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Design and installation of drilled and grouted anchor piles for a CALM Buoy in challenging ground conditions in the US Virgin Islands

Conception et installation de pieux forés cimentés pour une bouée d'export dans des conditions de sol difficiles dans les iles vierges américaines

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ABSTRACT: Limetree Bay Terminal is located in St. Croix in the U.S. Virgin Islands and includes a marine terminal for the storage of crude oil and petroleum products. The terminal has been expanded to include a Catenary Anchor Leg Mooring (CALM) buoy which was installed 2km offshore and is capable of loading and discharging Very Large Crude Carrier (VLCC) sized supertankers. The CALM buoy is secured to the seabed by semi-taut mooring lines connected to anchor piles. The offshore site posed significant challenges with variable water depth from 80m to more than 280m and the seabed slope approaching 20 degrees at some anchor locations. The complex ground conditions consisting of layered carbonate sand, weak coral and strong limestone meant that conventional driven anchor piles were not suitable and a drilled and grouted pile anchor solution was selected. Installation operations were conducted from a diving support and construction vessel and represented a world first for installation water depth and seabed slope. This paper describes the bespoke pile design methods adopted to accommodate the challenging ground conditions and complex load conditions (including cyclic loads and axial-lateral-grout interaction) as well as the innovative installation approach employed for the difficult terrain. This case study demonstrates how the combination of design and installation approach was implemented to deliver a robust anchor solution, within the accelerated schedule of a fast tracked EPCI project. The design and installation techniques employed have the potential for industry wide application for both oil and gas and offshore renewable energy projects.

RÉSUMÉ : Le terminal Limetree Bay situé à Sainte-Croix dans les îles Vierges américaines est un terminal maritime pour le stockage de pétrole brut et de dérivés. Le terminal a été agrandi pour inclure une bouée d'amarrage à ancrage caténaire installée à 2 km au large capable de charger et de décharger des super pétroliers (VLCC). La bouée est fixée au fond marin par des amarres semi-tendues reliées à des pieux d'ancrage. Le site pose des défis importants avec une profondeur d'eau variable de 80 m à plus de 280 m et la pente du fond marin approchant 20 degrés à certains emplacements d'ancrage. Les conditions de sol complexes constituées de sable carbonaté, de corail faible et de calcaire fort signifiaient que les pieux d'ancrage enfoncés conventionnels ne convenaient pas et une solution d'ancrage pour pieux forés et scellés a été choisie. Les opérations d'installation ont été menées à partir d'un navire de soutien à la plongée et de construction et ont représenté une première mondiale pour la profondeur de l'eau d'installation et la pente du fond marin. Cet article décrit les méthodes de conception de pieux sur mesure adoptées pour s'adapter aux conditions de sol difficiles et aux conditions de charge complexes (y compris les charges cycliques et l'interaction axiale-latérale-coulis) ainsi que l'approche d'installation innovante utilisée pour les terrains difficiles. Cette étude de cas montre comment la combinaison de l'approche de conception et d'installation a été mise en œuvre pour fournir une solution d'ancrage robuste, dans le cadre du calendrier accéléré d'un projet EPCI accéléré. Les techniques de conception et d'installation utilisées ont le potentiel d'une application à l'échelle de l'industrie pour les projets pétroliers et gaziers et d'énergie renouvelable offshore.

KEYWORDS: Drilled and grouted piles, pile installation, carbonate material, limestone

1 INTRODUCTION

Limetree Bay Terminal is an energy logistics hub located in St. Croix in the U.S Virgin Islands. Limetree Bay Terminals, LLC awarded IMODCO (a subsidiary company of SBM Offshore) a contract in December 2017 for the EPCI (Engineering, Procurement, Construction and Installation) of an expansion to the terminal. The infrastructure required for the expansion included a Catenary Anchor Leg Mooring (CALM) Buoy to facilitate the berthing and loading/unloading of Very Large Crude Carrier (VLCC) sized supertankers.

Figure 1 shows an overview of the main components of the terminal expansion. The CALM Buoy is secured to the seabed by seven semi-taut mooring lines attached to piled anchors. Figure 2 shows the layout of the seven anchors (A1 to A7) arranged in three clusters. A Pipeline End Manifold (PLEM) was located approximately 400m from the CALM buoy, leading to a unique submarine hose and umbilical configuration.

