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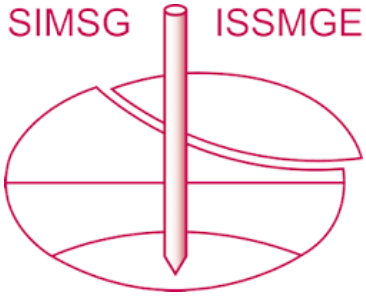

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Integrity and As-Built Capacity of Bored Pile Group

Intégrité et Capacité Portante d'un Groupe de Pieux Moulés

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SYNOPSIS This paper summarizes field testing and analytical methods used to evaluate the static as-built capacity of a large group of bored piles bearing on hard rock and underlying a practically rigid superstructure.

BACKGROUND

The subsoil conditions at a nuclear power plant in South America include about 35 m of saturated, compressive soils overlying metamorphic rocks. Consistent with these characteristics, the plant foundation is being constructed on large-diameter, cast-in-place, bored piles. These are socketed several meters into rock to carry nominal design static loads of 6.6 and 9.1 MN for diameters of 1.1 and 1.3 m, respectively, which is equivalent to an average concrete stress of about 7 MN/m^2. A total of 1,300 piles is being constructed for the plant with 202 of these piles supporting the Reactor Building, Figure 1.

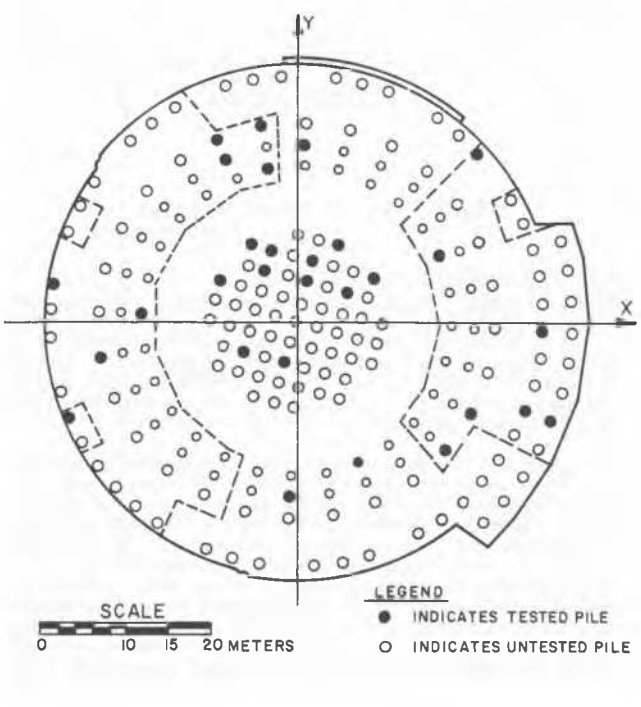

Figure 1 Plan of Tested Piles in Reactor Building

Although every effort was made by the several parties at the site to avoid construction problems during the extremely difficult installation procedure, a limited number of piles were noted by the site quality assurance team to have been subjected to construction difficulties, such as casing or tremie extraction problems, marginal concrete workability, etc. In order to quantify the potential consequences of such events, an "as-built" capacity verification program was undertaken on the Reactor Building pile group submitted to vertical static loads. This paper summarizes the field and analytical procedures and highlights the results obtained.

PILE INTEGRITY TESTING PROGRAM

Pile load tests conducted at the site had shown that the reserve capacity of the rock sockets was at least an order of magnitude beyond the nominal pile loads. Therefore, the emphasis of the pile integrity testing program was placed on verifying quality of the concrete shafts.

After reviewing the construction records for the 202 piles forming the Reactor Building foundation group, a number of piles were considered to have been affected by construction irregularities of varying severity. Because it would be impractical and unreasonable to contemplate testing the majority of the piles constructed at the site, the verification procedure had to make extensive use of statistical theory to evaluate the characteristics of the overall pile group. Standard statistical theory shows that a sample size of 29 provides reasonably sufficient information regarding the characteristics of the 202 total population. Accordingly, to satisfy construction and statistics, a sample of 29 piles was selected for testing (Figure 1).

The testing program entailed coring the selected piles using equipment to recover a 7.5 cm diameter core and performing several checks on the concrete of the pile shaft. Firstly, visual logging of the cores was done to provide a qualitative assessment of the concrete quality. Secondly, laboratory compressive strength testing was performed on those core samples which were visually observed to contain potentially anomalous concrete. Samples classified as "hard and sound" were also tested for comparison. Thirdly, in situ testing by geophysical sonic techniques in one-meter vertical increments along the core hole was conducted to check pile integrity in the volume of concrete surrounding the boring (Weltman, 1977). This information on in situ conditions was particularly useful to evaluate the cross-sectional credibility of the core strength values, as the results of small-diameter, core sample testing cannot be considered to provide a fair representation of mean cross-sectional capacity (Andres, 1973; Weltman, 1977).

