Victor F. B. de Mello

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W.F. VAN IMPE
Ghent University & Leuven Catholic University, Belgium

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Updating realism on large-diameter bored piles

V.F.B.de Mello & N.Aoki
São Paulo, Brazil

ABSTRACT: Bored piling, especially when bigger, has suffered from indeterminations of increasing responsibities: these are analysed probabilistically basing on case histories. Concomittantly the benefit-cost advantages are proposed, of systematically applying a driving blow to "set" on cured bored piles.

1 INTRODUCTION

The co-existence of big piling projects employing either bored or driven piles favours the critical examination of prevalent design-construction practices. Reasons historic are mostly forgotten or disregarded, and the gradual accumulation of inapplicable generalizations, standardizations and codes is found to lead to unperceived loss of engineering sense, generally in the direction of tremendously increased conservatism and buried costs. A case is presented of a statistically analysed foundation project of several hundreds of driven concrete piles. In conjunction, the data on some load-tested large bored piles are analysed, and a proposal is submitted both for significant improvement of the bored--pile load-settlement behavior and factor of safety, and for the appropriate distinct statistical-probabilistic analyses of bored piles, bored piles subjected to simple final "driving to set", and driven piling. The argument is strong in favour of systematically applying to in-situ concreted piles a final "driving set" hammer blow shortly after concrete set-up.

2 MISBEHAVIOR PROBABILITIES OF A STANDARDLY-DESIGNED DRIVEN CONCRETE-PILE FOUNDATION

A case history is presented of a recent exacting foundation for a MUD-TANK structure of tight working tolerances on incremental differential settlements. Correctly designed under good CODES and generalized teachings, it serves to expose the wastes imperceptibly accrued by casual insertions of arbitrary numbers for Factors of Safety FS devoid any behavioral meaning. Narrow compartmentalizations in subtopics, and in time, have marred a sane global view of methods and means of geotechnique as part of civil engineering.

The data analysed pertain to 792 centrifuged concrete precast piles of 26cm diameter, all individually controlled by simple routine regarding "ultimate dynamic resistance" under final penetration "set", 10 of them also subjected to Dynamic Load Tests DLT using the Pile Driving Analyser PDA, and finally, 4 Static Load Tests, all of them coincident with corresponding DLT tested piles.

2.1 Predicting pile lengths and load capacities for bid-design and budgeting. Direct use of SPT

This presentation is not a vehicle for noting one principal advantage of driven piling, that of predictability and of quality-control: the statistical data collected, notably rare, are used for pertinent probabilistic reasonings.

For anticipating driven pile lengths as required for guaranteeing code factors of safety on design load capacities two simple statistically derived equations, due to AOKI-VELLOSO (1975) and to DECOURT-QUARESMA (1978) are routinely used in Brazil. Both use UNCORRECTED SPT values, as they come from routine reconnaissance borings. Nevertheless Fig.1 shows good predictabilities (both of load capacity and of driven lengths) achieved by both, despite lack of sophistication. It proves, as happens often, that empirico-statistical correlations INVOLVING

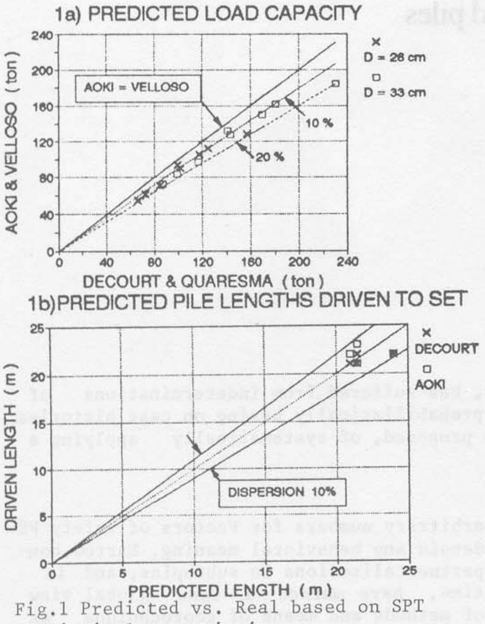


Fig.1 Predicted vs. Real based on SPT statistical prescription

ANALOGOUS PHENOMENA (e.g. in this case, driven penetrations) CAN BE VERY GOOD, and consequent ENGINEERING PRESCRIPTIONS, often better than those derived under analytical sophistications.

