Featured Technical Article

We have determined the capacity, then what?

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Summary The purpose of the static loading test is to find the allowable load, which is established by dividing the capacity with a factor of safety. The factor of safety normally applied in the industry ranges from a low of 1.8 through a high of 2.5, depending on several reasons, not least the method used to determine the pile capacity from the load-movement curve. However, the concept of ultimate load, failure load, or capacity is really a fallacy. A design based on the ultimate load is a quasi concept and of ambiguous relevance for the assessment of a pile. This because the pile-head load-movement curve is the combined effect of the load-movement to failure of the shaft resistance, the elastic compression of the pile itself, and the load-movement of the pile toe. Of the three, failure only develops for the first component. Even for a test where a plunging failure appears, the plunging is a combination of reduced shaft resistance due to strain-softening, shortening of the pile and residual load at the pile toe at the start of the test. Pile design should emphasize settlement analysis and give less weight to the capacity of the pile.

1. Factor of Safety

The capacity of a pile is the ultimate soil resistance of the pile determined from the load-movement behavior measured in the static loading test. But the purpose of the test is, knowing the capacity, to find a safe load that can be supported on the pile, which load is called the allowable load. The allowable load is established by dividing the capacity by a factor of safety.

The factor of safety is not a singular value applicable at all times. Its value depends on the desired freedom from unacceptable consequence of a failure, as well as on the level of knowledge and control of the aspects influencing the variation of capacity at the site. Not least important are, one, the method used to determine or define the ultimate load from the test results and, two, how representative the test is for the piles at the site. Most codes specify a single factor regardless of conditions, usually 2.0, frequently larger.

Where some freedom is granted the design engineer, practice has developed toward using a range of factors of safety, as follows. In a testing program performed early in the design work and testing piles which are not necessarily the same type, size, or length as those which will be used for the final project, the safety factor applied is high, usually 2.5, to account for the unknowns. In the case of testing during a final design phase, when the loading test occurs under conditions well representative for the project, the safety factor could be reduced to 2.2. When a test is performed for purpose of verifying the final design, testing a pile that is installed by the actual piling contractor and intended for the actual project, the factor commonly applied is 2.0. Well into the project, when testing is carried out for purpose of proof testing and *conditions are favorable*, the factor may sometimes be further reduced and become 1.8. Reduction of the safety factor may also be warranted when limited variability is confirmed by means of combining the design with detailed site investigation and control procedures of high quality. One must also consider the number of tests performed and the scatter of results. The applied factor of safety can often be reduced due to the assurance gained for driven piles by means of incorporating dynamic methods for controlling hammer performance and for capacity determination.

The value of the factor of safety to apply depends on the method used to determine the capacity. A conservative method, such as the Davisson Offset Limit Load, warrants the use of a smaller factor as opposed to a "liberal" method, such as the Brinch Hansen 80%-criterion. It is good practice to apply more than one method for defining the capacity and to apply to each method its own factor of safety letting the smallest allowable load govern the design.

Lately, the industry is required to evaluate the results of a static loading test according to Load-and-Resistance-Factor-Design, LRFD. The principle of the LRFD is simple. A "resistance factor" is applied to the capacity and a "load factor" is applied to the load. A load factor and a resistance factor specified to 1.4 and 0.6 "calibrate" to a conventional factor-of-safe-

