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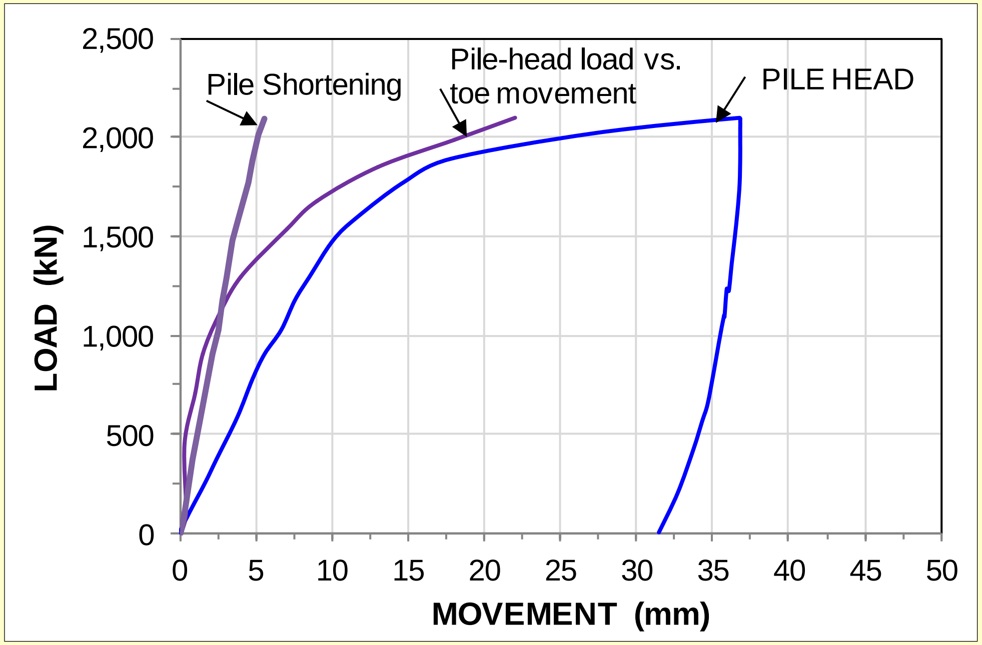
Bengt H. Fellenius

Best practice for performing static loading tests

Examples of test results with relevance to design

Typical results of a Head-down Static Loading Test



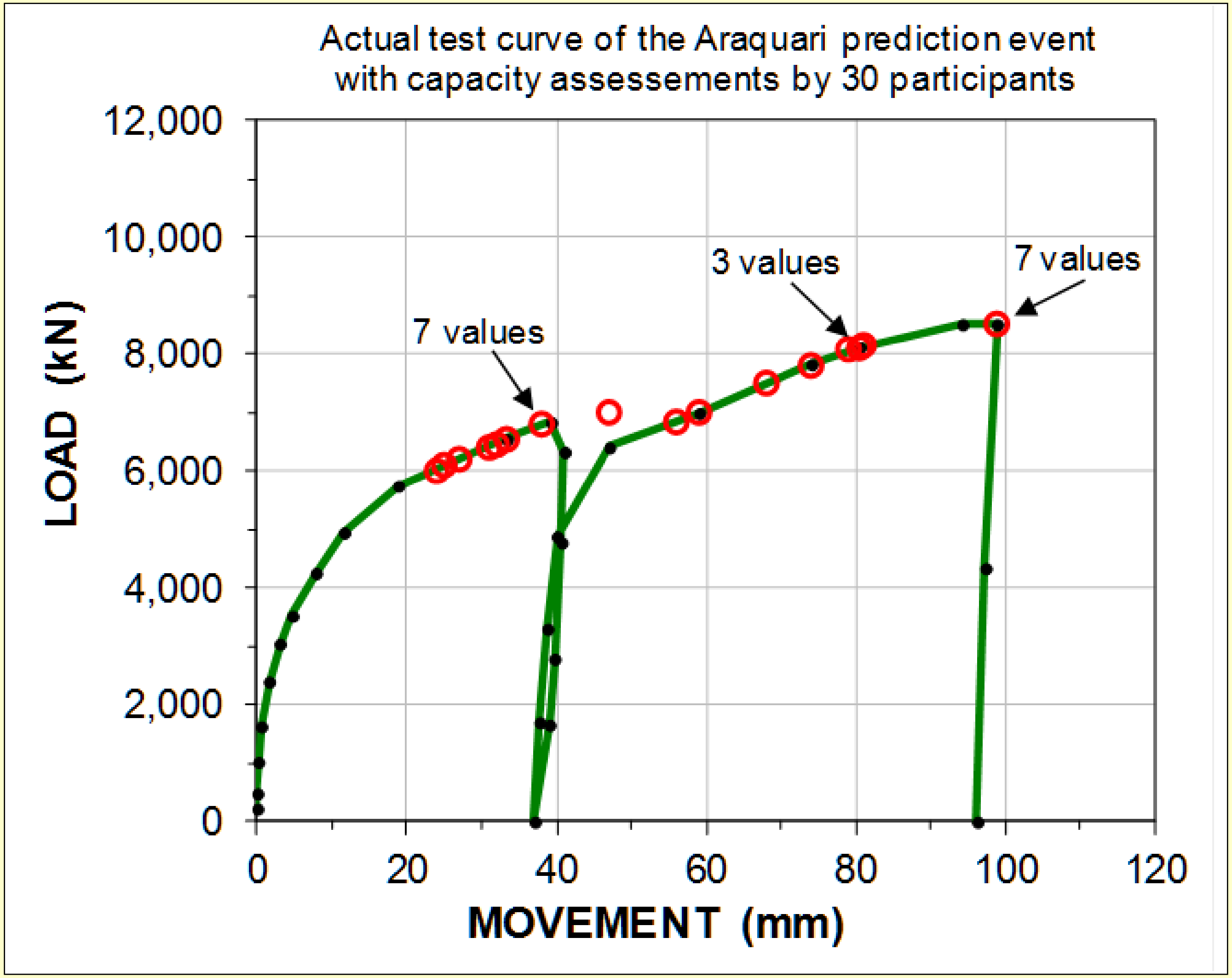
A routine conventional test with the minimum of instrumentation: a telltale to the pile toe.

