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Report on the B.E.S.T. prediction survey

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ABSTRACT. A prediction event organized in connection with the 3rd Bolivian International Conference on Deep Foundations attracted 72 contributions from all parts of the world predicting response to loading of four single piles, three tested in by head-down method and one by bidirectional method. The piles were constructed by different methods: one bored with slurry, one continuous flight auger, and two full displacement of the soils, one of which was the bidirectional pile. The predicted load-movement curves differed within a wide range. Most participants underestimated the actual pile response determined in subsequent static loading tests. The predictors were also asked to assess the capacities from the predicted load-movement response and the methods used and assessed values differed considerably. After all prediction had been submitted, static loading tests were performed on the piles. The participants were given the actual test results and asked to assess and submit capacities from the actual tests. The low and high of the assessed capacities ranged widely, making it clear the profession's concept of capacity deviates significantly between practitioners and not just between countries, but also within.

1. INTRODUCTION

In connection with the 3rd Bolivian International Conference on Deep Foundations, Santa Cruz de la Sierra, Bolivia April 27 - 29, 2017, site investigations were performed at the Bolivian Experimental Site for Testing Piles (B.E.S.T.) employing boreholes (SPT), cone penetrometer tests (SCPTU), pressuremeter tests (PMT), and dilatometer tests (DMT). The site investigation results have been reported in Volume 2 to the conference. The B.E.S.T. also included a total of 26 static and 4 dynamic tests constructed using different methods and employing different features for stiffening the pile response to load. The static tests of four single piles were selected for a prediction event. One pile (Pile A3) was drilled with slurry, one (Pile B2) was constructed with a continuous flight auger, and two (C2 and E1) were constructed by full displacement equipment. Piles A3, B2, and C2 were tested in head-down tests and Pile E1 by means of a bidirectional test. Pile E1 was supplied with an expanded base (EBI) with post-grouting at the pile toe. The others were straight-shaft piles.

Two months before the tests (January 2017), the profession was invited to submit predictions of the load-movements to be measured in the tests and to assess the capacity from these curves as well as predict the distribution of load in the piles at the so-assessed capacities. The invitees confirming interest in participation were supplied with the site and pile details. A few declined addressing the bidirectional test due to insufficient experience of this test method. Some submitted only the load-movement curves and no load distribution. All who submitted a load-movement prediction were then sent the results of the actual tests and asked to assess the tests as to pile capacity. The prediction of any group or individual are not disclosed to anyone.

A prediction event is a source of entertainment with a serious content. They usually attract considerable interest at many international and national conferences and this well beyond the conference attendees. I experienced recently a couple of such international geotechnical prediction events where the organizers, after receipt of predictions, requested payment from the participants and discarded received predictions when the predictor declined to pay. Moreover, the results were not disclosed to the participants, who had to wait for and purchase a summary publication of the results. I consider such events to be poorly and unprofessionally organized and hope they will not have followers.

A prediction event, such as the one reported here, must not be thought of as the same as a design effort. The main difference lies in the fact that a design involves liability while the only risk in submitting a prediction is for one's pride. Moreover, the effort that goes into a design of an actual piled foundation is that, in the latter, the engineer will have experience, or access to experience, of how other piles have responded at the site including construction methods and contractors' past performance, or no commitment will be made until results of suitable full-scale tests and other pertinent observations are available. The prediction presumes no such information.

It should be noted that the prediction pertained to the load-movement response of the test piles and that the part on the pile "capacity" was not a prediction, but an assessment. The following presents a compilation of the predictions and assessments.

2 SUBMITTED PREDICTIONS

2.1 Participants

A total of 72 separate predictions were submitted by 121 individuals from 30 different countries. Ten of the submissions were received from members of ISSMGE TC212. Appendix A lists the names, affiliation, and coordinates of all participants submitting predictions. A total of 94 of the 121 individual participants (54 of the 72 predictions) responded also to the second part of the survey and assessed the pile capacities as determined for the actual tests. While a couple of submissions were from students learning about analysis of pile response to load, most were submitted by practicing engineers and researchers knowledgeable in the field. Indeed, several of the participants are widely recognized for their expertise. I consider the results of the prediction survey to represent the current state-of-the-practice of analysis of pile response to load, i.e., what we know today and of what we typically accomplish in estimating expected pile response and how we assess the results of a static loading test.

2.2 Compiled Submissions

All submitted prediction results are presented in the graphs placed at the end of this paper. The diagrams have been separated on each pile type, Piles A3, B2, C2, and E1, respectively.

Figures 1, 6, and 11 compile all predicted pile-head load-movement curves. Figure 16 compiles the predicted upward and downward load-movement curves for Pile E1, the bidirectional test-pile. Each diagram is supplemented with the actual load-movement curve.

Figures 2, 7, and 12 show the assessed pile capacities of the three head-down tests and Figure 17 shows the submitted equivalent head-down tests constructed from the predicted Pile E1 tests. Each of the red dots in the graph indicates the capacity submitted as assessed from the curve by the submitting predictor.

Figures 3 and 4, 8 and 9, and 13 and 14 show the predicted distributions of load and shaft resistances for the head-down tests, as calculated for an applied load equal to the assessed capacity.

Figures 5, 10, and 15 show the plot of toe resistance (obtained from the load distribution data) versus the pile movement (pile shortening was negligible) for the load equal to the assessed capacity.

Figures 18A and 18B through 20A and 20B show a compilation of the predictors' assessment of pile capacity of the actual pile tests (54 participants). The A-part of the figure pairs shows the actual pile-head load-movement curve with the assessed capacities. The B-part shows the normal distribution of the capacity values and the corresponding standard variation (σ). The double-arrow indicates the range of capacity between one standard deviation below and beyond the average value. The average is the intersection of the double-arrow and the test curve.

2.3 Comments

In predicting pile-head load-movement curves, the participants relied on different sets of the site investigation results. Some elected only to use the SPT N-indices. Others used mainly the CPTU records applying different correlations to the cone stress records. A few preferred to rely on the pressuremeter records. Only one reported having used the dilatometer records. A few, like me, used "engineering judgment" and records of past tests (results of the test performed in connection with the 1st and 2nd Conferences). Many included a list of references for background information to their predictions.

A variety of software was used for the calculations: Plaxis 2D and 3D, Flac 3d, Piglet, CPeT-IT, SHAFT 2012, UniPile5, Piver by ISTAR, Apile5, Repute, general finite element methods, company internal software, Mathlab, and personal Excel sheet templates. Effective stress analysis appears to have been used by most, though a couple reported using total stress analysis with reference to literature for sources of shaft and toe resistances.

The range between underestimated and overestimated stiffness responses of the predicted load-movement curves is wide. For Pile A3 (Figure 1), an eyeballed average prediction curve would not be too far off from the actual test curve, albeit slightly stiffer than the actual. For Piles B2, and C2 (Figures 6 and 11), the predictions generally underestimated the pile stiffness.