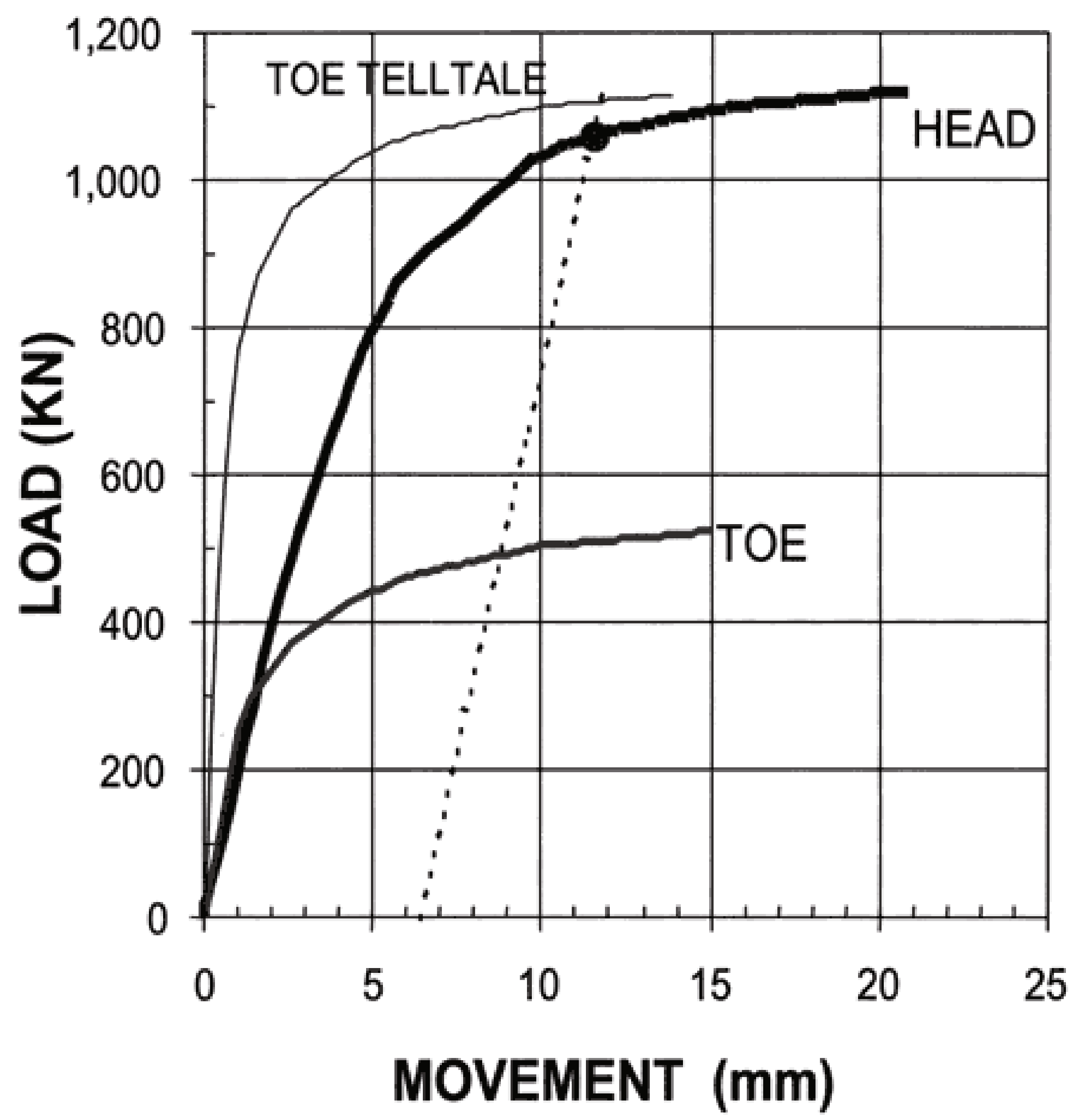

Fig. 1
Typical results of a static loading test on a telltale-instrumented concrete pile

