Overview of geophysical and geotechnical design factors for deep water development

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ABSTRACT
Oil and gas fields in deep waters are required to maintain the development of industrial and economical sectors. Based on this fact and to cope with these challenges, it is necessary to apply optimal technical processes and practices performed these days all over the world. Within this frame, adequate interpretation of results and application of geophysical and geotechnical techniques will impact offshore project developments and will minimize their respective risks. This article presents an overview of the main issues involved in geophysical and geotechnical explorations. The article contains a summary that outlines key points to consider to evaluate soil stability while designing sub-sea infrastructure: pipelines, submarine trees, suction caissons for production systems, and such. The techniques applied in exploration are a function of water's depth.

RESUMEN
La explotación de campos petroleros costa afuera, requiere de la innovación y adaptación de las técnicas exploratorias usadas en la práctica. El objetivo de las exploraciones geofísicas y geotécnicas, es obtener parámetros de diseño confiables para la construcción de infraestructura de explotación requerida. Los desafíos de los desarrollos petroleros costa afuera no dejan de presentarse día a día, lo que obliga a los técnicos a prever la aplicación de técnicas así como llevar a cabo la interpretación adecuada de los estudios. Los estudios exploratorios no están limitados, sin embargo dependen de la economía del proyecto y de las técnicas disponibles en el mercado. Este artículo presenta un panorama general de la importancia de los estudios geotécnicos y geofísicos, así como de los puntos clave relacionados con las evaluaciones de estabilidad de suelo necesarias para el diseño de la infraestructura submarina (ductos, umbilicales, árboles submarinos de producción, cimentaciones, anclajes, etc).

1 INTRODUCTION

Requirements for offshore hydrocarbons developments in water depths greater than 1500 m. require engineers dedicated to this matter to understand and implement new technical resources to accomplish successfully these challenges.

The initial exploration in geotechnical and geophysical underwater is extremely important for future phases of the project. This fact, due to the initial selection of exploratory process, has a large influence on the design parameters obtained for the submarine infrastructure. In the same way, a careful selection of exploration techniques reduces uncertainties in a specific project.

Under this scheme, an appropriate selection procedure for the technical equipment to be utilized in the exploration is required. Although this selection has no technical limitations, it depends strongly upon the budget and kind of the project.

To determine the essential geotechnical and geophysical factors, some requirements must be satisfied at the beginning of the investigation in situations like: what factors should be considered on the infrastructure design, what exploration is required to determine soil parameters and to obtain the bearing capacity to reduce the probability of failure, what kind of laboratory tests is necessary to obtain adequate parameters? These apparently basic questions provide a good beginning on planning site investigation process.

In the same way, it is necessary to consider the complexity of the project, also reflecting on the possible changes that may occur during its development and design. This estimation avoids some unnecessary costs when the exploratory techniques are not selected appropriately during early project stage.

Another important factor to consider is the sophistication of exploratory techniques existing on the market. On many occasions techniques can be appropriate, but under some circumstances they can exceed project needs.

Therefore, it is mandatory to have a detailed planning process, which involves all areas implicated in the offshore development.

This paper presents a summary of the basic points to take into account, for the selection of the initial geotechnical and geophysical exploratory tools, as well as key points to be considered for the infrastructure subsea design, such as pipelines, submarine trees, suction caissons, umbilical and mooring systems, etc, which are used on deep water production systems.

2 KEY FACTORS FOR THE SELECTION AND DESIGN OF THE HYDROCARBONS FIELDS

Main selection factors for the hydrocarbons developments are:

1. Reservoir characteristics: recoverable reserves, area, wells distribution, etc.
2. Drilling: drilling type, shallow risks, etc.
3. Production: oil/gas plateau, chemical composition, etc.
4. Infrastructure and hydrocarbons transport: pipelines, subsea systems, etc.
5. In situ conditions: water depth, environmental characteristics, topography, geo-hazards, etc.
6. Norms: design philosophy
7. Installation and construction: patios manufacturing, transportation and construction vessels, planning and time procedures, etc.

Figure 1 show an architecture scheme and subsea systems used in practice during hydrocarbons production.

