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Industry Trends for Design of Anchoring Systems for Deepwater Offshore Structures

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Abstract
This paper summarizes the current industry practice for the geotechnical design of anchoring systems of deepwater production units (TLPs, Spars, FPSOs, Semi-submersibles, etc.), with emphasis on in-place design conditions. The discussion includes anchoring system strengths and limitations, design criteria used, issues encountered, future studies needed, etc. Some deepwater anchoring systems, such as VLAs and suction piles, still do not have uniform or universally accepted design approaches.

This paper discusses the importance of site-specific geological and geotechnical characterization, in order to identify the foundation strength and deformation parameters, as well as geohazards that may affect a project's risk and reliability evaluations. Other issues discussed in this paper include short and long-term reverse end bearing for suction piles and holding capacity of VLAs; effects of cyclic and long-term environmental loading (e.g., Loop currents), such as soil cyclic degradation and creep; and soil set-up development with time.

Introduction
Heading more and more towards exploration and exploitation of hydrocarbons from ever-deeper waters, the industry has faced the need for more robust and specialized anchoring systems for drilling and production units (TLPs, Spars, FPSOs, Semi-submersibles, etc.). With the greater depths come greater mooring loads, new load sources such as different kinds of surface and deep currents, as well as the advent of taut and semi-taut leg moorings that have incurred greater uplift components. In particular, moving from shallow water to deepwater has called for qualitatively different tools to safely transfer predominantly tensile rather than compressive loads. For the most part, three distinct technologies are currently used in these new, uncharted waters, gaining more experience and confidence in their versatility and capacity; namely slender anchor piles, suction piles and Vertically Loaded Anchors (VLAs). This paper gives a snapshot of the current situation and state of the technology for these different types of anchoring technologies, citing their strong points and limitations, and pointing to areas that are in need of more development for better understanding of their behavior and more efficient designs.

This paper gives the state of the industry, rather than the state of the science, which may involve further developments that are yet to percolate through to the application arena. The authors, however, would like to point out the proprietary nature of much of the developments in this new field, which may, inadvertently, result in not presenting some efforts and developments in the area.

This paper presents information based mainly on projects in which the American Bureau of Shipping (ABS)[1,2] has participated. These projects cover major parts of the world, including the Gulf of Mexico, Offshore Brazil and South East Asia. Through the classification and certification of deepwater offshore projects, ABS has been involved in the assessment of unique aspects of anchoring system designs that are normally not the design concerns for shallow water foundations. Facing these new design challenges and lack of existing industry standards, ABS has been working closely with the offshore industry to seek solutions and achieve the proper implementation of new designs. For new designs, information (analyses, test data, etc.) is generally required, so as to establish that the strength and reliability of the design is comparable to those of established designs.

Normally, anchors need to be designed geotechnically for installation conditions and holding capacity as well as structurally for strength and fatigue under handling, installation and in-place conditions. Considerations for anchoring production units are generally different from those of Mobile Offshore Drilling Units (MODUs). This paper, however, addresses only the geotechnical design of the three main types of anchoring systems used for deepwater production units, under in-place conditions.

Site Investigations
The need for reliable and economic design of anchors for deepwater production units calls for a more detailed geotechnical investigation and advanced testing as compared to those done for less sizeable shallow water projects. An economic design of slender and suction piles requires less variability in soil parameters. More advanced testing is required to derive design parameters relevant to issues such as soil set-up and long-term, cyclic and anisotropic strengths. VLAs are known to call for the least of geotechnical information and analyses amongst different types of anchors. This may be attributed to several factors, such as their commonly simplified design ap-

proaches that involve mainly a conventional plate bearing mechanism, modified with mostly soil-independent empirical factors[3]. Also, procedures addressing more sophisticated processes, such as the holding capacity of VLAs under cyclic and long-term loading (which involves soil creep, set-up, drainage, etc.) have not been established yet. Another factor may be the lesser penalty, in terms of extra steel and installation cost, associated with greater uncertainty in the soil parameters.

Most deepwater structures, such as FPSOs and Spars, have very large footprints. Anchor locations can be several thousands of feet apart, as shown in Figure 1. For such projects, it is recommended that a minimum of two borings be taken at the site, in conjunction with a detailed geophysical survey. Also, it is recommended that every pile cluster location have a minimum of a boring or a probing (CPT or PCPT). Extra borings, however, may be required for more complicated geotechnical/geologic situations. Conversely, less geophysical information may be required if geotechnical information is obtained right at the anchor locations. However, geophysical information has, oftentimes, proven invaluable when the project mooring/anchoring pattern changed, or even slightly rotated, after finishing the geotechnical/geophysical investigation. With any rotation of a large spread mooring system, final anchor locations may well be quite far from original geotechnical information. In such situations, provided a simple uniform or layered profile exists, geophysical data can be used to establish the geotechnical conditions and properties at the new anchor location, where actual geotechnical data may not be available.

