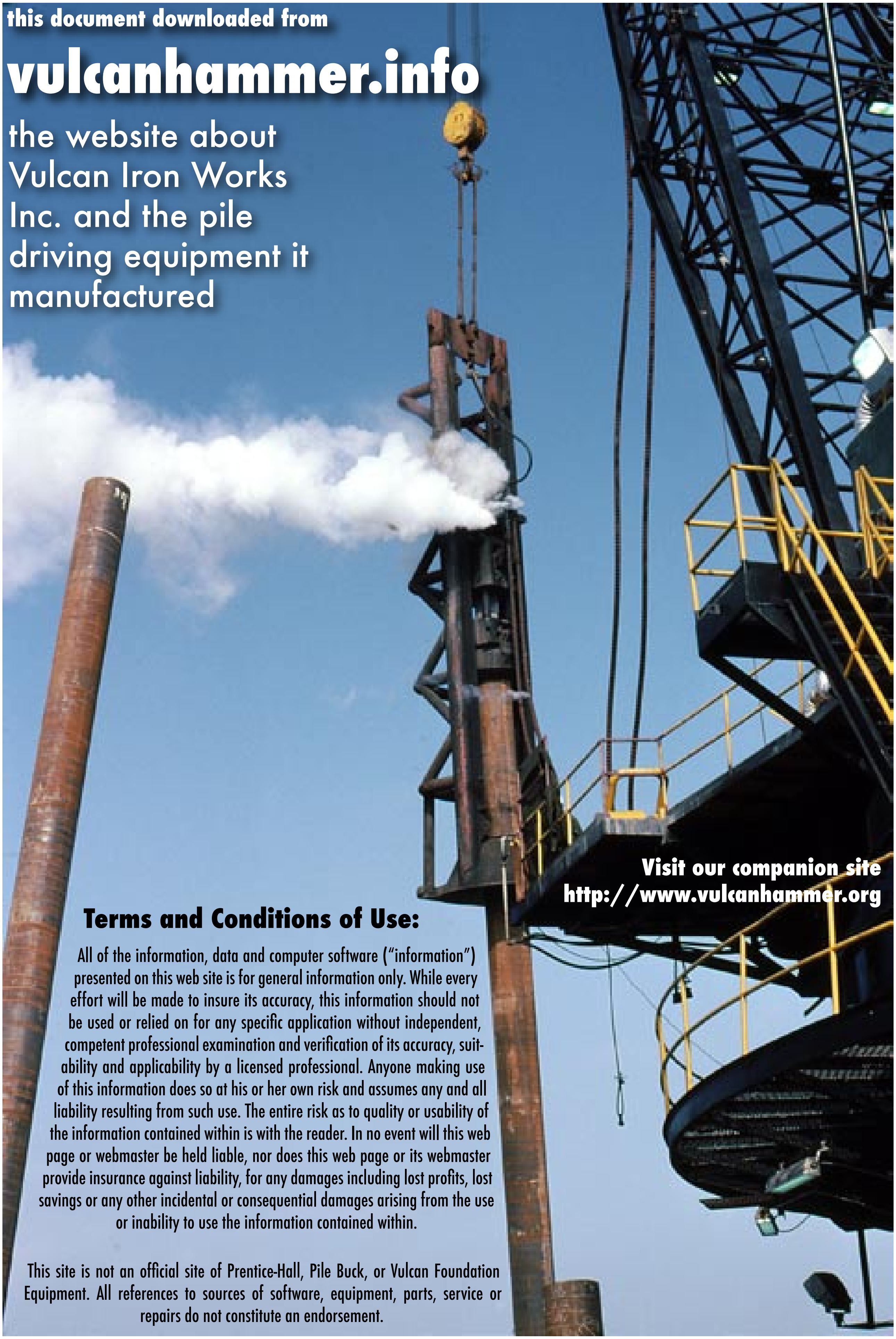

Pile Driveability Is Unpredictable In Sand Or Silt Foundation Strata

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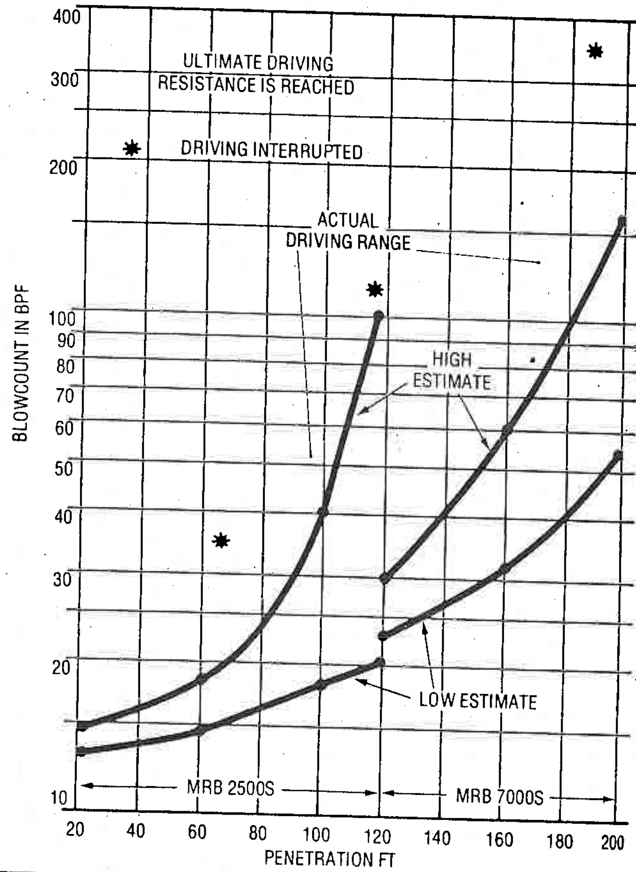
Fig. 1. Typical comparison between actual and predicted blowcount as a function of pile penetration.



Based on predictions by three independent consultants that piles for a northern North Sea platform could be driven more than 140 ft deep, a designer decided that no insert piles would be required for a particular installation. When this platform was installed, however, it was found that even the heaviest available hammer could not drive any of the 20 required piles beyond 70 ft through a sandy silt layer. After many re-evaluations the predicted pile capacities were revised upwards, and some insert piles had to be fabricated and installed.

The complete installation effort, consequently, took nine months longer and several million dollars extra in derrick barge time. This is indicative of the present state of the art of pile driveability prediction.

A typical installation with a large pile penetration of a deep water platform in the northern North Sea should consist of driving a primary pile to 50 or 60 ft and attaching it with grout to the jacket. The primary pile is drilled out and hole is continued to the desired full penetration of the insert pile. This pile, with diam smaller than the primary pile, is installed inside the primary pile in the drilled hole. The annulus between the insert pile, the primary pile, and the surrounding soil is again filled with grout.

Pile with an ultimate capacity of over 5000 tons can be installed in this way with relatively small pile driving hammers. Alternatively, a large diam pile is driven to grade by a gigantic hammer. If the object penetration is not reached, the pile is drilled out and an insert pile is driven through the main pile to penetration. This process is usually followed when large capacity pile driving hammers are available. A typical pile driveability prediction (Fig. 1) gives predicted and actual blow count ranges vs penetration for a particular installation. There is a significant difference.

Even small local changes in foundation soil are important because soil borings on which pile driving predictions are based are rarely taken at the driving location. Actual soil conditions can be expected to be different from the assumed soil makeup resulting in a large variation in blowcount rates found for successive unit penetrations driven.

One dimensional wave equation analysis is used most commonly to predict pile driveability. In this analysis, both hammer and pile are simulated by a combination of rigid masses and springs, and other devices simulate soil resistance. One hammer blow is studied at a time. Assumptions include pile at rest when hammer impact occurs, and concentric impact on pile. The hammer is simulated (Fig. 2) by rigid masses and nonlinear springs.

