards*, the results may also be useful in the wider process of selecting and prioritising well locations, by identifying areas of low drilling risk and / or significant foundation issues for the drilling or production rig and especially for any required *relief well*s.

3.3 SITE INVESTIGATION PLANNING

Planning a *site investigation* should draw heavily on the findings of the desk study, which will provide a direct input to the design of an appropriate geophysical survey programme and, if deemed appropriate, a geotechnical investigation. As a minimum, the desk study should provide a guide to the definition of survey line direction, line spacing and the areas of uncertainty that need to be established in order to reduce risk.

It is important to stress the influence of time on the well planning process. The time taken to plan, acquire, process, analyse and integrate geophysical and geotechnical data is typically 1 year. This is from first initiation to spud and assumes the drilling location has already been defined. The timeline illustrated in Figure 2 is for a typical bottom-founded rig and includes a geophysical survey, in which sonar and seismic reflection data to image the *seafloor* and *seabed* are collected, and a geotechnical investigation in which a 100 m deep *borehole* is acquired from a geotechnical drillship. For a floating rig a *borehole* is not normally required and the lead time can be reduced to 10 months. In both cases the well design is frozen 3 months before spud. Note that no consideration is given to regulatory requirements that may extend this in some countries.

It is therefore vital that the requirement for any *site investigation* programme is made as early as possible. It is preferable that this is an integral part of the well planning process.

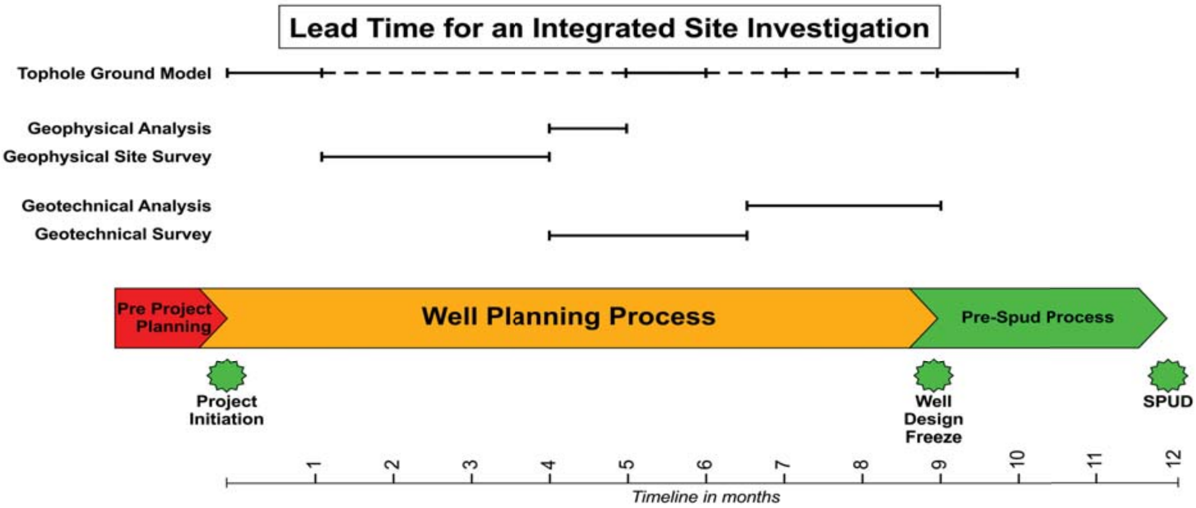

Figure 2: Timeline Relationship between a Typical Well Planning Process and a Typical Integrated Site Investigation Programme

3.4 GEOPHYSICAL SITE INVESTIGATION

When the need for a geophysical *site investigation* has been identified by the desk study it should be designed to specifically address the operational requirements at the site. Correct survey design is essential if the objectives are to be efficiently achieved. There are many industry guidelines and textbooks available to assist in this process (Refs. 1 and 2), and most operators will have their own specifications. However, each requirement will be unique. For example, the great variability in *seabed* conditions means that a given piece of geophysical survey equipment may perform very differently in one area compared to another. This is particularly true of *sub-bottom profilers*. Existing data from the area or *offset well* information will strongly influence survey design. "Standard" specifications should therefore be used with caution, and it is strongly recommended that survey design is undertaken by an experienced practitioner who has a full understanding of the detailed requirements, the desk study results and any other relevant information.

In general, depending on the site requirements, the geophysical *site investigation* should be designed to provide sufficient data to achieve the following objectives:

- Define the water depths and the *seafloor* topography across the area of operational interest;
- Identify any natural or man-made *seafloor* features that could influence the position of the well, or the rig installation operation;
- Identify any potential areas of environmental or archaeological interest or concern;
- Define the *stratigraphy* of the *foundation zone* to a depth of interest to cover rig emplacement and *conductor* installation;
- Define the sub-surface stratigraphic and structural elements, and identify and delineate any potential *geohazards* that could affect drilling operations, to a minimum depth of 200 m below the tophole section of the well or to a depth of 1000 m, whichever is the greater;
- Meet any local regulatory requirements.

Acoustic survey equipment, including *multibeam echo sounder* and *sidescan sonar*, will enable definition of the *seafloor* and thus provide data to select and evaluate a suitable location.

Sub-bottom profilers including *pinger*s, *chirp profilers*, boomers, sparkers and *mini-airguns* provide detailed data to evaluate the lateral variability of soils across the anchoring zone or rig footprint, and in support of well foundation design.

Multichannel seismic reflection data provide the means to define the shallow geological conditions to several hundred metres below the *seafloor* and identify potential *geohazards* within the tophole section. High *resolution* 2D seismic reflection systems designed to record frequencies up to 250 Hz are commonly used, although in areas of complex geology, or where a large number of *geohazards* are expected, consideration should be given to acquiring high *resolution* 3D datasets. Blanket spatial coverage, *multi-azimuth migration* and the ability to interpret data using time slices and random lines enables far more accurate and detailed analysis of sub-surface structure. 3D interpretation systems also typically provide more sophisticated software and attribute analysis. Through careful *seismic processing*, a detailed *seismic velocity* model can be produced that may improve the *resolution* of the pore pressure fracture gradient (*PPFG*) model (see Section 4.5). A further advantage of 3D datasets is their value in planning subsequent field developments and investigating the *foundation zone*.

3.5 GEOTECHNICAL SITE INVESTIGATION

Information on soil type and strength are important for *conductor* design and installation; strength, density and soil type for the *conductor* setting depth evaluation; soil strength and type for *axial capacity* and soil strength and stiffness for fatigue considerations. This information can often be derived from regional experience, but direct site specific sampling and testing will be more accurate, and may be required if certain *geohazards* have been identified and / or to optimise the tophole design. Geotechnical data acquisition is often required ahead of jack-up rig placement at a site, for example for leg penetration prediction, and the incremental cost for extending the depth of investigation to cover *conductor* setting depth may be more than covered by cost savings in the optimisation of the tophole well design and installation.

Geotechnical *site investigation* work will typically be undertaken by drilling geotechnical *boreholes*. Drilling operations can take two forms; drilling from the sea surface, referred to as vessel drilling, or drilling from the *seafloor*, referred to as *seafloor* drilling. Where drilling is performed from a floating vessel, it is essential that a heave compensation system is used and selected to take into account the environmental conditions. Great care is required not to disturb the ground immediately ahead of the drill bit so that undisturbed samples can be recovered. In certain cases where a *shallow gas* hazard has been identified by the geophysical survey and / or previous drilling, or cannot be discounted from the available data, mitigation procedures should be adopted, for example drilling a *pilot hole* to de-risk the geotechnical operations.

