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CONSTRUCŢII. ARHITECTURĂ

DESIGN OF MARINE FOUNDATIONS
DESIGN AND CONSTRUCTION MONITORING

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An introduction to marine foundations design is presented, with emphasis on pile design and driving operations monitoring. Piles are analysed for the bearing capacity, and then, the driving equipment is selected. A short sequence of a process design simulation is also described.

1. Introduction

The interaction between the driven piles and the surrounding soil is a complex process. However, a good design and a well-chosen construction technology will bring benefits to the project in terms of execution time, cost effectiveness and avoidance of errors. Misinterpreted results may affect the integrity of the construction materials and hence the service life of the structure.

As the pile loads increase and the pile driving equipment is becoming more sophisticated, to verify the load carrying capacity of a pile, the Engineering News (ENR) formulae appear to be unreliable and wave equation analysis and dynamic pile driving monitoring are required.

2. General Considerations

Construction monitoring area is considering the equipment to drive the piles, the static load capacity of the pile and the constitutive materials of the pile.

Structures supported with piles existed in prehistoric times and reference to timber piles in Babylon could be found in Bible. In Europe, especially in Italy and in Holland, pile supported structures are known since the Middle Ages. Initially, pile were made from trees and they were driven until penetration through soil was no longer possible, meaning that refusal has been reached. Driving was probably done with hand operated mauls. The first steam-driver hammer was invented by James

N a s m y t h in 1840: "In 1840 I furnished Sir Edward Parry with a drawing of my steam hammer, in the hope that I might induce him to recommend its adoption in the Royal Dockyards".

As the technology has evolved the complexity of pile design and construction increased, as well. A sequence for design and construction of pile foundations is indicated in [2] and it includes the following steps:

1° Determine foundation loads.

2° Subsurface exploration.

3° *In situ* and laboratory testing.

4° Prepare soil profile.

5° Consider alternate design (shallow/deep foundations) and prepare cost estimate.

6° Select optimum alternative.

7° If pile foundations are selected:

a) perform static analysis and design (perform pile load test for large projects);

b) perform wave equation analysis;

c) prepare plans and specs;

d) construction control (wave equation analysis, dynamic testing and load test);

e) post construction review.

3. Bearing Capacity

Examples of pile design procedures are given in [8], where pile foundations are subject to axial compression, axial uplift, lateral loads and bending moments. The Driven computer software for bearing capacity computation is described below.

N o t e. Usually, the software available for bearing capacity computations is not taking into consideration salinity of water, and, therefore the unit weight of the soil should be given – if possible – as a buoyant unit weight, and the water table depth set to a value below the soil profile depth. This procedure, however, does not work for light soils with "Driven", because, for example, a soil with 110 pcf has a buoyant unit weight of 46 pcf in marine environment, which is below the 63 pcf , the minimum limit accepted by the software.

The total bearing capacity of a pile is given by the bearing capacity at the tip of the pile plus the skin friction of the soil around the shaft

$$Q = Q_p + Q_s = A_p q_p + \int_0^L f_s C_d \mathrm{d}z,$$

where: A_p is the area of pile tip; $q_p = cN_c + qN_q + \gamma BN_\gamma/2 \cong qN_q$ – the bearing capacity at pile tip; q – effective vertical stress at tip level, N_q – factor; f_s – ultimate skin resistance per unit area of shaft; C_d – effective perimeter of pile; L – length of pile in contact with soil.

If skin friction, f_s, is computed with Nordlund equation and the integral is replaced with a sum so that to avoid numerical computations, the total skin friction capacity becomes:

$$Q_s = \sum_i^n K_{\delta i} C_{fi} P_{di} C_{di} D_i \sin \delta_i,$$

where: K is a coefficient of lateral stress at depth z; C_f – correction factor for K; P – effective overbuden pressure; δ – pile–soil friction angle; C_d – effective pile perimeter; D – thickness of single pile segment; n – number of pile segments.

With data obtained from boring logs and by means of engineering judgment, the soil stratum is divided into layers with similar characteristics. The type of soil differentiates the input data required for defining the soil profile and the bearing capacity.

For cohesion less soils like sands, silty sands and calcareous soils, the internal friction angle for the skin and for the end bearing are required. One could also provide the Standard Penetration Test (SPT) values and use the correlations between those and soil properties as suggested in [4]. For cohesive soils the undrained shear strength should be known. Given the type of the soil, estimates of soil properties can be found in [8]. In the next example, we assume that the soil is fully submerged and the soil profile is defined as follows:

a) Layer *1* extends up to an average depth of 15 feet and consists of a normally consolidated clay with unit weight of 100 psf and an undrained shear strength of 300 psf. It is assumed that strength loss decreases with depth and for the first layer an average strength loss will occur during the operation of pile driving.

b) Layer *2* extends up to an average depth of 40 feet and consists of a normally consolidated clay with unit weight of 120 psf and an undrained shear strength of 600 psf.