2.2 Dynamic resistance data available on all piles via DRR, and 10+1 dynamic load tests DLT (one repeated after a delay of days). Brief exposé

Accepting the premisse that the profession's specialists are conversant with pile driving developments associated with wave analyses, we refrain from mention of progressive digressions from the classical dictates and practices of the 1950's.

Old-fashioned pile-driving control, via final penetration "set" of each and every pile, received a significant improvement and credibility when the dynamic formulae were substituted by Smith (1960) model wave-equation PDA (Pile Driving Analyser) applications, with better instrumentation and on-the-spot-instant preliminary computing. For routine monitoring a special (but obvious) electro-mechanical equipment unit called the Dynamic Rebound Recorder, DRR, (analogous to the electro-optical unit of Sakimoto, 1985) was developed to record pile head displacements vs. time, wherefrom the pile Dynamic Mobilized Resistance load Rd is derived from rebound records in a manner analogous to the CAPWAP method employing its records of strains and two accelerographs. Thus, in the piling every pile is systematically associated with its Rd value.

Under classical concepts this Mobilized Resistance was considered to represent the pile Failure Load, QR, under postulated perfectly rigid-plastic behavior, and with engineering decision on the conservative side. Careful attention is drawn to the fact that with greatly increased pile diameters the same displacement dimensions have come to signify vastly different phenomenological behaviors. Suffice it to record herein that based on many analogous past load tests, and purposely on the safe side, the pile's estimated minimum failure load QR has been set as 1.15Rd (only 15% higher than the mobilized load at final driving "set"). Fig.2 proves that the present case is no exception.

Recognizedly there is no deterministic definition of a single failure load even in a single static load test. The very interpretation of such routine tests presents a variability within rougly ±20% of an overall average. Most internationally published criteria, both "analytic" and "graphical" as per references listed in Fellenius (1980), as well as Brazilian Code NBR-6122 under revision, were used for defining the nomi-

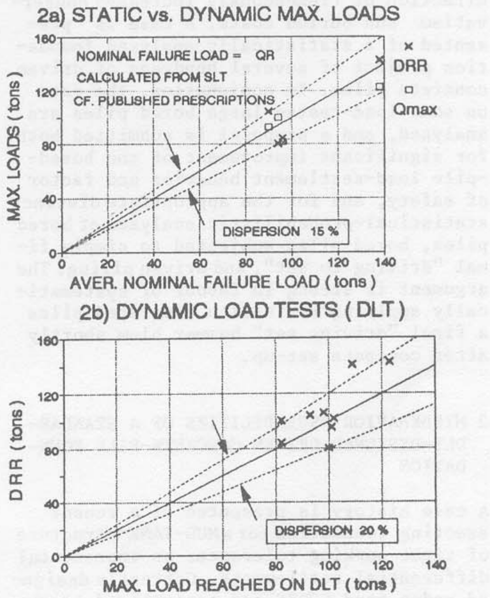


Fig.2 Comparisons of loads calculated from rebound data and load tests

nal failure loads from the static load tests, although the maximum settlements were small (2-3% of pile diam.). It is important to note that at a historic time when structures on pad foundations accepted settlements of a dozen to a score of centimeters, attention on piles (mostly of the 20-35cm diameter range) focussed on limiting settlements of 1-2cm and only on "failure" interpretations of load-displacement data. Deformability criteria on pile load test data are (almost) non-existent.

Concomittant with the static load tests we have the Dynamic Load Test, DLT, according to a procedure by now repeatedly published (Aoki 1991). The extensive experience of remarkable similarity of results of the DLT and SLT (cf. Fig.3 as one of scores of cases) is tied to a reasoning, and curiosity, now seemingly obvious a posteriori, that generated the DLT.