The offshore site posed significant challenges with variable water depths at the anchor locations ranging from 79 m to 273 m, and seabed slopes varying from 8° to 17°. The seabed bathymetry made this project unique and outside the standard CALM buoys typically delivered in the industry, requiring the adoption of an asymmetric semi-taut mooring system.

Complex ground conditions were present consisting of layered carbonate sand, weak coral and strong limestone. The ground conditions meant that conventional driven anchor piles were not suitable and a drilled and grouted pile anchor solution was selected. Installation operations were conducted from a diving support and construction vessel and represented a world first for installation water depth and seabed slope.

This paper describes the bespoke design methods adopted for the anchor piles to accommodate the challenging ground conditions and complex load conditions (including cyclic loads and axial-lateral-grout interaction) as well as the innovative installation approach employed for the difficult terrain.

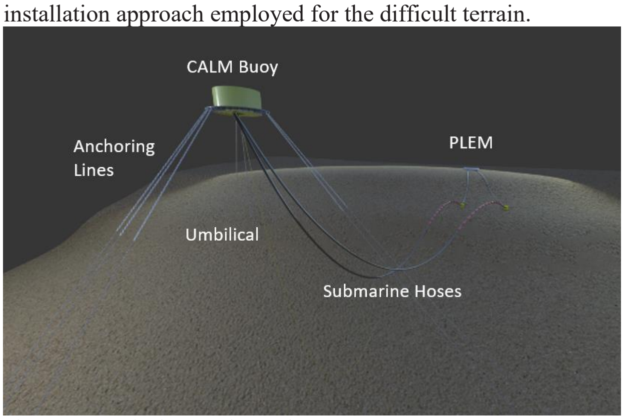

Figure 1. Terminal expansion main components

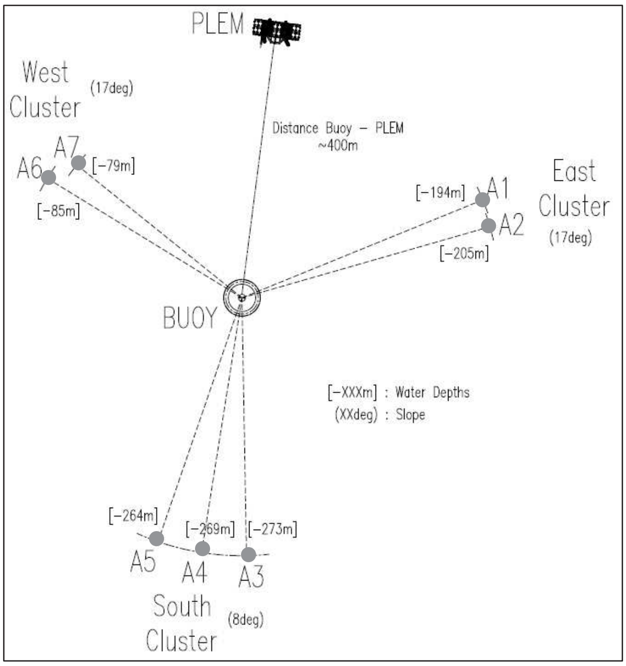

Figure 2. Anchoring Layout

2 GROUND CONDITIONS

2.1 *Site Investigation*

Limetree Bay Terminal, LLC engaged Benthic to manage both geotechnical and geophysical surveys. The geophysical operations conducted at the site included multibeam, magnetometer, side scan sonar and sub bottom profiling.

A geotechnical campaign was performed investigating a total of 15 locations to a maximum depth of 40.5 m below seabed, with both sampling and cone penetration testing (CPT). The testing was conducted from the seabed using Benthic's 3rd generation Portable Remotely Operated Drill (PROD3) which was best suited for drilling operations in steep slopes.

Visual classification, end logging and limited index testing were conducted during field operations in the vessel's offshore laboratory. An extensive laboratory testing program including soil and rock testing was conducted at NGI's Houston laboratory.

The main objective was to provide the necessary soil inputs for the design of the CALM bouy anchors, PLEM foundation, subsea hoses and connection points.

