What is Capacity

Is the concept at all useful?

By Bengt H. Fellenius, Dr. Tech

In his March 1973 Rankine Lecture, W.T. Lambe stated, "*A prediction is a forecast of some event yet to take place... Predicting constitutes an integral component – the very heart – of the practice of civil engineering... Geotechnical engineering is especially damned and blessed by the importance of predictions and the difficulty of making accurate predictions... The soil engineer is usually forced to work with insufficient and inaccurate information as he attempts to determine and delineate the actual situation.*"

Earlier the same month, Lambe organized an event at the Massachusetts Institute of Technology (MIT) that was the first pile prediction seminar. It addressed the force distribution of a pile subjected to downdrag with predictions from six invited professionals with Ralph Peck as referee.

The surveys reveal a real problem in our industry, and a serious one.

Background: kentoh/123RF

Since then, over the past 50 years or so, several additional pile prediction events have been organized. The results have often served as an entertaining piece at a conference. In 1986, Mike O'Neill organized the first prediction addressing capacity that was to be determined in a following static loading test. In 1988, an open-to-all prediction survey (unpublished) was performed in Raleigh, N.C. (DFI 1988). The outcome is shown in **Figure 1**. The pile was a precast concrete pile, 12.5 inches in diameter, driven to 45 feet in a silt and sand deposit. The figure shows an array of capacities predicted by the 60 event participants in the morning of the day the test was carried out. The array is superimposed by the load-movement curve of the test pile. Great entertainment and great food for thought.

In 2002, a capacity prediction event in Orlando, Fla., was arranged in reference to a loading test on a 46-foot-long, 12.75-inch-diameter, closed-toe pipe pile driven into loose to compact fine sand to slightly silty sand (Fellenius et al., 2002). The event attracted 31 predictors. As indicated in **Figure 2**, the test was terminated prematurely when the contractor's prediction of capacity and, therefore, also the amount of kentledge trucked to the site was short – obviously, the prediction of some participants is more important than that of some of the others.

Figure 3 shows the compilation of predictions of capacity of an event organized at the ISC'2 conference in Lisbon 2004 (Fellenius et al., 2007) addressing a 600-mm, six-meter-long bored pile installed in a saproplite composed of silty and clayey sand.

The results of the three prediction surveys are very similar in regards to the spread of capacities. However, no information

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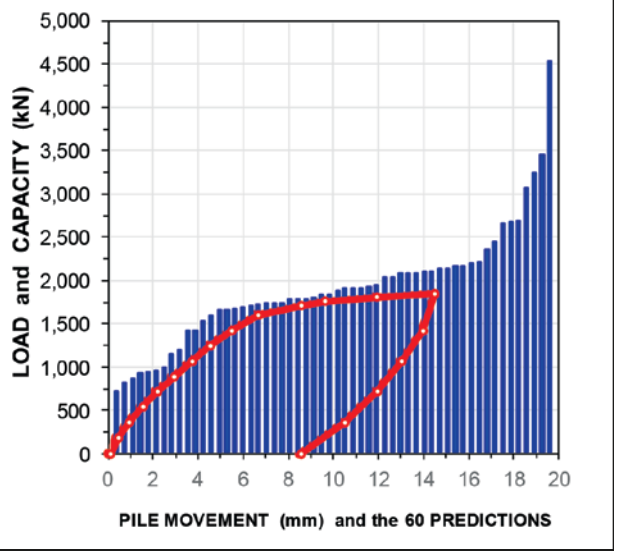