Recapitulating: in the classical routine of pile-driving control, the weight and fall (energy) had been kept constant, under the convinced fear that since dynamic ≠ static (conventional dogma), it was fundamental to respect avoiding any conscious differences. More recently, however, it was reasoned that if a given (arbitrary) Energy E_1 gives the unequivocal dynamic failure load $QR=\alpha(Rd)$, α traditionally taken as 1,0 , then any other energy E_2, E_3,... En should also give the same failure load.

Curiosity (and the principle that no two things are ever equivalent) led to questioning this would-be coincidence of the theoretical idealizations; and it was discovered that, quite to the contrary, on using progressively increased energies E_1... En at the point of final set, the CAPWAP analyses lead to data quite similar to those of loads-displacements of SLT. The easy and inexpensive test has invited repeated obvious uses. On the project herein reported we have 10 such DLTs, plus one repeated after some days. Understandably the use of DLTs is most inviting in bigger-diameter, higher-capacity, driven piles, of greater modern demand, associated with lesser base and head settlements expressed in percentages of diameter.

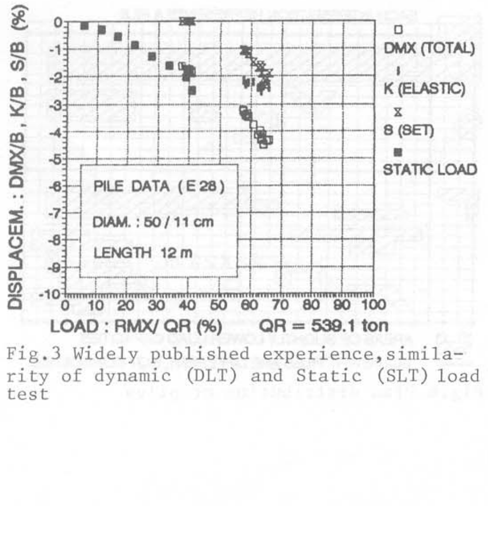


Fig.3 Widely published experience, similarity of dynamic (DLT) and Static (SLT) load test

2.3 Frequency distribution of the estimated QR nominal failure loads

The frequency distribution curve of all the values proves to be strikingly normal--Gaussian as represented in Fig.4a and also in Fig.4b of cumulative frequencies. It must be noted that according to code and design requirements about 5% of the piles would have failed to meet the REJECTION CRITERION of failure load $\geq$ 85 tons required FS=2 with reference to the design working load of 42.5 tons. In principle in the driven pile foundation under strict quality control easily applicable, those specific piles would be further driven (or redriven later).

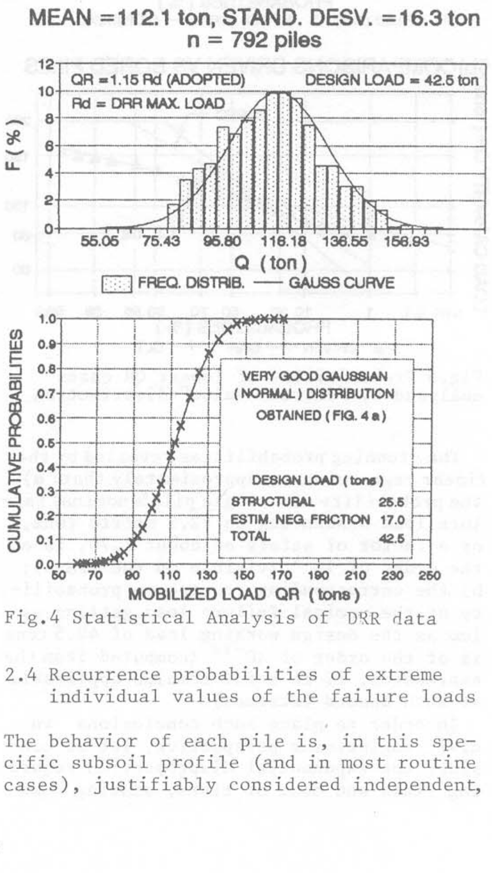


Fig.4 Statistical Analysis of DRR data

2.4 Recurrence probabilities of extreme individual values of the failure loads

The behavior of each pile is, in this specific subsoil profile (and in most routine cases), justifiably considered independent, and therefore the recurrence probability of each pile's maximum resistance (or nominal failure load) should be analisable under EXTREME VALUE DISTRIBUTION theories of statistics and probabilities. A fortiori the smallest values (of specific interest bacause of SAFETY) of the universe should be adjustable to one or other of such equations (or plotting papers) in use in engineering.