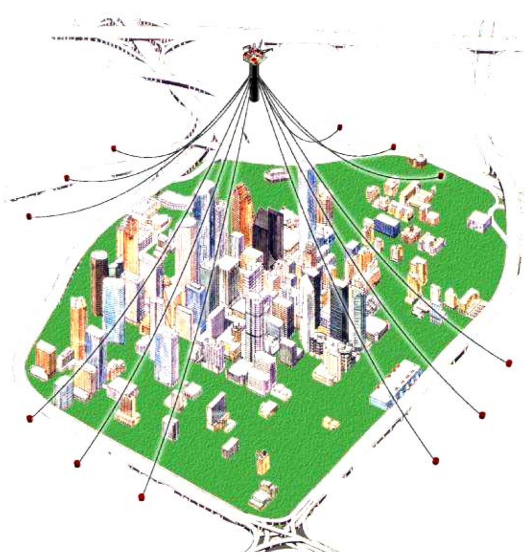

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Figure 1: Large Footprint of Spread Moorings

Independent of the available geophysical information, the boring depth should be a minimum of the anchor design penetration plus the affected depth below, based on the characteristic dimension of the anchor and the expected geotechnical failure mechanism. Generally, this extra depth is greater if a bearing mechanism is involved. In this regard, VLAs and suction piles have the edge in economy, for their lesser penetration

A new standard that has been established is the derivation of an integrated understanding that compiles findings of both geotechnical and geophysical investigations[4,5] and correlates features identified in them separately. This new interdisciplinary task should emphasize the importance of expertise that spans both areas.

Geotechnical Investigation. Soil properties obtained from deepwater geotechnical investigation usually include stratigraphy, type and consistency; unit weight; stress history; static and cyclic, anisotropic, undrained, undisturbed and remolded shear strength profiles; and hydraulic conductivity and consolidation properties. Anisotropic and cyclic soil strength properties, derived from consolidated triaxial and DSS testing, are especially required for the design of slender anchor piles and suction piles. Soil response to cyclic loading should be investigated under different cyclic/average load ratios, based on the actual loads. Normalized soil strength, obtained using the SHANSEP approach[6], is invaluable for gaining insight into the soil strength characteristics. Soil shear strength properties under sustained loading may be needed under certain long-term environmental loads. Thixotropy properties are rather helpful in soil set-up calculations

Sampling and in-situ testing technologies have also adapted to the new environment. The use of more economic and quicker gravity and piston coring has been in expansion, to supplement a reduced number of conventional driven borings. Larger drilling vessels with dynamic positioning are now commonly used in deepwater geotechnical and geophysical investigations. Procedures have been developed to mitigate sample disturbance due to stress relief, as sample disturbance generally increases with increasing water depth. Consolidated testing, the SHANSEP approach and in-situ testing (e.g., remote vane, CPT and PCPT) have become viable options to overcome this difficulty.

Geophysical/Geohazard Investigation. In addition to geotechnical investigation, geophysical investigation has become a standard in all deepwater projects[1,2,7,8]. This may be attributed to the great extent of spread mooring systems and to the fact that more complex geologic formations have been observed in deepwater exploration sites, as compared with shallower fields. Figure 2 shows a comparative representation of both shallow (continental shelf) and deep (continental slope) waters of the Gulf of Mexico, illustrating the relative complexities of both. In addition, most deepwater projects are developed in new territories, compared to new shallow water projects, which are in rather well developed and charted areas.

Geophysical investigation consists mainly of surface (e.g., bathymetry and side scan sonar) and sub-surface (e.g., sub-bottom profilers and high-resolution 3D seismic studies) investigations. These are used mainly to get an idea of geologic features, identify geohazards in the project site as well as to establish the uniformity (or the lack thereof) of soil formation.

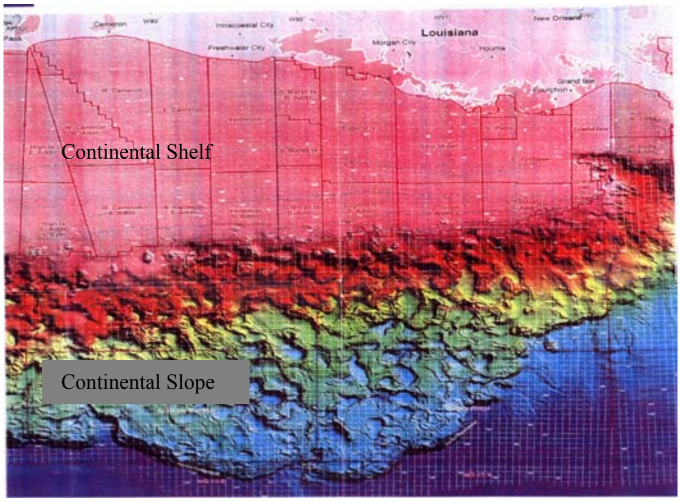

Figure 2: Shallow and Deepwater Gulf of Mexico

Geohazards such as gas and fluid seeps and expulsion, which might be a source of fire or loss of buoyancy for floating units, may constitute a global problem to the whole project. Other geohazards such as shallow faults, earthquakes, steep slopes and pockmarks may constitute a problem to the anchoring system only (at least initially). The zone of interest for foundation design is normally limited to a few hundred feet, below the mudline. The geologic features and geohazards in this zone may not be adequately identified by geological data collected for the hydrocarbon exploration. The different surface and sub-surface investigation tools mentioned above are recommended to identify geohazards, such as shallow faults, that may have adverse effects on the foundation design. With the increasing amount of site-specific data these tools can provide, designers are able to achieve higher levels of confidence in their foundation system designs and curtail some of the conservatism applied in earlier projects. An example of this is where foundations are installed closer to relatively benign shallow growth faults after an adequate characterization of the faults. However, no general guidance is set forth as to the effects of different geohazards, which should be assessed by a geotechnical/geophysical expert, on a case-by-case basis.

Geophysical investigation tools have also adapted to the new deepwater environment with the extensive use of ROVs. ROVs, however, have proved rather inconvenient and slow in deepwater, as a result of using umbilicals and cables in towing and communication. A number of Autonomous Underwater Vehicles (AUVs) are currently under development, and some have been tested in actual projects (Fugro's AUV and C&C Technologies's HUGIN).

