Drilled and Grouted Piles: Construction, Integrity, Capacity

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Objective: To develop guidelines for the construction of drilled and grouted piles, for the integrity testing of the grout curtain, and for the evaluation of the capacity of drilled and grouted piles.

A drilled and grouted pile is a type of pile used for the foundation of offshore platforms. The piles are installed by drilling a hole (for example, 1.2 m in diameter and 90 m deep) below the sea floor, removing the drilling tool, lowering a steel pipe (for example, 0.9 m diameter, 40 mm thick walls and 90 m long) into the open hole, and grouting the annulus between the steel pipe and the soil. These piles have advantages and drawbacks and in a number of cases represent a more attractive solution than driven piles. Cases include calcareous soils where driven piles have no friction capacity, hard or dense soils where it may not be possible to drive piles, and very deep waters where underwater hammers either do not exist or are very cumbersome and expensive.

Although used offshore in the past, the experience with drilled and grouted piles is limited, and there is a need to study various construction techniques and develop guidelines for construction and integrity testing of such piles. Although the capacity of driven piles can be evaluated in place by analyzing pile driving records, such in place evaluation does not exist for drilled and grouted piles; there is a need to develop one or more techniques to ensure the capacity of drilled and grouted piles.

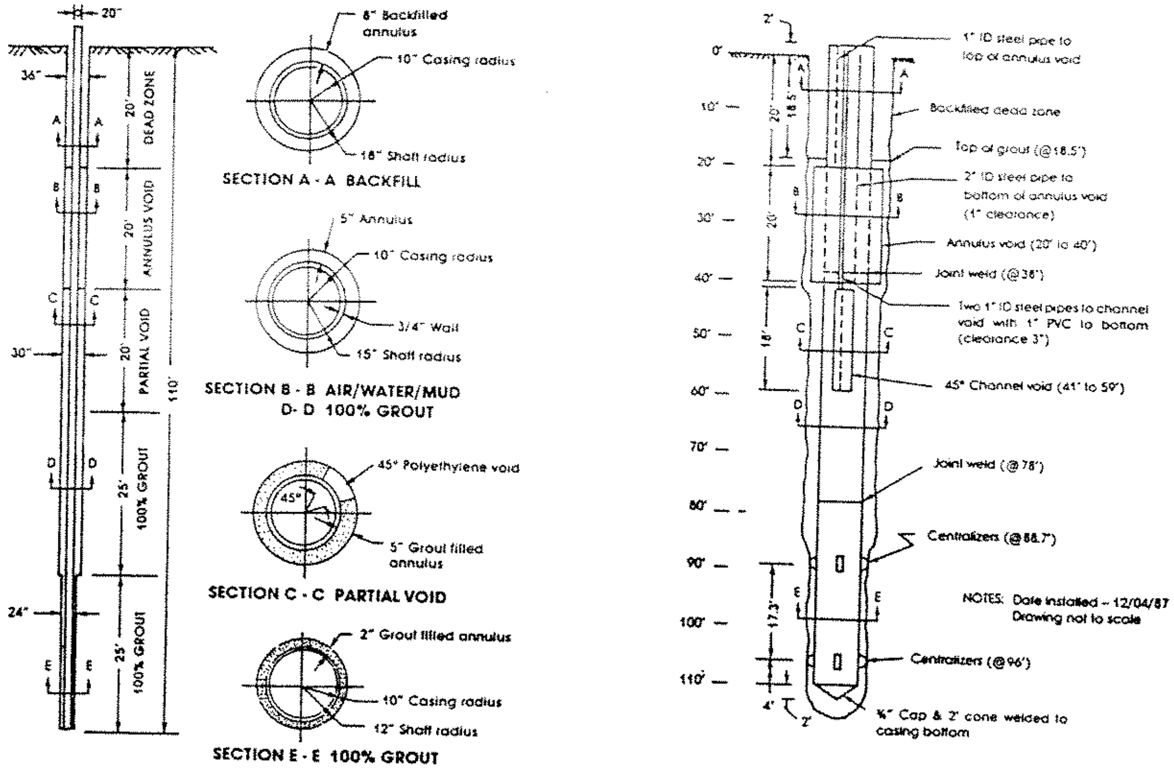
Integrity Experiment and Results

In the fall of 1987, a study was initiated at Texas A&M University (TAMU). The first phase of the program consisted of building a 34 m long, 0.8 m diameter drilled and grouted pile at the TAMU national site for geotechnical research on clay. This pile, Figure 1, was built with defects in order to check various defect detection methods. The defects consisted of a 360° chamber void where the grout was missing all around the pile over a 6 m length, and a 45° channel void where the grout was missing over a length of 6 m but only on one-eighth of the circumference.