Conventionally, the first question asked is:

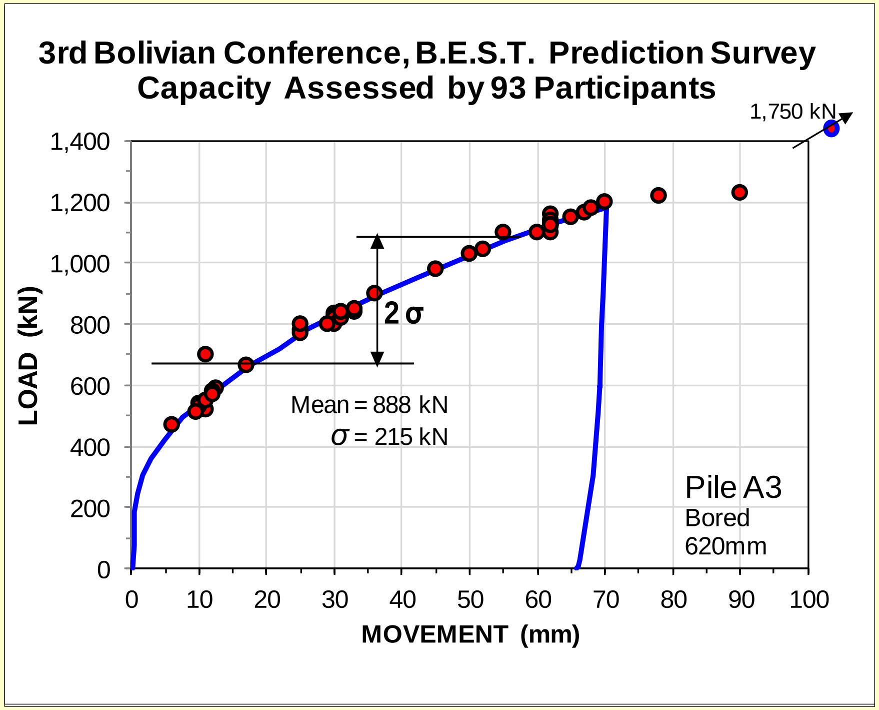
"**What is the pile capacity**"?

The question is better phrased:
"**what is "capacity?**"

