Response Paper to :

How Best Can One Estimate the Load Carrying Capacity of Piles Which Support Offshore Structures ?

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SYNOPSIS The evaluation of capacity of offshore piles should be a continual process. After the pile capacity has been computed in the design office, the capacities should be verified and re-evaluated in the field using dynamic pile monitoring techniques. The design should allow for revising the pile capacity based on a detailed study of the driving data. A database of offshore pile installation experience should be accumulated so as to advance the state-of-the-art in the Indian offshore areas.

INTRODUCTION

The construction of driven pile foundation for offshore structures usually involves the following six steps :

1) Performing a detailed geotechnical investigation at the proposed site;

2) Conducting field and laboratory tests to evaluate soil properties and to develop pile design parameters;

3) Computation of ultimate load carrying capacity of the piles using one of the several available methods;

4) Determination of pile penetration required based on design loads and applicable factors of safety;

5) Performing a drivability study to predict the driving system performance and estimate the field blow counts; and

6) Installation of piles in the field.

The authors recommend that the evaluation of pile capacity should not stop at Step 3 described above; it should carry on right up to field installation of the piles. The computed static capacity should only be a starting point. This should be followed up by monitoring the piles in the field to determine the adequacy of the as-installed piles. The field blow counts, hammer performance, driving stresses, etc., coupled with past experience in the area should be used to review the calculations in the design office. The field data obtained can be used to confirm the soil stratigraphy at the site, evaluate the soil resistance to driving, and to determine a lower bound static pile capacity. Field monitoring of pile driving provides valuable insights into hammer performance and soil behavior. These data can be used as a basis for evaluating the acceptability of offshore piles. Wiltsie et al (1984) discuss how dynamic monitoring of piles in the field has led to significant advances in the state of practice of pile installations in the ARAMCO concession areas of the Arabian Gulf.

COMPUTATION OF PILE CAPACITY

Rawat (1986) and Rao (1986) discuss several methods currently used to compute pile capacity. Different organizations involved in offshore geotechnical investigations and piling use different methods for computing pile capacity, usually based on their experience in offshore areas in various parts of the world. Focht and O'Neill (1985) conducted a survey to determine the state-of-international-practice of design of axially loaded piles. Their survey revealed that most pile designers all over the world generally use simple unsophisticated design method, empirical and semi-empirical formulae, heavily influenced by local experience and practices. Although considerable research has been conducted on evaluation of static pile capacity in academic and scientific circles, no real breakthrough has been made that has universally influenced practice. Pile design has, therefore, remained essentially an art that takes into consideration the geology of the area, local engineering and construction practices, applicable code requirements, case histories in the area, and acceptable risks and economic factors.

It is therefore essential that a database of piling experience in the offshore areas of India be developed in order to advance the state-of-the-art of pile design and installation in these areas. The data should then be analyzed to develop pile design methods specifically for Indian offshore soil conditions and to increase the "confidence limits" on the design and installation practices.

PILE DRIVABILITY STUDIES

A pile drivability study using wave equation should be performed prior to installation of the platform. Parameters required for this study include pile length, diameter and wall thickness, soil stratigraphy and water depth, and hammer and cushion properties. The pile and hammer data are provided by the platform designers and contractors. The soils data is obtained from borings drilled at the site, past experience and published values in literature. The analysis can be used to predict the expected range in the field blow counts, establish a minimum blow count criteria, anticipate refusal and other driving problems, and estimate driving stresses.

FIELD MONITORING OF PILE INSTALLATION

Field monitoring of piles may be used to evaluate the performance of the pile driving hammer and to confirm the soil stratigraphy at the site. It provides a basis for evaluating pile acceptability. This is particularly useful in cases where piles experience refusal above design penetration or where the blow counts at design penetration are lower than the predicted values. The following paragraphs briefly describe the instrumentation required, analysis and interpretation of the data obtained.

Instrumentation

The instrumentation required for dynamic pile monitoring include strain gauges and accelerometers fixed near the top of the piles. These are connected through an oscilloscope to a computer which stores the data for each recorded hammer blow.

Data Obtained

The force-time pulse is recorded on the oscilloscope for each hammer blow. A typical force-time record is presented on Fig.1. The energy transmitted to the pile is also obtained from the acclerometers.