A CFA pile is generally expected to produce a somewhat larger shaft resistance as opposed to a bored pile. Both piles are considered to show small toe stiffness due to debris collected at the bottom of the shaft despite cleaning efforts. The fact that the concrete in the CFA-pile, Pile B2, was placed by pressure-grouting may have increased its shaft resistance, a fact that was not known to the predictors (nor to me), when submitting the prediction. The predictions were quite shy of the actual pile response also for Pile C2, the pile constructed by full-displacement method (FDP). This may again be because the predictors may not have sufficient experience of this full-displacement construction method and how much it enhances the pile shaft resistance.

The law of averages ensures that some of the predicted load-movement curves must be close to the actual and a couple are. I have not checked whether a predictor whose prediction was close to the actual results on one test, also produced predictions close to the other tests. The prediction event is not a competition and no "winner" will be announced. All predictors have received copies of the actual test results and can judge for themselves as to how close or distant their predictions were from the actual pile response. All test results are also available for downloading from the 3rd CFPB web site.

Each participant also submitted a pile capacity value as assessed from their predicted load-movement curves. Note, this capacity is not a prediction, but a value that anybody applying the same definition (and judgment) would determine from the prediction curve. Some of the participants defined capacity as the load that produced a movement equal to 5 % of the pile head diameter. Some choose to use 10 % of pile diameter—no doubt in the common and quite erroneous belief that this a definition proposed by Terzaghi (Likins et al. 2011). Terzaghi stated the opposite; that no one should define a capacity unless the pile toe had moved a distance equal to at least 10 % of the diameter, and, N.B., that the then determined capacity could be smaller or larger than the load that produced that movement. The strange 10-% definition of capacity has lately slithered into the current geotechnical tool box due to it being incorporated—"endorsed"—by some major codes.

In assessing capacity, many applied the Davisson offset limit. A few defined the capacity as the load that resulted in a 10 mm pile head movement (regardless of pile diameter), or 25 mm, or adopted my approach that the load that caused a 30 mm pile toe movement is a reasonable value to use when now a capacity just has to be proclaimed. Others took the definition of capacity as the "ultimate resistance" to heart and indicated a capacity as the load that produced additional movement without any appreciable increase of load (when that trend was in their predicted load-movement curve). A few fitted the curves to either a Hansen 80-% function (parabolic) or a Chin-Kondner function (hyperbolic) and applied the capacity definition built into these curves. Two applied DeBeer's double-logarithmic method. A couple mentioned applying the Butler-Hoy method of the capacity being the intersection of two tangents to the load-movement curve. One participant predicted that the pile would show a post-peak softening response and defined capacity as equal to the peak load. Indeed, one participant, commendably, declined submitting a capacity contending that such assessment has no meaning.

The wide range of values shown in each of Figures 2, 7, and 12, and, even more so, in Figures 18A, 19A, and 20A, where the participants' capacity assessments were applied to the load-movement curves of the actual tests, makes it obvious that, while "capacity" might be considered a rather simple and direct concept, the profession assesses it from a wide variety of definitions, methods, and principles.

Figures 3, 8, and 13 show the load distributions for the head-down test piles when the applied load was equal to the capacity assessed from the predicted load-movement curve. The load distributions, be the predictions for shaft or toe resistance, show more or less equally large spread.

As toe resistance is generally manifested as a gently curving line for which an average slope can be thought representative of a pile-toe stiffness, the spreads between soft and stiff responses shown in Figures 5, 10, and 15, pretty well covers all potential pile toe responses, but for piles in very dense soil or on bedrock. It would seem that the profession does not have a solid feel what contribution to a pile response is coming from the pile toe.

Figure 16 shows the predicted response of Pile E1 to the bidirectional test. Unfortunately, the telltale measuring the BD cell downward movement did not function. However, judging from other BD tests on Expander Base equipped piles at the site, the movement will have been very small. Naturally, the predictors could not be expected to foresee the very definite improvement of the pile toe response provided by the Expander Base addition to the pile. Moreover, similarly to the head-down test on Pile C2, the other FDP pile, several predictions underestimated the improvement of the FDP construction method on the pile shaft resistance.

Figure 17 shows the Pile E1 equivalent head-down test construed by the participants from their predicted bidirectional curves and the capacities that each assessed from their curves. The curves were mostly produced by combining the upward and downward load-movement curves for equal movements and adding the piles shaft compression (almost nil in this case) to this. Such construction does not consider the fact that a bidirectional test engages the deeper located stiffer soils first and the more shallow soils last, while the head-down test does the reverse. The UniPile5 software has this effect built into the coding for calculating bidirectional and head-down tests from a soil-profile input. However, for these short and axially very stiff piles, the difference in response is minimal between loading from near the pile toe as opposed to loading from the pile head, in contrast to the case for long piles with larger amount of compression for the loads.

3. CONCLUSIONS

This said, the spread of the predicted pile-head load-movement responses certainly gives reason for reflection. The spread of the subject survey is not unique, but rather similar to many other prediction surveys. The spread pertains to both a limit value of load and to the movement required to mobilize this. No trend was discernible that could relate difference with regard to domicile of the predictor.

Most distressing is that the profession does not have a common understanding of the concept of capacity. Some may agree with me, as one predictor appeared to do, that "capacity" is a flawed and unnecessary concept that we would do well to abandon. However, the fact is that the prevailing design practice and most Codes and Standards do require a pile capacity value. Some such even define how to determine a capacity. For example, the EuroCode compels defining capacity as the load that gave a movement equal to 10-% of the pile diameter. However, I do not know of any structure that would care one whit about the diameter of the piles providing the support. Some definitions do make sense, e.g., letting the "capacity" to apply in the design effort be determined by a movement limit. A problem is that a "capacity" and its downgraded value after applying a safety factor or resistance factor correlate poorly to a limit of movement (settlement) for the piled foundation.

If fact, we do not need to base our designs on a "capacity". The response of the piles to load can easily be discussed—conservatively, of course—in terms of movement (settlement) for the actual foundation loads. Addressing the settlement for the sustained load on the foundation is certainly addressing the true issue of piled foundation design and a more rational approach than pursuing it in relation a load-value that will not ever be imposed by the structure or demanded from the soil.

Reference

Likins, G.E., Fellenius, B.H., and Holtz, R.D., 2011. Pile Driving Formulas—Past and Present. ASCE GeoInstitute Geo-Congress Oakland, March 25-29, 2012, Full-scale Testing in Foundation Design, State of the Art and Practice in Geotechnical Engineering, ASCE, Reston, VA, M.H. Hussein, K.R. Massarsch, G.E. Likins, and R.D. Holtz, eds., Geotechnical Special Publication, GSP 227, pp. 737-753.