Pile batter reduces hammer efficiency. This reduction amounts to some 10%. Efficiency of large steam hammers is approximately 65% to 75%, and is 40% to 80% for small hammers.

The hammer cage rests on top of

the hammer when driving activities start. It was found that hammer efficiency improves when the cage is supported by the hammer while driving.

The pile is simulated as a series of rigid masses connected by springs. This further improvement in the hammer simulation did not result in a significantly better driveability prediction.

Often, friction at shims is unjustly neglected. Because piles usually have a batter of approximately 7-1, in most cases friction forces can be large and can influence the driveability of the pile substantially. Initial soils tests and deformation conditions are derived from preliminary blows. No tensile stresses at a pile toe are usually allowed.

Free contact between pile and follower was found to improve the driveability of piles on land. This improvement was confirmed by theoretical calculation for piles used offshore. But, unconnected followers are hardly ever used because the follower could crumble or damage the top of the primary pile or the insert pile if driven. Fig. 3 shows the commonly used pile and soil simulation model. Pile simulation cannot be significantly improved to yield better pile driveability predictions.

Soil resistance usually is simulated by a combination of linear springs, dampers or dashpots, and slip resistance. The relationship between soil deformation and pile shear is simulated by spring and slip resistance. When dynamic pile shear exceeds certain value, soil deformation increases without an increase in pile shear. At the point where maximum pile shear is reached and plastic deformation of soil starts, or slip resistance starts acting, soil deformation is equal to the value of the soil quake. In conventional calculations, the soil quake is usually taken equal to 0.1 in.

The accuracy by which this number is defined is characteristic for the accuracy by which it is known. It is usually an assumed value because it is hard to measure. A small variation in the soil quake, however, has a dramatic influence on pile driveability on the order of ±100%.

The quake is not equal for pile motion up or pile motion down, and it also depends on how many blows in a row have been applied to the pile. Continuous pile motion causes soil softening which could be called soil fatigue of the slip plane along the pile wall. Static soil properties