2.2 *Ground profile and parameters*

The Limetree Bay terminal expansion site is located approximately 2 km off the south coast of St. Croix. adjacent to

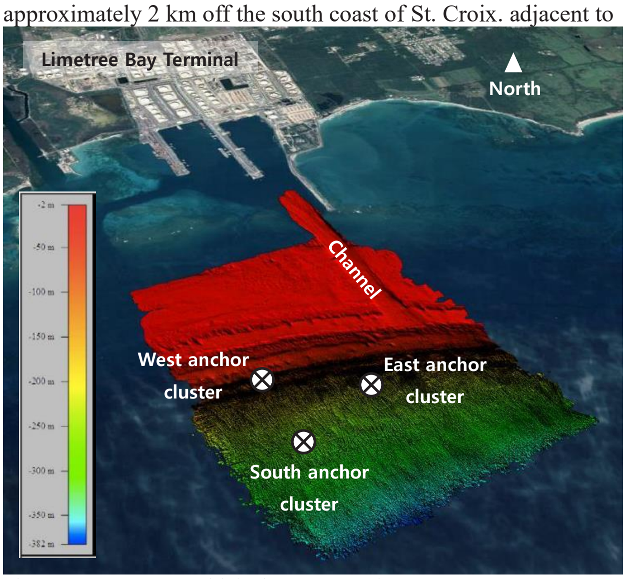

Figure 3. Survey area with bathymetry overlay

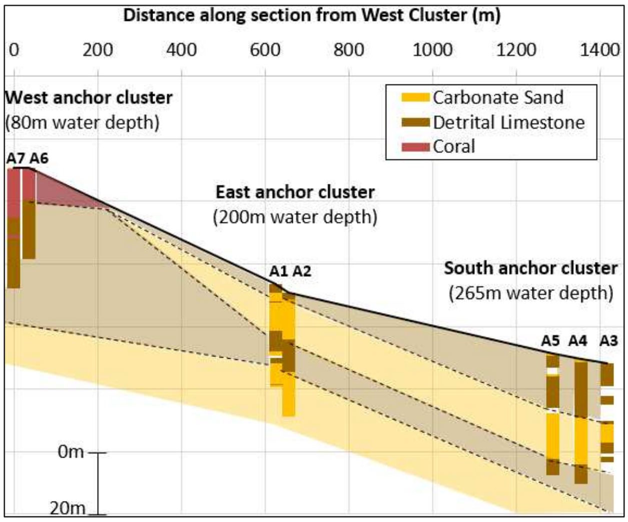

Figure 4. Borehole profiles with section of generalized site stratigraphy

the existing terminal. The site consists of a shelf to the north with an average water depth of approximately 14 m mean lower low water (MLLW), followed by a series of three breaks dropping down to a water depth of approximately 380 m MLLW at the southern extent of the survey (Figure 3). The water depth varies between approximately 80 m and 270 m (MLLW) at the anchor locations. The seafloor slope in areas of the site exceeded 30°, although at the anchor locations ranged from 8 – 17° (Figure 2).

Unlike much of the Caribbean, St. Croix is predominantly sedimentary in origin. Geological information available on the general area of the site indicated the presence of several carbonate formations, namely the Blessing, Kingshill limestone, and Jealousy limestone formations (Gill, 2002). Two or possibly three of the identified formations were found to be present within the investigated range of borehole depths. The ground conditions encountered at the boreholes consisted of coral, carbonate sands and detrital limestone. Figure 4 shows a generalized site stratigraphy based on the borehole results.

Cone penetration testing (CPT) was achieved through the sand and coral layers with occasional refusal, reflecting the variable cementation of the material. Attempts in limestone were generally characterized by rapid refusal, although in some locations limited penetration was achieved. Figure 5 presents an example of the CPT data.

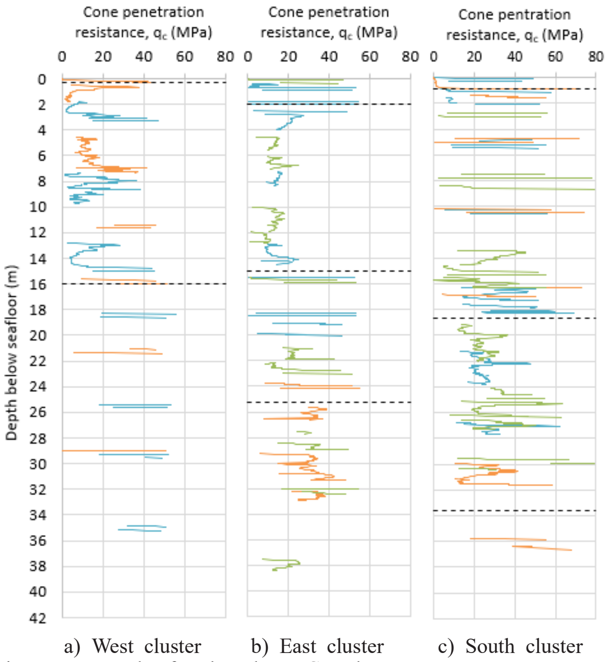

Figure 5. Example of anchor cluster CPT data

Table 1 summarizes typical parameters obtained from laboratory testing performed on the recovered samples and assessed from the CPT results. The material had a high carbonate content of 100%. The coral strength, as determined from point load and UCS testing, was typically very weak to moderately weak and the detrital limestone moderately weak to medium strong (ISO, 2017).