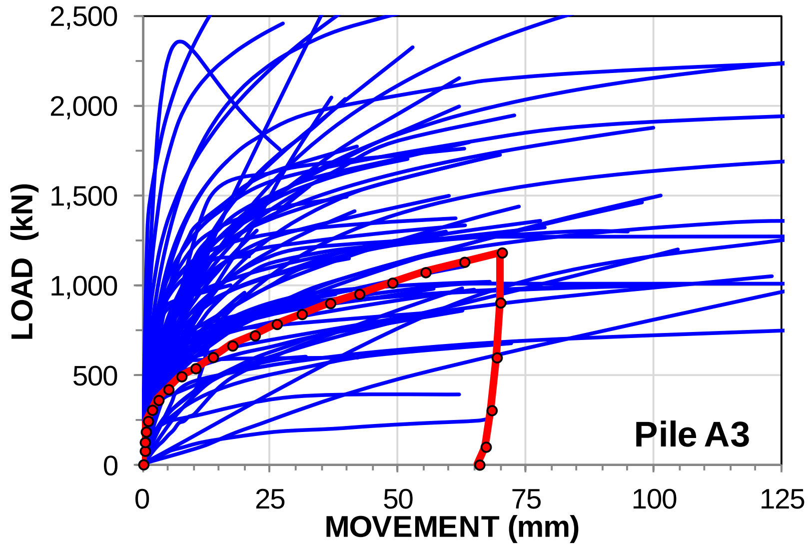

Fig. 1. Pile A3. Predicted and actual head-down tests pile-head load-movements.

Pile A3 was constructed as a bored pile excavated using bentonite slurry. The nominal diameter of the pile is 620 mm. The as-used concrete volume corresponds to 670 mm average actual diameter, but this is a very approximate value. The as-is pile depth was the designed depth, 9.3 m. Construction and test dates were March 8 and March 20, respectively.

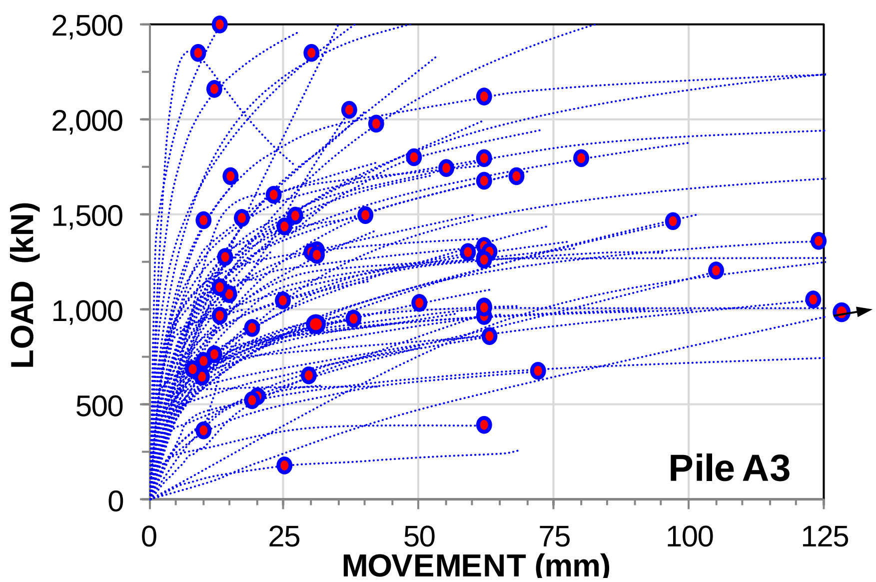

Fig. 2. Pile A3. Predicted pile-head load-movements and the respective assessed capacities.

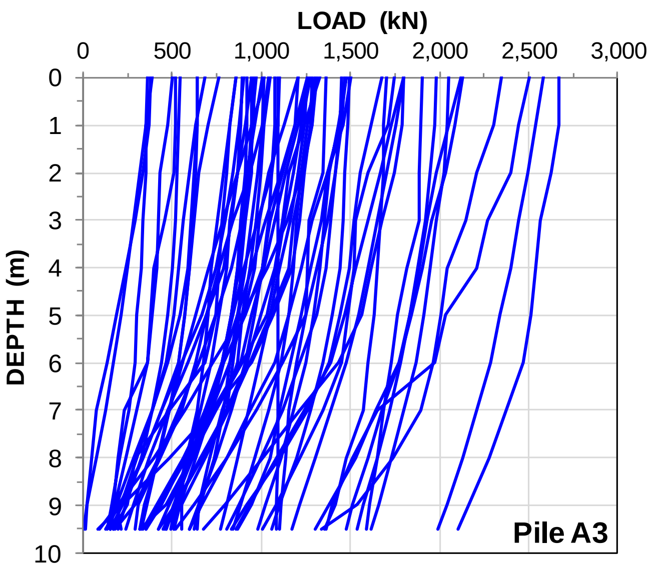

Fig. 3. Load-distribution at 'capacity'.

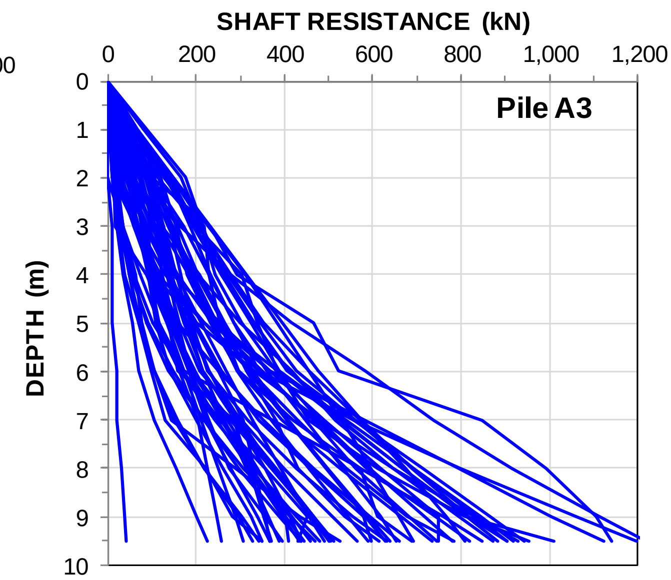

Fig. 4. Shaft resistance distribution at 'capacity'.

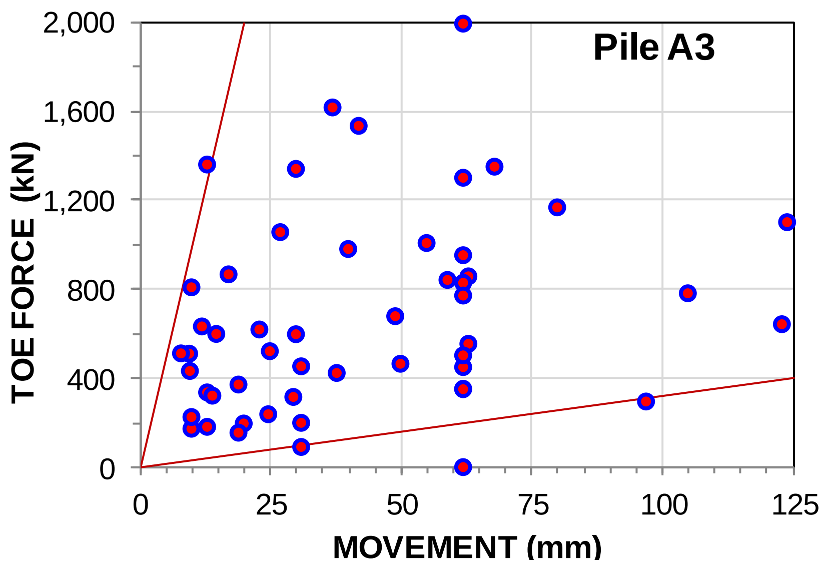

Fig. 5. Pile A3. Toe force at 'capacity' plotted at predicted toe movement.