Capacities assessed for an actual test as reported by 30 specialists

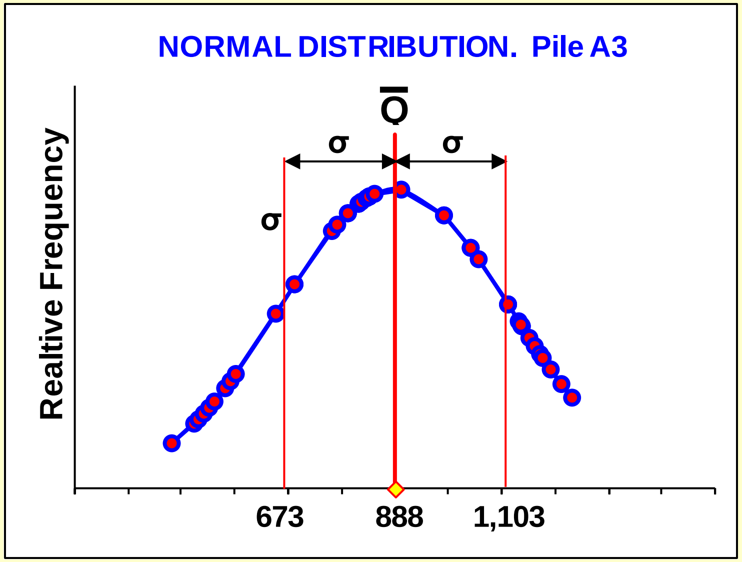


A repeat similar task on the occasion of the B.E.S.T. Prediction

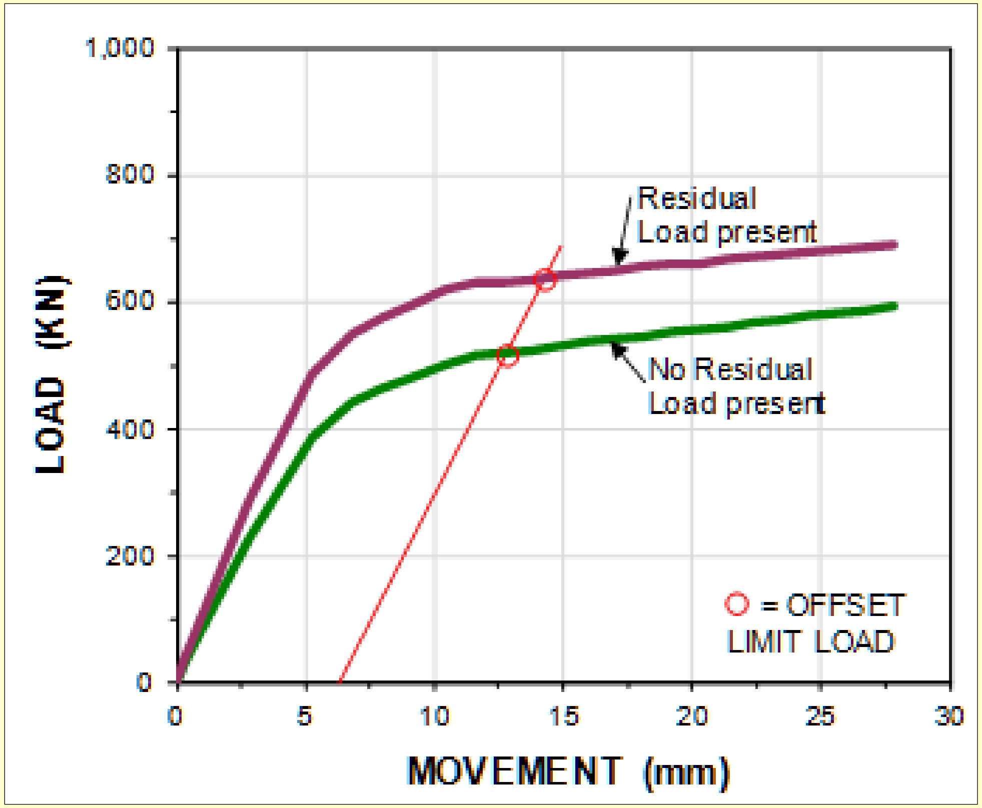


Each individual member of our profession may feel confident about how to assess "capacity", but, obviously, the profession on the whole does not have a clue as to what "capacity" is.

Assessing "capacity" is akin to diagnosing a medical condition. Suppose the medical profession have as little understanding of a patient's measured vital signs. They and the society would be quite concerned, I am sure. We should be as concerned about our inadequacy.



The concept of "capacity" as used in Codes and Standards is meaningless and illogical. It is also redundant, because we have other and better tools to use, as I will outline in the following.



The effect on the evaluation of "capacity" due to presence of residual load.

Pile Instrumentation

A routine head-down test on an uninstrumented pile does not provide us with much information for assessing the response of a pile to load. We need either to perform a bidirectional test (usually enough for a short pile), or include instrumentation down the pile to measure the distribution of axial load as the test progresses (instrumentation is best when combined with a bidirectional test).

Most instrumentation consists of pairs of strain-gages placed at specific depths in the pile. The measured strain are converted to load using the pile secant stiffness, E_sA. Because both the area, A, and the secant modulus, E_s, can vary quite a bit from pile to pile and, also, at gage location, the key to the evaluation lies in determining the applicable EA_s-relation. Depending on the imposed range of strain, the stiffness usually changes (reduces) with the magnitude of the applied load. The E_sA is difficult to determine theoretically, but, provided that the imposed strain range is wide enough, it can be determined directly from the test records.