With each of the two drilling approaches, the general principles of in-situ testing and sampling of the soils or rock are similar and are discussed below in more detail. The *borehole* itself is a means of penetrating the *seabed* to the required depth to enable in-situ testing and sampling to take place. For *conductor* installation purposes the setting depth of the *conductor* should be achieved as a minimum *borehole* depth. The quality of information obtained in a geotechnical investigation depends upon the tools that are deployed and how undisturbed the soil is at the start of any in-situ testing or soil sampling.

A geotechnical *site investigation* generally consists of the following 3 phases:

- Fieldwork;
- Laboratory testing of samples – this can be carried out either offshore or onshore;
- Derivation of soil parameters.

The international standard ISO 19901-8 (Ref. 3), contains both information and a standard for the planning and conduct of geotechnical operations.

3.5.1 In-situ Testing

Data on ground conditions can be obtained by in-situ testing. The most common type performed offshore is cone penetration testing. Cone penetration tests (*CPTs*) do not provide direct information on soil type and strength, but this information can be interpreted from test results, and provide a good overview of the layer *stratigraphy*. If soil samples are obtained (see next section) at the same position as the tests, the accuracy of the *CPT* interpretation is improved.

CPT acquisition is covered by many international references for example ISO 19901-8 (Ref. 3). It is performed by advancing the cone penetrometer into the soil either at the bottom of a *borehole* or from a seabed frame. The soil resistance acting on the cone tip and on the side of the penetrometer are measured. In-situ pore pressure can also be measured, either with a cone penetrometer or using a bespoke piezoprobe tool.

Where certain soil parameters are required to be determined, a range of additional in-situ tests can be included, for example:

- T-bar and ball tests for increased accuracy in very soft soils;
- Seismic cone to measure in-situ P and S wave velocity;
- Temperature cone;
- Thermal conductivity;
- Dilatometer test;
- Downhole geophysical techniques.

Hydraulic fracture testing can also be undertaken in geotechnical *boreholes* to directly calibrate *hydraulic fracture* assessments made for *conductor* setting depth purposes.

3.5.2 Sampling

Soil samples, collected either from geotechnical *boreholes* or from *seabed* coring systems, are tested in either offshore or onshore laboratories to measure the soil properties that enable the derivation of engineering parameters. Specialist onshore laboratories provide a wider range of advanced testing from which it is possible to establish advanced soil properties including stiffness, strength degradation and cyclic response.

Selection of the correct sampling tools for the particular soil conditions is fundamental to the quality of the samples recovered and the overall success of the investigation. Efforts should be made to minimise sample disturbance. In the methodology for sampling, special consideration should be given to unconventional soils, such as calcareous soil, silt and sensitive clays. Further information is available in ISO 19901-8 (Ref. 4). Techniques exist for retaining the ambient pressure of the formation in the recovered sample. These are used, for example, for sampling sediments containing *gas hydrates*. Calcareous and fractured soils deserve special attention as they are difficult to interpret for tophole design or casing strength interaction. Further guidance can be found in ISO 19901-4 (Ref. 4) and API RP 2GEO (Ref. 5).

4 Analysis

4.1 GENERAL

The data collected in geophysical and geotechnical *site investigation*s carried out in preparation for offshore drilling need to be analysed by specialists, and the results clearly communicated to those responsible for assessing drilling risks. It is often the case that separate geophysical survey and geotechnical *site investigation* reports are produced. In addition, environmental, archaeological or metocean studies may also have been carried out and their reports can contain relevant information. For this reason, the sections below separately describe the analysis of geophysical and geotechnical data. However maximum value will be obtained when the results of all relevant studies are considered together in an integrated assessment and a ground model (Section 3.1) produced that describes the *seafloor* and *seabed* conditions to the appropriate level of detail.

4.2 GEOPHYSICAL INTERPRETATION AND ANALYSIS

Seismic interpretation and the identification and analysis of potential *geohazards* should be performed by a qualified, experienced and skilled geoscientist who has specialised in high-*resolution* geophysics. New seismic reflection and acoustic data should be interpreted in the context of what is already known from the pre-survey desk study, providing a refinement of the ground model and enhancing geological understanding to the level required by the drilling activity.

The identification and analysis of *geohazards* can then be carried out within the context of the best possible understanding of *seabed* and shallow section geology. A rigorous approach should be made to the identification of *geohazards* as described in Hill et. al. (Ref 6), the most significant of which will often be *shallow gas*, although careful consideration must be given to all other potential *geohazards* at the *seafloor* and within the *seabed*. Geophysical data rarely enables an unambiguous interpretation, and conclusions should be arrived at following the systematic assessment of all the seismic properties and attributes associated with each particular geohazard, considered in the context of geological understanding. Results should be clearly reported in the text, maps and graphics that make up the geophysical *site investigation* report.

4.2.1 Purpose and Scope of a Geophysical Site Investigation Report

Geophysical *site investigation* reports are commonly produced to communicate the results of geophysical *site investigations* at offshore drilling locations in any water depth. The purpose of a geophysical *site investigation* report is to describe and assess *seafloor* and tophole geological conditions to help plan safe and efficient rig emplacement and drilling operations. The report is the permanent record of the site investigation. Often other relevant data will have been collected in the area, for example from environmental or geotechnical investigations. It is important that links to these studies are established at an early stage, that the data is integrated, and when separate reports are required there is consistency in the presentation of results.

The report will describe data collection, processing and interpretation and will often be split into operations and results volumes. Its primary purpose is to communicate the results of the survey to the end users through clearly worded text illustrated with maps, cross-sections, figures and data examples. Reports should be concise, objective and user-friendly, and clearly understandable regardless of the technical background of the reader.

A critical part of the report is the summary, normally presented at the beginning. It is extremely important that this presents the essential findings and conclusions in an easily accessible form and is tailored for the use of the end user. Short factual statements and tabulated results are preferred rather than sections of text that replicate the main text. Technical terms, such as geological ages and formation names, should be used with caution or avoided in the summary.

Geophysical *site investigation* reports should provide an integrated assessment of all *seafloor* constraints upon the emplacement and operation of the rig at the proposed location. Geological conditions should be described to a depth of at least 200 m below the tophole section, or to a depth of 1000 m below *seafloor*, whichever is greater.

For each geohazard identified, the potential should be simply stated in terms of the likelihood that the particular condition exists at a specific position and depth. The clear and unambiguous presentation of this information is a key input to the overall process of managing and reducing risk to offshore drilling that is carried out by those responsible for planning and operating the well.

4.2.2 Advanced Geophysical Analysis

Good quality seismic reflection datasets, especially 3D datasets that may be either high *resolution* or exploration, contain a great deal of information that when accessed through advanced geophysical analysis techniques can provide valuable insights into the identification and assessment of *geohazards* and aid the classification of fluids and lithologies. These include, but are not limited to:

- Amplitude versus offset (*AVO)* and pseudo *AVO* – using 3D offset data sets to classify *AVO* response and fluid estimation from intercept/gradient plots. *AVO* analysis can be reinforced using Vp, Vs and *RhoB logs* to generate synthetic seismic data and assess the expected *AVO* response through fluid substitution (Ref. 7);
- *Pseudo impedance*, matched to logs, for estimating relative soil properties/lithologies;
- *Inversion* based velocity models for hazard identification, and pressure transfer zones, e.g., full waveform *inversion* and surface wave *inversion* (Ref. 8);
- Combined analysis of *P-wave* and *S-wave* seismic for separating pressure and fluid effects;
- *Spectral decomposition* can aid facies classification and architecture description and the assessment of seismic reflection data *resolution* and *tuning effects*.