Fig. 1 Raleigh 1988

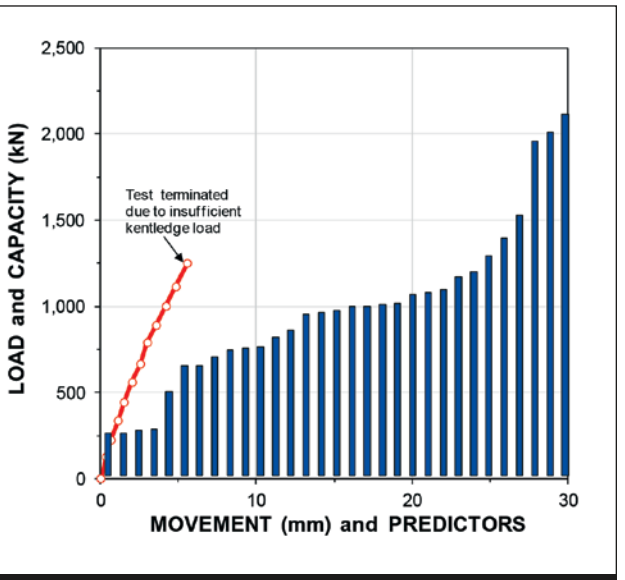

Fig. 2 Orlando, FL

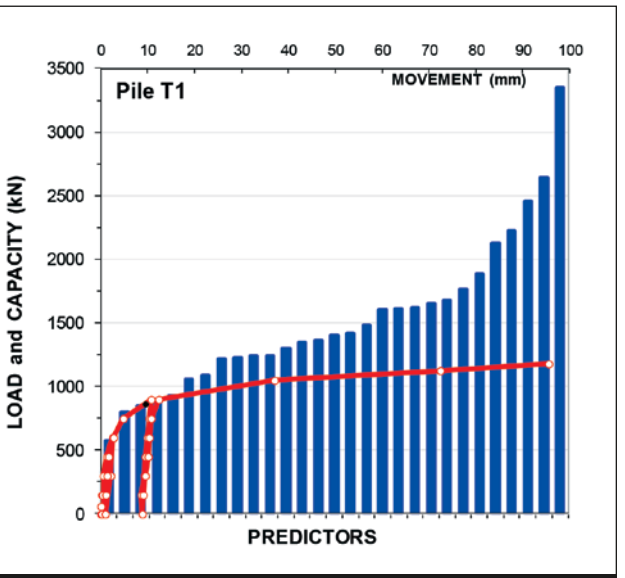

Fig. 3 Lisbon 2004

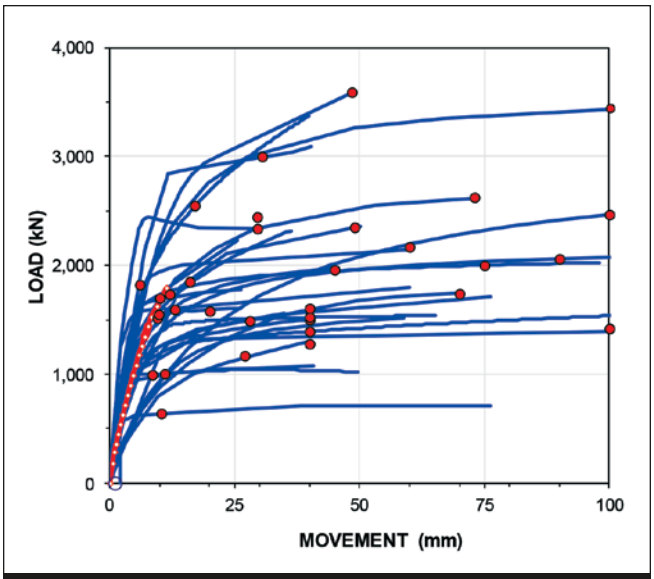

Fig. 4 Edmonton, AB 2011

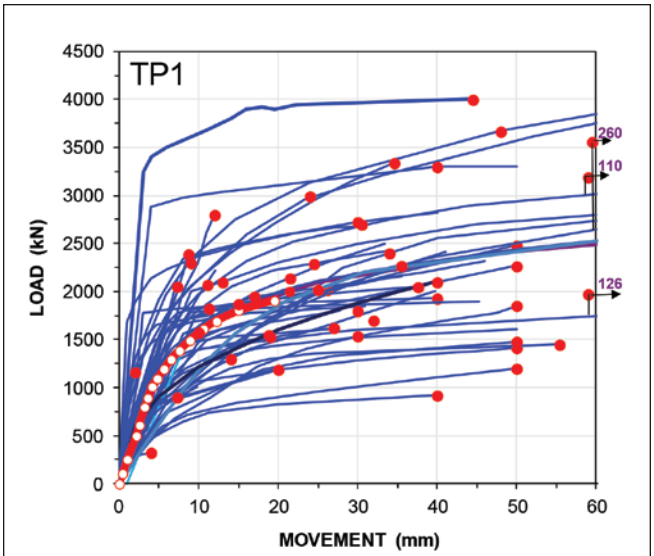

Fig. 5 Bolivia 2015

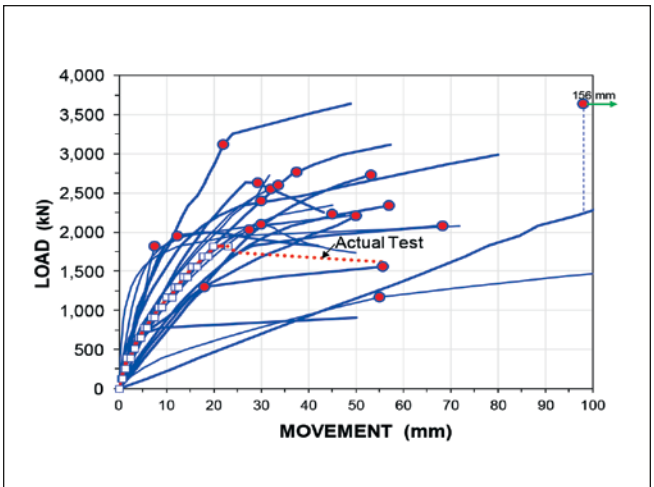

Fig. 6 Göteborg 2018

was presented on how the participants defined capacity and no capacity interpretation was offered in regard to the actual load-movement curves.

"Capacity" is a one-point value. One predictor may have applied a definition of capacity of little relevance to the load-movement curve measured for a test pile, whereas another may be using a definition that happened to deliver a value close to what some might subjectively accept as representing the capacity of the pile. However, only the load-movement curve can be a prediction. The capacity point is determined from that curve by one or other, not predicted but known, definition. Some rely on soil parameter manipulations, and some apply one or another formula to the load-movement response of a pile measured in the static loading test. A "prediction" event asking only for a "capacity" has little meaning beyond entertainment.

Fellenius (1975; 1980) presented close to a dozen capacity definitions then and still in use. For driven piles in North American practice, the Davisson offset limit is common. The EuroCode defines capacity as the load that resulted in a pile-toe movement equal to 10% of the pile diameter, which is based on an erroneous interpretation of a statement by Terzaghi (Likins et al., 2012). For larger diameter piles, this definition is obviously impractical. Therefore, many, retaining the percentage part, have changed the number to 5%. Indeed, if you need a certain capacity value, there's always a method to quote that will help you feel good. In pile dynamics, the definition issue is less complex, the PDA measure-ments and CAPWAP analysis will always apply elastic-plastic pile-soil response to the pile elements making up the pile. That is, the pile force-movement curve will always reach a plastic state.