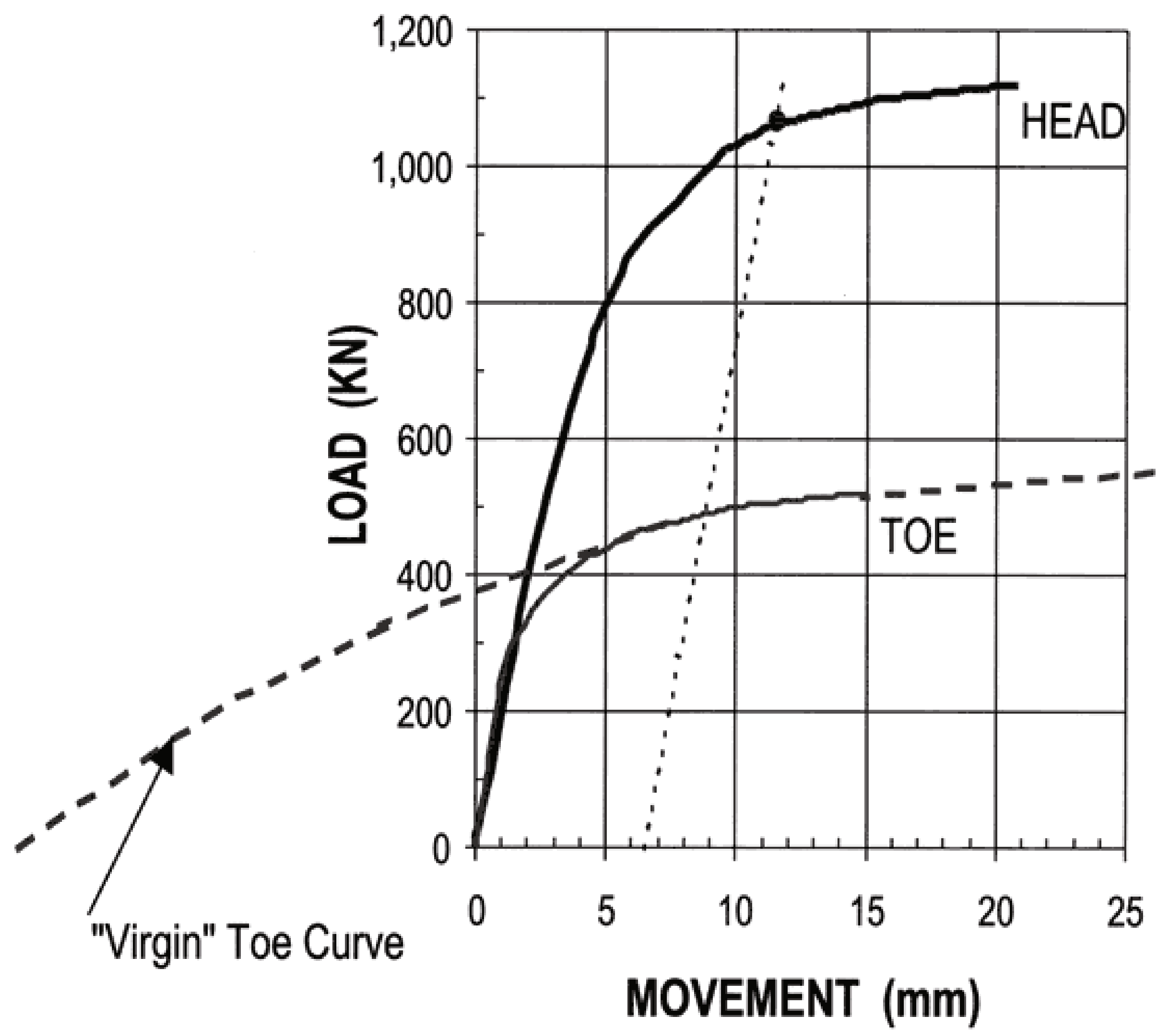

Fig. 2
Fig. 1 with superimposed "Virgin" toe curve

The figure includes the load-movement of the pile toe, measured, say, by a strain gage or a load cell at the pile toe and a toe telltale. The load-movement is shown both as the applied load and as actual toe resistance versus the measured toe movement. For the test shown, the Offset Limit Load occurs at a toe movement of about 5 mm. The test was continued until plunging failure appeared in the load-movement curve for the pile head at an about 22-mm movement of the pile head. The maximum toe movement was 15 mm. The maximum applied load at the pile head, the shaft resistance, and the load at the pile toe were 1,100 KN, 600 KN, and 500 KN, respectively. The round dot indicates the Offset Limit load to be 1,050 KN.