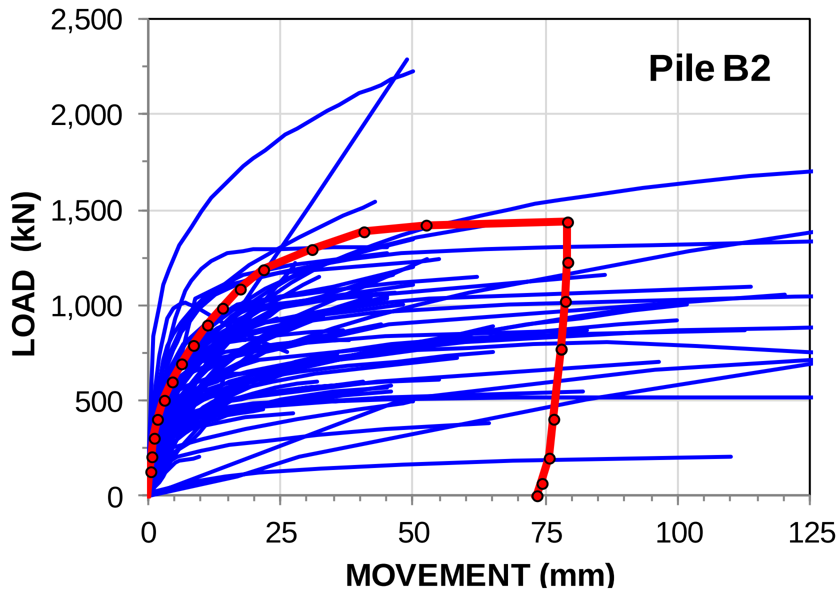

Fig. 6. Pile B2. Predicted pile-head load-movements and the respective assessed capacities.

Pile B2 is a CFA-constructed pile. The concrete was placed by pressure-grouting as opposed to gravity flow. The nominal diameter of the pile is 450 mm. The as-used concrete volume corresponds to 445 mm average actual diameter, which is practically the same value. The as-is pile depth was the designed depth 9.3 m. Construction and test dates were March 11 and March 23, respectively.

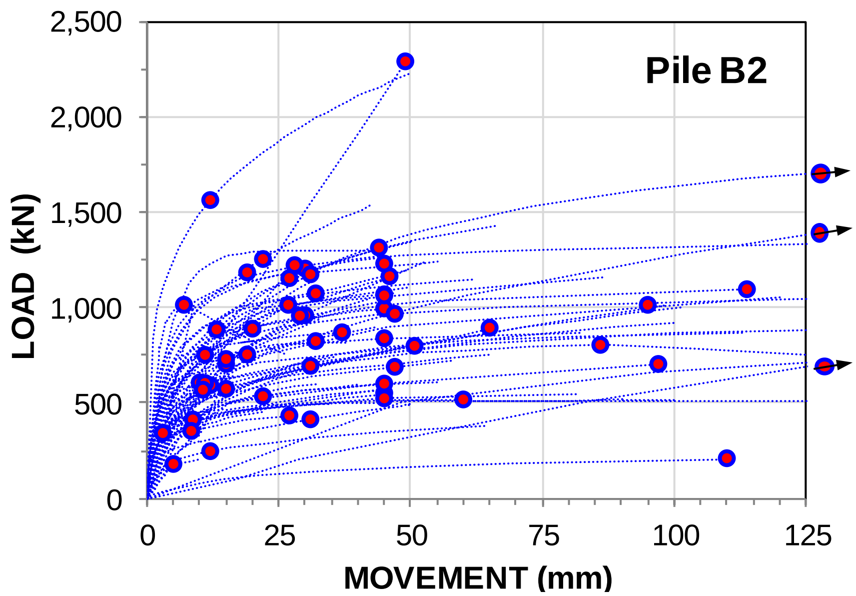

Fig. 7. Pile B2. Predicted pile capacities with predicted pile-head load-movement curves.

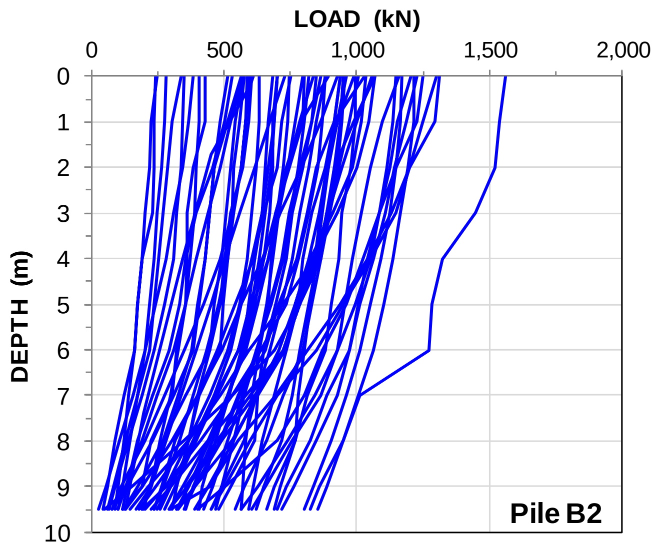

Fig. 8. Load-distribution at 'capacity'.

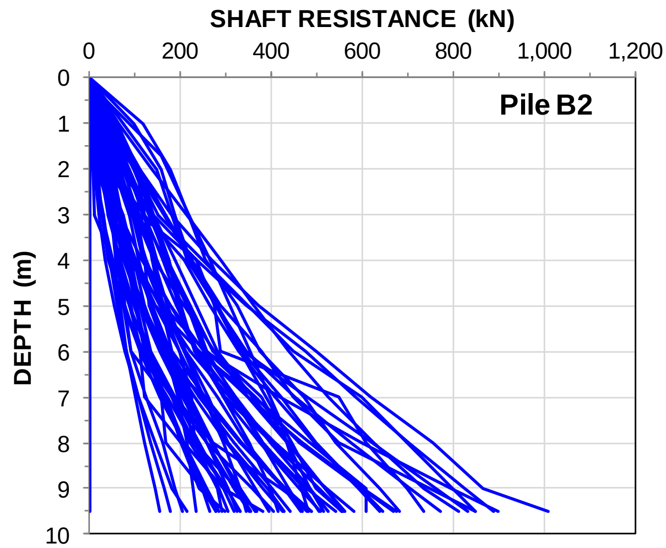

Fig. 9. Shaft resistance distribution at 'capacity'.