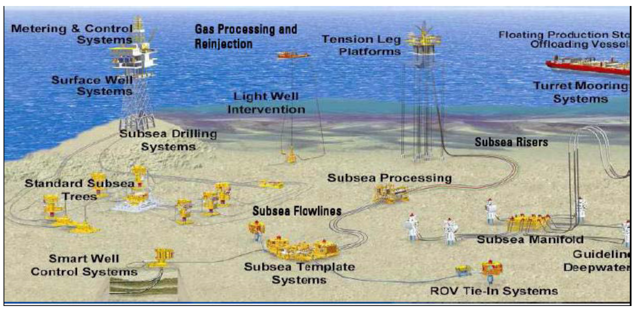


Figure1. Representation of the architecture systems used in offshore deep waters fields.

Many challenges within gas/oil fields are largely determined by the technical equipment applied and by a good interpretation of the geotechnical and the geophysical studies. The reason is because the parameters design obtained in this campaign are used for infrastructure design. In consequence the success in the production depends on a good system design.

3 GEOPHYSICAL AND GEOTECHNICAL STUDIES

In this context, the geophysical and the geotechnical studies are essential to the first stage of the project.

In the offshore hydrocarbon fields, topographical, geological and soil conditions depend on the situations that have been developed on the site such as meta-oceanic and seismic events, as well as depth of water on the field (Equihua, 2010).

The above considerations must be taken into account during the decision making process, and this should correspond with the selection of the technical equipment, tools and for the infrastructure's design considered in the field of hydrocarbons exploitation.

The infrastructure design process depends on the data obtained during exploration and on the boring samples taken. It is very important to define the accuracy of the equipment and the type of facilities that will be used during the exploration (see Figure 2), as well as the sampling techniques that will be applied and the laboratory tests to be carried out.

It is also important to consider the kind of vessel or the ring platform to perform the geotechnical and the geophysical campaign. This last consideration is very important because for deep water fields this kind of equipment needs to have special characteristics. Some of these special characteristics are: vessels that require having a capacity to support long moorings length; big boat decks, and large winch capacity, etc.

Hydrocarbon project developments and the site exploration studies must have at least the following information (ISSMGE TC1, 2005):

1. The bathymetry and morphology in situ: outcrops, shallow or deep faults, slopes, soil irregularities, landslides and scarps, gas presence probability, etc.
2. The soil nature, including its nature, stratification and variability.
3. The soil characteristics: shear stress, stress history, deformation and consolidation.
4. The influence of specific factors such as cycling loading, load ratios, sensitivity, and thixotropy.
5. Landslides risk and sediment transport.

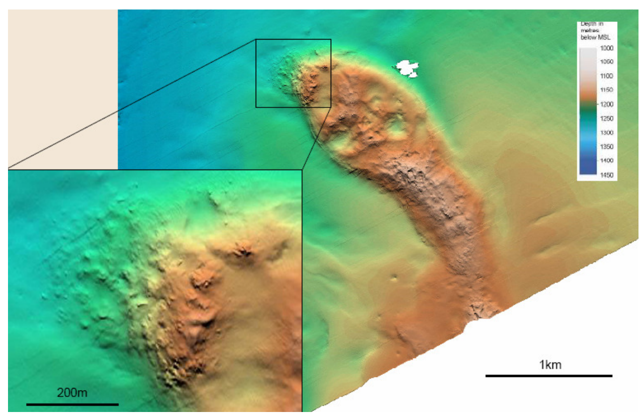


Figure 2. Example of bathymetric data obtained from underwater explorations (Fugro courtesy, 2009).

Depending on certain characteristics other information that may be required are:

6. Slope stability
7. Seismic susceptibility
8. Superficial presence of gas and hydrates

Figure 3 presents data obtained from a specific geophysical exploration method. This information assists in the determination of in situ morphology like: presence of the outcrops, faults, slopes, etc, and to determine the subsequent processes needed to determine slope instabilities, risks, gas or hydrates existence, etc.