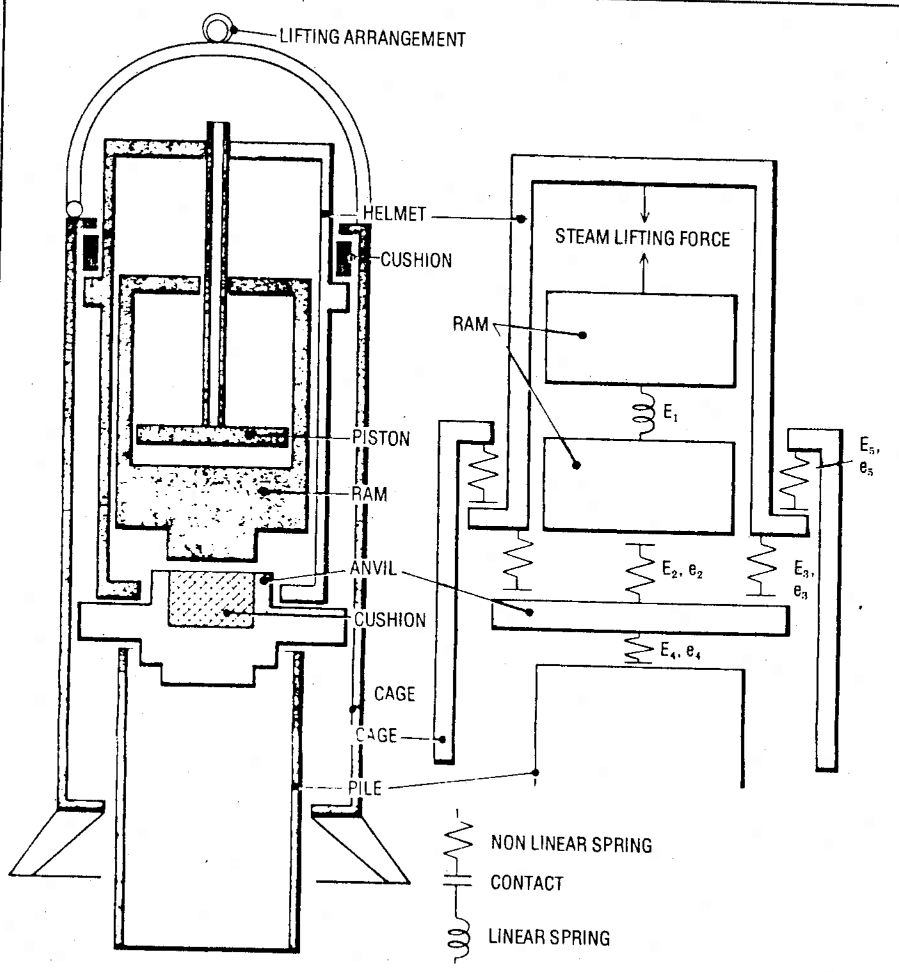


Fig. 2. Improved hammer simulation which became necessary after large steam hammers were introduced for offshore installation work.

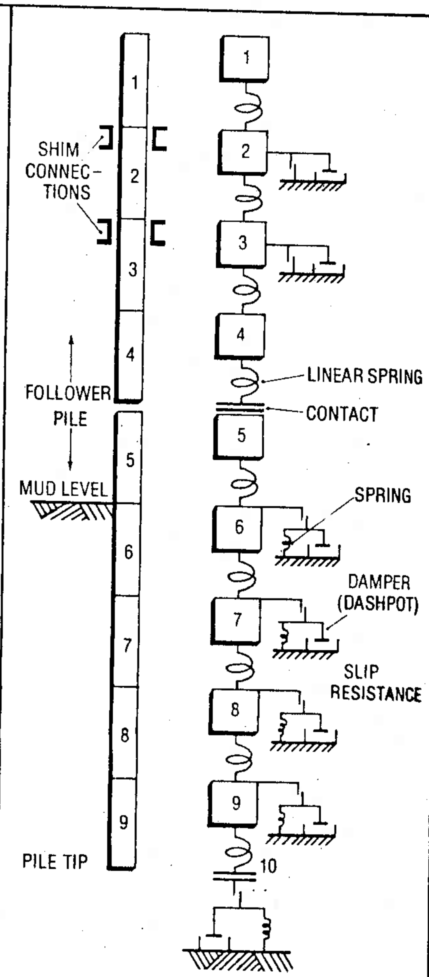


Fig. 3. Commonly used pile and soil simulation model.

are used for deriving dynamic soil properties and the conversion from static to dynamic soil properties is very hard to make. Soil set up occurs after a pile is being driven and the pile activities are temporarily stopped. This interruption of driving activity gives the soil time to redevelop its old strength properties, causing an increase in friction values and skin friction along the pile wall with time. It results in decreased driveability when driving activities are resumed.

Pile friction is velocity dependent because of Thixotropy effects and shock waves transmitted away from the pile. The assumed relationship between local pile shear caused by motion damping forces and soil deformation is shown in Fig. 4. The pile to soil shear deformation model used in one dimension wave equation analysis is independent of the way the pile shears through soil. Two ways are possible. Shear failure can occur at the pile-soil interface, but when there is soil attached to the pile, soil can fail within itself. The calculation model does not distinguish between either possibility and theoretical knowledge is not sufficiently reliable to predict which failure mode will occur at a given time.

Ideally, a pile is driven into an elasto plastic half space. This half space could be simulated in calculations by a finite element method. But these calculation methods have not yet been applied in current calculation systems because they are costly. The velocity of sound in steel is approximately 16,000

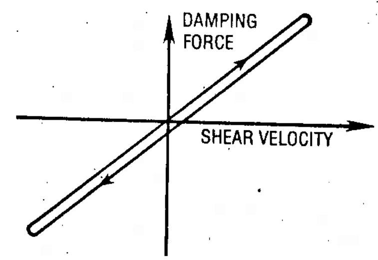


Fig. 4. Assumed relationship between pile damping resistance (treated as a force in the calculations) and pile shear velocity.