Although these analyses techniques are not routine workflows in drilling hazard assessment, when conditions at a drilling site are particularly challenging, they may provide a level of empirical data that greatly enhances the interpretation, and thus improves the quality of hazard assessment. It should be noted that most require good quality log data to be reliable, particularly *sonic* and *density logs*, which are often not available in the tophole section.

4.3 PURPOSE AND SCOPE OF A GEOTECHNICAL SITE INVESTIGATION REPORT

When a geotechnical *site investigation* is carried out a factual report will normally be produced containing the results of in-situ and laboratory tests carried out on recovered samples. The report should clearly indicate soil strengths and other geotechnical parameters measured at the appropriate depths below *seafloor*.

4.4 GEOTECHNICAL INPUT TO WELL DESIGN

4.4.1 Design Soil Parameters

The soil parameters typically needed for structural design analysis of the *conductor* casing are summarized in Table 4.1. Soil parameters classified as secondary (i.e. effective vertical stress, coefficient of lateral earth pressure at rest and *deformation parameter*) may be derived from those soil parameters classified as primary (i.e. *undrained shear strength*, *drained internal friction angle*, *submerged unit weight*, and *remoulded undrained shear strength*).

4.4.2 Soil Data Acquisition

In general, acquisition of site-specific soil data to beyond the setting depth of the *conductor* shoe is recommended for design. However, the project geotechnical engineer may revise this requirement, based on consideration of the following factors:

- Limitations in the availability of site-specific geotechnical data to a depth shallower than the setting depth of the casing. The lateral response of the composite well typically controls the section properties of the *conductor* casing and is governed by the soil conditions typically up to a depth of twenty (20) casing diameters. Hence, availability of site-specific soil properties to approximately twenty casing diameters below the *seafloor* will allow design of the casing section properties;
- Availability of geotechnical data in the vicinity of the well site, which could be extrapolated to the well site. Extrapolation of data may only be performed with confidence where high *resolution* geophysical data are available, which indicate that the soil conditions are laterally continuous between the location of the soil data and the well site;
- History of *conductor* casing installation in vicinity of well site;
- The cost of geotechnical data acquisition as compared to the expected (probabilistic) cost of casing failure.

For wells where there is a risk of *hydraulic fracture* of the formation, particular consideration should be given to acquiring site specific geotechnical data to beyond the depth of the *conductor* casing, and to include in-situ *hydraulic fracture* tests as part of a *site investigation*.

Soil Parameter		**Analysis**			
		Installation	***Axial Capacity***	***Hydraulic Fracture***	***Respsonse to Load***
Primary	*Undrained shear strength (s_u) or* *Drained internal friction angle (φ')*	●	●	●	●
	Submerged or effective unit weight (γ')	●	●	●	●
	Remoulded undrained shear strength ($s_u(r)$)	●			
Secondary	*Effective vertical stress (p'_0)*			●	●
	Coefficient of lateral earth pressure at rest (K_0)			●	●
	Deformation parameter (ε_c)				●

Note: Design soil parameters should be established by a geotechnical engineer. Profiles of the variation in the design soil parameters should be documented in the design report.

Table 4.1: Soil Parameters Needed for Structural Design of the Conductor Casing

4.4.3 Geotechnical Analysis

Geotechnical analyses should be performed to determine:

- The setting depth of the *conductor* casing (based on *axial capacity*, installation method, *hydraulic fracture*);
- The response of the casing to loads.

The load-deflection response analysis of the *conductor* casing influences the make-up of the *conductor* casing.

The methodology to carry out a successful *conductor* assessment is typically an iterative process: first an assessment of *axial capacity* and hydrofracture assessment are carried out and the *conductor* setting depth determined as the more onerous of the two; next the installation procedure is assessed. The *axial capacity* may need to be reassessed depending on the installation method, while the hydrofracture assessment could restrict the *conductor* installation process.

Factors of Safety

The allowable *axial capacity* and allowable *hydraulic fracture* pressure of the soil are computed from the ultimate failure values by application of an appropriate safety factor. Choice of the safety factor is dependent on uncertainties in the input parameters and consequences of failure. Further guidance is provided in ISO 19902 (Ref. 9) and API RP 2A (Ref. 10).

Setting Depth

The setting depth of the *conductor* casing is determined from the following criteria:

- The allowable *axial capacity* of the casing being sufficient to carry the required loads;
- The allowable *hydraulic fracture* pressure of the soil below the *conductor* tip, which needs to be sufficient to prevent *hydraulic fracture* of the formation during drilling of the hole for the *surface casing*;
- The depth that the casing can be installed to, which is dependent on installation method.

The *hydraulic fracture* pressure can be defined as the excess pressure (above hydrostatic), which causes fracture of the formation. The *hydraulic fracture* pressure may be measured directly in a geotechnical investigation, or may be assumed to be equivalent to the minor principal stress, which can be estimated from the design soil parameters.

The *axial* capacity of a *conductor* casing increases with time after installation due to the dissipation of excess pore pressures and thixotropic effects. This increase in *axial capacity* is referred to as set-up or soak.

The setting depth of a *conductor* casing can typically be selected without consideration of set-up effects. However, when the setting depth required to achieve the *axial capacity* exceeds the practical limit for installation, then consideration of set-up may be warranted.

If it is not possible to install the *conductor* casing to the depth required to prevent *hydraulic fracture* of the formation during drilling of the hole for the *surface casing*, then alternative approaches, such as restrictions on the drilling parameters and fluid during drilling of the *surface casing* can be considered.

Response of Conductor Casing to Load

The response of the *conductor* casing to load transfer is generally distinguished in either axial or lateral direction. For design capacity calculations in both directions or combination, general guidance is given in the API RP2 GEO (Ref. 5) and ISO 19901-4 (Ref. 4).

For lateral loading, besides the soil parameters and omitting the soil plug, additional information on the internal casings and stiffness should be incorporated appropriately.

A response analysis will determine the axial forces, shear forces, bending moments and deflections of the structural casing for applicable load combinations and thereby enables the casing to be appropriately sized, both in terms of strength and for fatigue considerations. The response of the structural casing is dependent on:

- The section properties of the casing;
- The section properties of the surface and internal casings;
- The verticality of the casing;
- The effectiveness of any *grout job*;
- The soil resistance and;
- Temperature and environmental loads.

The section properties of the surface and internal casings should only be included in the analysis if it is suitably centralised and connected to the structural casing.

Total Ultimate Axial Capacity

The immediate *axial capacity* of a *conductor* casing is defined as the ultimate shear transfer, which can occur at the outer wall of the casing, at the instant the casing reaches the required setting depth.

Since the *conductor* internal soil plug is drilled out during or after installation, no end bearing can be relied on, which means that the total ultimate immediate axial *conductor* capacity in compression or tension can be estimated according to the following equation:

$Q = f(z)\,A_s$

where

$f(z)$ = the unit shaft friction, in stress units

A_s = the side surface area of the *conductor*

General guidance on the soil input parameters for *cohesive* and *cohesionless soils* is detailed in the API RP 2GEO (Ref. 5) and ISO 19901-4 (Ref. 4).