Defect detection methods include vibration sensing and nuclear sensing. The vibration methods consist of lowering a cylindrical probe through the center of the pile and sending a sonic wave which travels radially from the probe, through the water, through the steel, into the grout, and returns to the detector in the probe.

The system is very similar to knocking on a wall to try to find where holes are behind the wall by listening to the difference in sound. The problem is that if the wall is too thick the sound is the same whether there is a hole or not behind the wall. This thickness problem happened with the test pile where the wall thickness of the steel pipe was 19 mm. The vibration methods did not detect the defect with satisfactory precision.

The nuclear methods were also tried. These methods (Figure 2) essentially consist of bombarding the wall of the pipe with nuclear rays and counting the number of particles coming back to the detector in the probe. The number of returns is associated with the density of the material penetrated. These techniques worked better than the vibration methods; the gamma ray technique worked particularly well and detected clearly the two defects (Figures 3 and 4). This method is recommended for the detection of defects in drilled and grouted piles.



SCHEMATIC OF DRILLED AND GROUTED PILE WITH DEFECTS

DETAILED FIELD PLAN

Figure 1—Drilled and Grouted Pile Details.

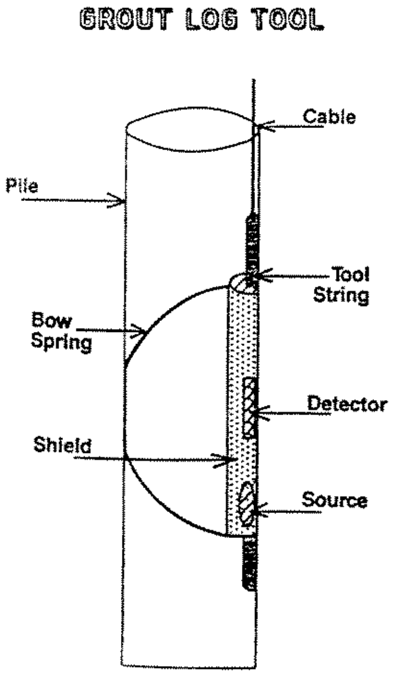


Figure 2—Grout Log Tool.

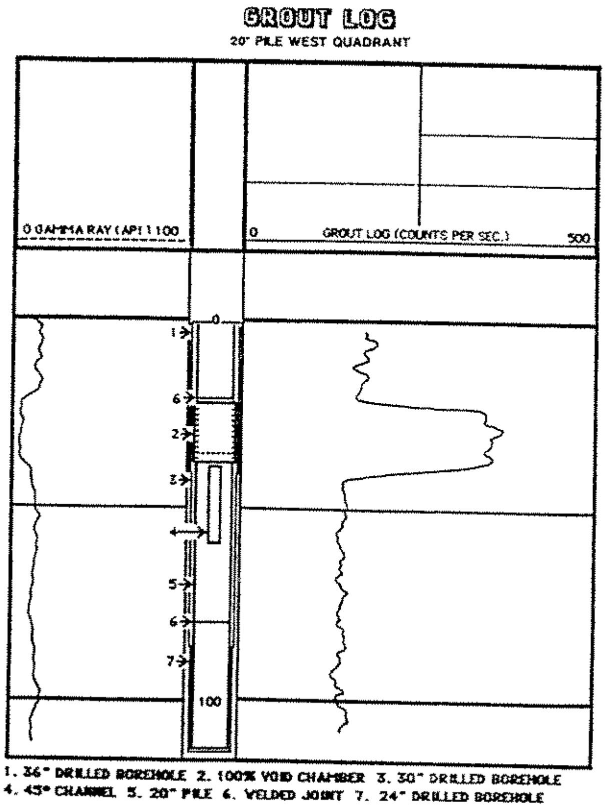


Figure 3—Grout Log Results—West Quadrant.