c) Layer *3* extends up to an average depth of 55 feet and consists of a medium to dense silty sand with unit weight of 130 psf and an internal friction angle of 35 degrees. With this data, for an 18 inch square concrete pile a total ultimate bearing capacity of 580 kips is obtained at a depth of 55 feet. To estimate the pile capacity, analytical calculations methods differentiated by the type of the soil – non-cohesive or cohesive [2] – are used and may include Nordlund, Tomlinson and beta methods. The total bearing capacity is compared with the desired driven ultimate capacity of the piles. If a precast pile design capacity is 125 t (compression) and 30 t (tension) and piles should be driven to a safety factor of 2, then the desired driven ultimate capacity for piles is 500 kips (compression) and 120 kips (tension). Therefore, driving the piles below the depth of 55 feet, where the soil is becoming stiffer with over 600 kips ultimate strength, may affect the integrity of the piles (6,000 psi). Because it has been defined a percentage of strength-loss for each of the layers, lower values for the bearing capacity of the soil are expected during the driving operation. A partial drivability file could be prepared for use and further simulation with GRLWEAP software. As described in the user's manual, the GRLWEAP program simulates the behavior of an impact driven pile. The program contains mathematical models which describe the hammer, driving system, pile and soil during the hammer blow. Under certain conditions, the models only crudely approximate often-complex dynamic situations. A wave equation analysis also relies on input data, which represents normal situations. The data may be the best available information at the time of the analysis; however, it may greatly differ from actual field conditions. Therefore, a pile dynamic analysis (PDA) should be performed to verify pile capacities in accordance with ASTM D4945.

4. Drive Ability and Hammer Selection

For the selection of the driving hammer it is a common practice to use the ENR - Dynamic Hammer Formula. An example of ENR bearing chart for the ICE Model 60S diesel pile hammer is shown in Fig. 1.

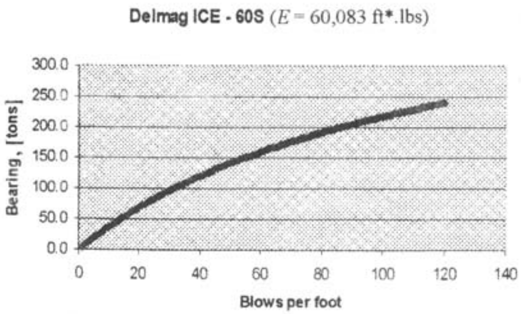

Fig. 1.– ENR bearing chart.

In selecting the hammer type, the ENR formula could be used:

$$P = \frac{2WH}{S + 0.1}$$

for single acting power hammer;

$$P = \frac{2E}{S + 0.1}$$

for double acting power hammer, where: P is the safe bearing value, [lbs]; W_t – weight, [lbs], of striking parts of hammer; H – height of fall, [feet]; E – ENERGY – approved hammer energy per blow, [ft.lbs]; S – SET=12 the average penetration, [inches per blow], for the last several inches of penetration [Blows per foot]. For certain types of hammer, some departments of transportation are indicating a multiplying factor of 1.6 instead of 2.

Example of pile hammer selection problem:

Select the proper hammer to drive an 18″ pre-stressed concrete pile 60 feet long, driven 50 feet to an ultimate static soil resistance of 500 kips in sand (which has no sensitivity and, therefore, the set-up factor is 1).

While selecting the hammer it is necessary to ensure:

a) The ability of the hammer to drive the pile at the desired penetration.

b) The ability to prevent overstressing of the pile.

It is important to choose the proper hammer size for a specific project, because a small hammer will not be able to drive the pile, while a too large one could damage the pile.

Example of pile hammer data, Delmag ICE 60S – type diesel is presented in Table 1.

Table 1
Pile Hammer Data

Stroke, [inches] – 103	Leads, [inches] – 26
W_t RAM, [lbs] – 7,000	Fuel Setting, n/a
Energy, [ft.lbs] – 60,083	Length hammer, [inches] – 203
Speed, [blow/min] – 41...59	
W_t Hammer, [lbs] – 13,900	

From the above shown ENR chart, for a bearing capacity of 250 t = 500 kips, the number of blows per foot is 120 which is considered the limit of final penetration resistance. Therefore, with the data provided, it appears that a larger hammer should be selected.

A more realistic methodology for hammer selection is based on the use of one or both of the following methods:

a) One dimensional wave equation analysis (considering the hammer–cushion–pile system).

b) Dynamic monitoring of the driving process by pile analyser.