Among a few trials, the Gumbel distribution (much used in hydrology of maximum yearly floods at a given damsite) was found to give a satisfactory linear fit Fig.5a.

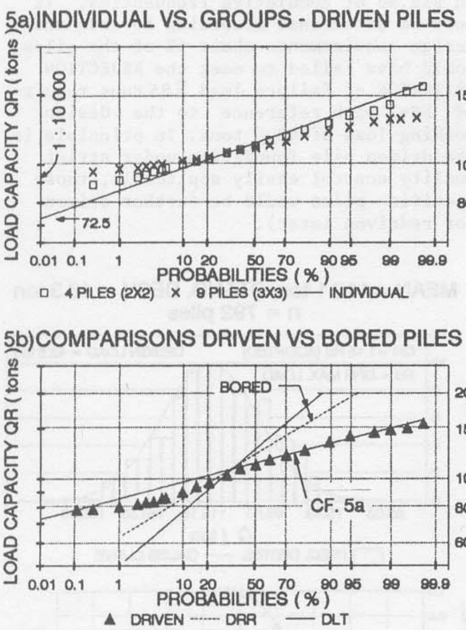


Fig.5 Probabilities of lowest QR cases analysed by "extreme value" distribution

The stunning probabilities revealed by the linear regression are approximately that: **a**) the probability of a single pile's nominal failure load descending to 72,5 metric tons, or a factor of safety of about 1.70, is of the order of 10^{-4} (visible on the graph); **b**) the corresponding recurrence probability of the nominal failure load getting as low as the design working load of 42.5 tons is of the order of 10^{-50} (computed from the expression, if it still remains applicable at such absurd extremes).

In order to place such conclusions in civil engineering perspective, let us consider the exponential disproportion regarding risks and cost of risks, stating summarily: a spillway is designed for the so-called 10 000-year flood, that is a 10^{-4} recurrence probability of the maximum yearly flood occurring in any year, and therefore, assuming a universe invariable with time, essentially a 10^{-2} probability of occurring within a 100-year useful life; as is well known, if an embankment dam fails by overtopping, material damages can be of billions of dollars, and losses of life can be of hundreds to several thousands. Meanwhile if a single pile in a group of 792 reaches a WORKING LOAD equivalent to its nominal FAILURE LOAD, absolutely nothing is at risk (even without considering structural load redistribution); but, to exaggerate in order to quantify something different from zero, possibly one might be risking a fissure of tenth of mm, worth 50 dollars of repair. Can Society countenance, and unknowingly pay for, such an absurd difference of design "risk-insurance" within the selfsame profession? To those who as members of Committees([1]) discussing Codes lightly banter around with changes of FS values from 1.5 to 2.0 (or vice versa) such a revelation should be a loud call for reflection. {([1]) "... a group of the unknowing, appointed by the unwilling, to do the unnecessary."}

Of the many absurdities in design practices, one lies in requiring the same FS per pile whether it is alone in supporting a column, or is one of a group for that task. Group vs. single pile soil disturbance is excluded from the present discussion, directed merely at the fact that a group of n independent piles working together should "statistically" behave more as the average of the n, rather than under the full variability-spread, pile per pile. The QR values associated with each pile were plotted on the foundation plan of Fig.6.