Data helps in the determination of:

9. Structure types
10. Installation and construction methods

11. Water depth
12. Existing site data
13. Phase of the project, for example the feasibility study and the final design
14. Acceptable risk
15. Loads to which the foundation is subject

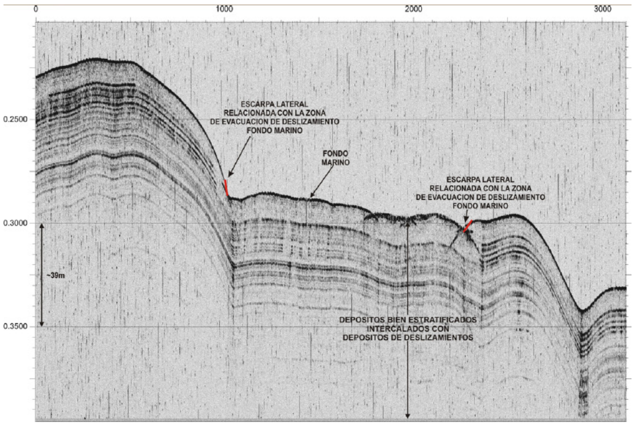


Figure 3. Example of data obtained from the geophysical surveys (Fugro courtesy, 2009).

It should be highlighted that the above information is obtained from the geophysical and the geotechnical explorations that were performed depending on the water depths.

The exploration campaign must contemplate the coupling of the geotechnical and the geophysical studies, and on the needs and soil characteristics identified at the initial geophysics exploration.

The geophysical techniques used internationally are divided into three categories with respect to the exploration of the offshore developments:

a) High-resolution reflection systems
b) Seismic refraction system
c) Electrical resistivity systems

These systems are used to determine the bathymetry and the seabed shape. With this information it is possible to make the decision on the amount and kind of sampling required for laboratory test, depending on the seabed conditions detected. It is also necessary to mention that for layer depths it is necessary to determine the selection of the geophysical equipment. Among the equipment used in exploration geophysics are the following systems: sonar, sidescan sonar pingers, boomers, etc.

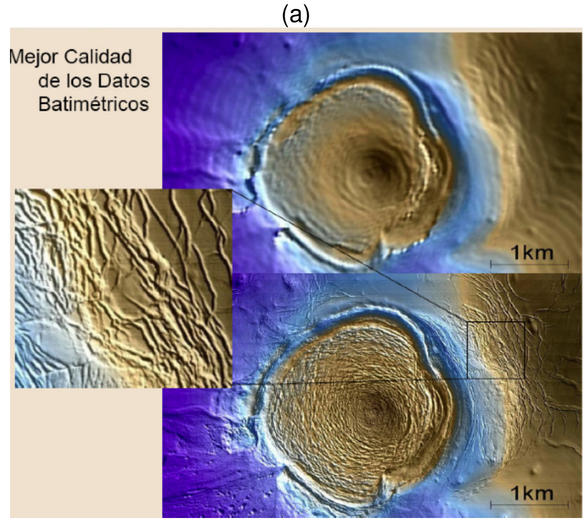
Other systems that have produced an excellent performance and results in the geophysical explorations used in deep waters is the remote equipment operated. Within systems, we can mention Remotely Operated Vehicles (ROV) and the Autonomous Underwater Vehicle (AUV) (see Figure 4). This equipment allows high definition images, which allows a more detailed interpretation of the seabed.

Depending on the needs required for the project, remotely operated equipment may be equipped with additional sensors that improve the quality of the exploration.

Subsequently, the geotechnical exploration allows for verification and defines in situ soil parameters, and also the parameters previously found by the indirect methods.

Additionally, it is important to highlight that a good selection of equipment and laboratory tests at the characterization process will define accurately the variability of the soil behavior and their properties in the function of the location and the water depth. One example of this, is the low mechanical strength for soft soils found in deep waters (until 0.5 kN/m^2), as well as its high plasticity (see Figure 6). Sensitivity and thixothropy are other particularities of marine soils, only to mention some of those (Colliat and Dendani, 2002).

(a)



(b)

Figure 4. (a) Autonomous Underwater Vehicle (AUV) to deep waters geophysics exploration and (b) data comparison obtained by conventional and AUV systems (Fugro cortesy).

Figure 5 shows CPT's profiles, obtained from a specific deep water hydrocarbon field.