Figure 4 shows the results of a 2011 prediction event, where, to avoid the assessment confusion, the participants were asked to predict the load-movement curve, not the "capacity" (Fellenius 2013). The participants were also requested to assess the capacity of the pile from their prediction curve. The test pile was a 406-mm-diameter, 18.5-meter-long CFA pile installed in Edmonton, Alta., Canada, in a transported and redeposited silty sandy medium plastic, very stiff, ablation clay till containing lenses of sand and gravel. The predicted load-movement curves are shown in blue solid line, the red dots are the assessed capacities as defined by the individual predictors. It is obvious that the participants did not use a common definition of capacity. The red curve with white dots is the load-movement curve of the test pile. (Also here, the test had to be terminated prematurely due to failure of reaction system.)

Figures 5 and 6 show the results of two similar prediction surveys reported by Fellenius (2015; 2019). The first prediction addressed a 600-mm-diameter, 16.4-meter-long bored pile con-structed in 2015 in silty fine sand in Santa Cruz, Bolivia. The second addressed a 275-mm-diameter, 50-meter-long precast concrete pile driven in 2018 in soft marine clay in Göteborg, Sweden. Again, the participants were asked to assess the pile capacity from their own predicted load-movement curve. As in the previous case, the red curve with white dots is the load-movement curve of the test pile, allowing comparing the array of predicted load-movement curves to the actual test results.

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A prediction event in Araquari, Brazil (Schneid 2015), asked only for the load-movement curve up to an applied load that resulted

in a pile-head movement equal to 10% of the pile diameter, which happened to be the preferred definition of capacity of the event organizers. On receiving the actual test results after the conference, I wrote to all predictors and asked them to tell me what capacity they would prefer to assess from the actual load-movement curve. Twenty-nine of the participants replied, giving me their capacity value, which are shown in **Figure 7** superimposed on the actual load-movement curve. Seven agreed with event organizers and 22 preferred other definitions.