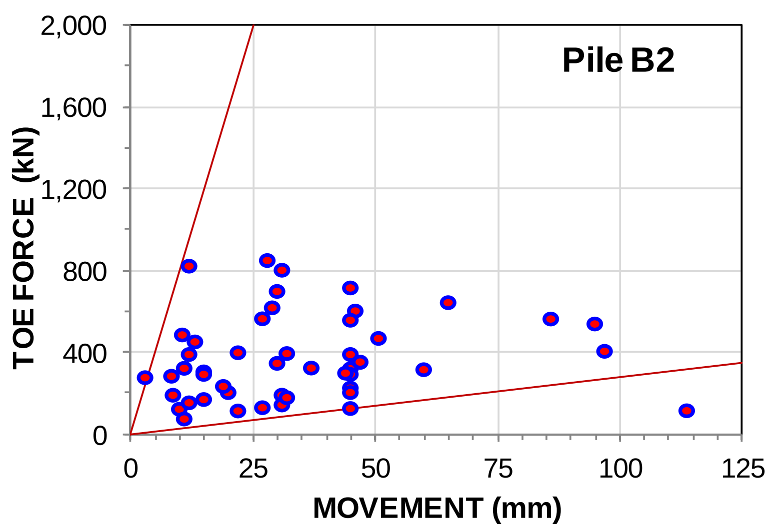

Fig. 10. Pile B2. Toe force at 'capacity' plotted at predicted toe movement.

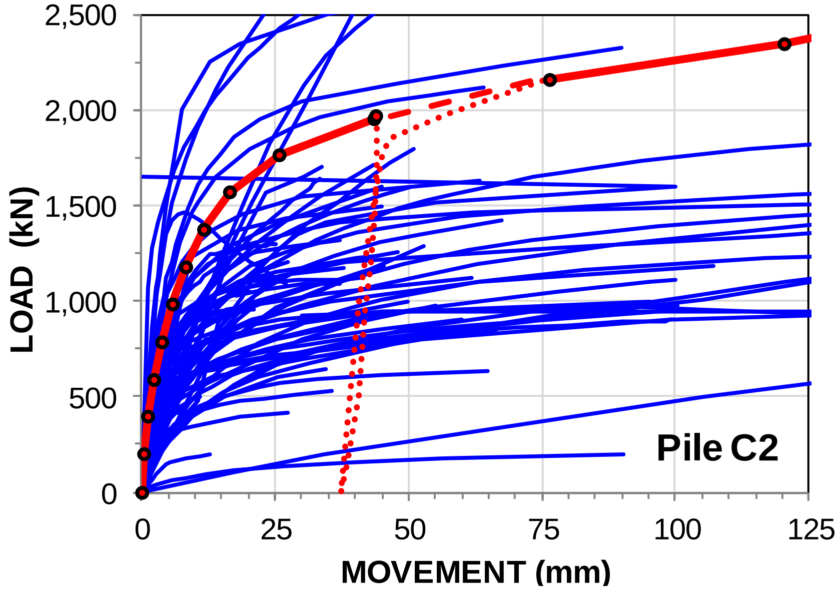

Fig. 11. Pile C2. Predicted pile-head load-movements and the respective assessed capacities.

Pile C2 is a Full Displacement Pile (FDP)-constructed pile. The concrete was placed by pressure-grouting. The nominal diameter of the pile is 450 mm. The as-used concrete volume corresponds to 446 mm average actual diameter, which is practically the same value. The as-is pile depth was the designed depth, 9.3 m. Construction and test dates were March 7 and March 25, respectively. The pile was reloaded to have the pile-head movement (at least 75 mm and beyond) as was the movement for the other piles.

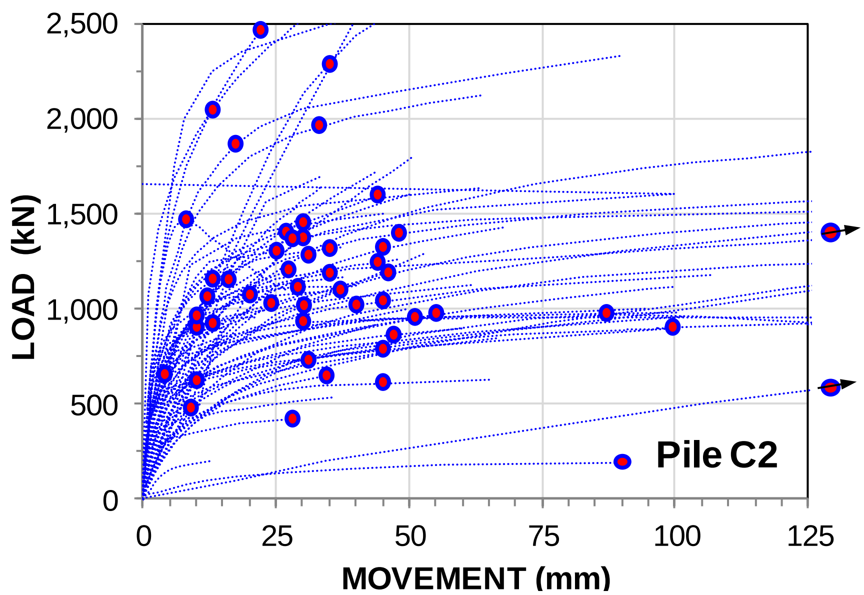

Fig. 12. Pile C2. Predicted pile capacities with predicted pile-head load-movement curves.

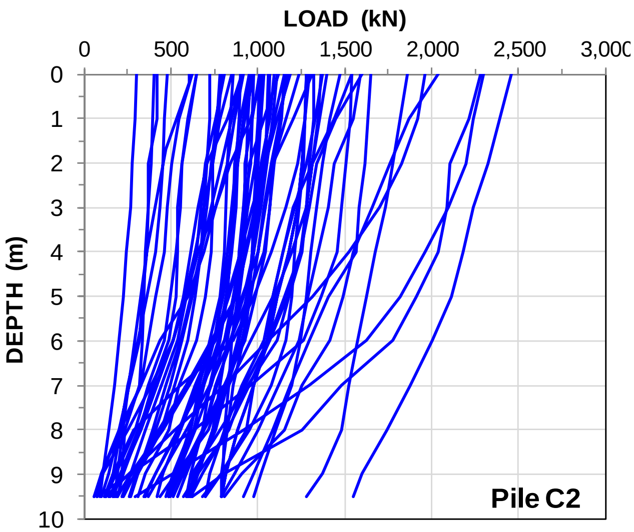

Fig. 13. Load-distribution at 'capacity'.

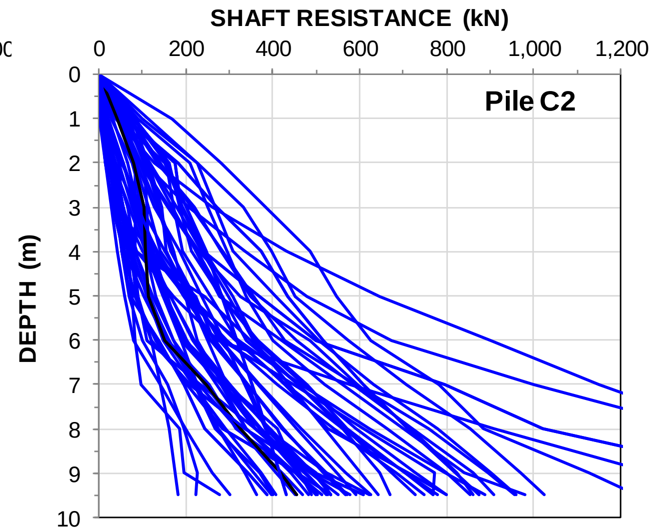

Fig. 14. Shaft resistance distribution at 'capacity'.