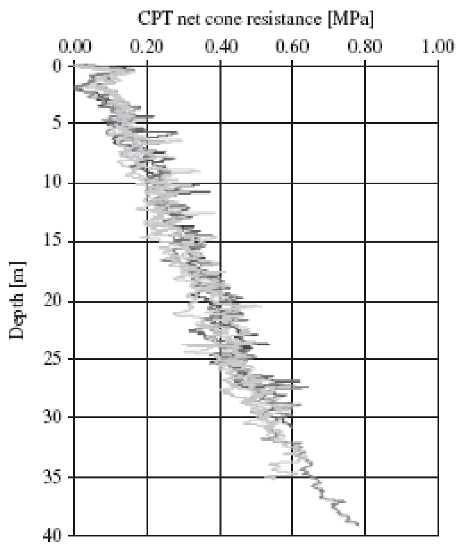


Figure 5. CPT's profiles, obtained from a specific deep water hydrocarbon field (Puech et al., 2005).

Tabla 1. Propiedades índices del suelo reconstituido.

Suelo	w	w_L	PI
	%	%	%
Golfo de Guinea, suelo natural	150-200	170	125
50Bentonita/50Caolín, suelo reconstituido	110, 150	163	132

Figure 6. Index soil properties obtained from a reconstituted laboratory soil, similar to these found on deep waters (Orozco, 2010).

It is possible to make a decision about soil boring methods equipment selection by directly positioning the sampler in the seabed or drilling a bore where sample tools are put. The method selection depends on the necessity to recognize the depth in the site.

Therefore, the equipment is chosen based the project needs. Today there are a number of samples which have evolved hand in hand with deep water hydrocarbon explorations. Examples of this type of equipment, are CPT´s (Cone Penetration Test), JPC (Jumbo Piston Corer), Miniature Cones, Vane Test Operated Remotely, T-Bar y Ball-Bar Penetration Tests, etc, (examples, see Fig. 7).

The performed laboratory tests correspond to the usual soil mechanics assessments. Some examples are: Triaxial anisotropic undrained compression test CAUc, Triaxial anisotropic undrained extension test CAUe, Direct Simple Shear DSS, Resonant Column Test, Consolidation Test, etc, as well as, index properties as water content, liquid limit, plastic limit, void ratio, sensitivity, thixotropy, carbonates content, etc.

Information is obtained from each sample boring that corresponds to the information of the particular site where this was taken. It is mandatory to have a set of sample borings to obtain a reliable definition of the site that is characterized when project allows an interpolation of data for the characterization site,

Data evaluation is the most important activity, followed by the specialists in the area checking the realistic or logical results. This is necessary due to the complexity during offshore exploration that can yield mistakes on the data obtained during the exploration process.

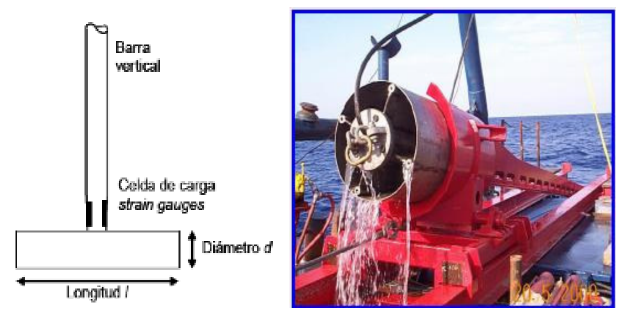


Figure 7. "T-bar" tool, used to obtain soil shear strength resistance and Jumbo Piston Corer to obtain core samples in deep waters.

4 SEABED STABILITY

Stability seabed evaluation is another important point on the infrastructure design (see Figure 8). Some basic questions must be resolved by the specialist at the begining of this stage.

1. How stable are the slopes in the seabed? What is the displacement of the soil in case of a slope failure?
2. Are there any faults or evidence of gas hydrates presence in the vicinity of the considered infrastructure?
3. Are faults active? If the answer is positive, what is the annual displacement of these?
4. If a displacement occurred in any event, does the movement of the soil reach the structures?
5. If a displacement reaches structures, what forces will be developed around these?
6. In the case of gas or hydrates presence, is it a menace to the infrastructure?
7. What is the seismic activity in the area?
8. Do Meta-oceanic events pose risks to the infrastructure stability?