Special attention should be given to calcareous soils since they can have a significant influence on capacity because of friction degradation during installation or in-place load conditions.

For *conductors* installed in *cohesive soils*, the unit shaft friction, f(z), is determined by the following equation:

$f(z) = \alpha\ s_u$

where

α= the dimensionless shaft friction factor.

s_u= the *undrained shear strength* of the soil at the point in question, in stress units

The α factor for jetting is dependent on the degree of disturbance to the formation caused by the jetting operation. The degree of disturbance to the formation is dependent on the following factors:

- Jetting procedure – installation by controlled jetting reduces the degree of soil disturbance;
- Type of connector – the use of flush connectors (i.e. connectors with the same outside diameter as the *conductor* casing) reduces the degree of soil disturbance.

Values of adhesion should be established from a review of casing installation histories in the vicinity of the well. Some additional guidance for the *jetted conductor* capacity and installation is given in Jeanjean and Evans (Refs. 11 and 12).

Installation Method

In general there are three methods of installing a *conductor*:

- Driven (possibly with drill-out and re-drive in case of large soil resistance to driving);
- *Drilled and Grouted;*
- *Jetted.*

The preferred method is usually dependent on the following:

- Water depth (deep or shallow);
- Soil conditions, including any identified tophole risks;
- Installation vessel and available equipment on board.

Driven conductors are common when the installation vessel has the ability to handle the driving hammer and soil conditions are suitable for *conductor* driving. In general *driven conductors* are not selected in deep water.

Drilled and grouted conductors are preferred in hard ground formations when either driving or jetting are unlikely to be successful.

Jetted conductors are becoming more popular at deeper water locations in low strength clay soils. The initial *axial capacity* of *jetted conductors* can be very low and may take a long time to develop. The body of experience in installing *conductors* using the jetting technique is growing. One publication which offers guidance is “Jetting of Structural Casing in Deepwater Environments: Job Design and Operational Practices” (Ref. 13).

4.5 PORE PRESSURE PREDICTION

Pore pressure fracture gradient (*PPFG*) prediction for wells attempts to predict the fluid pressure in the pore space of soils and rocks (pore pressure) and the pressure at which these fail under tension in the wellbore wall (fracture pressure). *PPFG* predictions are usually presented as a *PPFG* forecast in either pressure (psi, MPa) or as a pressure gradient (pressure / depth) presented in equivalent mud weight (ppg, gr / cc) (Figure 3).

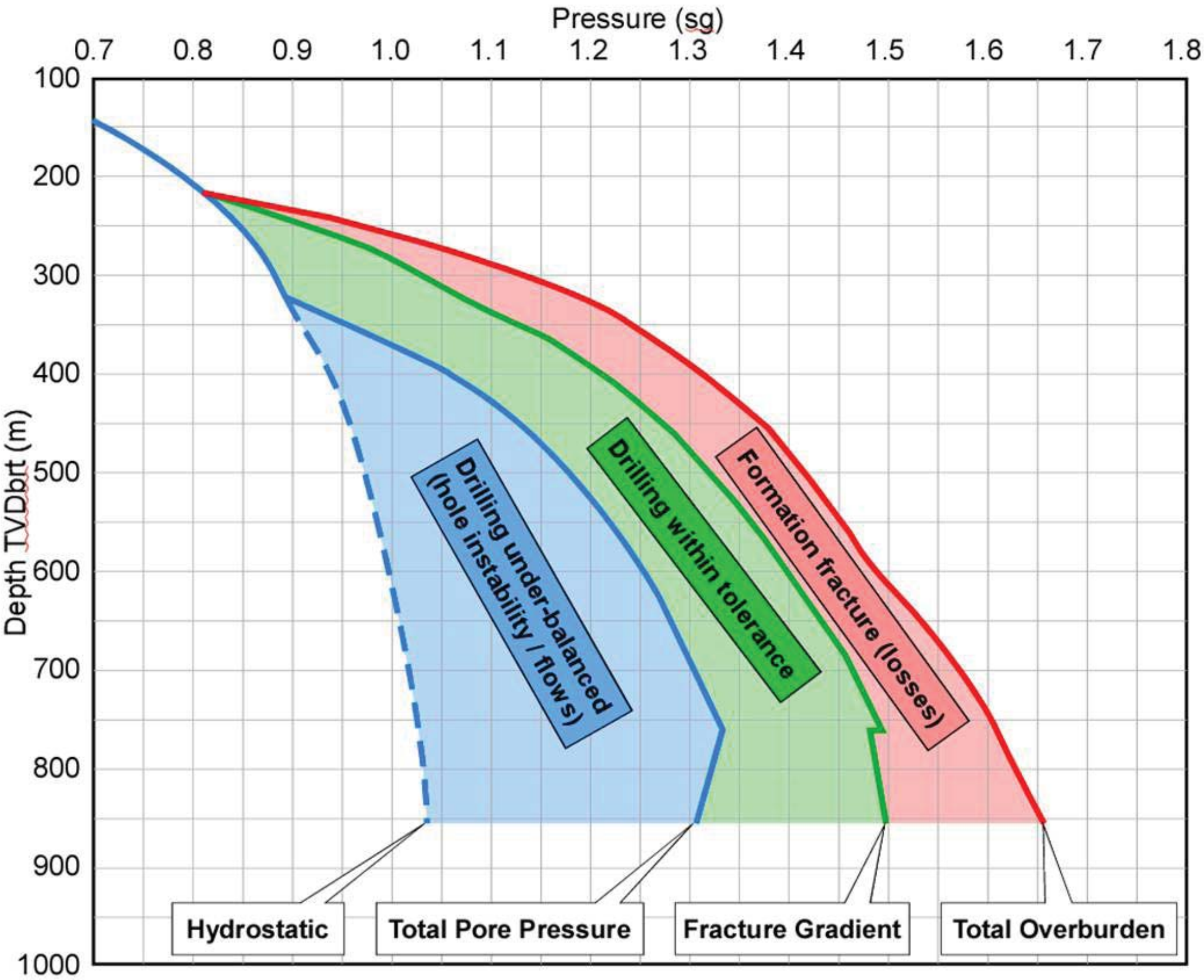

Figure 3: Example of a PPFG prediction

PPFG prediction is based on the analysis and integration of data from three main sources:

***Offset Wells*:** pressure measurements; drilling events (kicks and losses); petrophysical log data; formation pressure integrity tests (leak-off tests), drilling data and drilling parameters such as mud weight.

Seismic Reflection Data: inference of (shale) pressures from *interval velocities* obtained from the processing of seismic reflection data. Interpretation of seismic reflection data for understanding pressure build up and release mechanisms

Basin Modelling: pressure, temperature and vertical stress estimates based on simulations of fluid flow in a basin over geological time.

Both pore pressure and fracture pressure estimates are fundamental inputs for well design and construction, but are often poorly understood in the tophole section. The main constraints on tophole *PPFG* predictions are generally:

- The limited availability of quality data from the riserless section in *offset wells*;
- Poor *resolution* of 3D seismic reflection data and sub-optimal *seismic processing* for retaining fine detail in the shallow *overburden*;
- Poor understanding of appropriate 'normal compaction trends' (that is the expected increase of density with depth) for soils and less-consolidated sediments;
- Lack of calibration for porosity/permeability in poorly compacted sediments;
- Poor definition of permeable facies in the shallow section in basin models, which often have fairly coarse cell sizes and hence do not capture sufficient variability.