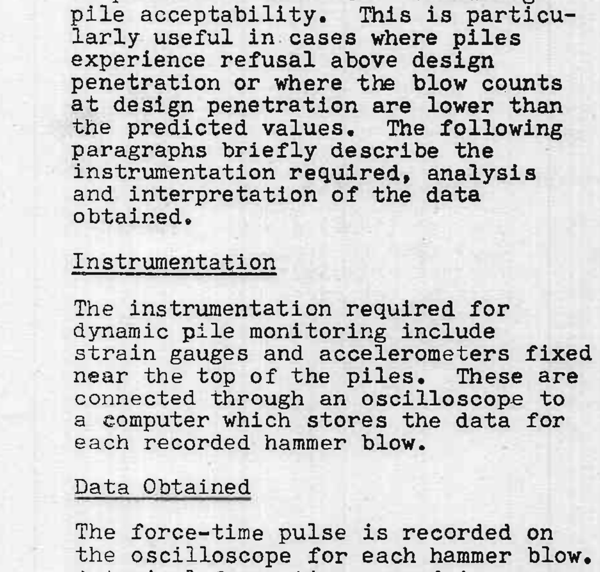


FIG. 1 TYPICAL FORCE - TIME CURVE

Analysis

The amplitude of the first peak of the force-time record and the hammer ram velocity are used to compute hammer efficiency. Next, the rise time for the first peak of the force-time record is compared for successive blows to assess cushion wear. The parameters evaluated include cushion stiffness and coefficient of restitution. If hammer efficiencies are consistently less than 50 percent or if significant cushion deterioration is suspected, driving is stopped and the hammer is replaced or repaired. Where hammer performance is within acceptable limits, the data is used to interpret soil conditions and evaluate pile acceptability.

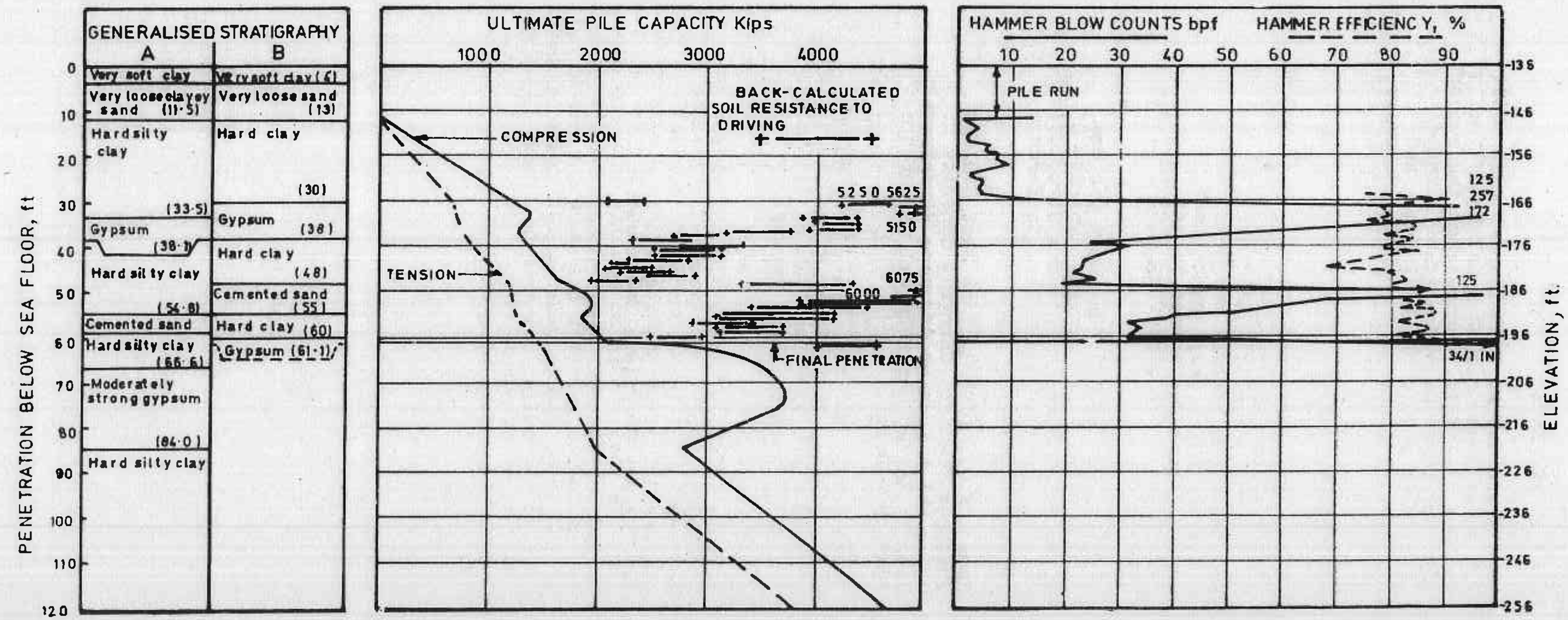
Interpretation

As the pile drives through strong soil or rock and refusal becomes apparent, force-time records for several consecutive blows are reviewed to estimate the percent of driving resistance due to end bearing. To do this, the magnitude of the reflected force-time peak is compared to the first peak. When the reflected wave exceeds 80 percent of the first peak, the force-time record is monitored closely to determine whether the pile can be driven further and to ensure that serious pile or hammer damage does not occur. To be able to confidently reassess the pile capacity, the end bearing should show an increasing trend and should be consistently over 80 percent for several consecutive blows. Also, the values of hammer efficiency, cushion stiffness, and coefficient of restitution should be within acceptable limits.