The evaluation of the seabed stability is required because at the seabed, displacements risk may be generated even on slopes of 1% or lower (Poulos, 1988). Another effect of the ocean floors is that the distance of the landslides is generally longer than that of the terrestrial soils and it poses greater risk especially for silty and sandy soils.

Chief factors that activate instability are among others, the existence of unstable and weak sediments and the presence of trigger factors such as: earthquakes, human activities and sediment overload.

Geohazard assessment usually starts with a 3D seismic exploration and with geomorphologic maps. Identified risks must be evaluated and organized by importance level. Some necessary information about the slope stability evaluation is to know the annual probability of failure occurrences and their consequences. In the same way it is important to have the study of the debris flow, considering the characterization of currents and its influence if that is the case (depending on the depth of water).

Regarding faults on the seafloor, it must be evaluated based on the relationship of the annual movements along the fault planes to interpret the damages caused by the displacement to the infrastructure.

In superficial faults, it is important to measure in situ to determine the variation of pore pressure, as well as the shear strength resistance. Another tool used in this process is extrapolations which are obtained from 3D seismic surveys. It is also essential to review deterministic analysis and estimate the annual failure probability by applying probabilistic analysis.

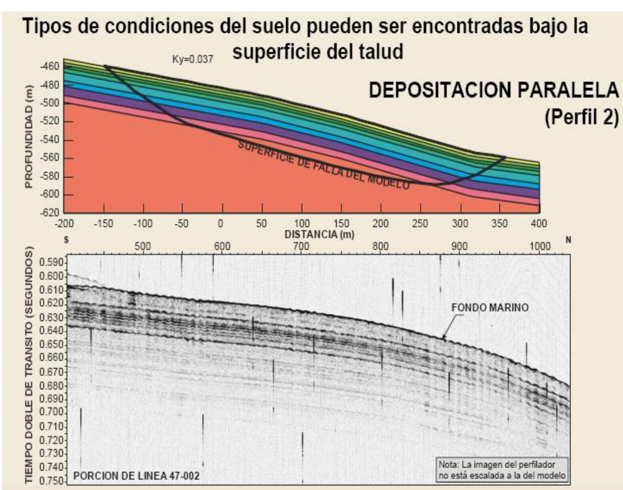


Figure 8. Review stability seabed evaluation process (courtesy Fugro, 2009).

Another effect to consider is the possible occurrence of the mechanism to submit incomplete consolidation. This effect is generated by rapid relations of consolidation or for the presence of gas in marine sediments. Gas presence can cause a significant disturbance during sample boring and also it can generate stress due to an increase on the pore pressure development and therefore a reduction in the effective stress.

Biogenic gas is developed and it can become a solution that is mixed with the soil pore water. Later, when more gas is produced, the soil saturation limit can be reached and therefore, pore water will be increased. Another effect of the gas presence is the possible increase on the compressibility of the soil.

When soils are found at the marine shelf it is required to consider the effect of the waves because the waves can cause pressure that will trigger instability on the seabed during certain events like hurricanes. A potential risk is sand liquefaction which puts a high risk upon the integrity of the structures.

Under these circumstances, the following information is necessary for risk evaluation (ISSMGE TC1, 2005).

a) Investigation and interpretation of geological history, stratigraphy, sedimentology and morphology of the area.
b) Identification and evaluation of the topographic profile and the deformation characteristics of the seafloor.
c) Seabed stability evaluation due to forces such as gravity, waves and earthquakes.
d) Analysis of the seabed stability under the effect of these forces.
e) Analysis of probable seafloor movement.
f) Effect of predicted movements and forces acting, foundations, anchors, pipelines, subsea systems displacements, etc.

Figure 9 shows an example of carried out test results on a pipeline to study soil-structure interaction.