Shallow geotechnical, geophysical and geohazard data and interpretation may be used to improve understanding of the tophole *PPFG* conditions.

Geotechnical Data and Analysis

Geotechnical data are often only acquired within the *foundation zone* to a depth of perhaps 30 m below *seafloor*, although in some cases this may be extended to 150-200 m, and occasionally to greater depths where geotechnical testing and sampling have been used to address particular tophole drilling issues.

Where available, geotechnical data and analysis may be used to infill tophole data gaps in *petrophysical logs* and drilling data. Density data from shallow cores may be used to guide the extrapolation of *density logs* to *seafloor* and determine the applicability of generalised density models. This is especially important in areas of *overconsolidated* sediments or *underconsolidated* sediments.

Piezo-probe tests can provide measured pore pressure values, both in permeable formations and in shallow, unconsolidated clays. *Hydraulic fracture* tests and Ko values derived from geotechnical testing and laboratory results may be used, in conjunction with drilling experience, to better define the stress state and fracture pressures in the tophole section.

Age dating of geotechnical cores may be used to aid the definition of recent sedimentation rates and provide a better understanding of compaction trends. This can be used to enhance basin models and the generation of reliable normal compaction trends in the shallow *overburden*.

Geophysical Data and Analysis

Currently, *interval velocities* derived from the (*seismic) processing* of high *resolution* (HR) seismic reflection data are not commonly used in pore pressure prediction because normal compaction trends in the shallow section are not well defined. Significant variations in predicted pressure can result from small variations in the normal compaction trend, on which *seismic velocity* is highly sensitive. However, when they are available, *interval velocities* from HR3D seismic reflection data may be useful for identifying pressure trends in the shallow section in greater detail than can be acquired from conventional *exploration 3D seismic reflection data*. Further work is required to understand the opportunities for using HR3D data to better define shallow *PPFG*. In addition, detailed seismic data interpretation can provide a better understanding of pressure transfer or pressure traps in the shallow *overburden*.

Geohazard Analysis

Integration of the various datasets available to geohazard specialists, as described in Section 5.3, provides the opportunity for detailed characterisation of the sub-surface in 3D, which can aid the understanding of the distribution of permeable layers and seals in the tophole section. Detailed maps of features and layers, in particular overpressured permeable zones and / or seals, can be integrated with basin models and *seismic velocity* volumes to better understand the distribution of pressures in the shallow *overburden* and provide a regional understanding of transfer and trapping of pressures.

4.6 SUMMARY OF INPUTS/OUTPUTS OF AN INTEGRATED SITE INVESTIGATION

Table 4.2 summarises typical *site investigation* and other data inputs for the various phases of a drilling operation together with the integrated outputs that would be used to design risk mitigation strategies for the tophole section of a well.

Table 4.2: Site investigation Inputs and Outputs

Phase of Drilling Operation	*Site Investigation* Data Inputs	Other Data Inputs	Integrated Outputs	Comments
Locating the well	*Multibeam echo sounder* Sidescan sonar Sub-bottom profiler Shallow geotechnical Sampling	Metocean Environmental Existing Infrastructure / obstructions / restricted area database	Topographic and *seafloor* hazard maps	
Conductor installation	*Sub-bottom profiler* HR 2D or 3D seismic Exploration 3D seismic Geotechnical samples / testing (*CPT*) from a *borehole*	Previous drilling or jetting histories	Identification and assessment of problem zones such as "hard layers", gravels, boulders, loose sands, channels, *shallow gas* etc. Isopach maps, integrated sections, soil zonation & parameter maps Ground model *Axial capacity* and *hydraulic fracture* pressure calculation *Conductor* fatigue analysis	Data type, analyses and outputs will depend upon installation methodology; jetting, *drill & grout,* driven etc.
Drilling open-hole section	HR 2D or 3D seismic Exploration 3D seismic Geotechnical samples / testing (*CPT*) from a *borehole* 3D *seismic velocity* models	*PPFG* prediction Wellbore stability - geomechanical study Previous drilling histories *LWD* logs Previous tophole observer logs and reports	*Shallow gas* distribution map(s) Ground model Stratigraphical & lithological predictions Identification of permeable zones Identification of faults Assessment of shallow water flow potential Integrated tophole geological, hazards & *PPFG* prognosis	Calculation of potential column heights / volumes of gas for input to *PPFG* *AVO* analysis and seismic *inversion* will assist in deciding if anomalies represent gas *Spectral decomposition* and wavelet analysis may inform on lithology
Casing installation and cementing	HR 2D or 3D seismic Exploration 3D seismic Geotechnical samples / testing (*CPT*) from a *borehole* 3D *seismic velocity* models	*PPFG* prediction Wellbore stability (geomechanical) study Previous drilling histories *LWD* logs Previous tophole observer logs / reports	Identification of permeable zones Identification of faults Assessment of shallow water flow potential Integrated tophole geological, hazards & *PPFG* prognosis Ground model	

5 Integrated Hazards Assessment and Risk Management

Previous sections have discussed the variety of *geohazards* faced while drilling the tophole section of an offshore well (Section 2) and the necessary geophysical and geotechnical data (Section 3) required to define the geological conditions across a well-site, the results of which are used in geotechnical analysis for well engineering design purposes (Section 4.4). Maximum value can only be gained from any *site investigation* programme through integration of all components of the well planning process, by the operator or the operator's consultants, as opposed to the treatment of each in isolation.

The following section discusses a generic approach to maximising value from *site investigation* data acquisition and analysis, and suggests a risk evaluation process through a multi-disciplinary workgroup, with the aim of devising a risk mitigation plan for management approval.

5.1 CHARACTERISING THE OVERBURDEN

Understanding the geological framework of the *overburden* is critical to successful and safe well planning in the tophole section. The primary elements required to produce a geological understanding will be described by the ground model and are:

- 3D geological framework (*stratigraphy* and structural components);
- Identification of *geohazards*;
- Geomechanical rock properties (induced fracture propagation, wellbore stability modelling etc.);
- Fluid evaluation (*offset wells*, *basin modelling*, *seismic velocity* etc.);
- Pore pressure fracture gradient (*PPFG*) assessment;
- Capture of uncertainties in each component.

In the tophole section many of the data elements required to assess geomechanical and fluid properties are not available, mainly because the necessary *wireline logs* are rarely acquired in larger diameter hole-sections. This leads to a higher degree of uncertainty, particularly in fluid evaluation. Therefore, careful management of the tophole section is critical for assuring well-integrity, and a systematic approach to geophysical and geotechnical data integration greatly improves the chances of executing the well plan successfully. Acquiring data, integrating them into the ground model and ultimately aiding construction of the *PPFG* model, updating the *geohazards* prediction and *PPFG* model with post well observations and feeding those lessons into future well planning, form the basis of this suggested best practice.

A combination of qualitative (geophysics and visual observations) and quantitative (measured) data are necessary to characterise the *overburden*. The basic elements are:

- Geophysical data (Section. 3.4);
- Geotechnical data (Section. 3.5);
- Logging While Drilling (*LWD*) Data;
- *Calliper logs*;
- *Completion logs*;
- *Offset well* drilling and cementing histories.

It will often be the case that only some of these data types are available. However, as long as the limitations are understood, much can be learned from the detailed analysis of non-ideal, existing datasets. Indeed, the effective use of existing data is one of the cornerstones of an efficient *site investigation* process.