Knowing the pile toe load-movement response is an obvious enhancement of the test results. However, residual load will always develop in a pile, a driven pile in particular. Therefore, at the start of the static loading test, the pile toe is already subjected to load and the toe load-movement curve displays an initial steep reloading portion. Depending on the magnitude of the residual load, the measured toe response can vary considerably. For examples and discussion, see Fellenius (1999).

Fig. 2 shows the probable "Virgin" toe load-movement superimposed in the diagram.

To indicate different magnitudes of residual load, the "Virgin" curve can be translated left or right. A small residual toe load would result in a small evaluated toe resistance. The pile head load-movement would then show a less stiff response and the Offset Limit Load would become smaller. Conversely, were the residual load to be large (the "Virgin" curve would be moved toward the left), a large toe resistance would be found and the pile head load-movement curve would be steeper, resulting in a larger Offset Limit Load. Yet, no change has been made to the load-movement response of any of the three components of the test!

The analyses behind Figs. 1 and 2, assume very simple shaft and toe soil responses. The pile toe load-movement is indicated in the figures. The load-movement of the shaft resistance is shown in Fig. 3.

Fig. 4 presents a diagram over shaft resistance versus relative movement between the pile shaft and the soil that is a bit more complex, but more realistic.

Fig. 4 shows a soil response where the shear resistance drops off to about 80 % of the peak value , after having reached a peak value, demonstrating a strain-softening response. This is more representative for the behavior of a pile shaft sliding past the soil. The test results for this shaft resistance are shown in Fig. 5.

As shown in Fig. 5, because of the effect of the strain softening, the evaluated Offset Limit has diminished. Adding the effect of varying degree of residual load in the pile, will affect the test evaluation in a similar manner as for the first case.

Were any of the other methods of determining the "Failure Load" used as reference instead of the Offset Limit Load, the results would be similar.

ty, ("global factor") of 1.4÷0.6 = 2.33. (When considering that factored design is an ultimate limit state design that always is to be coupled with a serviceability limit state design, the pile capacity should be determined by a method closer to the plunging limit load, that is, the Brinch-Hansen 80 %-criterion is preferred over the Offset Limit Load).

2. Choice of Evaluation Method

It is difficult to make a rational choice of the best capacity criterion to use, because the preferred criterion depends heavily on one's past experience and conception of what constitutes the ultimate resistance of a pile.

The Davisson Offset Limit is very sensitive to errors in the measurements of load and movement and requires well maintained equipment and accurate measurements. (No static loading test should rely on the jack pressure for determining the applied load. A load-cell must be used at all times. For a case in point, see Fellenius, 1984). In a sense, the Offset Limit is a modification of the "gross movement" criterion of the past (which used to be 1.5 inch movement at the maximum load). Actually, the Offset-Limit method is an empirical method that does not really consider the actual transfer of the applied load to the soil. However, it is easy to apply and has gained a wide acceptance.

The Davisson Offset Limit offers the benefit of allowing the engineer, when proof testing a pile for a certain allowable load, to determine *in advance* the maximum allowable movement for this load with consideration of the length and size of the pile. Thus, contract specifications can be drawn up including an acceptance criterion for piles proof tested according to quick testing methods. The specifications can simply call for a test to at least twice the design load, as usual, and declare that at a test load equal to a factor, F, times the design load, the movement shall be smaller than the elastic column compression of the pile, plus 0.15 inch (4 mm), plus a value equal to the diameter divided by 120. The factor F is a safety factor and should be chosen according to circumstances in each case. The usual range is 1.8 through 2.0.