General Geotechnical Design Procedures

Primarily, deepwater anchors are designed for mooring or tendon loads, which are evaluated based on the environmental conditions expected at the field. Most standards have adopted the probabilistic 100-year event (or storm) to represent the Extreme event[1,2,7,8,9], used in designing anchors of spread moorings. In association with the above design event, two conditions are of particular significance; namely, where all the lines are intact (Intact Condition) and the one mooring line damaged (Damaged Condition). For TLP piles, the designer is to consider tendon loads under the Extreme event, beside an Operating Condition usually based on a 1 or 5-year environmental condition. Additionally, a condition where a tendon is assumed removed should be considered in the design. In deepwater, dynamic analysis of the unit global performance has been the standard to evaluate mooring or tendon loads [1,2,7,8,9].

(Slender) Anchor Piles

Slender anchor piles designed for deepwater structures represent mainly a quantitative step, compared to the conventional anchor piles used in shallower waters, in terms of their size and the loads they help to transfer to the soil. No significant changes have been brought about in the geotechnical design of deepwater slender anchor piles, used for units other than TLPs, compared to shallow water designs. With the ever-increasing tensile and cyclic loads that are to be supported by these piles, more rigorous geotechnical and structural analysis and design procedures had to be developed, so as to keep the piles reliable, installable and economic. However, except for a limited number of examples, slender piles still represent the main option available to TLP foundation designers. With their extensive history, slender piles are considered the most reliable when dealing with the highly unfavorable type of loading applied by TLPs[8]. However, issues regarding stability of self-penetrated piles and the cost of underwater hammering start to come into view in deeper water. Also, the operating depth of hydraulic hammers is normally limited to about 5,000 ft.

Slender anchor piles may be divided into two main types; namely, TLP tendon piles (hereafter, TLP piles) and piles anchoring catenary and taut moorings (hereafter, anchor piles). A TLP pile is usually attached to the TLP tendon with a latch receptacle at its top, and mainly transfers the pre-tension and storm axial and lateral loadings. Anchor piles are used for most all other types of floating units. They are usually attached to the mooring lines with a padeye located at an optimum location below the pile top. The padeye location is chosen to strike an optimum balance between the pile length, governed by the axial component of the mooring load, and the pile cross-section, governed by the bending caused by the lateral component of the mooring load. Figure 3 illustrates the two main types of slender anchor piles.

Geotechnical Design Procedure. Usually, the geotechnical analysis of slender piles is decoupled, in the sense that axial and lateral capacities are considered independent. This is mainly because axial capacity is predominantly provided by the lower part of the pile, whereas lateral resistance is provided mainly by the upper part of the pile; no significant interaction is usually observed. The axial capacity is usually estimated with a limit equilibrium approach, similar to that described in API RP 2A[7]. The pile lateral performance is usually assessed based on a beam-column (otherwise know as P-Y) type of analysis.

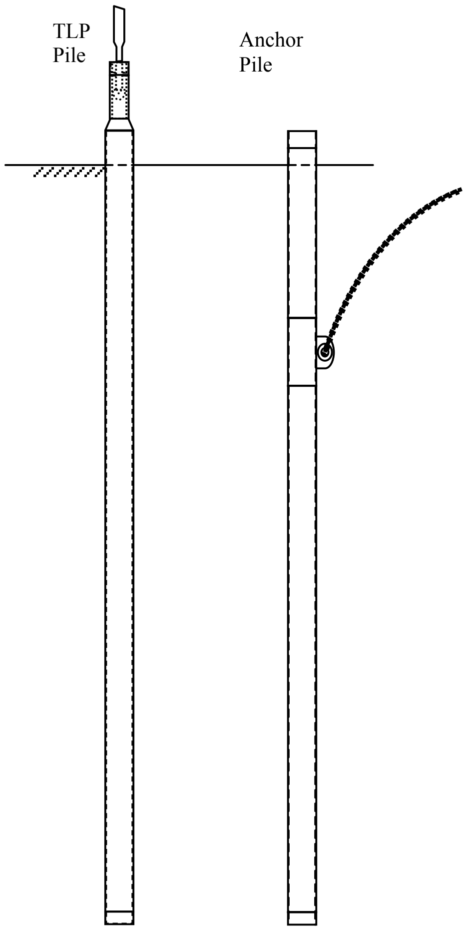

Figure 3: Types of Slender Anchor Piles

On the other hand, this simple P-Y procedure, as described in API RP 2A[7], is not totally free of challenges, because its parameters were originally derived from and calibrated with tests on piles that are much smaller than what is commonly used in deepwater projects. Some believe that these P-Y curves may be rather conservative when used with large piles[10]. Also, it is indicated that the cyclic P-Y curves, which are intended originally for fixed platforms, may be too conservative for anchor pile design. That is because soil supporting anchor piles under cyclic loading do not normally experience stress reversal. Therefore, anchor pile performance ought not to degrade as much as that of fixed platform and TLP piles. The above issues are still in need of further investigation.

In the design of TLP piles attached directly to tendons, the possibility of soil softening, or even gap forming, around the upper part of the pile should be considered. Soil softening or gap forming at the topsoil layers is attributed mainly to large deflections of the pile, because it is laterally loaded at the free top. The current practice is to ignore soil axial and lateral resistance at the top 30 ft. A more rational approach is also used, in which the extent (over the TLP pile length) is identified where a softening behavior of the P-Y curves is expected. For soft clays, softening of the P-Y curve generally occurs if the pile lateral displacement exceeds $3*y_c$, as defined in API RP 2A[7]. Conservatively, both axial and lateral resistances of the soil are ignored within this extent. While this may reduce axial capacity by a few percentages, it is quite significant for lateral resistance. The soil axial and lateral resistances for anchor piles are usually also reduced, to account for possible trenching caused by the padeye during installation.