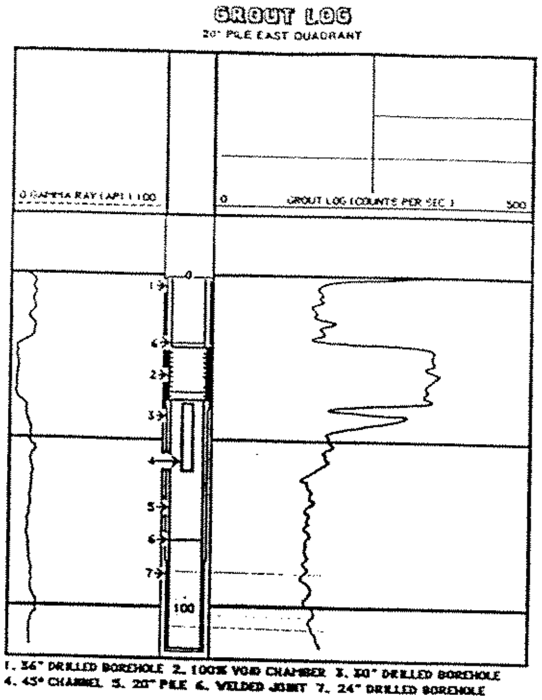


Figure 4—Grout Log Results, East Quadrant.

Capacity Experiment and Results

On phase 1 of the study, two 12.2 m long, 0.2 m diameter piles were drilled and grouted in stiff clay (Figure 5). These piles were load tested to failure in tension (Figure 6). The results show that the friction of the side of the pile was nearly equal to the undrained shear strength of the stiff clay. This is a very encouraging result which, if verified on other tests, shows a definite advantage of drilled and grouted piles over driven piles where the friction is a fraction of the undrained shear strength.

The same load tests showed that the response to cyclic loading and to various rates of loading is the same as for driven piles. These two experiments led to a phase 2 program which started in 1989 with a survey of the drilled and grouted pile practice. The following section summarizes the progress accomplished to date in phase 2.

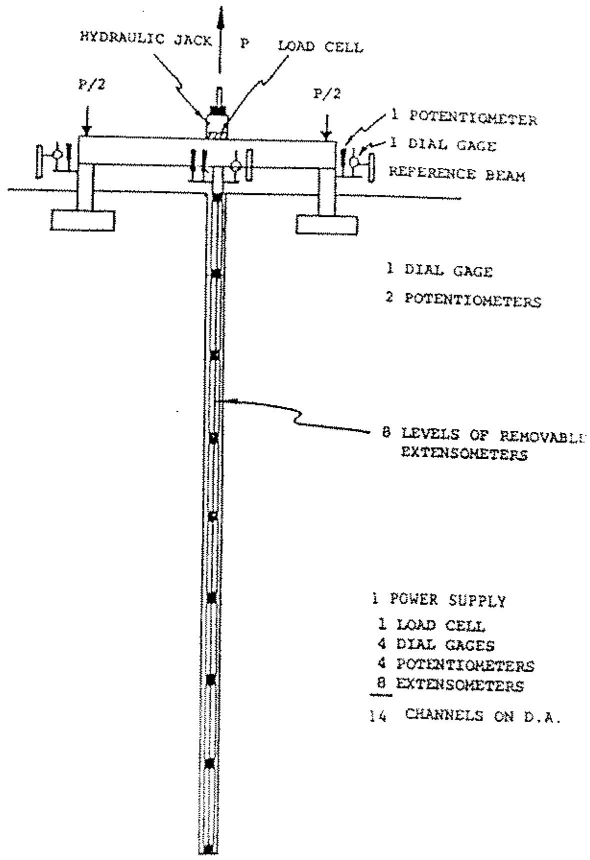


Figure 5—Load Test Set up and Instrumentation.