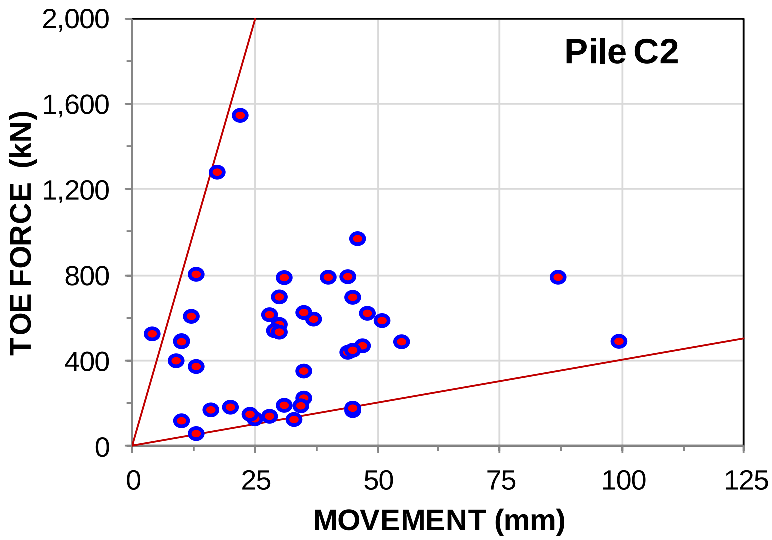

Fig. 15. Pile C2. Toe force at 'capacity' plotted at predicted toe movement.

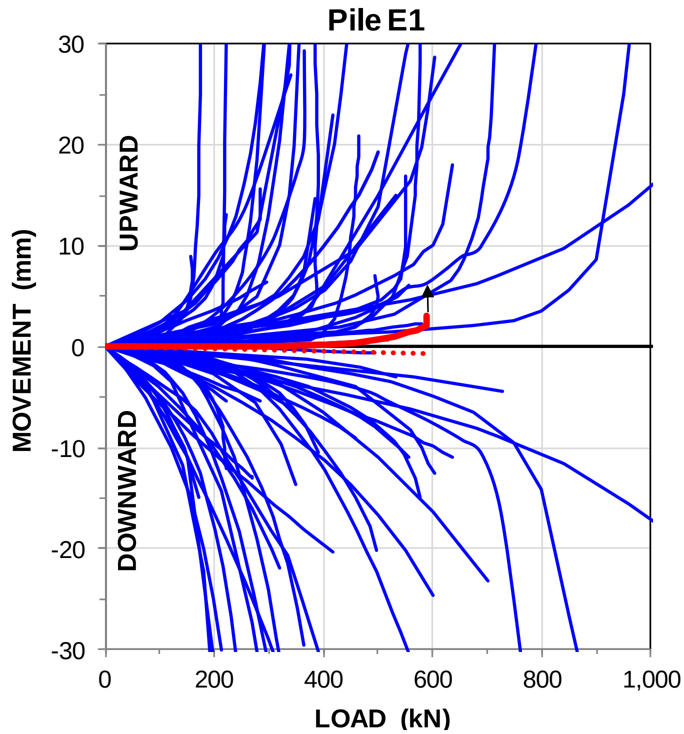

Fig. 16. Pile E1. Predicted upward and downward bidirectional load-movement curves.

Pile E1 is a Full Displacement Pile (FDP)-constructed pile and installed with an EB expanded to 300 mm width. The concrete was placed by pressure-grouting. The nominal diameter of the pile is 300 mm. The as-used concrete volume corresponds to 316 mm average actual diameter, which is practically the same value. The as-is pile depth to the end of the reinforcement cage was as designed, 9.3 m. The bottom of the bidirectional cell was at 8.3 m depth. Construction and test dates were March 10 and March 22, respectively.

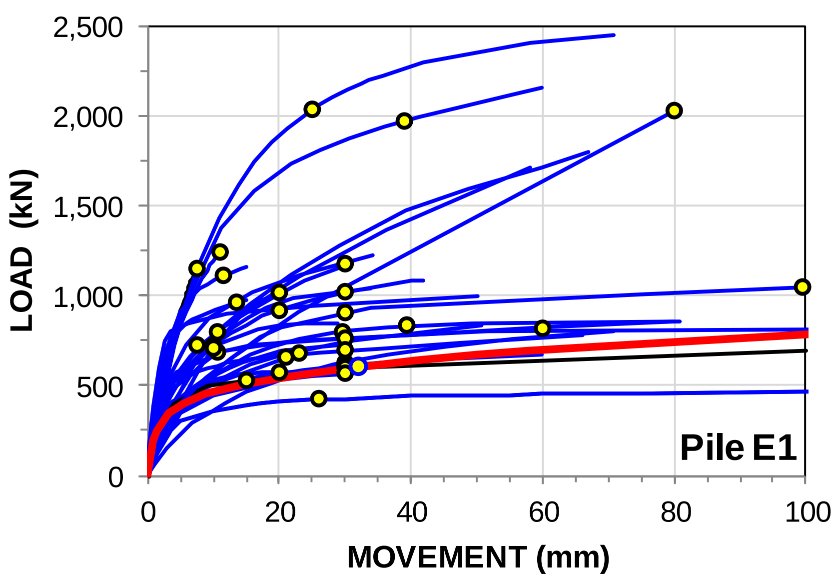

Fig. 17. Pile E1. Equivalent pile-head load-movement curves with assessed 'capacities'.