For TLP piles, group effects need to be considered due to their size and spacing. However, a standard procedure is yet to be established to calculate the reduced axial and lateral capacities due to the group effect. A number of publications are, nonetheless, mentioned in API RP 2A[7], in this regard.

Effect of the mooring line profile below mudline should be taken into account in evaluating the adequacy of the anchor to safely transmit the mooring loads[11]. That is since the line profile (inverse catenary) usually increases the vertical component of the load at the pile padeye, which is usually the controlling component. VLA design is understandably the least sensitive to this effect. Another factor that may affect (slender and suction) piles' axial capacity, and sometimes overlooked, is the surface treatment and painted markings, which should be taken into account if it affects the soil adhesion with the pile steel[12].

Design Issues. A number of design issues that are in need of further investigation and/or standardization are discussed below.

Evaluation of Soil Set-up. Soil set-up is the process whereby the soil, in the immediate proximity of the pile, regains its shear strength after being disturbed/remolded by the pile installation. The soil strength increases with time after installation through consolidation and thixotropy. Soil set-up is an effect that is to be taken into account in evaluating a pile's axial holding capacity. This effect is not as critical for compression piles of shallow water fixed platforms. They are typically in a stable equilibrium, in which the pile capacity increases following a failure towards stronger layers. Considerable experience and data are available regarding this issue for piles in the Gulf of Mexico[13]. This experience is formulated in, mostly, empirical procedures to evaluate soil regain of strength with time. As these procedures are empirical, they are less valid outside the Gulf of Mexico and for situations and conditions outside the limits of the data set used in deriving them. However, these procedures are now stretched by extrapolation to be applied for much larger TLP and anchor piles and suction piles, as well as for other types of soil outside the Gulf of Mexico. A more rational method is needed to provide more insight into the set-up process, and to evaluate the soil-set up as a function of the site's soil properties and pile dimensions. This method may ideally isolate effects of the extent of the remolded soil, pile plugging, thixotropy, and pore pressure build-up and dissipation. In line with these requirements, a rational approach based on the Strain Path method[14] with an appropriate constitutive representation of the soil/pore water behavior[15], has been developed by the Massachusetts Institute of Technology.

Currently, the industry practice is to install the piles in advance, so that the soil achieves adequate set-up before installation of the hull when the pile capacity is to achieve the required factor of safety. If the soil set-up is not sufficient to meet the requirements, consideration may be given to measures to curtail conservatism and/or the fact that the pile is indeed subject to a reduced factor of safety only for a limited time. The first approach is to take into account that the design load is indeed variable with time, as a result of changes in the rigs and risers attached to the unit and in the environmental loads with the seasons. The other approach is to consider reduced design criteria, based on an appropriate risk assessment, given the limited time that the piles go through with a reduced factor of safety. The regulatory requirement in the United States is such that the full required factor of safety be fulfilled at the time of first oil production.

Effects of Sustained Loading. Anchor piles in deepwater have to support higher levels of sustained tensile and cyclic components of the mooring loads. Unlike in most shallow water environments, oftentimes long-term sustained loads govern the mooring anchor design in deepwater, particularly in the Gulf of Mexico where Loop currents may continue for days in a particular site. Besides its increasing magnitude in deeper water, sustained loading has an adverse effect on soil shear strength, referred to as "creep." Another type of sustained loading is the pre-tension in TLP tendons. Even though the pre-tension is a sustained load, it comprises a smaller portion of the design load and is unlikely to be of any concern. On the other hand, it has been reported that sustained tensile loading of as little as 30% of a pile's ultimate capacity may lead to a creep-related failure[16]. Further study of the issue is needed.

For the pile geotechnical design, sustained tensile loading required further study on how the soil would respond to such loading. Drainage and creep are the two main effects of long-term loading on soil. Drainage may not constitute a significant effect, because most designers neglect reverse end bearing when designing slender piles. (See discussion on the issue for suction piles in the next section.) Conversely, longer durations may lead to a degree of consolidation of the soil under shear at the pile sides and consequently to a higher strength. (The practice, again, is not to use this strength increase in the design.) In order to consider creep in the geotechnical design of the piles, additional lab testing of the soil is required to determine the rate of loss in strength with time under such a load. The current practice is to take creep into account as a reduction in the soil strength, after a period corresponds to the maximum expected duration of the sustained load.

Effects of Cyclic Loads. Significant cyclic loading is liable to cause degradation of the soil strength and elastic properties. The adverse effect of combined sustained and cyclic loading is usually evaluated with contour charts that give the maximum number of cycles before failure, under a specific combination of average and cyclic stresses. This usually calls for an extended program of lab testing of high quality undisturbed samples of the site soil. The maximum number of cycles in a design storm does not typically exceed 1,000[17], which is the contour usually considered for design.

In API RP 2T[8], the combined adverse effects of sustained and cyclic loading on TLP piles are taken into consideration (together with other effects) by applying a 'Bias Factor' to the factor of safety usually applied to design of compression piles under similar conditions. This factor ranges from 1.0 to 1.5. This factor is selected by the designer based on the level of geotechnical information and confidence in the design parameters. However, most TLP pile designers apply the maximum Bias Factor in addition to the appropriate extensive testing and evaluation programs as the minimum requirement. Considering the less severity of sustained and cyclic loading on anchor piles, the industry practice is to use a Bias Factor of about 1.33 for the anchor pile design.