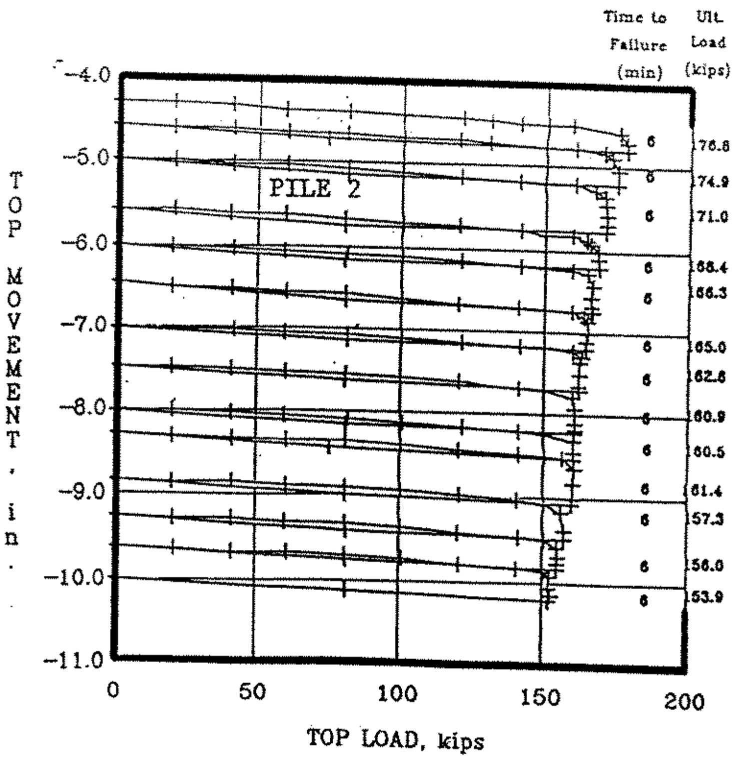


Figure 6—Cyclic Tests to Failure on Pile 2.

Questionnaire

Thirty-six questionnaires were sent to oil and offshore engineering companies. Fifteen have been returned with responses to the questions. The following is a summary of the responses.

General

QUESTION 1. What is your/your company's experience in drilled and grouted piles (location and type of project)? Have you drilled and grouted any underwater storage tanks, platform foundations, drilling templates, oil well conductors, etc.?

ANSWER: 61 percent of the respondents have had experience with drilled and grouted piles. 100 percent of the oil companies have had experience with drilled and grouted oil well conductors.

QUESTION 2. Please list the companies which you know have had experiences with drilled and grouted piles.

ANSWER: Phillips Petroleum, Aramco, Chevron, Exxon, Smith Drilling Co., A to Z Drilling, SBM, McDermott, Raymond Solmarine, Franki, Sonat, Zapata, Reading and Bates, Fugro-McClelland, Conoco (Arabian Gulf), Shell, Occidental Petroleum (Piper-Alpha, Aberdine), Elf Oil Co., Britoil, Woodside (N. Rankin), Petroland B.V., Petromina-Indonesia, Union Oil Co., Mobil, Texaco, LOOP, Inc., Solmarine, Colcrete Ltd., Wimpey Offshore, Bauer, Fundex, GKN Keller, Halliburton, Dowell-Schlumberger, Santa Fe, Brown & Root, Saipem, Micoperi, ETPM, Bouygues Offshore, and Chicago Bridge & Iron Co.

QUESTION 3. What pipe diameters and depths are you aware of that have been used for drilled and grouted conductors or drilled and grouted piles? List range from smallest to largest for each.

ANSWER: The diameter of drilled and grouted piles varies from 24 in. to 120 in., the length varying from 100 to 500 ft.

The diameters of oil well conductors vary from 18 in. to 36 in., and the length may be up to 1500 ft.

The diameters of oil well casings vary from 2 in. to 26 in., and the depth may be several thousands of feet deep.

QUESTION 4. When would you be most likely to use drilled and grouted piles? (Water depth, soil type, structure type, etc.).

ANSWER: 67 percent responded—If soil conditions are not applicable to pile driving, that is, very stiff clays, cemented soils, and calcareous sands.

33 percent responded—When water depth is greater than 3500 feet.

17 percent responded—When a floating facility is used.

It was also mentioned that drilled and grouted piles would be used when they would be more cost effective than other foundations, and in deep waters areas where pile driving would be impractical because of a lack of reliable pile driving hammers.

QUESTION 5. When would you be least likely to use drilled and grouted piles?

ANSWER: In soft clay, where high lateral capacity is required. When pile driving can be effectively accomplished. Conventional platforms in less than 1000 feet of water. Relatively good soil conditions.

