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# Modeling spatial variability in offshore geotechnical properties for reliability-based foundation design

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ABSTRACT

Design of foundations for offshore energy production typically requires soil characterization over large areas. Often, in uniform geological settings, it is neither practical nor economical to acquire geotechnical data at every foundation location. Additionally, the zone of interest for the foundation may extend deeper than the available geotechnical data. This paper describes a model of spatial variability in geotechnical properties for foundation design in deep water Gulf of Mexico. The geology consists of normally to slightly over-consolidated marine clays. Data are available for about 100 locations with soil borings, jumbo piston cores and cone penetration tests. A random field model that describes spatial variations in the design undrained shear strength is formulated and calibrated. This model is incorporated into a reliability-based framework to account for uncertainty due to spatial variability in foundation design. In this setting, depth-averaged values of design undrained shear strength are correlated over longer distances than point values due to stratigraphic features. There is less variation and greater spatial correlation in the design undrained shear strength for deeper versus shallower deposits and along the continental shelf versus off from the shelf. The increased conservatism required in foundation design due to spatial variability when site-specific strength data are not available is generally small.



## 1. Introduction

As energy production moves into deeper water, challenges have arisen in designing foundations for offshore structures (Fig. 1) due to the cost and logistical difficulties in obtaining geotechnical data at the location of every foundation. The final locations of foundations may not be known until after the site investigation. Also, the footprint of a facility may be large with numerous foundation elements spread out over kilometers. These elements can include anchors for mooring systems, foundations for wells and well manifolds, and foundation for pipelines and flow lines. Lastly, the cost and time required to perform site investigations is significant in deep water. Therefore, it is not generally possible or feasible to perform a site-specific investigation for every foundation element.

The objective of this research is to model spatial variability in geotechnical properties and account for this variability in foundation design in a deep water region. The potential contributions of this work are: (1) to understand the magnitude of and sources of spatial variability in geotechnical properties for foundations in a deep water offshore region; (2) to be able to use this understanding to design a foundation in this region to achieve a target reliability without having a site-specific investigation; and (3) to assess the value of information to decide whether obtaining additional geotechnical information at a new site in this region would be worthwhile.

The geologic setting is described, a random field model is formulated and calibrated, the random field model is incorporated into a reliability-based design framework, and an illustrative example is presented.

## 2. Geologic setting and geotechnical data

The study area is located in the Gulf of Mexico below the continental shelf (Fig. 2). The water depths in the study area range from 1000 to 3000 m. The soils over depths relevant for deep foundations are normally to slightly over-consolidated, highly plastic marine clays. The liquid limits range from 50 to 135 percent with an average of about 80 percent. The liquidity indices range from one to two at the mudline to about 0.5 at a depth of 60 m. The sediments consist of a thin (typically less than 3 m thick) hemipelagic Holocene drape overlying sequences of hemipelagic sediments deposited during relatively high sea levels and turbidites deposited during relatively low sea levels [1,2]. Numerous shallow faults and landslide scars dating to pre-Holocene are present in the study

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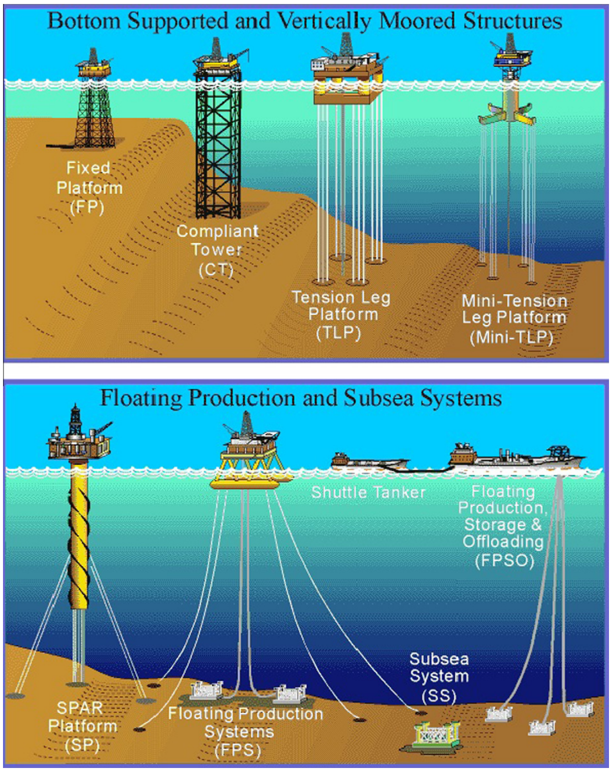


**Fig. 1.** Schematic of typical energy production facilities in deep water (MMS 2011).

area; these features are detected by geophysical surveys and faults are generally avoided in sitting facilities.