The Brinch-Hansen 80%-criterion usually gives a Qu-value, which is close to what one subjectively accepts as the true ultimate resistance determined from the results of the static loading test. The value is smaller than the Chin-Kondner value. Note, however, that the Brinch-Hansen method is more sensitive to inaccuracies of the test data than is the Chin-Kondner method. The usual range is 2.0 through 2.5. The Chin-Kondner Extrapolation and the Decourt Extrapolation limit load values are approached asymptotically. Therefore, the these two methods are always obtained by extrapolation. It is a sound engineering rule *never to interpret the results from a static loading test to obtain an ultimate load larger than the maximum load applied to the pile in the test.* For this reason, an allowable load cannot, must not, be determined by dividing the limit loads according to Chin-Kondner and Decourt methods with a factor of safety.*)

The Brinch Hansen's 80%-criterion and the Chin and Decourt extrapolation methods allow the later part of the load-movement be continued beyond the maximum load applied, extrapolating the curve. This is very tempting. That is, it is easy to fool oneself and believe that the extrapolated part of the curve is as true as the measured.

3. Bearing Capacity Is No Simple Matter

The load-movement consists of three components: the load-movement of the shaft resistance, the compression of the pile, and the load-movement of the pile toe. The combined load-movement response to a load applied to a pile head therefore reflects the relative magnitude of the three. Moreover, only the shaft resistance exhibits an ultimate resistance. The compression of the pile is really a more or less linear response to the applied load and does not have an ultimate value (disregarding a structural failure when the load reaches the strength of the pile material). However, the load-movement of the pile toe is also a more or less linear response to the load that has no failure value. Therefore, the concept of an ultimate load, a failure load or capacity is really a fallacy and a design based on the ultimate load is a quasi concept, and of uncertain relevance for the assessment of a pile.

The statement is illustrated in Fig. 1, which presents the results from a typical test on a 15 m long, 300 mm diameter, driven concrete pile.

***)The presentation of the Decourt method in the Winter 2001 issue of Fulcrum included an erroneous version of the equation for the "ideal" curve. Eq. 6 should read:**

$$Q = \frac{C_2\delta}{1 - C_1\delta} \qquad (6)$$

Where	Q_u	=	**capacity or ultimate load**
	Q	=	**applied load**
	δ	=	**movement**
	C_1	=	**slope of the straight line**
	C_2	=	**y-intercept of the straight line**

Moreover, Figs. 5 and 6 in the article, should correctly be numbered Figs. 4 and 5.