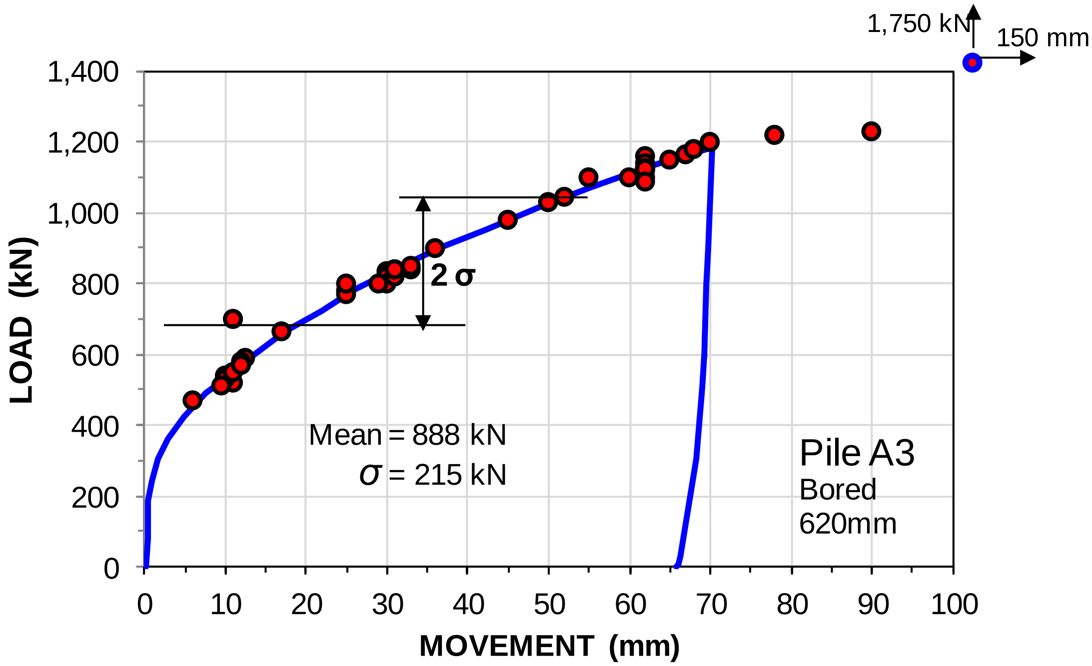

Fig. 18A. Pile A3. 54 'capacities' assessed from actual pile-head load-movement curve by 94 participants.

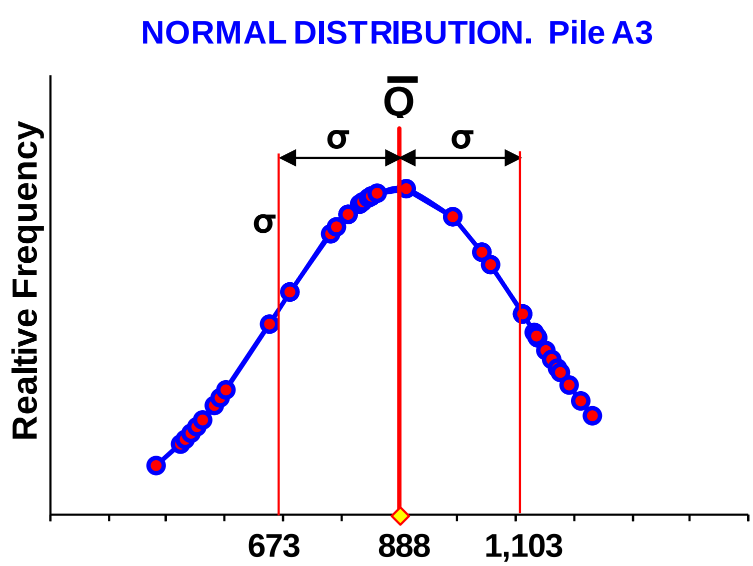

Fig. 18B. Pile A3. Normal distribution of capacities assessed from the actual test by 94 participants. The 1,750-kN outlier value is not included in the normal distribution calculations.

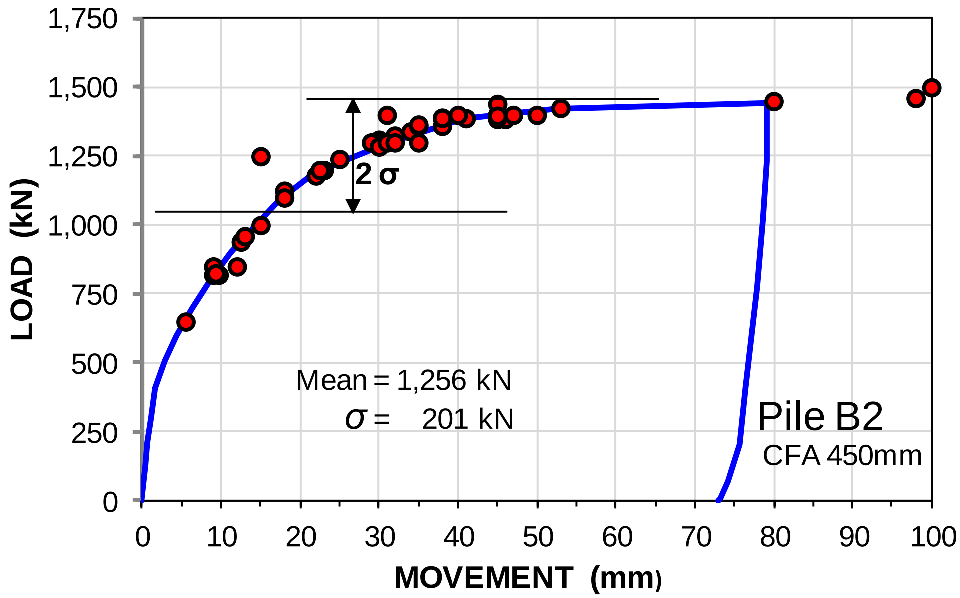

Fig. 19A. Pile B2. 54 'capacities' assessed from actual pile-head load-movement curve by 94 participants.

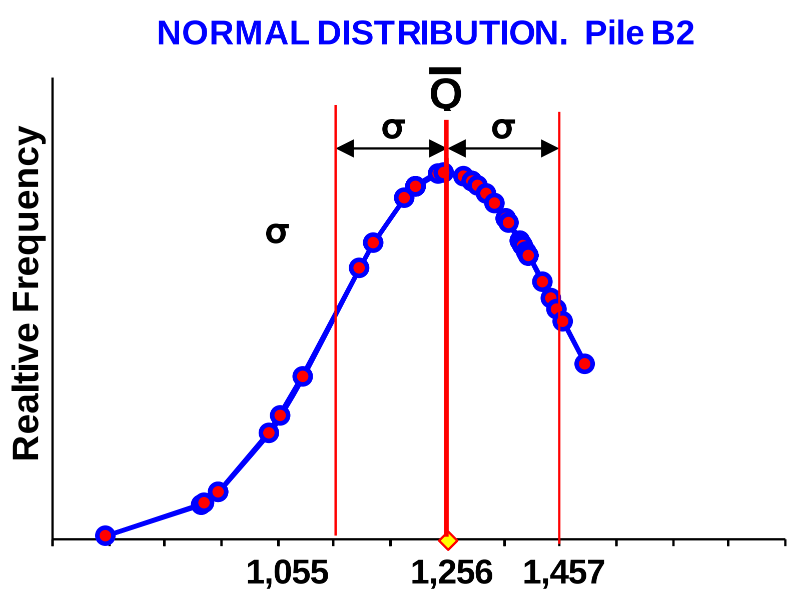

Fig. 19B. Pile B2. Normal distribution of capacities assessed from the actual test by 94 participants.

