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In situ and laboratory tests on a novel offshore mixed-in-place pile for oil and gas platforms

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ABSTRACT

For the majority of offshore jackets, driven piles are the preferred foundation solution; however difficult soil conditions may preclude conventional pile driving. In such circumstances, methods of grouting a pile into an oversized hole or drilling and underreaming for a cast-in-place pile have received considerable attention. Drilled-and-grouted (D&G) piles are normally used in challenging geologies, such as very dense sands, very stiff clays and in calcareous deposits. However, D&G piles are normally time-consuming to construct. To address this challenge, the MIDOS pile system, which minimizes the number of offshore operations, was created and subjected to a suite of field tests. Cyclic tests were conducted on a pile installed in a silica sand deposit, where over 1000 loading cycles in between 1000 kN and 5000 kN (in tension) were applied. The evaluation of the cyclic test data clearly shows that the serviceability of the pile is unaffected by the cyclic loads. A feasibility study of the MIDOS pile in carbonate sands (Dog's Bay sand) was also explored in a laboratory test program. Carbonate sands are particularly relevant for drilled foundation solutions as the shaft friction of driven piles is typically very low due to the high radial contraction of such material adjacent to the pile shaft during impact driving. A finite element model (FEM) developed for this calcareous sand was used to compare the lab test results. The outcome of the laboratory testing program demonstrated that the MIDOS pile would have similar geotechnical and structural properties in both calcareous and siliceous deposits, suggesting that this novel offshore foundation type is suitable for a range of sand conditions.

1. Introduction

Jacket structures are still the most common form of fixed offshore platform, with the design evolving gradually from their first use for the shallow offshore fields in the Gulf of Mexico, and are now used in water depths of up to 400 m. The platforms are fixed to the seabed by piles inserted through sleeves attached to the jacket, with the piles eventually grouted to the sleeves after installation (e.g. Randolph et al., 2005; Spagnoli et al., 2015). About 95% of the offshore platforms in the world are jacket structures (Dowling and Burgan, 1997). Driven piles are typically installed using impact hammers. However, there are certain conditions, where drilled-and-grouted (D&G) piles are preferred, such as very dense sands, very stiff clays and in carbonate deposits. Carbonate (or calcareous) sands, which are an accumulation of sand-size pieces of carbonate materials, are typically encountered in the warm seas between latitudes 30°N and 30°S (Le Tirant and Nauroy, 1994). The behavior of calcareous soils often presents the geotechnical engineer with foundation difficulties during the construction of offshore hydrocarbon facilities (e.g. King and Lodge, 1988; McClelland, 1988). Existence of carbonate deposits at many strategic petrochemical reserves implies the necessity to study the behavior of these soils (Airey, 1993). From a mechanical perspective, these sands are often very angular and their friction angle at low stress level can be even higher than those for silica sands. However, carbonate sands tend to crush under higher stress and therefore are characterized by high compressibility, as opposed to the dilating behavior of dense silica sands. This crushable and brittle response can result in serious difficulties during impact driven pile installations where pile free run is often encountered and minimal blow counts are observed due to very low shaft friction. Demars et al. (1976) and Colliat et al. (1999) – to name a few – identified the parameters affecting the engineering behavior of calcareous soils as: carbonate content, crushability, degree of cementation, index properties, and geologic processes. Because of the crushability of carbonate grains drilling may be employed, with the pile being grouted into the drilled hole (Gerwick, 2007). The piles are placed within a drilled hole, which is held open

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Fig. 1. Top drilling RC unit BA2500 used for installing offshore piles of the Chiapas Bridge in Mexico.

temporarily either by seawater or drilling mud. A casing is then placed through the water and seated into the soils. Usually this is accomplished by just driving the casing into the overlying soils to a moderate penetration. The hole is drilled ahead, using either direct or reverse circulation drill rigs, see Fig. 1 (Gerwick, 2007). D&G piles are used as an alternative to driven piles in calcareous soils as they do not suffer from radial contraction at the shaft interface during installation and as a result can mobilize higher shaft friction values. Special foundations such as belled footings (4–5 m diameter) have been utilized in the Arabian Gulf and Australian Northwest Shelf. Reverse circulation with top drilling units is often employed with drilling mud as the drilling fluid in order to gain discharge velocity to remove the cuttings (Gerwick, 2007). Conventional D&G piles overcome many of the technical limitations associated with impact piling in carbonate deposits, however such additional offshore operations make D&G piles both expensive and time consuming to construct (e.g. De Mello and Amaral, 1989; Duvivier and Henstock, 1989; Khorshid, 1990). A new technology, the MIDOS (MIxed Drilled Offshore Steel) pile has been developed which minimizes the number of offshore operations and is therefore significantly quicker than D&G piles and therefore more cost effective. The following paper describes some cyclic tests performed on the MIDOS pile and model pile lab tests results in calcareous sands are briefly described.