The program involved 63 core holes for a total of approximately 1,900 m of 7.5 cm diameter core. Approximately 3,000, 15 cm long core samples were strength tested, with a mean cylindrical strength of about 46 MN/m^2 and a standard deviation of about 14 MN/m^2. This proved that most of the concrete was sound, with strength well in excess of the B 25 design specifications (25 MN/m^2 crushing strength on a nominal cube) and a number of test piles were determined to have excellent concrete capacities. However, in some cases, deficient concrete core strengths or geophysical readings were observed. A typical summary log is shown on Figure 2.

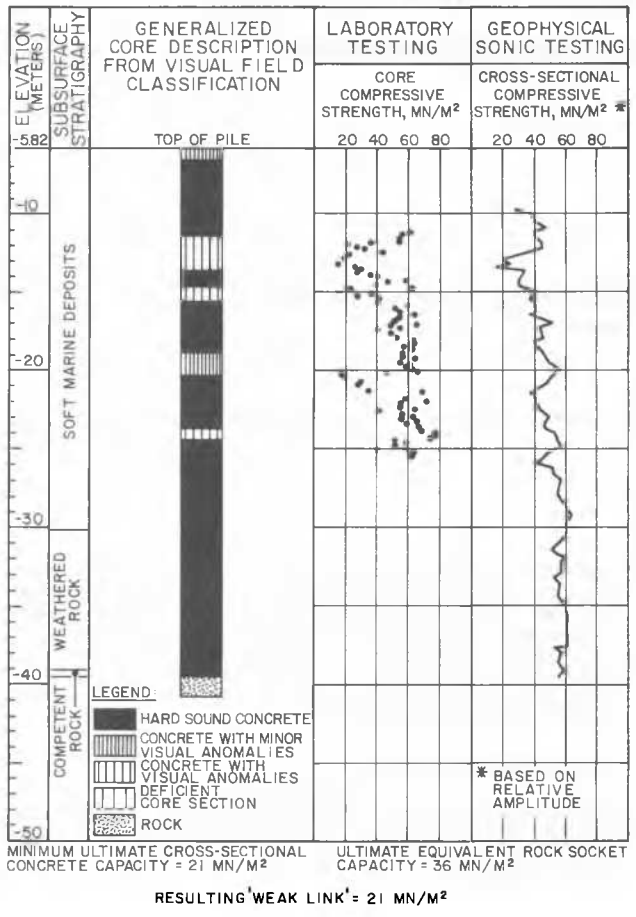

Figure 2 Summary Log of Testing Program

AS-BUILT CAPACITY ANALYSIS

A four-step analysis procedure was developed to provide quantification of the as-built capacity of the Reactor Building pile foundation group under static loading. These are discussed in the following sections.

Step 1 - Data Evaluation

The purpose of this step was to define the ultimate, as-built capacity of each of the tested piles to serve as a basis to assess the capacity of the untested sample.

The method used a detailed integration and foundation engineering analysis of all available pile construction/testing data, including rock and concrete characteristics, with prime emphasis on the sample of 29 test piles for which detailed quantitative results were available (construction records, core logs, laboratory and geophysical strength testing, pile load tests). As a result, each pile was characterized by its "weak link," i.e., assuming the pile to be a chain in series. This step determined the weakest link or lowest applicable, as-built, cross-sectional ultimate capacity along the shaft, which was assumed to control the overall ultimate capacity of that pile. In summary, a total of 29 weak link values reflecting each tested pile's ultimate capacity was derived in Step 1.

Step 2 - Single Pile Capacity Model

The purpose of this step was to develop a probability distribution of the as-built ultimate pile capacity. This probability distributic represents the variability of "single" pile capacity in the Reacte Building foundation area. In agreement with standard practice i statistical engineering, several probability distributions were reviewe to define the mathematical model which provides the best fit to th observed pile capacity data. Figure 3 presents the distribution plot o ultimate as-built capacity versus probability level and indicates that the Weibull distribution (Weibull, 1939) provided the most suitable fit to the data. Finally, because the piles tested were selected on the basis of having experienced a construction difficulty and not at random, it was found that the data were biased toward lower-bound strengths. Therefore, no consideration of statistical uncertainty associated with sampling was required.

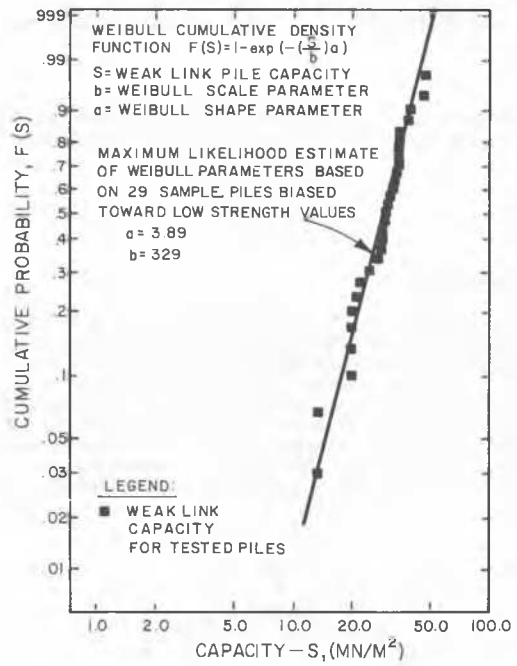

Figure 3 Single Pile Weibull Distribution

Step 3 - Number of Unusual Piles

Recognizing that a limited number of individual piles may have variable stiffness due to variable as-built concrete characteristics, this step entailed definition of the number and geometric distribution of these "unusual" piles so that the designer can subsequently consider this variance of pile compliance on structural designs. This analysis was primarily based on an application of the binomial distribution theory (Benjamin and Cornell, 1970) to the results of Step 2.