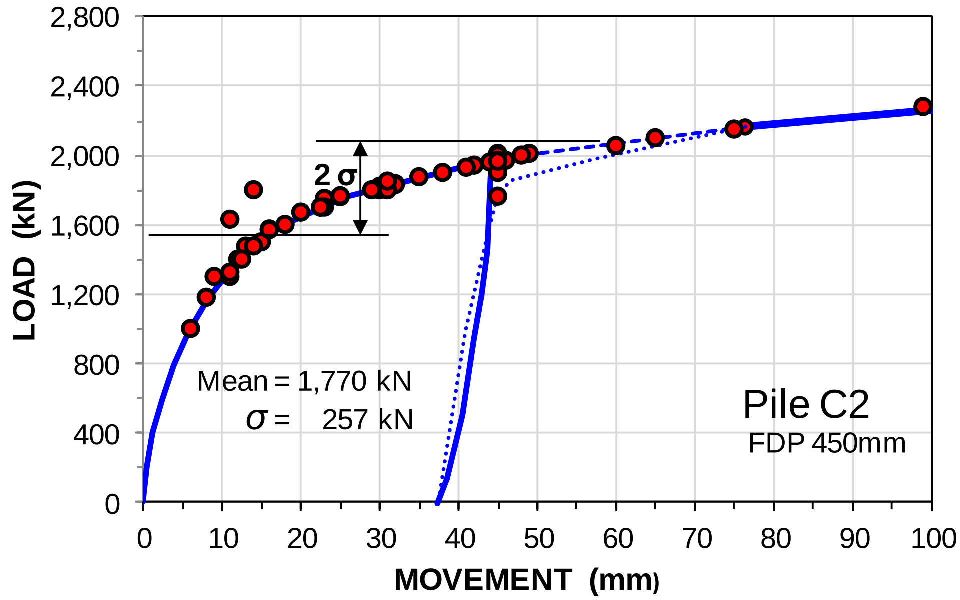

Fig. 20A. Pile C2. 54 'capacities' assessed from actual pile-head load-movement curve by 94 participants.

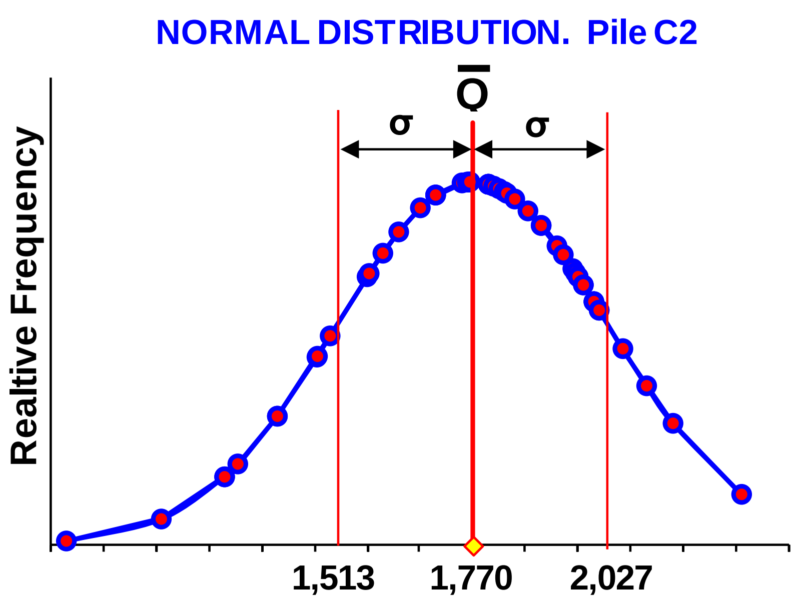

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Fig. 20B. Pile C2. Normal distribution of capacities assessed from the actual test by 94 participants.

Appendix A

Prediction Participants

(participants shown in **bold** have submitted prediction papers which have been included in Volume 3: B.E.S.T Predictions)

Abchir, Zineb, University of Paris, Champs-sur-Marne, France
Abrams, Tim, Terracon, Dallas, TX, USA
Affi, Liiban, Foundation Engineering Consultants, Anaheim, CA, USA
Akcakal, Önder, ZETAS Zemin Teknolojisi A.S., Istanbul, Turkey
Albuquerque, Paulo, University of Campinas, Sao Paulo, Brazil
Aljanabi, Hijran, Ferdowsi University of Mashhad, Mashhad, Iran
Amorim, R. K., Egenharia Geotecnica, Brazil
Bandeira, Neto L.A., Egenharia Geotecnica, Brazil
Basile, Francesco, Geomarc Ltd., Messina, Italy
Behroozian, Khalil, AUT, Tehran, Iran
Bejancu, Ion, AATech, Ottawa, ON, Canada
Bohn, Cecilia, Keller Holding, Frankfurt, Germany
Burlon, Sebastien University of Paris, Champs-sur-Marne, France
Buttling, Stephen, National Geotechnical Consulting, Yaltala, QLD, Australia
Camacho, Boris, UMSS-Laboratorio de Geotecnia, Cochabamba, Bolivia
Camacho, Marco Antonio, UMSS-Laboratorio de Geotecnia, Cochabamba, Bolivia
Chan, Kim F., GHD Pty Ltd, Atarmon, Australia
Chaudary, Sikander, Dente Engineering, New York, NY, USA
Comodromos, Emilios, University of Thessaly, Greece
Crawley, Charles, GeoEnvironmental Resources Inc, Virginia Beach, VA, USA
Cunningham, John, Alder Geotechnical Services, Portland, OR, USA
Dajani, Tareq, Vancouver, BC, Canada
de Chaunac, Henri, UCL, Louvain-la-Neuve, Belgium
Decourt, Luciano, Decourt Eng., Sao Paulo, Brazil
Dei Svaldi, Andrea, University of Venice, Venice, Italy
Edwards, Stuart, Michael Baker Int. Inc., Pittsburgh, PA, USA,
Eriksson, Håkan, Geomind, Stockholm, Sweden
Eslami, Abolfazl, AUT, Teheran, Iran
Fakharian, Kazem, AUT, Tehran, Iran
Fellenius, Bengt, BKFC, Sidney, BC, Canada
Ferreira, Diogo, University of Coimbra, Coimbra, Portugal
Fiorelli, Federico, Teleios srl, Castel Maggiore, Italy
Franceschini, Marco, Teleios srl, Bologna, Italy
Frank, Roger, University of Paris, Champs-sur-Marne, France
Gao, Youi, China
Gharsala, Haythem, UCL, Louvain-la-Neuve, Belgium
Gidely, Iain, Thurber Engineering, Calgary, AB, Canada
Grazina, José, University of Coimbra, Coimbra, Portugal
Greaber, Steve, Terracon, Dallas, TX, USA

Gunjan, Shimant, Fugro, Dubai, UAE
Gwizdala, Kazimierz, Gdansk University, Gdansk, Poland
Haghi, Iman, Cathie Associates, Nanterre, France
Harris, Dean, CH2M, Sacramento, CA, USA
Holeyman, Alain, University de Louvain, Louvain-la-Neuve, Belgium
Hosseininia, Ehsan Seyedi, Ferdowsi University of Mashhad, Mashhad, Iran
Iamato, K Y., Egenharia Geotecnica, Brazil
Illingworth, Fernando, Tecnac Subterra, Guayquil, Ecuador
Jeong, Sang Seom, Yonsei University, Seoul, Korea
Jesswein, Markus, Ryerson University, Toronto, ON, Canada
Jhalani, Mohit, NTPC Ltd., Noida, India
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