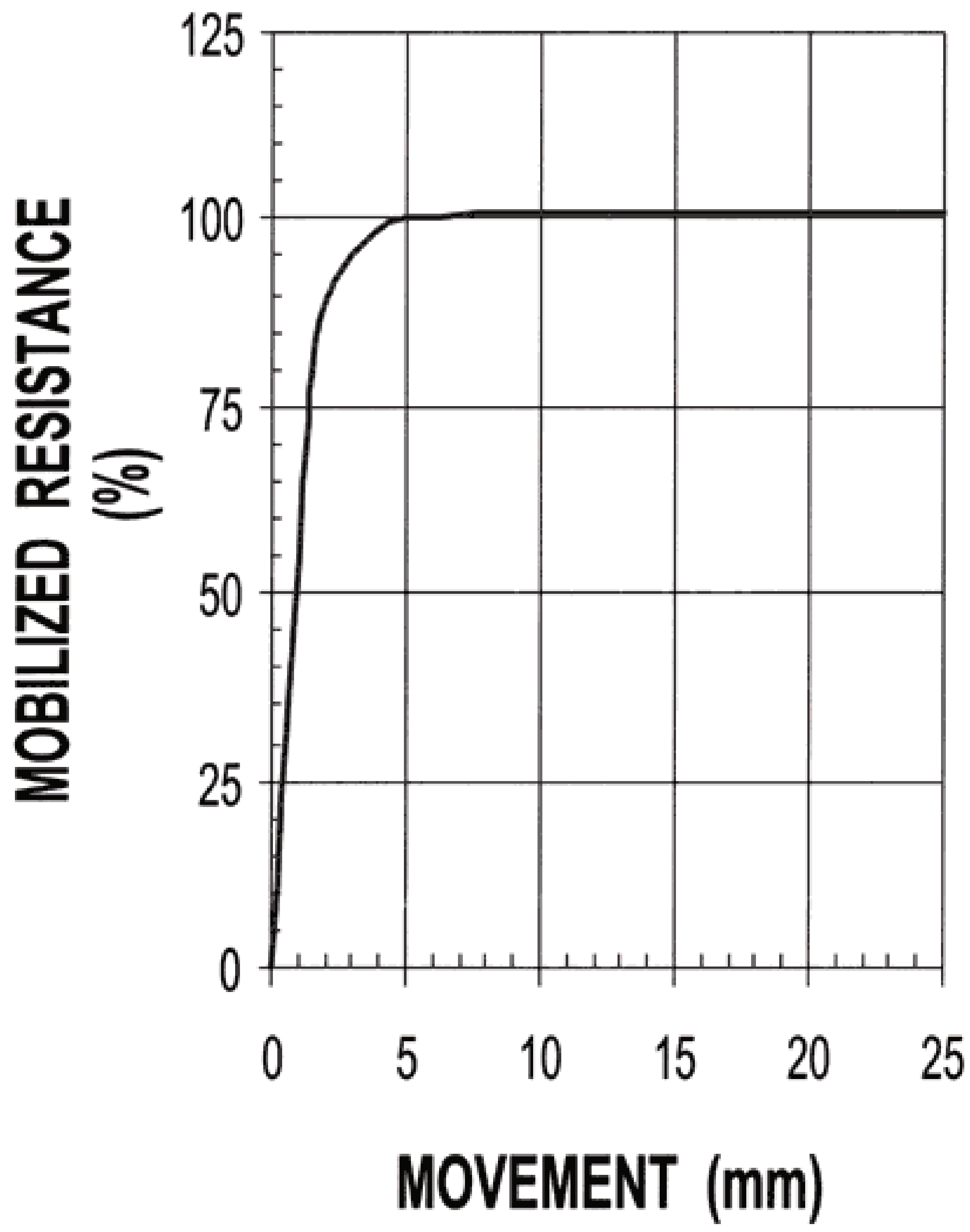

Fig. 3
Percent shaft resistance as a function of relative movement between pile shaft and soil