The results of this analysis indicated that, for a probability level near 10^{-5} of finding a given number of softer or stiffer piles, two separate load cases should be considered by the foundation mat designer. Firstly, a total of six extremely soft or stiff piles would be considered to occur randomly over the entire foundation area. Secondly, two adjacent soft or stiff piles would be considered occurring as a cluster at critical locations. The equivalent concrete elastic modulus for the soft piles was found to be 20,000 MN/m^2, whereas for the stiff piles the elastic modulus was to be assumed at 35,000 MN/m^2. The selected probability level of 10^{-5} was considered conservative enough in that the designer accommodated the resulting stresses in the foundation mat using "allowable" stress level, rather than "at-yield" level. The designer's mat analysis indicated that the mat/superstructure system was extremely rigid and resistant to the extent that bridging over soft piles or resisting punching shear over stiff piles did not result in any undue problems.

Step 4 - Pile Group Capacity

The purpose of this step was to establish the probability distribution of the global, as-built, ultimate capacity of the entire 202-pile group subjected to vertical static loads–and to compare this capacity to the design static load.

The pile group model was developed upon verification of the following assumptions. Firstly, the mat and overlying superstructure behaves rigidly under static, vertical loads and the loads were assumed to produce a uniform vertical displacement of the foundation. Due to the large number of piles, tilting caused by variations in pile capacity is a secondary effect which may be neglected. Secondly, the piles act as 202 parallel elastoplastic elements with random strengths defined by the single pile capacity probability distribution determined in Step 2. In order to bound the as-built pile group capacity, two possible stress-strain behaviors were parametrically evaluated. Thirdly, the bedrock mass is sufficiently rigid to neglect interaction of the pile sockets through rock.

Given the probability distribution of individual pile strengths and the mechanical model of the piles, including load-deflection relationships, the probability distribution of the global as-built capacity of the entire pile group was determined using classical statistical methods. The ultimate capacity is represented by the summation of the individual ultimate pile loads resulting from the assumed physical model and load-deflection relationships. By the central limit theorem of statistics (Benjamin and Cornell, 1970), the global capacity approaches a normal distribution. To determine the mean and standard deviation of the normal distribution of ultimate capacity, a Monte Carlo simulation was performed (Tocher, 1963). Once the probability distribution of the as-built ultimate capacity of the foundation was defined, it was compared with the global design static load on the foundation, which is equal to approximately 1,500 MN and the following Capacity to Load Ratio (CLR) was defined:

$$CLR = \frac{\text{Global As-Built Ultimate Capacity}}{\text{Global Design Static Load}}$$

Cumulative probability distributions for the CLR are presented in Figure 4 for two stress-strain models. The obtained CLR values indicate that the safety of the 202-pile group under design static loads is satisfactory.

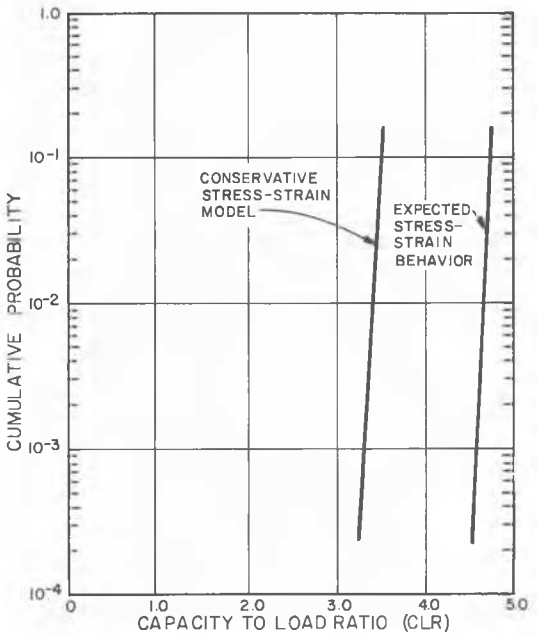

Figure 4 Probability Distribution For Capacity to Load Ratio of Pile Foundation Under Static Load

CONCLUSIONS

This paper summarized field testing and analytical methods used to evaluate the static as-built capacity of a large group of bored piles bearing on hard rock and underlying a practically rigid superstructure. The ultimate, as-built Capacity to Load Ratio was determined as a function of a variable probability level. To the authors' knowledge, such an approach has never been applied to pile group foundations. It is felt the four-step procedure represents a significant contribution to the state-of-the-art of practical control methods in pile construction and pile foundation analyses for buildings which require unusually high safety standards.

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