Suction Anchor Piles

Their name reflects the main difference that distinguishes them from conventional slender piles. That is, suction piles are installed by applying differential pressure by way of pumping out water from the pile's interior[18,19]. The differential pressure constitutes the driving force necessary to overcome resistance by the penetrated soil. This installation technology is virtually the only alternative to using submerged hammers for driving piles in deepwater. Installation by suction is, however, less efficient in cohesionless soils. Figure 4 shows a sketch of a suction anchor pile.

Figure 4: A Suction Anchor Pile

Due to the need for a great driving force, with the limited feasible and safe differential pressure available, a change in the pile aspect ratio (Penetration : Anchor Diameter) was inevitable, hence the characteristic shape of suction piles. Based on needed driving force, the suction pile aspect ratio may range between 2:1, for stiff clay, and 7:1, for very soft clay.

If the pile top is kept and pump vents are sealed, the trapped water would transfer part of the mooring load, under tension, from the pile top to the soil plug, which in turn transfers it to the pile base in terms of reverse end bearing. The aspect ratio of suction piles has the effect of giving more importance to reverse end bearing, compared to the case of slender anchor piles. Due to the lower aspect ratio and rigidity of the suction pile structure, the suction pile holding capacity, under general loading, is usually attained through an undrained end bearing mechanism that combines both bottom and side bearing mechanisms.

Loaded in a general direction, a suction pile usually achieves its maximum holding power when it fails in a non-rotational (or plowing) mode[18,19]. This mode reduces the chance of a pile pullout should the actual loads exceed the holding capacity. That is, the pile would have a residual capacity that is not substantially lower than the peak capacity, rendering the pile failure ductile. To achieve such an effect, the mooring load is applied so that it passes through an "optimum depth" on the pile axis. For normally consolidated clays, the "optimum depth" depends mainly on the pile aspect ratio. For pile aspect ratios around 5:1 the "optimum depth" is usually located around the two-thirds point of the pile penetration. With the controversy about the possibility and conditions of forming a gap on the active wedge side, the trend is to apply the mooring load slightly below the optimum depth, so as to cause it to tilt backward, closing any forming gap.

Geotechnical Design Procedure. A single analysis/design method has yet to gain universal acceptance among researchers and designers as a fully reliable method to model suction pile behavior. Therefore, the trend has been to adopt at least two methods to analyze the problem, with the aim of cross-checking and verifying both methods. Two of the main methods that have gained increasing acceptance among designers are the 3D Finite Element and the limit equilibrium methods, as described below.

The first of the methods mentioned above is a straightforward application of the well-established Finite Element method, with all its known advantages and limitations. Its main advantage is its ability to accommodate general loading and boundary conditions, with no major assumptions; intense computation power requirement is its main disadvantage.

The second method involves assuming a number of failure mechanisms, or a general mechanism with a number of variables, with the least resisting mechanism being deemed the correct one[20,21]. Accuracy of the results depends on how close the assumed failure mechanisms are to the actual one. Two-dimensional mechanisms are often assumed, with 3D effects being taken into account by way of equivalent side friction and/or empirical factors[18,19]. Research in this area is underway.

Some research work has also been directed towards establishing a shape for the interaction diagram between axial and lateral capacities for specific soil profile, loading, and pile displacement conditions. Assuming its applicability in closely configured problems, the interaction diagram may be built starting with the easier-to-estimate axial and lateral capacities[7,22]. An elliptic interaction diagram has generally been observed, with the degree depending on the problem conditions and configuration[23,24]. The method potentially provides a simple way to analyze suction piles under general loading. More research is, however, needed to establish interaction diagrams for different conditions and configurations.

It has also been observed that axial pullout mode of failure would control the suction pile design within a considerable range of load angle, away from actual axial loading[20]. Designers have adopted this observation to significantly simplify the suction pile design to one of a vertically loaded suction pile. In this case, the suction pile total holding capacity is determined simply by following the procedures given in API RP2A for axial capacity of slender piles. The axial load to be considered in this case is the axial component of the total load.

Additionally, some designers advocate using conventional beam-column analysis procedures (otherwise known as the P-Y method, intended for slender piles) for preliminary sizing of suction piles, or even for final design of short-term temporary suction piles.

Two issues that are usually addressed and account for few percentages of reduction in the suction pile holding capacity are soil trenching by the padeye during installation and torsional loading caused by out-of-plane mooring load. Similar to slender anchor piles, suction pile axial resistance is usually reduced from the mudline to the padeye center, to account for possible trenching caused by the padeye during installation. The reduction is normally based on the ratio of the trenched (or padeye) width to the total pile circumference. A simplified way to quantitatively account for torsion due to out-of-plane mooring load is by estimating the soil stress due to the torsional moment, and combining this horizontal shear component with the axial component of shear due to uplift; the resultant shear stress should be within the limits.

Design Issues. Several issues are still in need of further research. Indeed, suction piles share many of the issues discussed above regarding axial capacity of slender anchor piles, particularly those relevant to soil set-up, sustained and cyclic loading, drainage, creep, mooring line profile, and surface treatment. Additionally, below are some examples of issues uniquely applicable to suction piles.