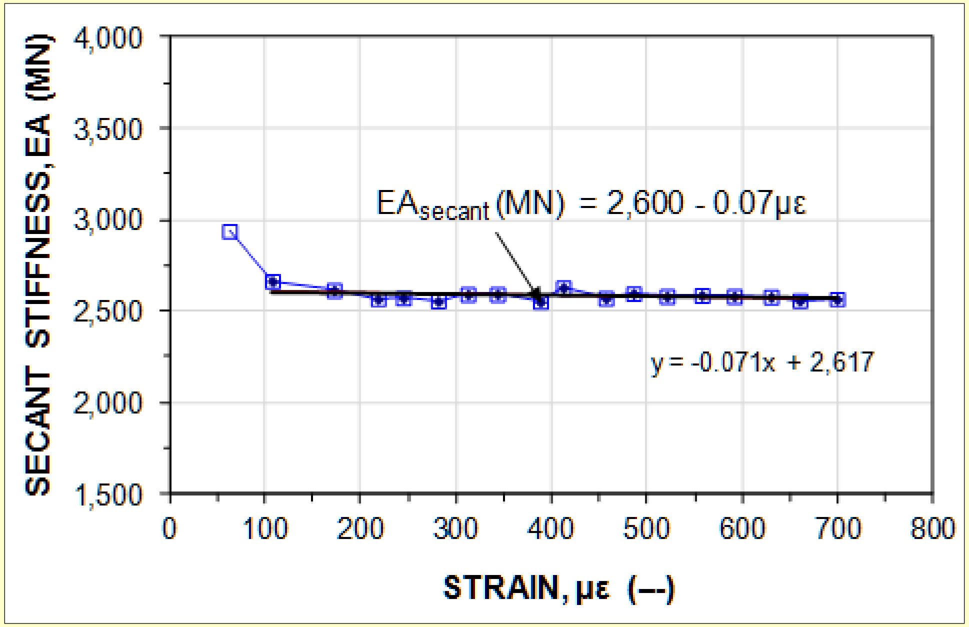
Evaluating pile axial secant stiffness, E_sA

Near the pile head, where no shaft resistance has affected the pile, the stiffness, E_sA, is best determined from the gage records by the direct secant stiffness method.

E_sA

Load/Strain

(Q/ϵ)



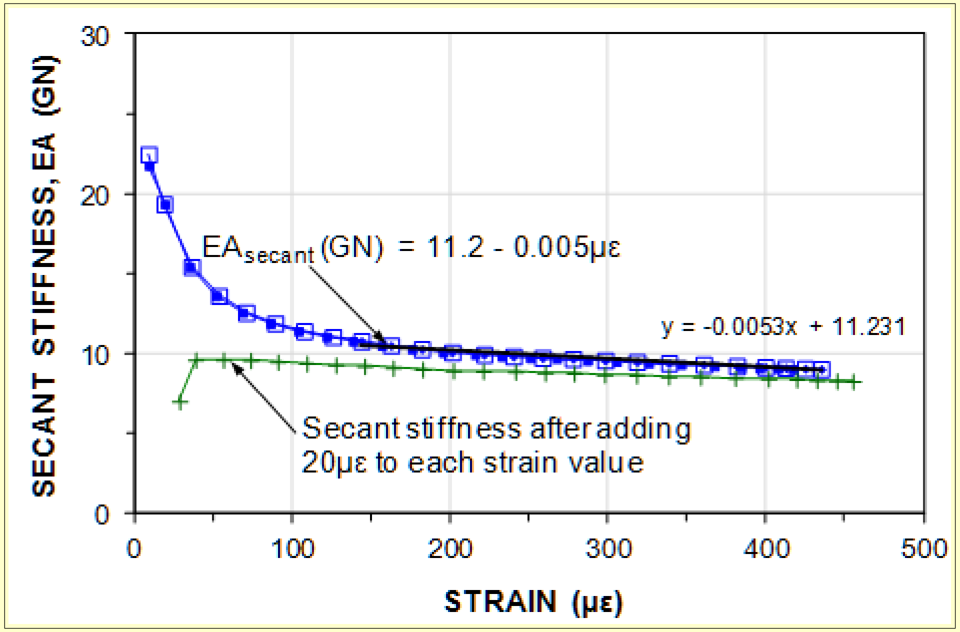
Pile stiffness for a 400-mm CFA pile (Fellenius 2012)

An additional example.