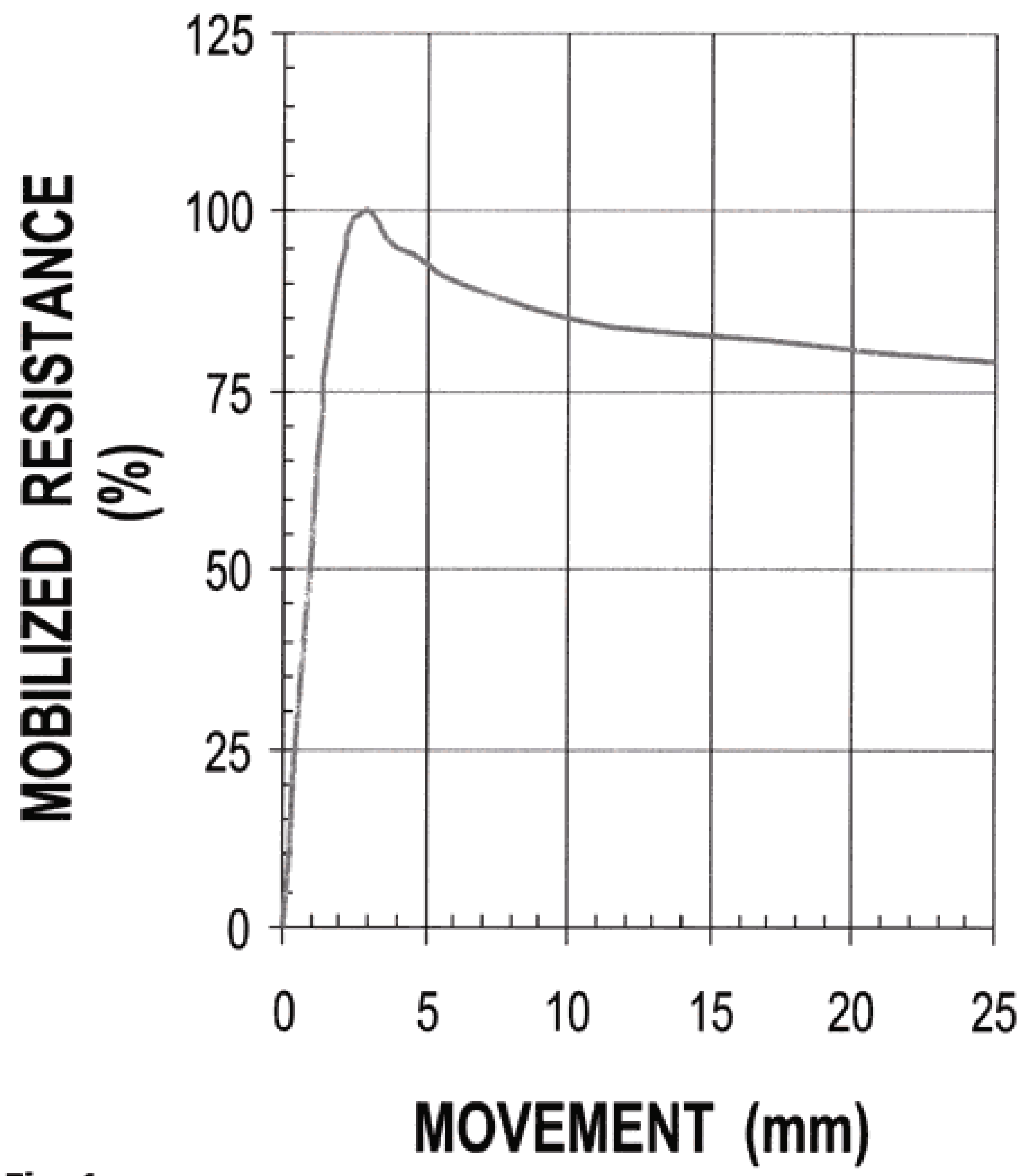

Fig. 4
presents a diagram over shaft resistance versus relative movement between the pile shaft and the soil that is a bit more complex, but more realistic.

4. Conclusions

The result of a static loading test does not provide the simple answers one at first may think. First, there is a considerable variation in the methods of "Failure Load" interpretation used in the industry. Then, the effect of residual load and varying degree of strain-softening will appreciably affect the interpretation. Indeed, a static test that measures only the applied load and the pile head movement is a very crude test. For small and non-complex projects, such level of sophistication, or lack thereof, is acceptable if the uncertainty is covered by a judiciously large factor of safety. For larger projects, however, this approach is costly. For these, the test pile should be instrumented and the test data evaluated carefully to work out the various influencing factors. For projects involving many piles, several test piles may be desirable, though this could be prohibitively costly. If so, combining an instrumented static loading test with dynamic testing, which can be performed on many piles at a relatively small cost, can extend the application of the more detailed results of the instrumented static test.

The potential presence of residual load and its varying magnitude makes methods of interpretation based on initial and final slopes of the load-movement curve somewhat illogical.

Design of piles should be less based on the capacity value and more emphasize the settlement of the pile under sustained load. It will then be easier and more logical to incorporate aspects such as downdrag and dragload into the design.