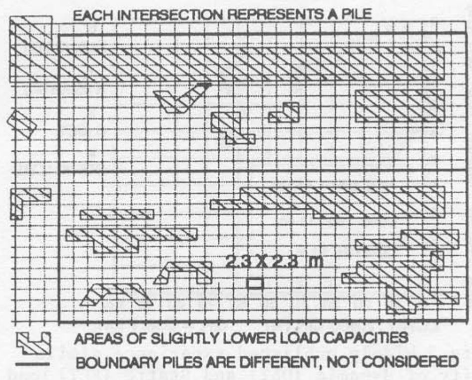


Fig.6 Plan distribution of piles

For a first feel of grouping advantage the plan distribution was considered under two arrays: Firstly, groups of 2x2 adjacent piles, averaged for the available QR; secondly, groups of 3x3 adjacent piles similarly averaged. The resulting Recurrence Probabilities plotted on the Gumbelpaper are shown on Fig.5b, with obvious indications. The median values coincide, but the best-fit line obviously flattens more and more as the number of group-averaging adjacent piles is increased to 4, and further to 9. Obvious: extreme unitary values are attenuated, at both extremes. The risk and fear of extremely low values, (already astoundingly low on single piles), decreases further very considerably.

2.5 Area distribution of QR values

There is interest in drawing in plan the distribution of QR values pertaining to different magnitude-ranges: consistent differences either due to geological variation, or due to construction differences etc. can be evidenced. In Fig.6 we only show separated the areas of QR values lower than 80 metric tons. The geometric pattern sets aside any subsoil influences. On investigation it was identified that one of the five mobilized pile-drivers was associated with these areas, producing the consistent difference which could have been easily corrected in the process were it not for the unusual urgency required of the pile driving.

2.6 Judicious evaluation of consequence of less-than-satisfactory performance

In every structure we must be keenly attentive to a "water-divide" between the early phases when decisions (and risks) are generated on the basis of loads (predictively estimated) and stresses, and final phases when the only thing that matters is deformations and incremental deformations. Engineers aim at creating forms (shapes, functional), and fear de-formations: all the rest is but means to an end. Under such thinking Fig.7 shows that for any unforeseen incremental loading, or any unforeseen insufficiency of load capacity, the only consequence is a minimal RATE OF INCREASE OF SETTLEMENT of the order of 0.1mm per 35 tons. Such an absolutely inconsequent incremental settlement confirms with regard to deformabilities, the already discussed highly overdimensioned condition with regard to FS.

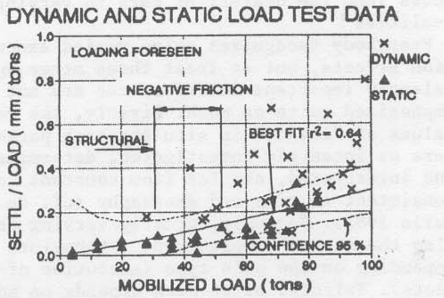


Fig.7 Interpretation of load test data ref. incremental loading & consequent settlement

2.7 Miscellaneous

Because of space limitations and the paper's intent, many important issues on practices of design and construction-plus-inspection, plus codes, load tests, etc. cannot be expatiated. For instance: 1) the case concerned piles point-bearing in dense gneissic saprolite, driven through compressible marine clays under fill, and therefore anticipated for negative skin friction, on which factors of safety merit radical rethinking; 2) in big-diameter point-piles, the tight (unnecessary) settlement limitations, not justified in the superstructure's tolerances, also lose rationality if presumed derived from the pile-soil load-settlement behavior, which, being of microstrains (justifying dynamic ≡ static) fall far short from failure; judgement and prescriptions must consider settlements as a percentage of diameter; 3) once the mud-tank dead load is totally acting and ulterior sensitive levellings finalized, what incremental loading could possibly require a global FS, and how incomparable is this with buildings of greatly different proportions of final dead load vs. incremental uncertain live loadings?

This study's aim is to employ the statistical data and manipulations of REJECTION CRITERIA extracted from such a documented foundation in order to transplant to the analogous but recognizedly different bored pile case, without or with a final routine DRR hammer blow on the set concrete.

3 SOME TYPICAL PILE LOAD-TEST BAHAVIORS IN A GNEISSIC SAPROLITE PROFILE

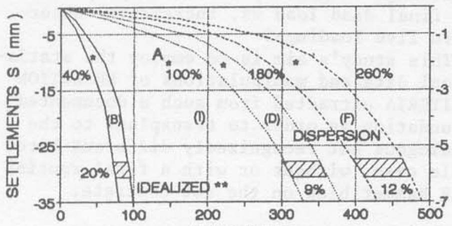
Many suggestions have been published regarding differences for bored vs. driven piles, both of lateral friction and base resistance ultimate loads. By far no generalizations should be permitted in fairness, yet most

Codes lend the deafest of ears to varying realities!