General. Unlike for slender piles, end bearing has a rather significant effect in the total holding power of suction piles. However, reverse end bearing of suction piles is usually considered ineffective when the suction pile top is open, or when suction piles are subject to significant long-term loading. Due to the shortage of model and field data on suction pile response to long-term loading, most designers assume a fully drained condition and a total loss of suction beneath the piles, and consequently, the loss of reverse end bearing and the activation of internal friction. A number of research efforts have been directed towards identifying actual potential for long-term capacity of suction piles. Long-term loading conditions are often met in the deepwater of the Gulf of Mexico, where Loop currents oftentimes govern suction pile designs.

Limit Equilibrium Method. Some of the issues, relevant to evaluating the suction pile axial capacity, using limit equilibrium methods, are the proper value for reverse end bearing factor, N_c, a representative soil strength parameter (or test), as well as the compatibility between peak values of the side friction and end bearing components of the total resistance.

With the increasing importance of end bearing in suction piles, more interest has been directed towards identifying a more appropriate value for N_c than that recommended for slender piles under compression[20]. The new factor should reflect the fact that the inherently anisotropic soil, involved in the reverse end bearing mechanism, is subject predominantly to conditions similar to triaxial extension tests, as opposed to the triaxial compression conditions for compression piles. Due to a lack of agreement on a different value, designers tend to use values recommended for compression piles. Also, there is a need to identify a representative strength parameter for end bearing calculations. This parameter should reflect the fact that a sizeable soil bulk is generally involved in the end bearing mechanism, which usually extends below the anchor tip, slightly more than half the anchor diameter. An average of the soil strength over a half diameter below the pile tip is one of the most popular candidates in this regard.

The issue of compatibility between ultimate values of the side friction and end bearing capacities has essentially come about as a result of the large pile diameter, characteristic of suction piles. That is, with the observation that the end bearing normally peaks at a displacement of about 10% of the pile diameter[7]. The side friction peak is, however, normally associated with as little as one tenth of the above displacement[7], after which the side friction is reduced to a residual value. Residual side friction depends on the soil consistency and its stress history; a minimal reduction of 10-30% of the peak is normally expected for soft normally consolidated clays[7], as opposed to harder or overconsolidated clays. The practice is leaning towards considering the ultimate end bearing, together with a reduced peak side friction to represent its residual value.

Finite Element Method. For Finite Element Analysis, the need is evident to identify a uniform recommended practice as to the proper soil strength and elastic parameters to be used as well as the necessary degree of sophistication (modeling soil disturbance after installation, local soil imperfections, surface sliding, gap and crack formation, etc.) and/or nonlinearity (material behavior, large deformations, etc.). As discussed above, predicted anchor/soil displacement and assumed soil residual strength may affect considerably the assessed ultimate capacity of the anchor. The anisotropic soil properties have also proven of importance; in particular, which soil strength tests (in-situ, vane, triaxial compression, triaxial extension, DSS, etc.) should be used to derive the design soil strength and elastic properties for the Finite Element Analysis. The current industry practice is to develop the design soil profile based on DSS tests. Indeed, this issue of the relevant strength parameter applies also to other analysis methods, where the procedure parameters should be tied to its factors of safety. Three-dimensional Finite Element Analysis is increasingly used in actual design analyses, whereby plastic constitutive models may model anisotropy in way of using a non-circular section for the yield surface deviatoric plane. These models use different strength tests to identify the anisotropic behavior of the soil, and automatically use the appropriate strength parameter based on the relevant local and current stress state.

A soil modeling issue that is characteristic of suction pile analysis involves external and internal unit skin friction of the soil. It has been observed that soil penetrated by suction is affected such that a full regain of its undisturbed shear strength is not achieved even after full set-up[18,19]. This is attributed mainly to the suction causing most of the soil, displaced by the pile steel, to move inward, rather than splitting as is the case of driven piles. A reduction factor, otherwise known as the NGI factor, of 0.65[18,25] for the unit friction of soil in this area is now widely accepted to account for this effect. No agreement, however, has been achieved as to the effect of this soil displacement behavior on the internal friction. Internal friction is even more challenging when considering the effect of increased thickness of the pile wall at the tip (driving shoe) and ring and internal stiffeners[26]; particularly for harder clay. A consensus is yet to be established as to how to model internal friction, which is particularly critical when end bearing is ineffective. Figure 5 illustrates different factors needed to be considered in calculating the suction pile's axial capacity.

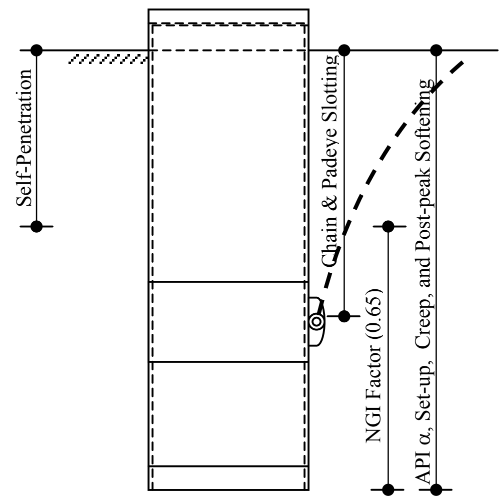

Figure 5: Factors That Affect a Suction Pile's Axial Capacity

Vertically Loaded Anchors (VLAs)

Otherwise known as plate anchors, VLAs differ from conventional drag anchors in that they are installed in a configuration (or mode) that is different from that in which they resist pullout. In cases, this is accomplished with the help of a mechanism to change the anchor structure configuration, such that the load is applied perpendicular to the pullout-resisting surface (shear pin mechanism in Bruce Denla[27] and Vryhof Stevmanta[28] anchors). In other cases, the anchor is installed with a line; then, the mooring load is applied to another line, with each causing the anchor to be pulled to a different configuration and orientation (double line installation of Vryhof's Stevmanta[28]). The above-mentioned anchors are examples of drag-embedment VLAs. Other VLA designs use the help of a push mechanism to deliver the anchor vertically to the required depth, followed with a keying process to align the anchor with the mooring line under the environmental design load (SEPLA of Aker Maritime and SEA of Suction Pile Technology). VLAs installed in this way are called direct-embedment anchors. New innovative designs emerge continuously in this new field to fulfill the ever-increasing need for higher load-resisting anchors. Examples of VLAs are shown in Figure 6.