Table 1. Soil parameters

Soil type	*Typical values*			
	CaC03 content (%)	*qc (MPa)*	*Peak friction angle, ϕ (°)*	*UCS (MPa)*
Carbonate sand	100	5 – 30	38 - 44	-
Coral	100	5 – 40	-	0.5 - 6
Detrital Limestone	100	> 80	-	2 - 45

3 ANCHOR PILE DESIGN OVERVIEW

3.1 *Concept Selection*

The ground conditions posed some key challenges to the anchor design and installation. These included:

- High seabed slopes reducing anchor capacity and complicating installation;
- Carbonate soil and rock which provide low axial capacity for driven piles;
- High rock strength complicating pile driving or drilling;
- Interbedded soil and rock causing the risk of hole collapse.

An anchor concept screening study was carried out at an EPCI level with all stakeholders: client, engineering team, project management team, installation team and drilling contractors to select the most suitable option to meet the schedule, risk and cost requirements. The following options were considered, listed in order of increasing typical installation complexity:

i) Gravity base
ii) Driven piles
iii) Drive-Drill-Drive piles (DDD)
iv) Drilled and grouted piles

The follow conclusions were made from the study:

- A gravity base solution was excluded due to the risk of sliding on the slope. Sourcing the large amount of ballast required would result in schedule delay. Less ballast would be needed if skirts were included. However, given that little or no surface sand was present there was a risk that skirt penetration could not be achieved.
- The driven pile option was excluded due to a high risk of early refusal and the heavy installation aids (pile guide frame) required. In addition, the axial shaft resistance of driven piles in carbonate material is low leading to long piles and thus schedule delay.
- A DDD solution was excluded due to the large pile guide frame (which are not available off-the-shelf for such seabed slope) required to guide and stab the piles at the beginning of the driving which was not compatible with the schedule. Combined with the low shaft friction of driven piles in carbonate material and the uncertainty in the capacity that could be obtained from drilled sections, DDD piles proved to be too onerous to adopt.
- Drilled and grout piles were deemed the most favourable solution in terms of design and schedule. The main challenges to overcome were drilling initiation in the steep slopes, installation/retrieval of temporary casing, and start/restart of grouting.

3.2 *Drilled and grouted pile arrangement*

Figure 6 shows the drilled and grouted pile arrangement used for the anchors. Figure 6 illustrates the East Cluster in which an outer permanent casing was also used for hole support. The drilled and grouted anchor piles consisted of a drilled hole of 2.3 m diameter in which a steel tubular insert pile of 2 m diameter and 51 mm wall thickness was installed (Figure 7). The annulus between the pile and the ground is grouted. The total pile length is made up of the embedded length and limited stickup above seafloor where the padeye is connected at the top of the pile.

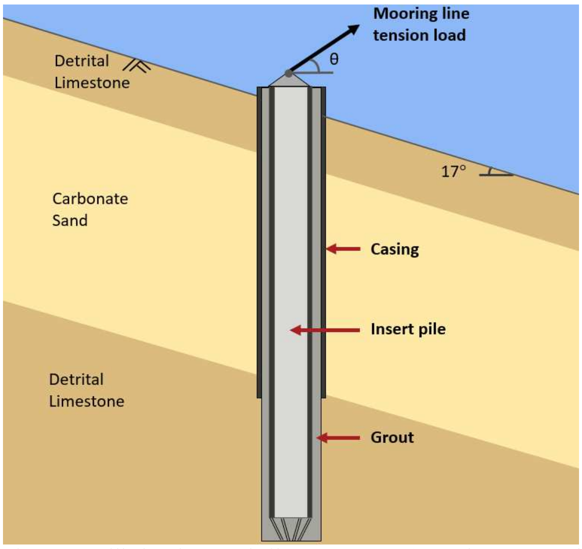

Figure 6. Drilled and grouted pile arrangement (East cluster example)

Figure 7. Insert pile being lifted onto the vessel

3.3 *Anchor loads*

The mooring line tension load is applied at pile head and can act up to a given maximum design angle, θ. The mooring line load may act downslope or upslope depending on the cluster. Operational and Survival load conditions were considered for both intact and damaged cases. The maximum factored axial load acting on an anchor was approximately 1000 kN and the maximum lateral load was approximately 5000 kN. The maximum angle of the applied load was θ = 30°. The cyclic nature of the loading was also taken into account.