Everybody recognizes quite varied execution effects, but at least three other equivalently important interferences are not emphasized quite as much. Firstly, the very values of "intact" in situ strength parameters as intensely investigated, determined, and interpreted, are far from constant or consistent in time and geography (cf. de Mello 1981). Secondly, greatly varying are also the stress-displacement behaviors depending on the pile type (execution effects). Thirdly, often much depends on how load tests are interpreted regarding stress distributions, "failures", and settlements, shaft friction with mm, and base with % DIAMETER.

Fig.8 is presented for piles executed for each specialized Company's working load according to best practice and slightly adjusted to identical dimensions (7,5m long, 0,5m in diameter) in a dense gneissic saprolite profile (very susceptible to stress release and densification effects). The slight adjustments necessary and judiciously applied gave results remarkably atuned. The three pile types were **a)** auger bored and/or bentonite-stabilized bored **b)** precast concrete driven **c)** standard Franki-type driven without pedestal.

We concentrate on the bored piling, but first some comparative points are of interest. The driven piles achieve considerably increased rigidities, above all, besides the higher ultimate loads (Franki justifiably more): also, dispersions tend to be smaller (seems reasonable). Bored pile stress releases show-up principally in much increased deformabilities within ranges of centimetric settlements mentioned in Codes, and in practically no incremental resistance from the base.



NOTES: —— BORED —— DRIVEN ------ FRANKI
* REFERRED TO A
** SLIGHTLY ADJUSTED CURVE BASED ON "VERY GOOD" TEST RESULTS USED FOR IN SITU INTACT BEHAVIOR DISPERSION, INEVITABLE, NOT REPRESENTED

Fig.8 Comparative load-settlements of analogous pile in dense gneissic saprolite

Incidentally, once again (cf. de Mello 1981) it does prove increasingly odd to pursue further and further perfections of in situ "intact" definitions without concomittant FACTORS OF ADJUSTMENT regarding execution effects. Factors of Adjustment higher than 1.0 (driven) or lower than 1.0 (bored) must be further discussed regarding the concepts of Factors of Safety.

4 TYPICAL BEHAVIORS OF A DLT ON A BORED PILE IN THE ABOVE SUBSOIL, AND COMPARATIVE SUBSEQUENT SLT

We presume that the existence of a DLT on a bored pile must as yet be extremely rare. INTEGRITY TESTING of bored piles is well established, by recording changes of downward and upward travelling stress waves due to impact (energies, filters, and recording equipment duly adjusted). The parallel idea of applying to the bored pile, with concrete duly set, the advantages of a hammer "driving set" seems to be novel. The acceptance of fair equivalence of DLT and SLT, although already mentioned, must be recalled because it is not yet widespread. However, putting together these three principal enticements, one sees that all arguments point to a vast potential market for all BORED PILES TO BE SYSTEMATICALLY SUBJECTED TO DRR IMPACTS AND PERIODICALLY TO DLTs. The higher capacity, bigger diameter, bored piles invoke even more cogent reasons for the practice, because SLTs become increasingly cumbersome and expensive, and, on the other hand, the increasing use of high-capacity piles as single supports per column implies heavier responsibility per pile.

Fig.9 presents the results of a 30cm diameter, 6m long augered pile in analogous subsoil profile, investigated by an initial DLT (B) with a follow-up of SLT, comparatively with an equivalent adjacent pile subjected only to the SLT (A), and further, with another driven pile of exactly same dimensions subjected only to the SLT (C). The results are put forth as being of great interest, specifically because of the interpretable differences of load-settlement curves and ultimate loads with regard to foundation design.