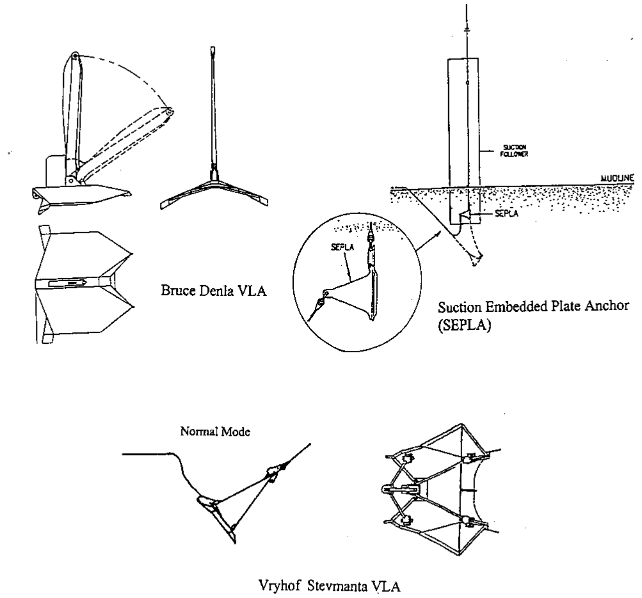

Figure 6: Examples of VLAs

More understanding is needed of the behavior of plate anchors in layered soil and long-term loading. Vertically loaded anchors have the potential for reducing anchoring cost, though pending achieving more confidence and experience with production units.

Geotechnical Design Procedure and Design Issues. The general design approach for VLAs is also different from that of conventional drag anchors[2,9]. The latter tends to require minimal geotechnical information and design effort, depending mainly on empirical design charts, as a function of generic soil types and anchor model and weight (or size)[3,9,28], in addition to in-situ proof testing. What helped to adopt this design approach is the fact that installation and mooring loads are applied in the same manner, with the installation load applied to the level of proof testing, quite close to the design mooring load. Having the installation load applied with a small uplift angle, drag anchors drag automatically to the depth and soil strength necessary to stabilize the applied installation/proof-test load. When higher loads (yet with a small uplift angle) are brought about during the service life of the anchor, conventional drag anchors tend to drag to deeper, stronger soil, stabilizing the new level of load.

Vertically loaded anchors do not have the above-mentioned property of dragging into deeper soil under higher loads. This results in an anchoring system with a residual strength that reduces gradually to a null, or full pullout; hence, the need for more rigorous geotechnical investigation and design approach for sizing VLAs, compared to those for conventional drag anchors. A design approach for VLAs has to be based on sound geotechnical theories and calculations. Higher factors of safety are also deemed necessary[2], compared to those of drag anchors, citing the greater consequences associated with the VLA's mode of failure, which leads to an inevitable pullout of the anchor.

Most design approaches for VLAs are based on plate bearing idealization, calibrated with factors relevant to parameters such as the anchor shape and method of installation, which cause a certain degree of soil disturbance characteristic of the specific anchor type. These factors need to be derived through model and field tests for new anchor designs. A full Finite Element Analysis may sometimes be warranted for complicated soil formations and complicated boundary conditions. However, Finite Element Analysis is used to a lesser extent, because it requires special care in implementing all involved non-linearities, such as the material behavior and large deformations, as well as other significant effects, such as soil disturbance after installation and local soil imperfections.

Usually, the design penetration is governed by the ability of the installation method to reach that depth. Ideally, the design penetration should be a minimum of 3-4 times a characteristic dimension of the plate size, to fully utilize the soil shear strength in a deep failure mode. Taking into account the design penetration, the anchor plate (fluke) size is defined by the plate bearing capacity equation, appropriately calibrated, as discussed above. The design penetration is then considered as the target in the installation procedure, just like anchor piles[2]. In some anchor designs, design parameters may be involved in more sophisticated relations, such as when the maximum achievable penetration in drag embedded VLAs is affected by the anchor size[28]. In such cases, non-standard proprietary procedures are developed to achieve the desired goals.

Depending on their position at the end of the installation process, some anchors may need keying to align the anchor-normal with the mooring line, such as in the case of SEPLA. If the keying process is expected to cause some loss of anchor penetration, this should be taken into account in the calculation of anchor holding capacity. Sometimes, a complete keying to the load direction may not be essential. However, keying at the installation time is preferred so as to limit anchor rotation at the time of the design event, which may result in soil disturbance, causing a reduction in the holding capacity.

Other Types of Anchors

Besides the above-mentioned major contributors in the industry, new ideas and improved designs of older ones have also started to emerge from the development stage to actual application in deepwater projects. Torpedo piles of Petrobras, grouted piles, near-normal load drag anchors and conventional drag anchors are examples of new and improved older technologies, respectively.