5.2 IDENTIFICATION AND INTEGRATION OF SUBSURFACE UNCERTAINTY

All geoscience activities in support of well planning should aim to assess subsurface uncertainties and their impact upon the fundamental objectives of the well, together with the choice of well design and drilling concept. Only through discerning, understanding, communicating and, where possible, managing and reducing the range of uncertainties inherent in the subsurface, can a well planning team hope to optimally reduce risk exposure during drilling operations.

In general, and as part of the prospect definition process, geoscientists who are specialists in *geohazards* and the shallow geological section will have evaluated the conditions in the entire *overburden*. The process will have identified key stratigraphic and structural elements controlling the geological development of the *overburden*, and identified a number of hazards to drilling, either through direct analysis of seismic reflection data, or from *offset well* drilling histories.

Early acquisition of appropriate *site investigation* data will assist with reducing technical uncertainty in the tophole section. However, any *geohazards* identified from the *site investigation* campaign must be promptly discussed and understood by both subsurface geoscience, and drilling engineering disciplines. All identified *geohazards* must be integrated with the other elements of subsurface description, and most importantly, with the pore pressure prediction analysis.

The **key** component of subsurface analysis used by the drilling engineer, is the pore pressure fracture gradient plot. As discussed in Section 4.5, refining the "Drilling Window" from detailed *overburden* analysis is fundamental in reducing drilling induced non-productive time, and successful well planning hinges on reducing uncertainty regarding the onset of over pressure.

Any uncertainties in the pore pressure prediction must be explained and included in well planning. The presence of *geohazards*, such as s*hallow gas* or loose uncemented sands locally affect the pore pressure and fracture gradient. Therefore, all *geohazards* should be placed in their correct geological context and correlated against the pore pressure, fracture gradient analysis and the results utilised in defining the proposed drilling fluid types and weights. Failure to do so may result in *wellbore instability* and pressure kicks where the hydraulic pressure is less than pore pressure, or *hydraulic fracture* and *lost circulation* where the hydraulic pressure exceeds the fracture gradient.

One suggested methodology for capturing subsurface uncertainties, and ensuring they are evaluated and integrated with all other aspects of well planning, is through adoption of integrated multi-disciplinary workgroup sessions and reviews.

5.3 INTEGRATED MULTI-DISCIPLINE APPROACH TO RISK EVALUATION

A typical well planning team may comprise the drilling engineer, a well planning geoscientist tasked with coordinating subsurface analyses, an operations geologist and a pore pressure fracture gradient (*PPFG*) specialist (or equivalent role). Figure 4 shows the basic composition of a typical well planning team responsible for identifying, assessing and ranking geological risk. A *geohazards* specialist and a geotechnical engineer are further important team members.

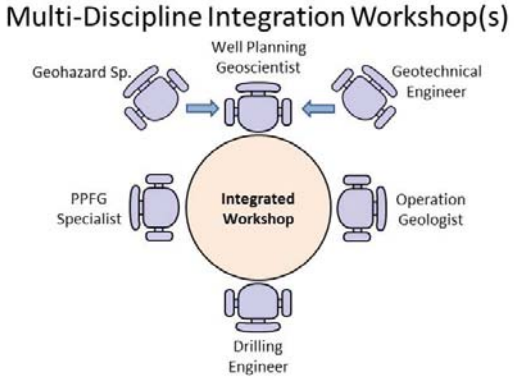

Figure 4: A typical Well Planning Team for Integrated Hazard Assessment, Risk Identification, Ranking and Mitigation

In general, the roles for each of these disciplines can be defined as:

Drilling Engineer
- Defines the well trajectory and casing design specifically to meet the conditions identified throughout the *overburden*. This input is critical in the development of risk mitigation, reduction and elimination processes either through well design, or drilling practice.

Well Planning Geoscientist
- Coordinates characterisation of the subsurface for the entire depth of interest of the well;

- Identifies key data inputs required to define the *overburden* which meet regulatory requirements, company requirements, and best define the geological and geohazard conditions at site;
- Facilitate identification, evaluation and ranking of all potential subsurface hazards.

Operations Geologist

- Provides input to defining the *overburden* through analysis of *offset well* petrophysical, lithological and drilling data;
- Collates a record on non-productive time from *offset wells* and in collaboration with the well planning geoscientist, identifies problematic facies, and correlates to the proposed well.

PPFG Specialist

- Develops a pore pressure prediction through analysis and integration of data from *offset well*s, seismic volumes and geological *basin modelling*;
- Identifies potential well control and *lost circulation* zones;
- Makes recommendations on the selection of drilling fluid / weight, casing string design, setting depth, and geohazard mitigation.

For the *site investigation* the relationship with the well planning geoscientist is key to successful communication of *geohazards* to the multi-disciplinary team. Generally, it is the well planning geoscientist who evaluates the requirement for a *site investigation* programme based on the expected conditions at site, regulatory conditions and intra-company policy compliance. In some cases collaboration between the *site investigation* specialists and the well planning geoscientist is achieved through specialists within the operator, but in most cases, it is through client / consultant / contractor relationships. In either case, communication is key to success.

The primary objective of multidisciplinary reviews is to record the range of uncertainties and their potential impacts on well design, and devise a mitigation plan to reduce or remove the associated risks. All hazards identified through the various subsurface analyses (*geohazards*, *PPFG* prediction, depth uncertainty, presence of H_2S etc.) need to be captured, and all potential and actual risks and uncertainties documented and communicated to the well planning team.

There are a number of tools and methodologies to assist with this including hazard and risk registers, risk assessment tables or matrices, risk maps etc., but essentially, the process by which *geohazards* are captured and risks evaluated should be similar to the approach shown in Figure 5 and described in the paragraphs below. The purpose of such tools and working sessions is to maximise the use of all available subsurface data, from surface to total depth, and transform that data into driller useable information.

(i) Review Specialist Studies and Capture Geohazards and Uncertainties

Evaluating and integrating the individual components that comprise the *overburden* ensures that all *geohazards* are placed in the appropriate geological environment, and the interpretation and analyses by the different subsurface contributors are consistent.

During a review process each discipline is asked to input the results of their analysis and to place identified *geohazards* within the specific zones of influence affecting the well design, i.e. all factors affecting *conductor* installation, such as presence of boulders, or installation methodology. In doing this, the inter-relationship between *geohazards* can easily be identified.

At this stage the ground model can be evaluated against the *PPFG* prediction and analogues from *offset well*s identified.

(ii) Review Geohazards and Uncertainties against the Well Design and Drilling Programme

During this phase of the workshop(s) input from the drilling engineer on the potential impacts and consequences that each identified *geohazard* may have on the proposed well design and drilling methodology are reviewed.

(iii) Generate a Risk Register and Rank Risks

Through discussion and understanding of the relationship between *geohazards* and the well design, a variety of credible scenarios can be discussed and consequences established. This will guide ranking the risks against the objectives of the well, and help focus attention on the risks that pose the greatest threat to the operation. The end result should be that no surprises occur and that all credible scenarios have been explored.

The risk assessment process should look for any analogues or benchmarks to aid assessing the consequences of an event occurring, and look for mitigation strategies used.

(iv) Devise a Risk Mitigation Plan

The end result of the integrated workshop should be a strategy with which to remove or reduce risk through avoidance, change of well design, adoption of alternative drilling practices, alternative technology or recommendations for further data acquisition and refinement of inputs. The well planning team should have devised a drilling programme that not only delivers a cost effective operation, but also resolves each key uncertainty.