The Third B.E.S.T. conference in Bolivia included prediction of load-movement and capacity of several piles constructed in six meters of loose silt and sand on compact silty sand (Fellenius 2017). After the tests and dissemination of the predictions results, all participants were asked to assess the capacity of the actual tests. Two of these are presented here: Pile A3, a 650-mm-diameter, 9.5-meter-long bored pile, and Pile B2, a 450-mm-diameter, 9.5-meter-long CFA pile. Both piles were equipped with an expanded base cell, EB.

A total of 72 separate assessments were submitted by 121 individuals from 30 different countries. **Figures 8 and 9** show the actual curves with all received "capacities" plotted on the curve. A few overlap.

Recently, a prediction event was organized in Mobile, Ala., and similarly to the 2017 event, the participants having submitted a prediction of the load-movement curve were then given the results of the actual test and asked to assess the capacity using their preferred definition (Fellenius 2025). The actual load-movement curve of the static loading test and the assessed capacities are shown in **Figure 10**.

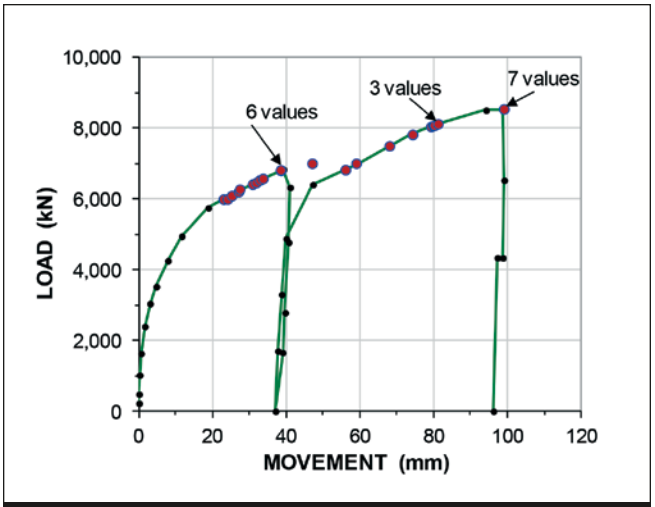

Fig. 7 Araquari, Brazil, 2015

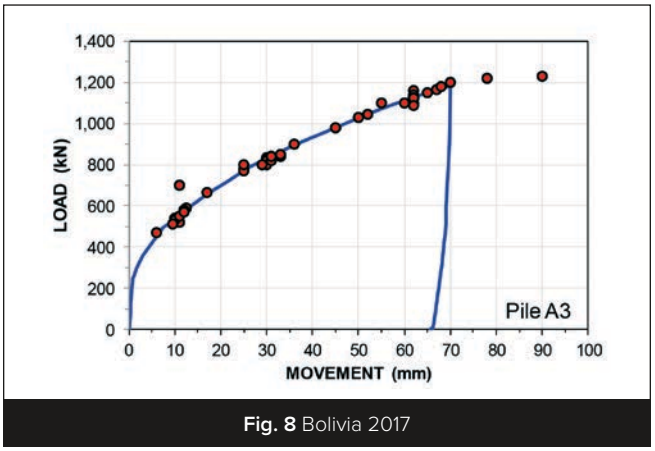

Fig. 8 Bolivia 2017

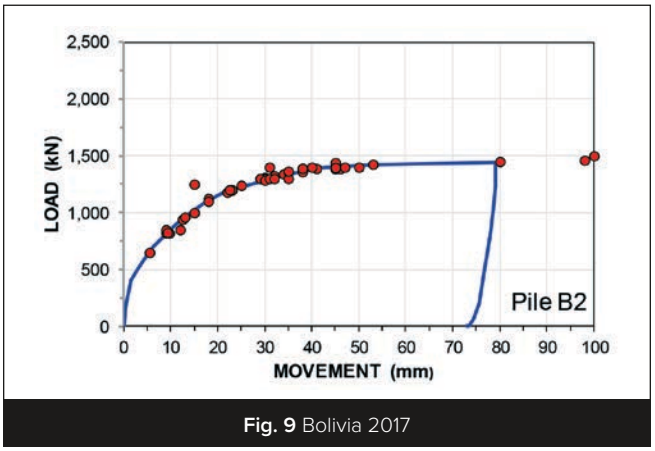

Fig. 9 Bolivia 2017

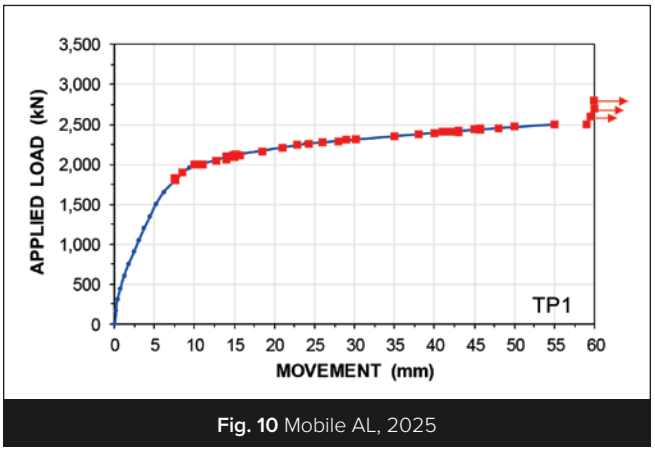

Fig. 10 Mobile AL, 2025

Conclusions

Figures 1 through 6 show the predicted load-movement curves with capacity predictions, as assessed by the predictor in combining soil data, textbook information and standard recommendations. The curves vary widely from each other and from the curve obtained in the actual test. Similar scatter has been shown in other prediction surveys not quoted here. The capacity prediction submitted to a prediction survey is for entertainment, much like a door prize at a meeting. Good fun, little else.

Some have concluded from the prediction events that the current state of practice is not able to reliably predict the response of loading a pile, i.e., not able to reliably design a piled foundation! That conclusion is incorrect. It presumes that the process of the load-movement prediction is the same as the design process. However, in contrast to the single outcome of the prediction analysis, a design involves not a single-step effort, but an elaborate process comprising steps of assessments of expected response and verification of assumptions, known influence of local geology, past construction observations, results of past tests and other information, personal or available from others, and it often includes a static loading test to confirm assumptions and observations