QUESTION 6. What are the major limitations of driven piles offshore?

ANSWER: Incompetent formation where driving energy can be expected to break down the formation such that low skin friction will be developed on a driven pile. Lack of experience in water depths greater than 3000 feet. Possible early refusal of the pile and pile running. Expense and handling of the hammer and subsea power pack in very deep waters.

QUESTION 7. What needs to be done before drilled and grouted piles can become a well accepted conventional offshore construction technique, and a deep water technique?

ANSWER: Definition of ultimate capacity requires verification of installation methods and effects of surrounding soil. Must prove cost competitive with conventional construction methods. A construction technique must be developed and proven by field techniques (solve problems of grout channelling and hole stability in soft clay). A better way to assess the capacity is desirable. In deep water, additional problems of low temperature, requirements of low density grouts, and soil fracture become important. More testing, long term stability of driven vs. grouted piles (creep test). Good estimates of pile-grout-soil load transfer.

Drilling

QUESTION 8. Briefly describe the drilling operation (including hardware) that is used for drilling and grouting piles? Please attach sketches if available.

ANSWER: Drilling equipment—air assisted reverse circulation for drilled and grouted piles, drilling module containing rotary table and shale shaker, stiff leg module to handle heavy pile sections and long drill strings, may use portable pile top rigs, skid mounted rigs, large mandrills, work deck with skid rails, deck mounted cranes for moving mounted rigs between jacket legs, complete mud plant, and extensive grouting plant.

Drilling procedure—Drillings may be done using reverse circulation rigs; guides are positioned on the jacket. Often a first casing is driven over a few meters to prevent soil collapse at the mud line. Then the rig is positioned above the casing, or connected to its top with heavy strings above the tool (stabilizers, drill collars). The casing is continuously fed with mud or water. Air is sent along the drilling string down to x meters above the tool. From there it surges back, up inside the drill string and creates a depression and an upward flow which carries the cuttings up to the deck. Mud and cuttings may be lost or may go to a desander where mud and soil are separated. Then the mud is sent back into the hole. The drill string, connected by flanges, is often a double concentric tube, the central tube for upward flow and the annular space for air.

QUESTION 9. Are you aware of situations where the drill hole collapsed during a drilling and grouting operation? If so, what is your opinion about what led to the collapse?

ANSWER: Loose soil/sand formations running into the hole; seawater used instead of drilling mud; clay hydration; and another problem that should be considered is hole squeezing in normally-consolidated, non-carbonate clays.

QUESTION 10. How can the probability of collapse be reduced? What remedial measures would you expect be required?

ANSWER: A) Reducing the probability of collapse: Proper design and monitoring of drilling procedure (rotation and penetration rate) and mud program (mud composition, weight, viscosity, pumping rate, etc.); accurate soil survey; use of a shallow casing to prevent surface collapse, and monitoring of hydrostatic head and surge pressures due to running and pulling the casing.

B) Remedial measures: During drilling the hole can be calipered and redrilled, reamed, or reconditioned. After installation the pile could be regrouted using preinstalled hardware.

QUESTION 11. What can be done to reduce the risk of hydrofracture?

ANSWER: Determine the *in situ* fracture gradient of the soil prior to installing the drilled and grouted pile, so that a well engineered drilling and grouting program can be implemented.

QUESTION 12. Would you use reverse circulation or forward circulation drilling?

ANSWER: Seven responses were made. 72 percent would use reverse circulation on piles larger than 36 in. diameter, 14 percent would use forward circulation, and 14 percent have both processes for piles.

Admittedly, most companies said reverse circulation causes problems with borehole stability, but reverse circulation is used for hole cleanliness. Reverse circulation air lift allows for better cuttings removal because of high velocities up the drill string.

One respondent preferred forward circulation because reverse circulation would require an external riser to the surface.

The respondent that has used both did so because of the equipment required—forward circulation with a pile top rig and reverse circulation with a drilling module.

Grouting

QUESTION 13. How can the problem of pressure build-up be alleviated when grouting to get sufficient height or grout curtain? (Single step grouting, stage grouting, etc.).

ANSWER: Out of seven responses all acknowledged that stage grouting could be used to prevent pressure build-up. However, two suggested using low density cement slurries instead of stage grouting because of concern in implementing the multiple grout stages.