2. Design methodologies for drilled piles in silica sands

The load transfer mechanism for jacket structures usually results in axial loading controlling the pile design. Axial pile design loads for offshore oil and gas platforms vary depending on the type and size of structure, water depth, expected loading conditions etc. (Igoe et al., 2014). An advantage of D&G piles is that installation can be achieved while minimizing the destructive geotechnical processes which occur during pile driving. As suggested by Lehane (2008) and described by Igoe et al. (2014) the ultimate unit shaft friction, τ_f, may be derived from the Coulomb friction relation as follows:

$$\tau_f = \sigma'_{hf}\tan\delta = (\sigma'_{h0} + \Delta\sigma'_{hc} + \Delta\sigma'_{hd})\tan\delta \quad (1)$$

where σ'_{hf} is the lateral effective stress at peak unit skin friction and δ is the interface friction angle between the soil and pile shaft. The value of σ'_{hf} differs from the in-situ lateral effective stress (σ'_{h0}) because of changes which occur during installation ($\Delta\sigma'_{hc}$) and loading ($\Delta\sigma'_{hd}$). Randolph and White (2008) state that for D&G piles in silica sands any temporary loss in effective stress during drilling is assumed to be mainly recovered through grout pressure during the grouting operation. Providing the installation does not cause excessive disturbance of the surrounding soil, $\Delta\sigma'_{hc}$ can often be ignored in design. Traditional pile design theory relates the unit shaft friction to the in-situ vertical effective stress, σ'_{v0}, as follows (Igoe et al., 2014):

$$\tau_f = K\sigma'_{v0}\tan\delta = \beta\sigma'_{v0} \text{ with } \beta = K\tan\delta \quad (2)$$

where K is the coefficient of earth pressure ($=\sigma'_{hf}/\sigma'_{v0}$). For large diameter drilled and grouted piles where the installation effects ($\Delta\sigma'_{hc}$) and dilation effects ($\Delta\sigma'_{hd}$) are thought to be minimal then $\sigma'_{hf} \approx \sigma'_{h0}$ and hence $K \approx K_0$ (the coefficient of earth pressure at rest, $=\sigma'_{h0}/\sigma'_{v0}$). Rollins et al. (2005) back-figured K values from a database of bored pile tension load tests (with pile diameters varying from 0.43 to 1.5 m) and noted that K consistently reduced with depth, which was not attributable to a reduction in OCR and hence K_0 with depth (Fig. 2). The back-figured K values were notably higher than the K_0 condition estimated for normally consolidated soils suggesting that dilation ($\Delta\sigma'_{hd}$) may have a significant contribution to the shaft capacity. Given the large range of design methodologies in use for drilled piles, the newly developed pile installation system was compared by Igoe et al. (2014) to existing design practice, as outlined above, in order to validate the geotechnical performance of the novel MIDOS pile.

3. Brief overview on the MIDOS pile

The MIDOS pile system (Fig. 3) was intensively investigated in the past years as described by Igoe et al. (2014); Spagnoli et al. (2014, 2015a, 2015b); Doherty et al. (2015, 2016); Spagnoli and Doherty (2016).

The MIDOS pile is based on deep-mixing technology and consists of a hollow steel tube, which is lowered into the soil while at the same time a mixing tool, which is advanced inside the hollow pipe, mixes the in situ soil with cement slurry. Hence, a mixed soil cement body is created. A test pile was installed in a field test facility, which comprises silica sand with intercalated clay lenses. The steel pile had an external diameter of 1.5 m with a wall thickness of 15 mm. The pile incorporated, at its lower end, a mixing chamber with an outer diameter of 1.9 m. Holes in the steel pile and in the mixing chamber allow the soil-cement-mix to flow between the inside and outside of the steel pipe. The steel pile with the mixing chamber remains in the soil, surrounded by a soil-cement-mixture. Samples were taken from the top of the backflow material during construction of the pile and unconfined compressive strength (UCS) tests were undertaken. The test pile length was 17 m. Igoe et al. (2014) described the application of this pile for offshore oil and gas platforms and the ultimate tension showed