Geotechnical and geological data for the study area (Fig. 2) were compiled from site investigations conducted for a variety of different projects over the past twenty years, including 64 engineering reports for 16 different project sites. The sources of data are soil borings in which samples were obtained with 75-mm diameter pushed tubes, 100-mm diameter by 15 to 20-m long jumbo piston cores advanced via free fall, remote field vane tests and cone penetration tests. The undrained shear strength of the clay for foundation design was measured using torvane and miniature vane tests on pushed samples, unconsolidated-undrained triaxial shear tests on pushed samples, anisotropically-consolidated-undrained triaxial compression and extension tests on pushed samples, direct simple shear tests on pushed samples, and field vane and cone penetration tests in situ. An example of a design profile for undrained shear strength versus depth, together with the strength measurements used to develop it, is shown in Fig. 3. Note that there is considerable judgment employed by the geotechnical engineers in establishing a design profile in combining all available geotechnical and geological information into design [3]. Design profiles were available for 115 different locations, ranging in depth from about 10 to 400 m below the mudline.

The design profile of undrained shear strength versus depth is used to design the axial capacity of deep foundations, such as suction caissons (Fig. 4), using the following formula [4]:

$$Q = Q_s + Q_p + W' = \alpha_{avg} s_{u,avg}(L)\pi DL + N_c s_u(L)\frac{\pi}{4}D^2 + W' \quad (1)$$

where $Q$ is the axial capacity; $Q_s$ is the axial capacity due to side shear; $Q_p$ is the axial capacity due to end bearing; $W'$ is the net weight of the caisson; $L$ is the length and $D$ is the diameter of the foundation; $\alpha_{avg}$ is an empirical adhesion factor averaged over the length of the caisson, $\alpha_{avg} = \frac{1}{L}\int_0^L \alpha(z)dz$, and typically equal to 0.8; $s_{u,avg}(L)$ is the design undrained shear strength averaged over the length of the caisson, $s_{u,avg}(L) = \frac{1}{L}\int_0^L s_u(z)dz$; $s_u(z)$ is the design undrained shear strength at a depth $z$; and $N_c$ is an end bearing factor that is typically equal to 9. For typical suction caissons in practice, $L$ is between 10 and 50 m and $L/D$ is between one and six.

## 3. Random field model

The variability in the design profile of undrained shear strength, and subsequently in the axial capacity of a deep foundation, from location to location in this study area could be due to a variety of sources: variations in test methods, variations in sample quality, variations in test type, variations in interpretation of a design strength, and spatial variations in the soil. Detailed statistical analyses of the data indicated that the primary source of variability was

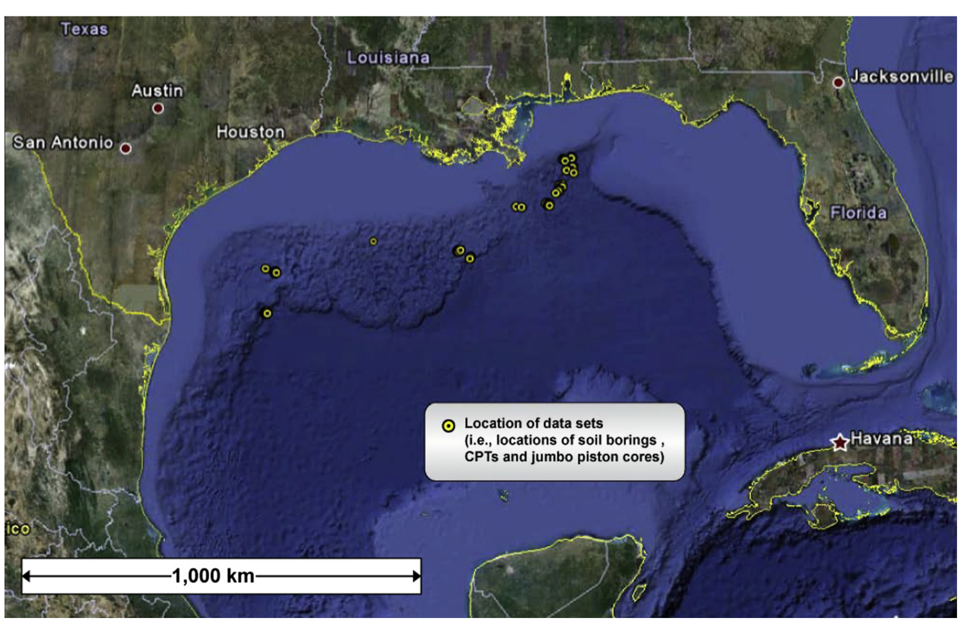


**Fig. 2.** Study area.