QUESTION 14. How can excessive loss of grout from blow outs and seepage be prevented?

ANSWER: Blow outs can be prevented by using either stage grouting or low density grouts. Seepage can be prevented by using a fluid loss limiting additive, such as walnut shells.

QUESTION 15. What is an optimal grout mix? How does the optimal grout mix change for differing soil types? (Add-mixtures, salt, etc.).

ANSWER: An optimal grout mix will: Work well at low temperatures (2–4 degrees C); have low density (9.5–10.5 lbs/gal); be able to displace and scour drilling fluids without channelling; have a reasonable set time; be able to handle temperature differentials between the surface where it is mixed (90–95 degrees F) and the sea bed where it is placed (35–40 degrees F); have sufficient strength; and limit the heat of hydration, which is a problem in large piles.

QUESTION 16. What equipment would you use for grouting, and how is the grout typically placed?

ANSWER: Grout would be batch mixed on the deck of the work vessel in slurry blenders. It would be pumped using mud or cement pumps (positive displacement type pumps) down the drill pipe through a float shoe (check valve) near the bottom of the pile into the annulus of the pile. Use standard oil well cementing equipment and practices where possible.

QUESTION 17. What grout thickness would be used in the annulus?

ANSWER: Of seven respondents: 14 percent said 1–2 in., 14 percent said 2–3 in., and 72 percent said 3–4 in.

QUESTION 18. What techniques are used for high pressure, multiple injection grouting? How successful are these methods?

ANSWER: This method is usually only applied as a remedial "squeeze job" to correct a poor primary cementing.

QUESTION 19. How can the integrity of grout jobs be determined?

ANSWER: Temperature surveys can be used to detect the top of the cement. In addition, radioactive sensors may be used to measure density of outflow. Use sonic logs (the use of logging tools seems limited because the piles are beyond the tool size applied to oil well cementing). An external grout line may be used to physically "tag" the top of the cement for indication. The returns may be collected and tested. Cement volumes pumped into the pile annulus can be controlled. Applied water pressure-volume response may be measured through valves installed in the wall of the insert pile. A method which ensures quality grout placement needs to be developed.

Construction

QUESTION 20. What types of vessels and support vessels would you anticipate using for construction of drilled and grouted piles?

ANSWER: Derrick barges are used for piles drilled and grouted with pile top rigs on the continental shelf. Dynamically positioned barges could be used in deeper water. A semisubmersible drilling vessel would probably be used for most deep water applications. Tug and supply boats also would be required for support and supply.

QUESTION 21. What problems can be expected with the construction of drilled and grouted piles? Contrast with driven piles.

ANSWER: There are more pieces to handle with more stages (drilling, rigging, and cementing) and more complicated quality controls (mud program, slurry control, and logging). In drilled and grouted piles, two different types of equipment have to be handled. In addition, drilling and grouting requires specialists from both areas (hammers are used by most contractors everyday). Other problems include loss of circulation, loss of grout, junk in the hold, tight hole, and grout bonding questions.

QUESTION 22. What problems can be expected with the construction of driven piles?

ANSWER: Problems include early refusal, pile running, dynamic buckling, insufficient hammer capacity, handling hammers and umbilicals in deep water, risk of pile tip collapse in hard soils, and mechanical failures of the hammers.

QUESTION 23. How often do insert piles have to be used as a remedial measure in the installation of driven piles?

ANSWER: This procedure is rare in most parts of the world. In the Gulf of Mexico (Louisiana and Texas) this remedial measure is hardly ever used. However, insert piles have been used in the Gulf of Mexico (Florida), in certain rock formations in the Middle East, and in the calcareous sands of Australia.

QUESTION 24. Are insert piles driven or are they drilled and grouted in place?

ANSWER: Insert piles may either be drilled and grouted or driven, the preference of the method depending on the soil formation.

QUESTION 25. What are typical costs (time and money) involved with the remedial measures mentioned in question 23?

ANSWER: Time: 2–3 days/hole, but as experience is gained duration can be decreased to 1–2 days/hole. Cost: Lost day rate could range from $50,000–$400,000/day.

QUESTION 26. What is the construction sequence of a foundation template for a subsea production system and for a tension leg platform?