The typical lower-capacity and higher deformability behavior of the bored pile is confirmed, and, within the moderately limited strains, also the near perfect coincidence of the DLT and SLT results on the equivalent adjacent augered piles A and B. Meanwhile the analogous driven pile C also gave the expected typical behaviors of very significantly reduced deformability and much increased ultimate load (estimated at over 140 tons).

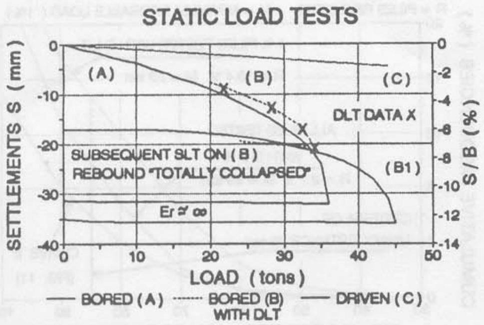


Fig.9 Load-displacement behaviors of bored pile improved by DRR and DLT

Attention is drawn to **1**) the "collapsed" infinitely rigid rebound data of SLTs on Bored A and B1; **2**) the increased rigidity and ultimate load of the SLT (**B**) on the (Bored **B1** with added DLT). In cases, repeated load--unload-reload reproduced such characteristic behavior of **a**) much higher rigidity up to an equivalent pre-load; **b**) a 10-15% increase of ultimate, due to "added penetration" and/or "prestress". Such facts, mostly attributed to "base" or "friction" residual stress, depend on unavailable short and LONG-TERM load distributions. For rebound $E \simeq \infty$ and Nature's relaxation trend we admit residual strains and not stresses. But the trusted behaviors are used to profit while pending explanation.

A typical DRR blow on the bored pile is trusted to produce same benefits as the highest energy (and displacement) of the DLT.

5 SUMMARY CONCEPTS OF FACTORS OF SAFETY, OF GUARANTEE, AND OF INSURANCE

Fig.10 repeats emphasis, cf. de Mello 1981(1), that whereas only one definition of Factor of Safety FS, has been used, we must recognize at least 3 distinct Factors (corrected to incorporate dispersions on Resistance, R, without delving into histograms of acting Stresses, S). FS implies histograms on both S and R. Factor of Guarantee FG is when by some LOWER REJECTION CRITERION(2) we guarantee that the histogram can only be higher than some value (secondary dispersions set aside) already pretested, checked. Obviously FG=1.5 implies higher capacity than FS=1.5. A pile jacked down (MEGA) under 60 tons to penetration/settlement "stoppage" has FG=2 with a working load of 30 tons: if the design R (estimated) is 60 tons it has the conventional FS=2 of lesser guarantee. Setting aside the discussions of dynamic vs. static (sensitive clay, large-strains, etc.) DRIVEN PILES checked by "refusal" observations, DRR, obviously imply factors FG. {(2) for the detailed statistical procedure see de Mello 1959}.

In contrast, BORED PILES suffer from impaired load-settlement behavior, and lacking pretest could suggest FS conditions: however, we realize it is even worse. {**N.B.** The localized "extreme-value" risks and damages during execution cf. Fig.10 are outside present scope, concentrating on post-concreting AVERAGED GLOBAL BEHAVIOR per pile}.

All (geotechnical) advancement aims at minimizing sampling and testing disturbances, for better in situ soil parameters (intact soil elements). Thus the "intact" R distribution curve shifts more to the right, increas-

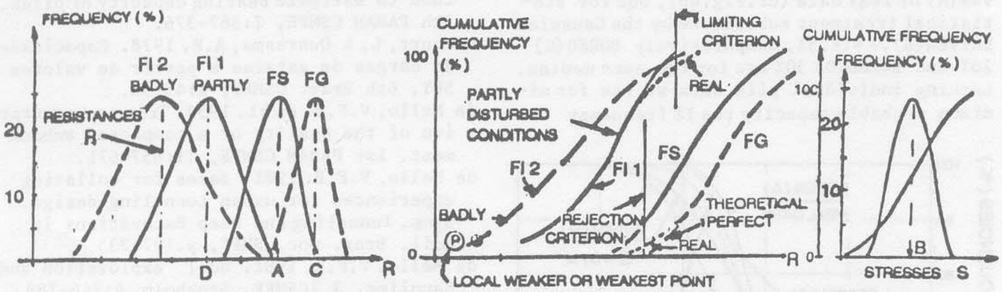


Fig.10 Concepts of FS corrected to incorporate resistance dispersions (cf. de Mello 1981-1)