E_sA

Load/Strain

(Q/ϵ)



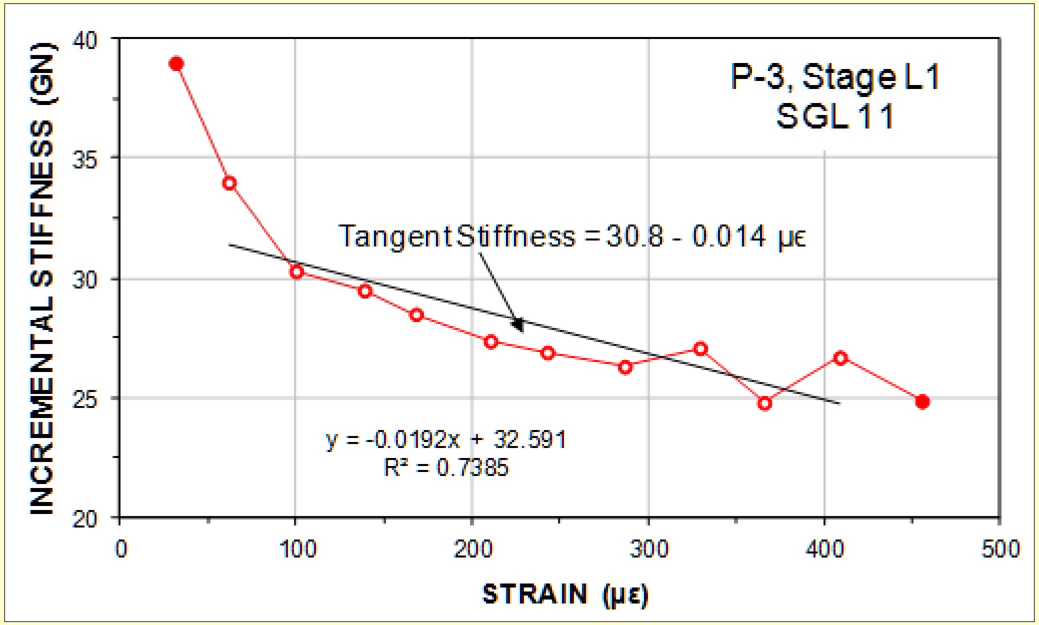
Pile stiffness for a 600-mm diameter prestressed pile (Fellenius 2012)

For gages further down the pile, the direct secant method cannot be used due to the influence of shaft resistance. However, deeper down, the indirect "tangent stiffness" ("incremental stiffness") method applies .

$E_t A$

Load/Strain

($\Delta Q/\Delta \epsilon$)

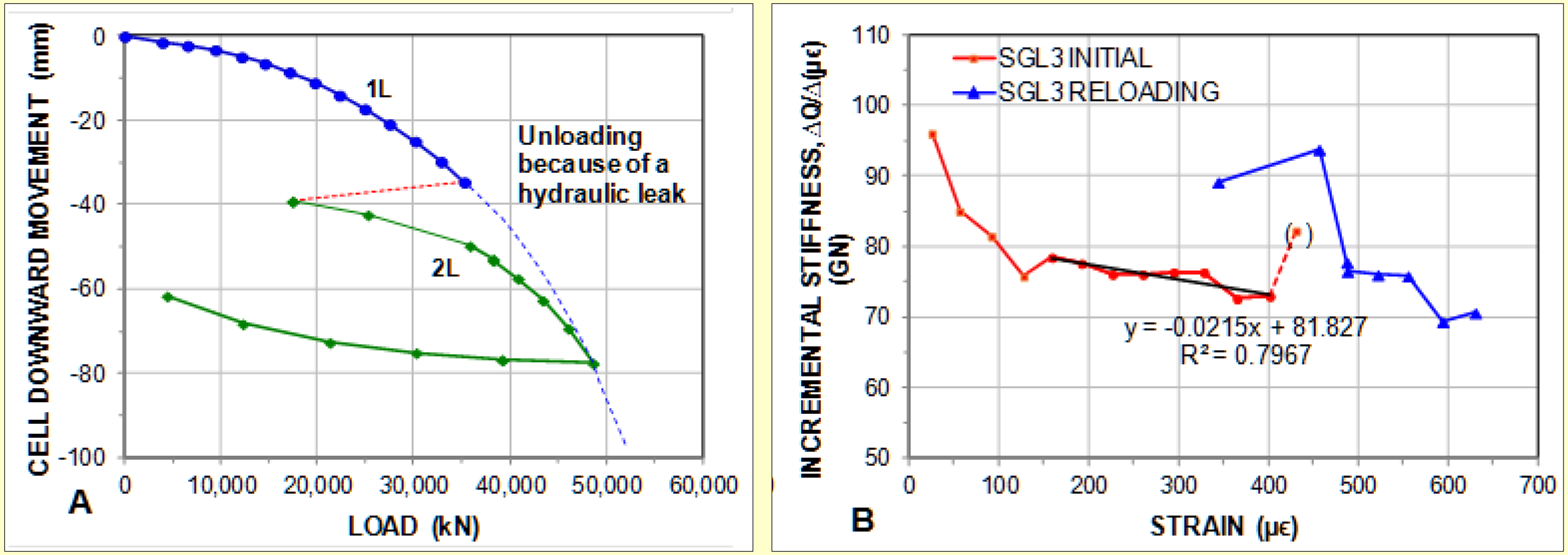


Pile incremental stiffness for a gage level 12 m down in a 1,000-mm diameter bored pile. (Fellenius and Tan 2010).