(v) Management Agreement

The final stage of the well planning process is to demonstrate that:

- Best efforts have been made to identify all uncertainties, and where necessary, reduce those uncertainties through additional data acquisition;
- All credible scenarios have been explored and;
- A risk mitigation plan is in place.

It is essential to document all decisions taken, and advice given, together with the associated rationale, assumptions and any limitations or exclusions.

Figure 5: A Suggested Workflow for Tophole Risk Evaluation and Mitigation

6 Tophole Execution and Post Well Review

Much of the guidance provided thus far has focused on reducing uncertainty in the drilling of the tophole during the well planning process. However, risk reduction continues beyond planning the well and there is much value to add through being vigilant during the execution of the tophole section, and ensuring any observations and lesson-learned are captured and used to refine the understanding as work progresses.

6.1 TOPHOLE DRILLING OBSERVATION ON THE RIG

For wells planned in a previously undrilled basin, or where a critical *geohazard* issue has been highlighted during the planning process, it is recommended that particular attention is given to monitoring operations in real-time during tophole drilling, possibly involving a *geohazard* specialist. The objective is to verify the predicted conditions and to identify any variations as quickly as possible. Information can then be passed straight to the drilling team, thereby allowing prompt action to be taken in order to improve the chances of avoiding major issues.

For example, informed observation of *ROV* video of the well during connections while the pumps are off will quickly identify any signs of flow (be it water or gas), or if there is a drop in drilling fluid in the well. Monitoring the real-time drilling data, careful logging of observations and cross correlating back to the tophole prediction will not only reduce risk on the drill floor, but also provide invaluable data to improve understanding of the geological and drilling conditions. This will help to reduce uncertainty for future wells in the area.

6.2 POST WELL REVIEW AND FEEDBACK LOOP

On completion of the well, all available data sources and observation records should be collated and reviewed by the same multi-disciplinary team involved in the planning of the well. This review should include but not be limited to:

- End of well reports;
- Daily reports (drilling, geological, mud-logging etc.);
- Real-time drilling data;
- *LWD* logs;
- *Geohazards* observer logs.

Following the review an agreed set of conclusions should be compiled and published, the results of which should be fed back into the documentation supporting the well planning process. Adjustments to the geological / *geohazards* prediction should be made and communicated back to all parties involved in the tophole prediction. This should not exclude the *site investigation* contractors responsible for the geophysical and geotechnical survey work.

Formalising the post well knowledge capture will ensure that the next well to be planned in the area will have direct observations with which to reduce uncertainty. Updating the ground model and improving the geological prediction for future wells should be a cyclical process.

7 Glossary

Term	Definition
Annulus	The space between two concentric objects, such as between the wellbore and casing or between casing and drillpipe, where fluid can flow.
AVO	Amplitude Versus Offset. Variation in seismic reflection amplitude with changes in the horizontal offset between source and receiver
Axial capacity	The magnitude of the soil resistance that supports a pile or conductor against movement in the direction of its long axis (i.e. vertical)
Basin modelling	Term broadly applied to a group of geological disciplines that can be used to analyse the formation and evolution of sedimentary basins, in this context in order to make predictions of parameters that determine pore pressure
BHA (Bottom hole assembly)	The lowest part of the drill string, extending from the bit to the drill pipe
Boomer	Marine seismic energy source that operates by the rapid movement of a restricted metal plate using an electrical pulse applied to a coil
BOP	Blowout Preventer. A specialized valve or similar mechanical device, used to seal, control and monitor oil and gas wells to prevent blowout, the uncontrolled release of oil and/or gas from well
Borehole	Hole drilled into the seabed for the purposes of carrying out in-situ geotechnical testing, or to collect samples for geotechnical laboratory testing and analysis
Calliper log	Well log which measures hole diameter
Chirp profiler	Energy source used in sub-bottom profiling that emits a frequency modulated pulse over a specified range of frequencies
Coefficient of lateral earth pressure at rest (K0)	Ratio of effective horizontal stress in soil to effective vertical stress
Cohesive soils	Soils whose strength comes from undrained behaviour (e.g. clay)
Cohesionless soils	Soils whose strength comes from drained behaviour (e.g. sand)
Completion log	Graphical log containing all the primary measurements in a wellbore. Also known as a Composite log
Conductor	Large diameter pipe that is set into the ground to provide the initial stable structural foundation for an oil/gas well
Consolidated	The process, including compression and cementation, by which a loose deposit is transformed into a hard rock
CPT	Cone Penetration Test. In-situ soil strength testing device that makes real time soil resistance measurements as it is pushed into the seabed by mechanical means at a controlled rate; can be used to determine soil strength and also soil type (e.g. sand or clay)

Deformation parameter	Soil property used to define the stiffness of soil load – deflection response in soil-structure interaction analyses, typically defined as the strain, ε50, at which half the ultimate strength of the soil is mobilised in a laboratory vertical compression test
Density log	Well log which records formation density by measuring the backscatter of gamma-rays
Drained internal friction angle	Soil parameter used defined the strength of cohesionless soil in conjunction with the stresses acting
Drilled and grouted conductor	A conductor installed by drilling a hole into which it is lowered and the annulus between the outer pile wall and the soil is filled with grout (cement), bonding the pile to the soil
Driven conductor	A conductor installed by use of a percussive or vibratory piling hammer to force it into the ground
ECD (Equivalent circulating density)	The equivalent mud weight corresponding to the circulation pressure, which is always higher than that of the static mud column
Effective vertical stress	The vertical pressure caused by the buoyant weight of the overlying soil, i.e. the integral of the submerged unit weight with depth from the seafloor
Exploration 3D seismic reflection data	3D seismic reflection data collected for the purpose of exploring for oil and gas rather than studying geohazards and the shallow section
Foundation zone	The maximum depth below seafloor of interest for foundation design and installation
Gas hydrates	Solid ice-like compound in which a large amount of methane is trapped within a crystal structure of water. Large amounts of gas hydrates are found within seabed sediments where temperatures are low
Geohazards	Geological state or feature which is or has the potential to be a hazard that poses a risk to one or more aspects of the proposed activity or development at a site
GIS	Geographic Information System. A system that captures, stores, analyses, manages, and presents data that are directly linked to the coordinates of the data's origin
Grout (cement) job	The result of filling the annuli between conductor and the surrounding soil, or between successive casing strings, with grout (cement) to bond the two together
Gumbo	A nonspecific type of shale that becomes sticky when wet and adheres aggressively to surfaces. It forms mud rings and balls that can plug the annulus and components of the drilling system
Highly structured clays	Clay soils possessing significant secondary features resulting from their geological history such as bedding layers, fissures and pre-existing failure planes, that affect the strength of the clay that can be mobilised; typically weakening
Hydraulic fracture	Fracture within the formation adjacent to the wellbore caused by high water or drilling fluid pressure acting against the soil wall of the wellbore