5. Operations Analysis and Scheduling

A very simple sequence of process design simulation adapted from a Light Rail project in Baltimore is shown in Fig. 2. Driven piles support foundations for five piers. For each foundation a test pile is driven using one crew of pile drivers and one hammer. To drive each of the test piles it is allocated a period of time described by a triangular distribution with the low value of one day, the mode of two days and the high value of three days. After driving all test piles at different locations, obtained lengths are submitted for approval, and it takes about fifteen days to order and deliver the production piles. During the approval and procurement process, the pile driving crew excavates the locations for the future foundations. The same crew drives all fifty piles, for each of the pile being allocated a period of time given by a triangular distribution with the low, the mode and the high values of 0.5, 1, and 2 days, respectively (Fig. 2).

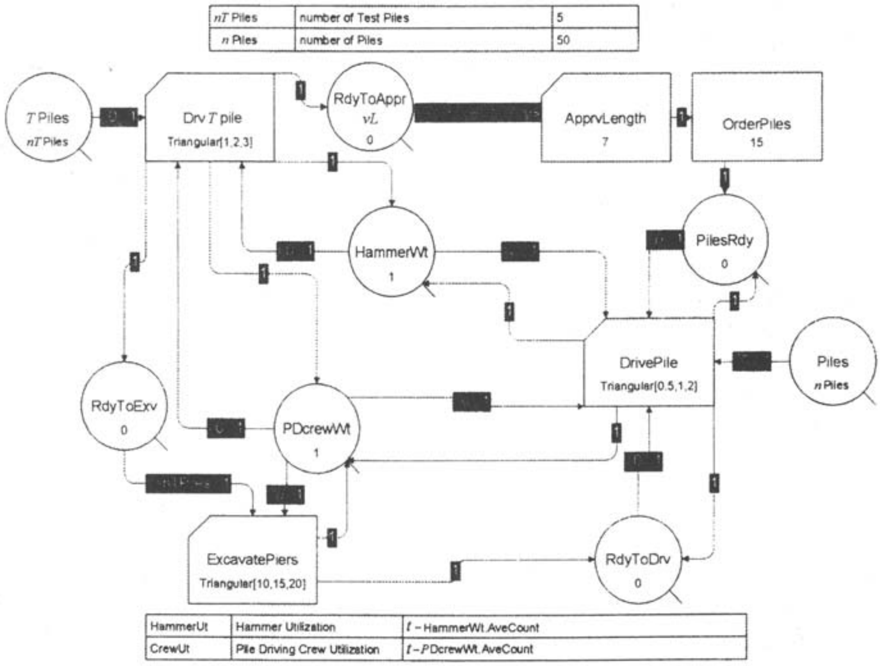

Fig. 2.- Stroboscope model pile1.vsd (163462744); A - model input parameters: number of test piles: 5; number of piles: 50. B - calculated results after simulation: hammer utilization: 0.758917; pile driving crew utilization: 0.921986; simulation time 91.255.

Running a simulation with Stroboscope [6], many variables can be defined to monitor the performance of this process. In this particular case, it has been obtained a hammer utilization of 76% of the time and Pile Driving Crew utilization of 92%, and the project will be completed in about ninety days. The input parameters were the number of the test piles and the number of the driven piles.

Pile driving operations are also highly probabilistic processes, because the nature of the soil is not precisely known and may change drastically at small distances. To select an optimum acquisition of piles, a probability decision theory and/or simulation could be used, based upon the complexity of the project and its importance.

Another example of problem statement, which can be solved with simulation or decision theory: given the probabilities of reaching refusal at certain depths, what is the most convenient buying alternative: a) purchase only 60 feet piles or b) purchase an optimum combination of 40 feet and 60 feet long piles.

After deciding on the most feasible solution, a schedule of operations is developed taking into consideration all the execution constraints, such as seven days wait period – for soil setup to occur – before test piles are re-driven.

6. Conclusions

The use of different simulation media in correlation with manual computations and sound engineering assumptions will generate good design results and, therefore, the project will benefit at least in terms of duration and quality of execution, cost effectiveness, reliability and safety. Each of the topics briefly introduced in this paper could be developed as separate courses, but parts of the presented procedure of analysis are currently used in all stages of a construction project development, starting from design and planning, and finishing with execution and control. A scheduling tool gives an early warning for potential delays and indicates possible corrective measures to be taken when problems occur, while a process design simulation tool offers unlimited capabilities to analyse the optimum resource allocation and most appropriate sequence of operations. Interest areas that could be further addressed include planning, scheduling and simulation of driven pile operations, resource allocation and financial modeling. Construction and design companies, as well as educational and research institutes may benefit from this report, while teaching or solving pile related problems.

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PROIECTAREA FUNDAŢIILOR MARINE
Proiectarea pilonilor şi monitorizarea construcţiilor

(Rezumat)

Se prezintă o introducere în proiectarea fundaţiilor marine cu accent deosebit în proiectarea pilonilor şi a operaţiilor de monitorizare a lucrărilor. Pilonii sunt analizaţi din punct de vedere al rezistenţei după care este selectat echipamentul necesar operaţiilor. Este descrisă, de asemenea, o secvenţă de simulare a proiectării.