Load at a gage level is $E_s A$, not $E_t A$, but they are related—correlated. The slope of the tangent stiffness is twice that of the secant stiffness

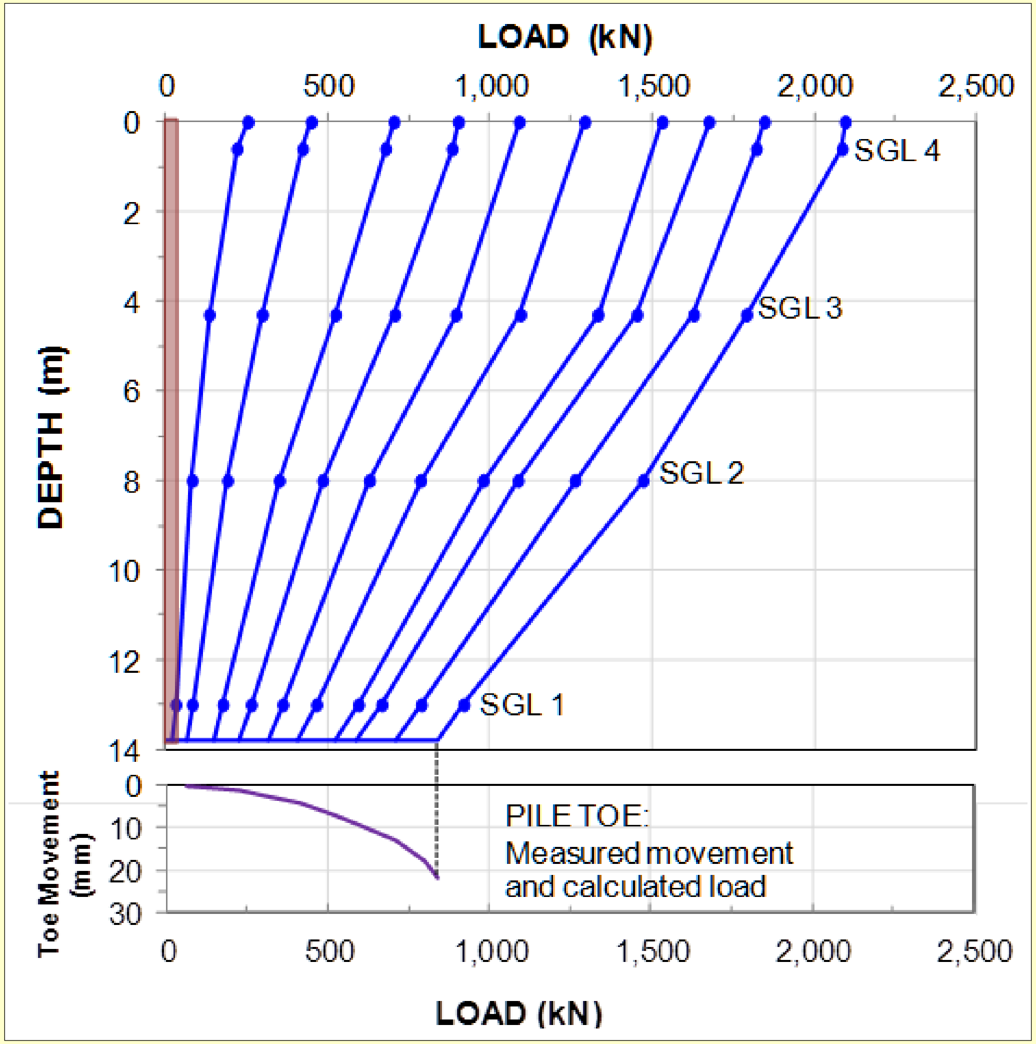
If $E_t A = 30.8 - 0.014\ \mu\epsilon$, then, $E_s A = 30.8 - 0.007\ \mu\epsilon$

Converting strain to load only looks simple. For example, to ensure useful measurements, do not include unloading/reloading "cycles" in the test.