ANSWER: Subsea Production System (SPS): install well/foundation template with semi-submersible drilling rig; drill wells with vessel, and tie-back to production platform. Tension Leg Platform (TLP): lower template; set on sea floor; install piles (driven or drilled and grouted); grout or hydrolock piles to the template.

QUESTION 27. How do weather conditions affect construction?

ANSWER: Adversely. Stormy seas cause excessive barge movement which restrict drilling and limit crane activity. Seas can prevent resupply due to the inability to unload supply vessels. Weather down time is about equal for drilled and grouted piles and for driven piles.

QUESTION 28. What is the time required to drive piles offshore? How does this time vary with pile diameter and length?

ANSWER: One of the biggest variables is whether the pile comes in one piece or is shipped in sections (add-ons; 60–100 ft.) which have to be welded together to make up a single pile. The diameter is not as big a factor as the length because hammers can be sized for a particular pile. On average one pile can be placed in one day; the majority of the time is for pipe preparation, not driving.

QUESTION 29. What is the time required to drill and grout piles? How does this vary with diameter and length?

ANSWER: Again, a single pile or a pile in sections is a variable which influences installation. Estimated times for drilled and grouted piles vary from 3–7 days. Drilled and grouted piles take longer because they have a higher probability of construction delays resulting from drilling, grouting, verification, and remediation difficulties. Installation time increases with diameter and length, but not proportionally.

QUESTION 30. What delays can occur when driving piles?

ANSWER: Hammer delays (premature cushion breakdowns, steamhose failure, etc.); weather delays; construction vessel, for example, mooring or dynamic positioning problems; unanticipated soil conditions which lead to driving difficulties; crane breakdowns; and accidents.

QUESTION 31. What delays can occur when drilling and grouting piles?

ANSWER: Drilling rig breakdown; rigging failure; mud losses; hole collapse; weather delays; construction vessel, for example, mooring or dynamic positioning problems; unanticipated soil conditions, for example, clean, running sand; grouting problems; for example, hydrofracture, loss of grout, grout channelling, flash set, and poor hole cleaning; and verification and remedial measures.

QUESTION 32. What is the current maximum depth of water in which pile driving hammers can be used effectively?

ANSWER: A test pile was driven in 3300 ft. of water in the Gulf of Mexico with an underwater hammer. Deeper depths require additional umbilical (capability to go to 5000–8000 ft. would require 12--18 months lead time) Underwater hammers have proven themselves in water depths of 1700 ft. on Conoco's Jolliet TLP.

QUESTION 33. What is the projected water depth for offshore platforms in the next 10 years?

ANSWER: In the Gulf of Mexico industry currently hold leases out to approximately 10,000 ft. Thus, the maximum water depths is expected to be 10,000 ft., with activity increasing in the 3000–6000 ft. water depth range.

QUESTION 34. Do you feel that pile driving hammer capabilities can keep up with the rate at which water depth is increasing for offshore platforms?

ANSWER: All respondents said "yes", with only one questioning the cost of underwater hammers that will have to be developed.

Costs

QUESTION 35. What aspects of driven piles should be considered in a cost analysis?

ANSWER: Material and fabrication; transport to construction site; offshore construction cost (materials, personnel, and vessels); possible prorated costs for fabrication of a new hammer and/or umbilical for deepwater sites, and weather down time. (Note: the type of vessel employed is one of the major cost considerations.)

QUESTION 36. What aspects of drilled and grouted piles should be considered in a cost analysis?

ANSWER: Material and fabrication; transportation; mud supplies; cost of grouts and additives; cost of offshore grout mixing; handling and pumping equipment; offshore construction costs, that is, costs for offshore materials, personnel, and vessels; weather down time; and risk associated with unproven, deepwater grouting methods and possible imposed verification and remediation requirements.

Conclusion

Progress has been made in the development of drilled and grouted piles for offshore applications. The two major results to date are:

1. The gamma ray method is favored over other methods to check the integrity of the grout curtain.
2. The friction values obtained in the load tests are much higher than anticipated.

A number of reports and papers have been written and published; these are listed in the references. Phase 2 of the project has started and the results of a questionnaire have been presented. Future plans consist of performing large scale tests on drilled and grouted piles near shore to:

1. Establish which construction technique is preferable.
2. Confirm and implement the defect detection method.
3. Accumulate more data on capacity.

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