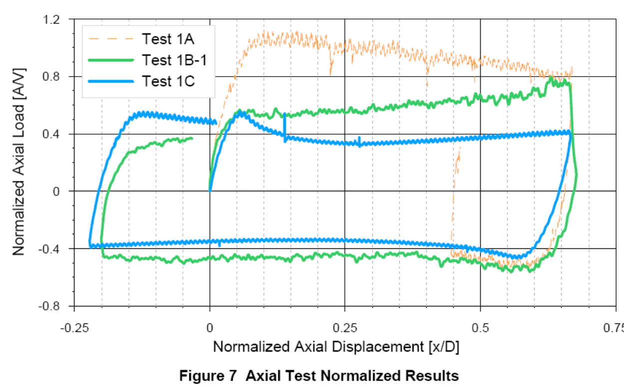


Figure 9. Example for the in situ assessment of axial loads applied on a pipeline (Hill and Wintgens, 2009).

The above studies will be generated during the project development and from the geophysical and geotechnical studies initially planned which don't necessarily limit the need to develop additional researches depending on the needs and the evolution of the hydrocarbon project.

5 GENERAL COMMENTS

An overview was presented on the main points to be considered in a deep water development from the point of view of geotechnical and geophysical studies and also for subsea infrastructure design.

Among the factors regarding design structures it is also important to consider the installation of subsea equipment, since these processes generate additional efforts that need to be considered while doing structural analysis (see Figure 10) and also consider that they are linked to the soil interaction. An example is the analysis to obtain the touchdown point of the risers and pipelines. This design analysis is critical in offshore projects.

Each element used at the hydrocarbon production field must be carefully analyzed by taking into account the points mentioned above and also the final approval needed as a whole to prevent the structures loss.

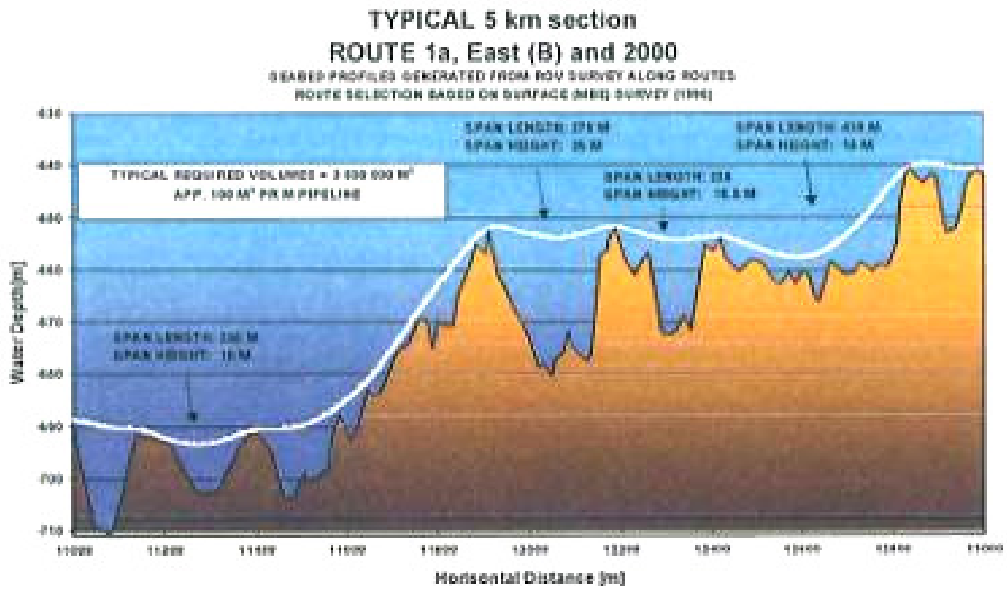


Figure10. Topographic profiles are illustrated and representation of a submarine pipeline.

Figure11. Anchor / suction pile is shown.

Another important factor on the geotechnical studies that geotechnical specialists must consider is the study done at the time of consolidation and subsidence of the crude oil field. This last issue was not discussed in this article but it has great importance for the life of exploration structures.

The conclusion is that the geotechnical design process is a main point for structure integrity. On the other hand, planning of geophysics and geotechnical exploration should take into account the appropriate equipment depending on the exploration at certain water depth. Both considerations are central to obtain effective design of offshore projects.

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