3.4 *Drilled and grouted pile design approach*

The anchor pile size and length had to be designed to accommodate the tension loading to meet the required factor of safety. Both lateral and axial capacity was required to be assessed.

Lateral pile analysis

The lateral anchor pile response was assessed by constructing lateral soil resistance deflection (p-y) curves. The curves are calculated using the pile geometry, ground properties and based on the applied loading being static or cyclic.

The carbonate sand p-y curves were modelled using the method suggested for calcareous sediments by Novello (1999). The Novello method was calibrated against soils with carbonate contents greater than 90% and so was deemed as a suitable model for the carbonate soils of Limetree Bay. Under cyclic loading, the static p-y springs are modified by reducing the static p values by a multiplier that incorporates the excess pore pressure profile generated down the length of the pile (Novello, 1999).

Limestone layer p-y curves were modelled using the method recommended by Abbs for weak carbonate rock (Abbs, 1983). Figure 8 illustrates this method which uses a hybrid combination of the sand curves (Reese et al., 1974) and stiff clay p-y curves (Reese et al., 1975). At the point at which the peak capacity has been mobilised, further displacements are taken to cause the rock to "degrade" to a sand/frictional material reflecting the brittle nature of the material. The form of the p-y curve from this point is given by the sand method described in Reese et al., (1974). In the degraded limestone a friction angle of ϕ_{res} = 25° was adopted (following Abbs, 1983). The depth to which the rock degradation might occur was checked using a "chipping" (shallow wedge failure) method similar to Erbrich (2004).

In the case of the coral layers, a low estimate capacity was assessed by modelling the coral as a sand. This was to reflect the possible lower cementation (demonstrated by the CPT) and installation effects. Hence the low estimate p-y springs for the coral were formulated using the Novello (1999) method.

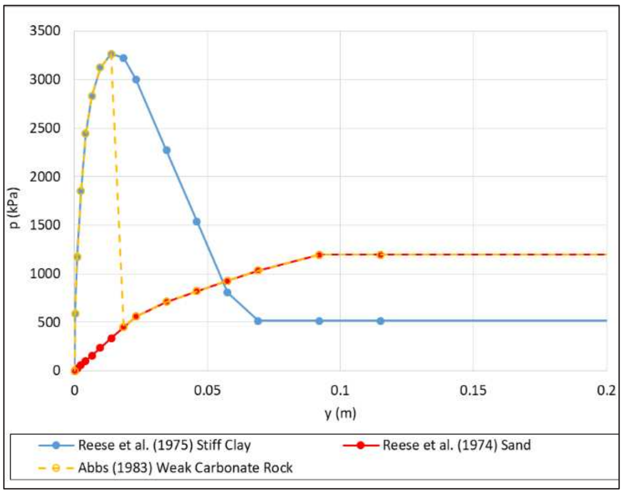

Figure 8. Abbs (1983) p-y curve for weak carbonate rock

The high estimate capacity of the coral was modelled as a weak rock using the method by Abbs (1983).

The sloping seafloor impacts the lateral soil resistance on the downslope side of the pile. This is due to a reduction in the horizontal confining pressure which can affect the shallow wedge failure mechanism. Deeper flow-around mechanisms can be unaltered by a slope, however the minimum depth at which such a mechanism occurs may increase. To account for the slope, modifications given by Reese and Van Impe (2010) were applied.

Axial pile analysis

The axial pile response was assessed by constructing axial soil resistance displacement (t-z) curves. The analyses of the axial capacity of the anchor piles were performed using the NGI proprietary program AxWellCy (Zhou et al., 2018). This program is capable of modelling the complicated axial and/or torsional grout-soil and steel-grout interactions under cyclic loading. The t-z model used in the AxWellCy axial analysis represents an enhanced version of the RATZ model (Randolph, 2003). Figure 9 depicts the general form of the t-z curve incorporating monotonic and cyclic loading. The peak skin friction for the sand and coral layers was calculated using a modified approach to Gunasena et al. (1995). The peak skin friction for the limestone was calculated using the method given by Abbs & Needham (1985). The residual skin friction for all soil types was selected as 0.2 of the peak value (Randolph et al., 1996).