of the final pile construction. This is the prediction approach – design is a prediction effort – which is what Bill Lambe had in mind. Therefore, a local practitioner, participating in a prediction event, can sometimes, while relying on a minimal analytical effort, get closer to the actual response than someone applying the most sophisticated theoretical construction, but without the benefit of local experience.

The surveys reveal a real problem in our industry, and a serious one. The scatter of capacities assessed from the load-movement curves, particularly in Figures 7 through 10, makes clear that our practice neither has a common definition of capacity. Just as well, capacity is a tenuous and contrived quasi concept. Our practice would be

justified to simply abandon it. While we cannot do this – the concept of capacity is important for maintaining connection to past design experience – we should critically review the capacity-based design recommendations in current text books, codes, and standards.

It is frustrating that so many authors of papers, even in distinguished and recognized journals, ostensibly presenting new insights in the response of piles to load, still address the results in the obtuse term of "capacity," often undefined, disregarding most of the value that the tests could have presented if the result had been addressed in terms of movement and settlement.

The absence of a common approach to pile capacity and the large disparity in applying the concept is a testament to the fact that regardless of the definition applied, "capacity" is a meaningless concept in piled foundation design. The scatter of definitions in use demonstrate that, if it had meaning, there would have been many foundation failures. A piled foundation is not overly concerned with capacity. The pile-supported structure cares about settlement for the actual load, the load-movement response, which is a process similar to estimating the settlement of a piled foundation. Design of a piled foundation must be based on settlement analysis, not capacity. If the design is for settlement, capacity will follow, but designing for capacity does not ensure that settlement of the structure supported on the piled foundation will be okay. And when it does and the associate factor of safety or load factor delivers a "safe" settlement response to the sustained load, money may have been wasted.

Is it possible that so many still base a design of a piled foundation on capacity – and on code-assigned factors of safety or resistance factors – because they are unsure about how to calculate – predict – the settlement of the foundation? ▼

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