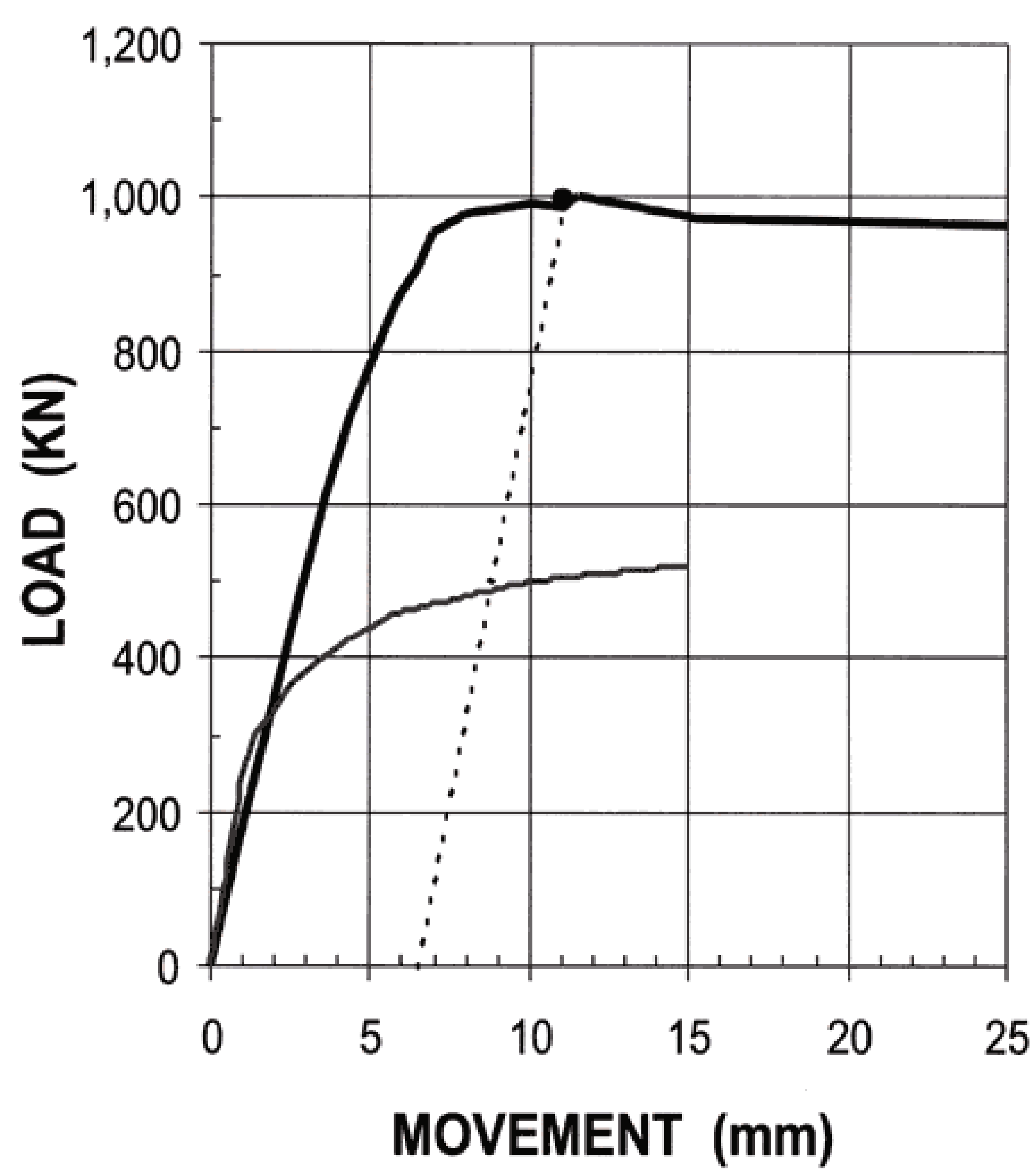

Fig. 5
The effect of strain-softening shaft resistance

References

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