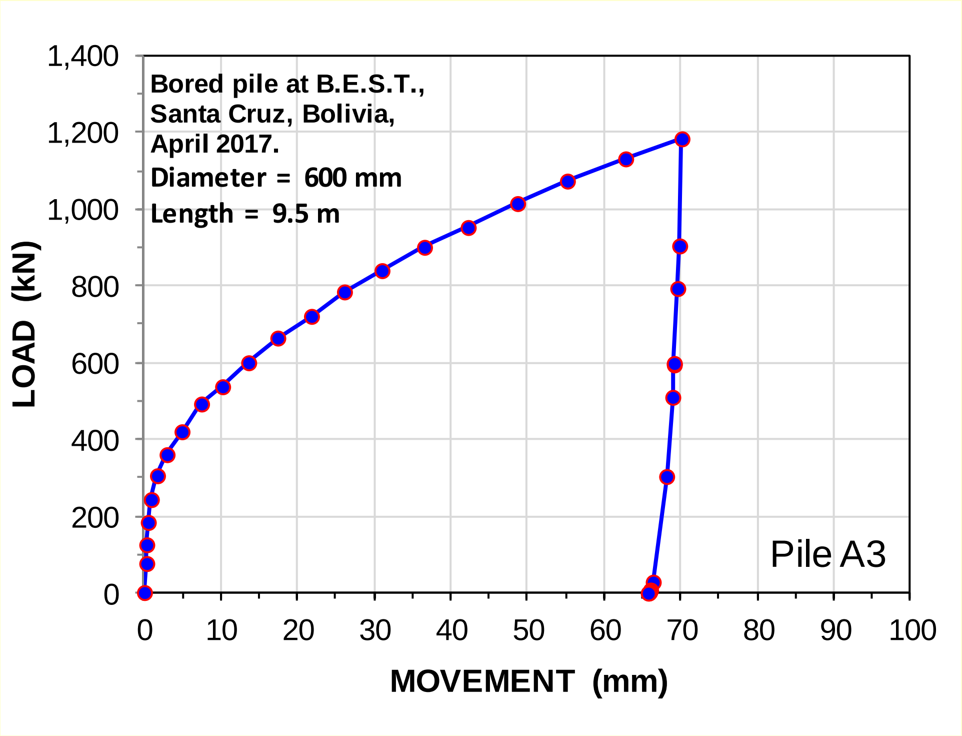
Effect on the incremental stiffness curve from an unloading-reloading cycle (Fellenius 2016a)

The end result of the analysis of the strain-gage instrumentation.



Load distribution determined from strain gage records.