As piles drive through weak soils, and the blow counts are low, dynamic monitoring can be used to determine pile acceptability. A minimum blow count is established for a particular hammer efficiency using wave equation analysis. The driving system performance is evaluated to determine whether the pile can support the design loads. If the final blow count is less than the specified minimum blow count and the end bearing component is negligible, it may be necessary to over-drive the pile. The depth of overdrive required to ensure the design pile capacity should be decided in the field based on the driving performance.

DYNAMICALLY RECONFIRMED PILE CAPACITY

Piles accepted in the field through verification of hammer performance are reevaluated after installation to confirm pile capacity using "back calculated" soil resistance to driving. Wave equation input for this calculation include measured values of hammer properties interpreted from the force-time records and integrated acceleration records. This provides the



NOTES

(1) Stratigraphy

A : Soil stratigraphy based on soil boring drilled at the site.

B : Soil stratigraphu interpreted from blow counts and pile monitoring data.

(2) Pile capacity calculation
Ultimate pile capacity presented above is calculated using the API RP 2A (1981) method using the soil boring data.

(3) Design load
Design penetration of 67ft (20.4m) is based on a required ultimate compressive load of 2450 kips (10.9 MN). This includes a safety factor of 1.5 against the maximum storm load.

(4) Pile data
Pile type : Driven steel pipe pile
Pile diameter : 42 inches (1.07 m)
Wall thickness : 1.5 inches (37 mm)

Total pile length : 230 ft (70.1 m)

(5) Platform data
Platform type : Six well
Water depth : 136ft(41.5m)

(6) Pile driving hammer
Hammer Name : Vulcan 560
Hammer type : Single - acting steam hammer
Weight of ram: 60,000 pounds (27,236 kg)
Hieght of fall: 5 ft (1.5 m)
Rated energy : 300,000 ft - lbs (407 kN - m)

(7) Pile driving information

a) Pile run due to self weight of pile and hammer placement was 13ft (4.0 m)
b) Blow counts are recorded as blows per foot (bpf)
c) Pile driving was generally continous except for a 98 minute delay at 31.6 ft (9.6 m) for hammer repair.
d) After pile driving, the soil plug inside the pile was measured. It was observed to be 5.3 ft (1.6 m) above the seafloor.

(8) Wave equation analysis
Range in back calculated soil resistance to driving corresponds to the coring and plugged cases.

FIG.2 PILE INSTALLATION SUMMARY-CASE STUDY additional confirmatory data required to ensure that the as-installed piles can carry the design loads. Stevens et al (1982) present a methodology for hindcast wave equation analysis that has been very effectively used in the Arabian Gulf to compute soil resistance to driving based on dynamic pile measurements and driving experience from numerous platforms.

CASE HISTORY

A case history where dynamic monitoring was used at an offshore site to evalute pile acceptability is presented here. The stratigraphy at the site consisted of hard clay, cemented sand, and gypsum. Six 1.07-m (42 in.) diameter pipe piles with a wall thickness of 37 mm (1.5 in.) were planned to be driven using a Vulcan 560 hammer (a steam hammer having a rated energy of 300,000 ft-lbs) to a depth of 20.4 m (67 ft). Soil stratigraphy and driving data for one typical pile is given on Fig.2. This pile refused at 18.6 m (61 ft). Dynamic pile measurements confirmed that the Vulcan 560 hammer performance was well above the acceptable limits. As the pile drove through the upper gypsum stratum below 9.1 m (30 ft), the reflected peak on the force-time record showed that the gypsum was not competent and was shattering under the hammer blows. Therefore, the pile was driven through this stratum and down to the lower gypsum stratum where the pile refused with a final blow count of 34 blows for 1 inch of penetration. At final penetration, the computed hammer efficiency was greater than 80 percent. The dynamic measurements also indicated the hammer cushion to be in fairly good condition. The cushion stiffness and coefficient of restitution were within the range expected values. The maximum driving stress measured was 179.3 MPA (26 ksi). Soil resistance to driving was calculated to be in the range 17.8 to 20 MN (4000 to 4500 kips), indicating a safety factor of at least 2.45. Therefore, the pile was accepted 1.8 m (6 ft) short of design penetration with reconfirmation of pile capacity using dynamic monitoring. Remedial measures such as placing a grout plug or installing a grouted insert pile were not required to accept the pile.

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