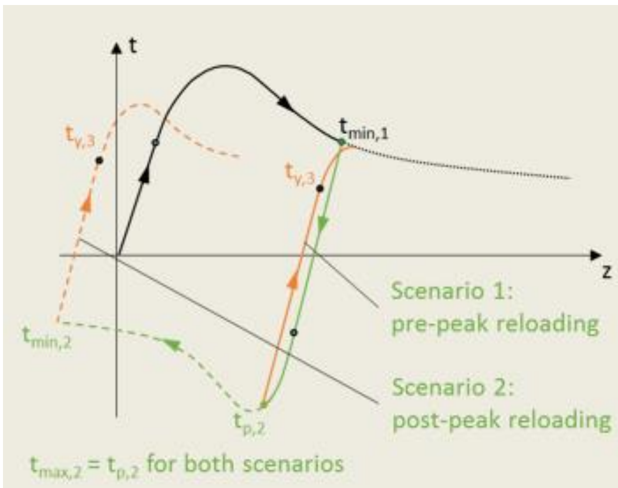

Figure 9. t-z behaviour of yield stresses under cyclic loading (Zhou et al. 2018)

In assessing the axial capacity, the following key aspects were also considered:

- Steel-grout bond stress: Assessment of the pile steel-grout allowable bond stress to compare with the soil-grout resistance so that the governing case is considered.
- Axial capacity reduction due to grout cracking: As a result of the bending moment generated in the pile by the lateral loads, there is potential for the grout on the tension side of the pile to crack. Grout cracking could compromise the integrity of the soil-grout interface and cause a reduction in the available skin friction that can be mobilised. Assessment of the depth of potential cracking was made and the shaft area over this depth was reduced.
- Axial capacity reduction due to post-holing: Cyclic lateral loading can cause a gap to open up around a pile near ground level, which can be termed "post-holing". This gap means that axial load transfer from the pile to the surrounding soil will be reduced when post-holing is present, which was taken into account in the design.

Adopting the design methodology described, anchor pile lengths ranging from 13 m – 20 m were selected across the pile clusters.

4 ANCHOR PILE INSTALLATION

4.1 *Installation spread*

Several challenges made the project pioneering, not only from a design perspective, but also from an installation point of view. Installation of the drilled and grouted piles in highly variable water depths, challenging soil conditions and steep seabed slopes required the adoption of innovative drilling solutions.
Large Diameter Drilling (LDD) were contracted to provide installation services for the seven anchor piles. LDD selected to integrate their reverse circulation LD2500 drill rig with Barge Master's motion compensation platform (BM-T700). The LD2500 is a rig capable of drilling through different soil types, accommodating standard LDD drill bits up to 2500 mm with under-reaming options allowing the drilling of much larger holes.

LDD's rig was cantilevered from the Barge Master motion-compensated platform which was sea fastened on the SBM Installer vessel (Figure 10). The platform allowed the drill system to maintain a constant and stabilized position in relation to the seabed, thereby eliminating the effect of vessel's motion. The combination of the drill system and motion-compensated platform operated in wave conditions up to 2.5 m Hs (significant wave height).

Figure 10. Drill Rig and Barge Master on the SBM Installer

LDD's track record at that time was in water depths up to approximately 80m. An engineering phase together with Barge Master and SBM installation vessel was performed to assess the feasibility to operate in 273m water depth.

4.2 *Description of installation sequence*

The complex ground conditions encountered at each anchor cluster required strategies to be developed in the preparation and set-up to enable successful drilling, pile insertion and grouting at each location. The following main steps were implemented during the installation campaign:

- Casing installation, to prevent collapse and an unstable hole;
- Drilling using a reverse circulation system, a method of drilling that uses dual wall drill rods, having an outer drill rod with an inner tube. These hollow inner tubes allow the drill cuttings to be transported back to the surface in a continuous, steady flow.
- Pile installation, in which the pile was suspended vertically off the heave compensated winch, orientated and lowered into the hole until reaching the base. Once secured, the verticality, orientation and stick-up were assessed against the design installation limits.
- Grouting was performed by means of a stinger to achieve adequate returns at mudline. This operation was carefully monitored and typically required around ten cubic meters of grout per pile to guarantee a proper sealing. Some piles, where soil collapse happened, required more grout.