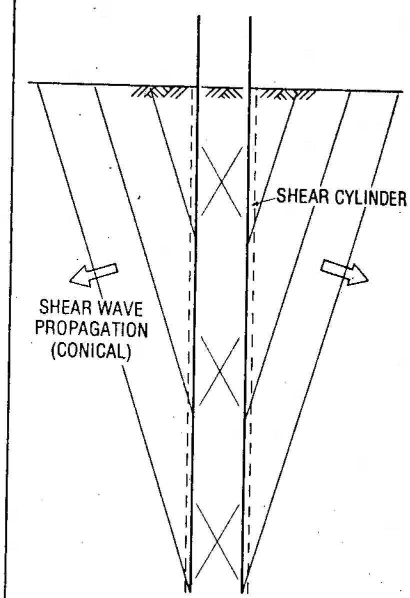
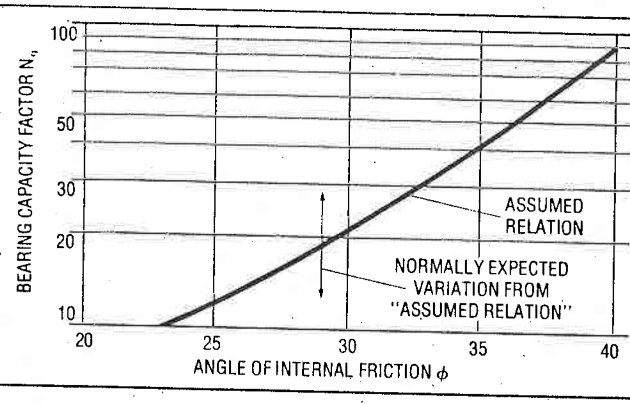


Fig. 5. General shear failure of a rapid single-stroke penetration.

Fig. 6. Relationship of angle of internal friction (which also depends on sand density) and bearing capacity factor for sand. Speed of failure is not accounted for in standard soil mechanical tests.



ft/sec, while in soil it is approximately 5000 ft/sec. When a pile is driven, a wedge of soil around it will, therefore, be vibrated (Fig. 5). This actual system is entirely different from the calculation model.

By the time driving shock arrives at pile tip, the soil area which has been vibrated radiates out from the pile to a maximum of approximately ⅓ of pile penetration. Interaction between the vibrating soil and pile motion is not at all included in commonly used calculations. This difference will be particularly significant for deep piles. Therefore, predicted driveability rate will be less reliable the deeper piles are driven.

During pile driving interruptions and after completion of driving activities, soil plug elevation inside the pile is usually measured. It was found that the pile plug can both drive up or down with respect to original soil level. Measured movements of the pile plug between successive driving stops indicate that gentle plug motion is rather erratic and cannot be predicted with any success.

When the pile is driven to refusal in a sand lens it usually cannot be driven any further unless the pile plug is drilled out completely. Even if a ten foot pile plug near the tip is left, the pile won't advance at all when driven. The pile tip, in fact, cores through the soil with the driving shoe acting as sort of a cookie cutter into the soil.

Calibration calculations which try to assess end bearing resistance of piles during driving activities, show that the end bearing of the pile is in excess of values predicted statistically using pile capacity formulas. The end bearing resistance of piles correlates with sampler blowcount resistance data which are collected during geophysical investigations of a nearby soil boring hole.