A torpedo pile is installed by dropping it under its own weight, to penetrate to the design depth by means of its kinetic energy. Torpedo piles are currently tested in actual projects. They are more suited to clayey soils. Offshore grouted piles have been studied and field-tested, but are yet to be applied in actual deepwater projects.

Conventional drag anchors are much less common in deepwater than VLAs, as they call for catenary mooring systems, which are not used as much in deeper water. On the other hand, recent experience has indicated that the anchor uplift angle may be increased over what currently is acceptable for drag anchors, provided a reduction in the design holding capacity is considered. The practice is to use this type of anchor for less deep water and/or temporary drilling mooring, owing to the much less geotechnical information they require. A near-normal load anchor is a hybrid between conventional drag anchors and VLAs. It has recently been introduced as a way to increase the allowable uplift angle and holding power over those of conventional drag anchor, yet avoid the pullout failure mode of VLAs.

Factors of Safety

For geotechnical design of anchors, the factor of safety is usually defined as the ratio of the ultimate holding capacity of the anchor to the maximum applied load. The factors of safety used by the industry for axial capacity of anchors in catenary and taut leg systems are around 2.0 and 1.5 for the 100-year design event, Intact and Damaged conditions, respectively[2]. Though specified in a number of codes, the factor of safety for the lateral capacity of slender anchor piles hardly ever controls any aspect of the pile design. TLP piles have mostly been designed with factors of safety around 3.0 and 2.25, for Category A and B safety criteria, respectively, as detailed in API RP 2T[8]. Generally, Category A, safety criterion is intended for conditions that exist on a day-to-day basis, whereas Category B criterion is intended for rarely occurring conditions.

Less agreement has been shown in identifying a proper factor of safety for suction piles. This may have resulted from the lack of a uniform practice as to the method of calculating the suction pile's holding capacity. Some codes assign different factors of safety to each of the axial and lateral capacities, citing the difference in residual capacities after failure for either modes of failure. Others assign a single factor for the total capacity, alluding to the notion that suction piles actually fail in an interactive mode, where axial and lateral failure mechanisms interact and depend on the load angle. This factor of safety is usually around 2.0 and 1.5 for Intact and Damaged conditions, respectively[2].

With the fundamental behavioral differences between conventional drag anchors and VLAs, factors of safety have been increased for VLAs, relative to conventional drag anchors, as given in Table 1. The table summarizes factors of safety commonly used in the industry. With the short experience with mooring in deepwater, more reliability-based studies are needed to rationalize the mostly experience-based factors of safety[29].

Load and Resistance Factor Design (LRFD) method is currently gaining popularity, with its advantage of assigning partial factors to different contributors in a process, to better model their different inherent uncertainties. However, more experience and studies are needed to isolate and identify the different factors.

Table 1: Factors of Safety for Holding Capacity

	Taut and Semi-Taut Leg Systems under 100-year storm	
	Intact	Damaged
Anchor Piles, Suction Piles, and VLAs	2.0	1.5

	Catenary Systems under 100-year storm	
	Intact	Damaged
Conventional Drag Anchors	1.5	1.0

	TLPs	
	Category A Event	Category B Event
TLP Piles	3.0	2.25

Installation Tolerances

Usually, anchors are installed at the design location, penetration and horizontal and vertical orientations within specified tolerance limits. Most installation tolerances need to be addressed in the design process. The industry has commonly used a set of tolerance limits for different anchor types, based on the extent of adverse effect of excessive departure from the design parameter (position, penetration, etc.) relative to the cost of minimizing it. Verticality tolerance for slender piles, however, is sometimes controlled by the geotechnical and structural stability of the pile after self-penetration. For anchor piles in spread moorings, pile tilt may be more tolerable when it is such that the pile is tilted away from the mooring line; location tolerance is also more liberal if it results in a longer mooring line. In most such instances, pile capacity actually benefits from the tilt or increasing stiffness. Generally, tolerance of the anchor location in the site is controlled by mooring line sensitivity to the anchor location, which is maximum for TLPs, and more for taut leg systems than for catenary systems. Table 2 summarizes installation tolerances commonly used by the industry for different types of anchors. Vertically loaded anchors have proven the most tolerant of all anchor types.

Summary and Conclusions

Exploring potentials of the deepwater is not yet a routine undertaking. This is equally true for anchoring floating units involved in the process. In this paper, different anchor technologies, suitable for long-term deepwater production units, have been discussed, citing their particular elements of strength, limitations and design aspects. To a large extent, the discussion has been limited to the in-place geotechnical side of the above subjects. Also, a number of issues in need of further investigation and/or standardization have been identified, to optimize anchor designs.

Table 2: Anchor Installation Tolerances

	TLP Piles	Catenary and Taut Leg Lines		
		Anchor Piles	Suction Piles	VLAs
Location[3,4]	Radius of 1.0-2.0 ft	-1% to 2% of mooring line length inwards; more outwards		
Penetration	- <1.0 ft[4]; + Few feet [2]			- <1.0 ft[4], + virtually unlimited
Misverticality (Tilt)	±1.0-3.0 deg[1]	±3.0-5.0 deg[1]		N/A
Padeye Misorientation	N/A	±7.5 deg[1]		Virtually ±180 deg

Notes:
(1) Needs to be explicitly considered in the design
(2) Usually Controlled by the fact that tendon receptacle connection, water relief vents and suction pile top should be kept above the mud, taking plug heave into account.
(3) Usually controlled by the mooring/tendon system sensitivity to pile location.
(4) If deviation is within the specified tolerances, further verification may not be warranted; otherwise, it needs to be explicitly considered in the design

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