4.3 *Installation Results*

The offshore work started with temporary casing operations at the West and South Clusters. The 3.2 m casings for West Cluster (piles A6 and A7) were successfully vibro-hammered into the seabed with an acceptable tilt angle of less than 1°. At the South Cluster location there was no penetration of any of the three casings. Beneath the surface sand layer (0.20 m to 0.60 m thick) was a hard limestone layer, which could not be penetrated by the vibro-hammered casing. At the East Cluster, the drill bit could not make progress into the limestone because of the 17° inclination of the seabed (Figure 6), which caused the drill bit to spiral across the seabed. The lateral sliding movement of the drill bit prevented being able to collar a start to the socket. A guide frame for the Bottom Hole Assembly (BHA) was fabricated in order to prevent sliding of the drill bit and thus initiate the hole. The BHA Guide Frame was engineered and the design provided to a local fabricator in St Croix. It was constructed for delivery to the vessel (Figure 11) while drilling at the West cluster piles.

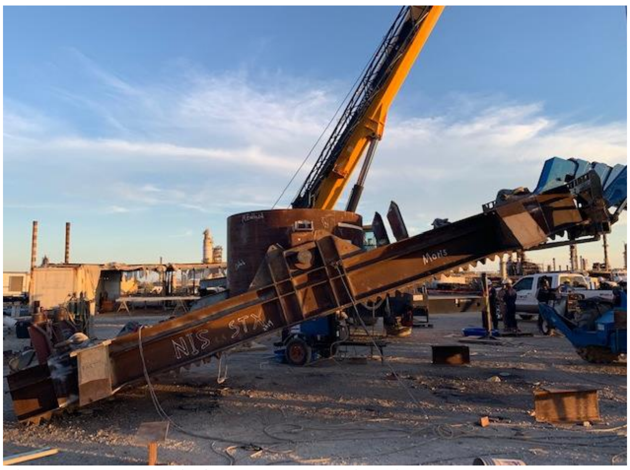

Figure 11. BHA guide frame at construction site

Figure 12. Grouting operations – observing visual marker released by stinger at pile base to check obstructions are not present

At the West cluster, a degree of soil collapse happened due to the presence of sand below the casing tip. The BHA had to be removed and sequence resumed several times to reach the target depths.

At the East cluster, due to the BHA guide frame, the starter holes were successfully drilled, and then the casings were driven through the sand layer using the vibro-hammer until their target depth. Drilling then resumed through the casing to reach the target depth.

At the South cluster, the starter holes were drilled using the BHA guide frame. The guide was then removed and drilling resumed to reach the target depths.

After the holes were successfully drilled the insert piles were installed. The insert piles were fitted with a guide at the pile tip to ease the stabbing in the hole (see Figure 7). Each pile was also fitted with two grouting injection tubes with a quick coupling ROV connection at pile top. However, the connection broke during the grouting of the first pile (A7). It was decided to use the contingency procedure of a stinger in the annulus. This approach was successful, being fast and straightforward to put in place and control. It became the base case grouting procedure for the remaining piles (Figure 12).

4.4 *As built validation*

During the drilling phase, a 24/7 hotline was put in place with the offshore team, the geotechnical team and the hydrodynamic team in order to:

- Provide guidance when required;
- Re-run hydrodynamics models and pile capacity when outside tolerances;
- Provide evidence for approval by ABS surveyor onboard;
- Limit risk of planning delay and vessel stand-by.

Before the offshore operations, several scenarios were anticipated, and sensitivity calculations run in order to facilitate the decision making offshore.

The anchors installation was approved by ABS. The as-built pile position and heading were within the design tolerances, between -0.94m to 1.69m, and -5.0° to 4.0° respectively.

5 CONCLUSIONS

Several challenges made this project a first-off in the industry, not only from a design perspective, but also from an installation point of view. The highly variable water depths, the challenging ground conditions and steep seabed slopes required innovative drilling solutions to be adopted. This case study demonstrates how the combination of design and installation approach was implemented to deliver a robust anchor solution, within the accelerated schedule of a fast tracked EPCI project. The installation techniques described in this paper have the potential for industry wide application for both oil and gas and offshore renewable energy projects.

6 ACKNOWLEDGEMENTS

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