In conventional pile driving calculations, the ratio of ultimate tip resistance to total dynamic driving resistance often is prespecified as a

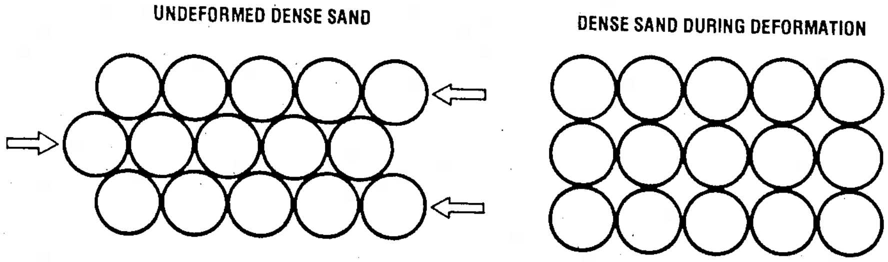


Fig. 7. Expansion of dense sand by deformation.

certain ratio for calculations. This precludes any exact description or introduction of the actual mechanism of resistance at the pile tip. The ultimate tip resistance is calculated using static ultimate pile capacity formulas which use, among others, a bearing capacity factor Nq. This factor Nq depends on the angle of internal friction of sand and also failure rate speed of the pile through sand. Crushing effects of sand are completely neglected. Nq varies significantly for a given angle of internal friction. A normally expected variation from the assumed value of Nq is shown in Fig. 6.

It is obvious that ultimate tip resistance, whether for driving or static ultimate pile capacity calculations, cannot be very accurate. Why does a pile when driven into a sand or silt layer so easily reach refusal? Perhaps the answer can be found from the interaction between the pile coring through sand and changes in sand density.

When densely packed sand undergoes deformation it expands in volume. This is explained by Fig. 7 where it is shown how a sand layer increases in height when a certain intermediate layer is forced to shear between sand layers overlying and underlying it.

Schofield describes in more detail what happens if dense sand is deformed. First the volume increases. Second the water pressure of wet sand decreases. These combined effects cause soil pressure (sand pressure) to increase drastically. An increase in soil pressure is equivalent to increase in pile resistance. Thus, when a pile tip is driven into a sand lens, deformed sand which penetrates inside the pile will cause very high friction forces to occur at the pile tip at the inside and outside surface area. This also explains why partially drilling out a pile does not enable the operator to resume driving the pile.

The pile plug must be completely drilled out and possibly even a pilot hole drilled before the pile advances again when driven. Dense clay hardly expands when deformed, but silt behaves the same way as sand.

Because drilling out takes time, setup or freezing of sands and clays inside and outside the pile can increase the skin friction for sand by approximately 100%. The increase in resistance caused by set up outside the pile is approximately half the increase in resistance caused by set up inside the pile for sand. In boulder clay, the plug appears to have only 30% of the friction it has at the outside, but set up is hardly noticeable. The local increase in driving resistance in soft unconsolidated clays is found in excess of 300% and often equal to about 500% of the dynamic resistance found during continuous driving activities. In stiff over-consolidated clay this value reduces to approximately 200%.

Pile motion can easily be recorded at the pile top by unskilled barge personnel. It is a hand job which requires that a piece of paper be attached to the pile with tape. On the jacket, three pieces of welding rod form the base to support a pencil which can be pulled across a piece of paper while the pile is being driven. A fairly accurate motion record results, particularly when the pencil is drawn evenly over the piece of paper. An example of abstracts of these records is shown in Fig. 8.

Comparing actual records to the calculated records shows that pile rebound is not at all as strong and oscillatory as the calculation shows.

At all penetrations it was found that recorded pile motion was less violent than predicted by calculations. Pile motion near the pile top is primarily influenced by soil resistance of the top seabed strata. Thus, from the pile rebound it cannot definitely be determined whether or not refusal is caused by excessive driving resistance or a boulder. Consultants who predict pile driveability never show predicted pile motion records in their calculations. Usually, they restrict themselves to predicting a blowcount or a blowcount range.

Sometimes reports are submitted on what stresses can be expected when the pile is being driven. Measurements always duplicate almost exactly the calculated results simply because the stress waves propagate in the steel pile almost exactly as the theory predicts until the stress waves hit uncertain resistances, such as those caused by shim friction resistance or soil resistance. Because maximum pile stresses usually occur before these nebulous resistance influences have had their effect on the stress waves, it is plausible that predictions of maximum stresses in the pile are very accurate.