Hydraulic fracture testing	The process of establishing the maximum formation pressure that a well can withstand by increasing the pressure in the well to the point at which fractures form and fluids are lost into the formation
In situ testing	Soil parameter testing carried out using tools that penetrate into the undisturbed seabed in the field as opposed to in the laboratory with recovered samples. For example a CPT
In situ vane	A vane shear test can directly measure peak and remoulded undrained shear strength of the soil. An in situ vane is typically pushed 0.5m into the soil before being activated and can be deployed at the seafloor or in a borehole
Interval velocities	Seismic velocity measured over a depth interval.
Inversion	The process of transforming seismic reflection data into acoustic impedance, which may be informative of rock or sediment-properties
Jetted conductor	A conductor installed by weakening / removing the soil by the action of pumping sea water or drilling fluid through the conductor and into the soil via nozzles in the conductor shoe
Logging while drilling (LWD)	Technique of conveying well logging tools into the well as part of the drilling bottom hole assembly and obtaining measurements either in real time or after the tools have been withdrawn
Lost circulation	The loss of drilling fluid, known commonly as “mud”, into one or more geological formations instead of returning up the annulus
MTC (Mass transport complex)	Chaotic marine stratigraphic deposits that can originate from a range of geological processes including slides, slumps, turbidity currents and debris flows
Mini-airgun	A low power airgun (commonly used seismic source which injects a bubble of highly compressed air into the water to generate a pressure wave) designed for high resolution surveys
Multi-azimuth migration	Migration of dipping seismic reflectors to their true spatial positions in three dimensions, rather than limiting it to the two dimensional plane of a section
Multibeam echo sounder	Bathymetric measuring instrument employing multiple acoustic transmitting and receiving elements arranged transversely across a transducer to provide data across a swath of seafloor, enabling the acquisition of bathymetric data over a corridor of width typically more than twice the water depth. Enables complete seafloor mapping at high spatial resolution
Multichannel high resolution seismic reflection	Seismic survey data recorded simultaneously on multiple receiver channels at varying distances from the seismic energy source, to enable data processing to improve data quality and signal to noise ratio. Designes to image the shallow section beyond the depth range of single channel profilers.
Offset well	Existing well from which information is available to tie back to and assist with making predictions about conditions at a proposed well location

Overburden	All of the geological formation that lies above an oil or gas reservoir as far as the seafloor
Overconsolidated	Sediments that have had their compressional load removed, e.g., areas that have been subject to Ice loading or significant uplift and erosion
Petrophysical logs	Information on physical and chemical rock properties and their interaction with fluids derived from well logs.
Piezo-probe tests	Measurement of the dissipation of the soil pore water pressures generated by the insertion of a small diameter probe into the seafloor. An in-situ test used to determine the consolidation properties of the formation and to determine if the pore water pressures are in excess of hydrostatic
Pilot hole	(Small diameter) hole drilled in advance of a borehole or well in order to test the formation for geohazards such as high pressure zones or shallow gas
Pinger	High power transducer acoustic source (or the complete system in which it is used) employed in single channel seismic profiling, usually achieves seabed data down to a few metres
PPFG	Pore Pressure Fracture Gradient. A plot of increasing pressure with depth that also illustrates the difference between pore pressure (the pressure needed to prevent pore fluids from entering the well), and fracture pressure (the pressure at which drilling fluids will be lost to the formation)
Pressure containment string	Casing system installed in a well that has the capacity to control the pressure in a well and contain unexpectedly high pressures using a blowout preventer
Pseudo impedance	Acoustic impedance derived from non-seismic means such as petrophysical data
P-wave (Pressure wave)	An elastic body wave in which the particle motion is in the direction of propagation.
Reactive clays	Clays that swell and become sticky when exposed to seawater or drilling fluid
Relief well	Well designed to provide intervention in the event of a well control incident at depth
Remoulded undrained shear strength	The undrained shear strength of the soil after being heavily worked / deformed
Resolution	The minimum distance between two features that may be separated
Response to load	The deflection of a structure when subjected to loading, e.g the vertical deformation of a conductor when the BOP is added
RhoB Log	A logging while drilling density log
RoP (Rate of penetration)	Rate of penetration of the drill bit when drilling
ROV	Remote Operated Vehicle. Tethered underwater mobile device

	that may carry cameras and other sensors and tools, operated from the surface
Seabed	Materials below the seafloor
Seafloor	Interface between the sea and the seabed
Seismic processing	The computer-based treatment of digital seismic data (typically multi-channel) to enhance the signals that relate to the geological interfaces being investigated, and to remove various artefacts and noise, to obtain the optimum image for interpretation
Seismic velocity	The velocity of the seismic wave through a particular medium, water, soil or rock. Knowledge of the velocity is critical to optimising seismic processing
Shallow gas	The presence of shallow biogenic or hydrocarbon-originated gas charged sediment. Any gas pocket encountered above the setting depth of the first pressure containment string
Shallow water flow	Flow of overpressured pore water into a well from a geological interval causing difficulties in well control and effective cementing of casing
Short offset processing	Multi-channel seismic reflection data processed using only the traces that have a short horizontal source to receiver distance and discarding the rest. High frequencies are selectively retained resulting in improved resolution in the shallow section
Sidescan sonar	Instrument for the efficient mapping of seafloor morphology and features by the transmission and reception of fan-shaped acoustic beams from the sides of a towed or vessel mounted transducer, and measurement and display of the backscattered acoustic energy. Creates an oblique acoustic image of the seafloor
Site investigation	Investigation of the physical properties of the geological conditions in a drilling or development site to determine and inform the safe installation of a temporary or permanent structure. A site investigation may involve the collection of geophysical and / or geotechnical data. Geophysical site investigations are often referred to as site surveys
Soil province	A three dimensional unit within which soil conditions are generally uniform or are within some specific range.
Sonic log	A well log of the travel time for acoustic waves over unit distance, and hence the reciprocal of P-wave velocity
Spudding	To start the well drilling process by removing rock, dirt and other sedimentary material with the drill bit.
Spectral decomposition	Breakdown of a seismic signal into its component frequencies
Stratigraphy	A branch of geology that studies rock layers and layering (stratification) primarily used in the study of sedimentary rocks and also soils
Structure map	Map of geological features or an interface usually constructed from seismic information

Stuck pipe	Drill pipe that cannot be freed from the hole without damaging the pipe, and without exceeding the drilling rig's maximum allowed hook load. May be caused either by differential pressure or by mechanical trapping
Sub-bottom profiler	Seismic reflection instrument for investigating the upper few tens of metres of the seabed with as high a vertical resolution as possible
Submerged unit weight	The net weight per unit volume of the soil after correction for buoyancy; the saturated weight per unit volume of the soil minus the weight per unit volume of water
Surface casing	Usually the first casing to be run in a well after the conductor is installed. A blowout preventer is normally fitted to the surface casing before further drilling takes place
S-wave (Shear wave)	A body wave in which the particle motion is perpendicular to the direction of propagation
Swelling clays	The expansion of clays or clay fractions in the sub-surface caused by the adsorption of water or water based fluids
Tuning effects	Modulation of seismic amplitudes because of constructive and destructive interference from overlapping seismic reflections. This effect is commonly seen in thin beds and can produce false high amplitudes
Underconsolidated	The condition of sediments immediately after a new load is applied but before the excess pore water pressure has had time to dissipate. Areas with high sedimentation rates or gassy sediments are often underconsolidated
Undrained shear strength	The strength of a soil under shear loading when rate of loading is such that pore water pressure is not allowed to dissipate. The main parameter defining the strength of cohesive soils
Washout	Enlargement of the wellbore beyond the original hole size. May be caused by excessive jetting, or soft or unconsolidated formations
Wellbore instability	An open hole interval that does not maintain its gauge size and shape and/or its structural integrity
Wireline logs	Various physical measurements of soil or rock properties made by geophysical tools lowered into a borehole

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