ing the UNKNOWN DISTANCE (patently not constant) to the disturbed R-histograms FI1, FI2: the assessed intact parameters, integrated by the concreted pile, as test-checked via the HIGHEST SINGLE-PILE CAPACITY STATISTICALLY OBTAINED set an UPPER REJECTION CRITERION. The R-histograms always lowered by varied degrees of execution effects are truncated at the upper value, thus directly opposite to FG, of a lower rejection criterion. Name this ratio of average R/S a Factor of Insurance: insurance is against a loss inevitable to be attenuated.

Thus FI< FS < FG, the differences increasing with higher dispersions. Codes and designs using a fixed FS (e.g. 2) without these distinctions, incur in more trouble if FI is at stake, and in wasted higher safety if FG is at stake.

For Bored Piles advances of time and presumed progress cause 2 basic changes, 1) Unless execution improves exactly compensating as INTACT SOIL PARAMETERS improve, the unknown gap increases. 2) Since EXPERIENCE dictates progress of codes and practices (based on Bayesian adjustment of posterior vs. prior probability estimates/data) we note the psychological bias widely divulged generally denying symmetry of Bayesian DECISIONS: trends are greater towards RISK-AVERSION to avoid losses, than RISK-SEEKING desiring gains (de Mello, 1987). Thus individual failures plaguing bored piles pushed Code prescriptions to severe rejections, now avoidable by systematic DRR hammering on every single pile.

6 BORED PILES WITH DRR OR RESEARCHED BY DLT. BENEFITS WITHOUT CORRECTIVE MEASURES

In Fig.11 we first plot the frequencies DRIVEN(A) of real data (cf.Fig.4b), but for statistical treatment substitute by the Gaussian DRIVEN(B), δ=14.5%. Comparatively BORED(C) 20% and BORED(D) 30% are for the same median. Lacking individual pile data we use for minimum probable capacity the 1% frequency

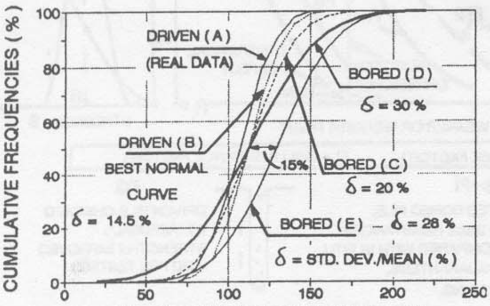


FIG. 11 FAILURE LOADS QR (tons)

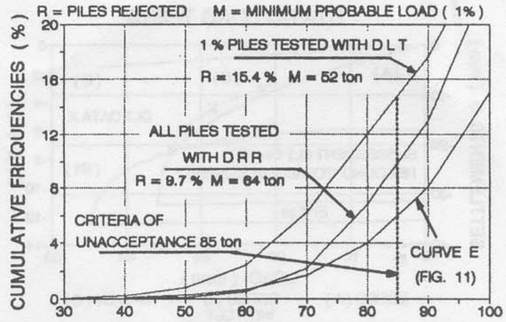


FIG. 12 LOAD CAPACITY OF BORED PILES (tons)

(FS=1.5). Curve BORED(E) is fitted to same limit of 1% R (piles rejected) and requiring a 15% greater median, a typical safe chosen design-aim.

Fig.12 expands the tails of Fig.11: Curve D adjusts A to higher dispersion, and D' comes from D by rejections based on few tests. Benefits-costs exemplified: for a case of 300/15m piles cost increases 7% by DRR checking on all, against good savings via 15% increased QR (cf. Fig.9) and reliance on FG vs. FS permitting relaxed requirements. Meanwhile "researching" by 3 DLTs (1% of piles) increases cost 1.8% with no true benefit. Final benefits derivable by acting on" the DRR, increasing energies on weaker piles detected.

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