For short piles which are not driven to great penetration, the pile motion records predicted are

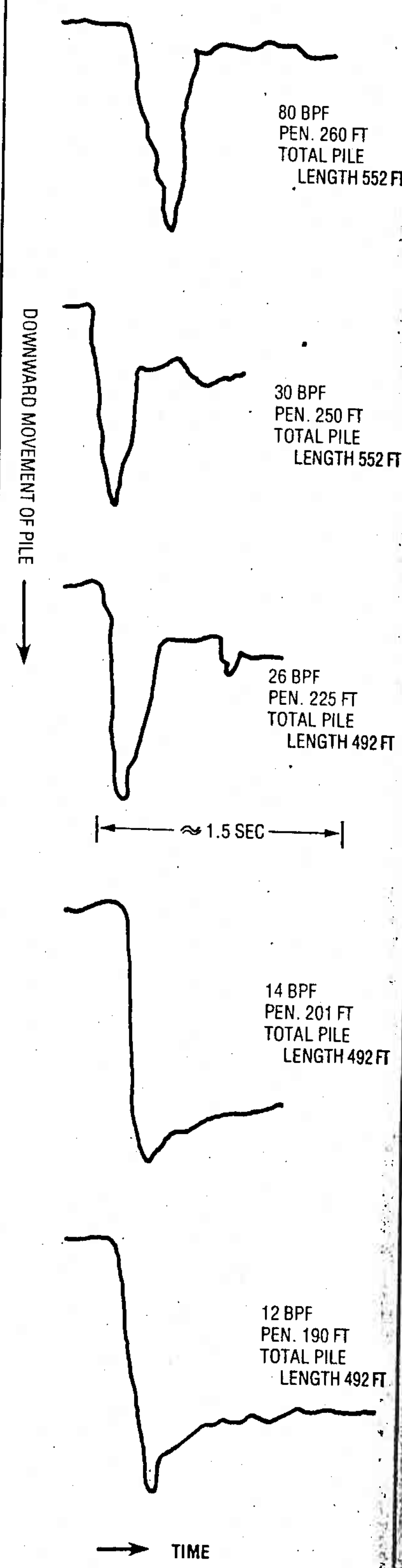


Fig. 8. Records of pile motion at top of jacket level as a function of time (data collected by J. Beers of Heerema Engineering Service, B.V.).

fairly accurate simply because the downward stress waves cannot transmit much energy laterally to the soil.

It has not been found possible so far to duplicate actual driving motion records of deeply driven piles by calculations unless unrealistic values for soil quake and soil damping were introduced.

Decision making in the field offshore would be helped if reliability of pile driveability calculations could be assessed on the spot. This could be done by comparing both predicted blowcount and pile head motions with actual recorded pile motions at the top of the jacket. A comparison between predicted and actual blowcount is very sensitive to slight increases in soil resistance. Thus, even a large difference between the two must always be expected. It does not prove the unreliable blowcount calculations right or wrong. Differences in predicted and actual pile motion at the jacket top show whether or not calculations were based on representative soil resistance data. This is an indication of quality of the simulation of total dynamic soil resistance along the pile. This, perhaps, is a challenge for future consulting activities for major pile driving jobs.

In the meantime, while reliable pile driveability predictions for very deep piles cannot be made by any particular consultants for areas which have sand and silt lenses in the foundation of the soil, it is wise to make provisions just in case the pile cannot be driven to grade in spite of the best available predictions. Even better, begin with a foundation design which avoids these uncertainties altogether, such as deep pile installation procedures now common in the northern North Sea which consist of driving a primary pile to approximately 50 or 60-ft penetration. This main pile is connected to the jacket by grouting. Then, the main pile is drilled out and an oversized hole for the insert pile drilled to full penetration. The insert pile is sunk inside the hole and grouted in place. ■

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