Let's work through a B.E.S.T. example, Pile A3

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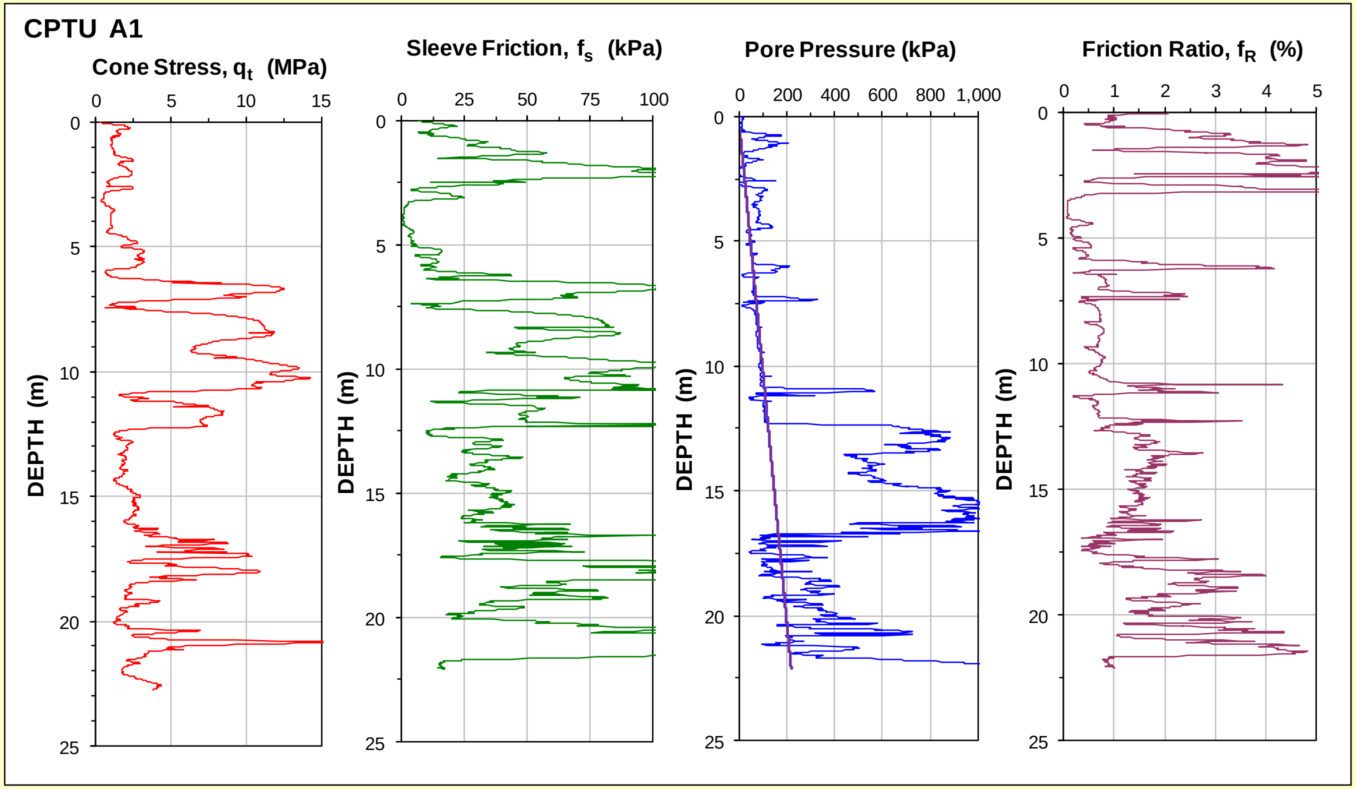
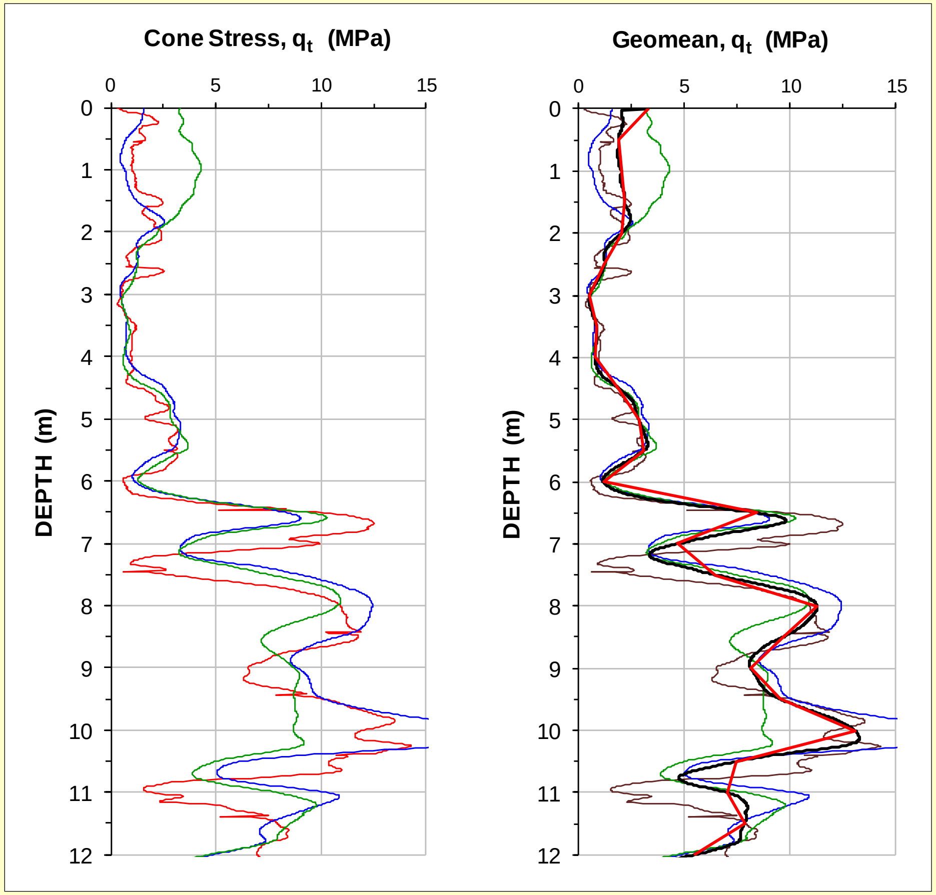
2017/03/20

First, a look at the soil profile represented by a CPTU-diagram

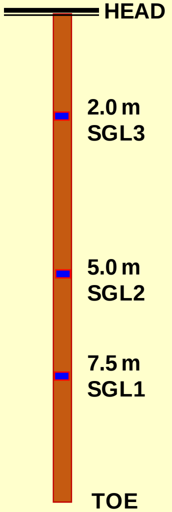


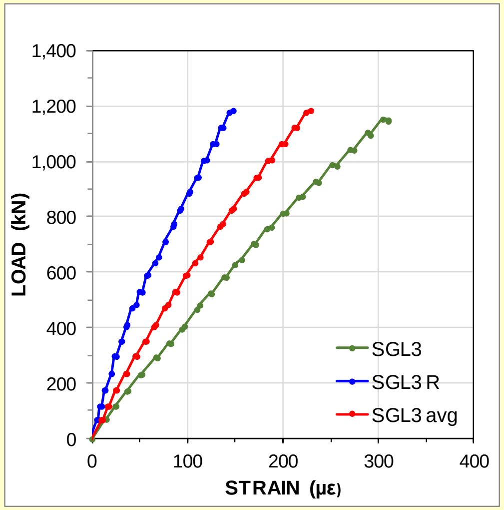
The CPTU soundings (to about 12 m depth) near the B.E.S.T. test piles show the soil profile to consist of two distinct soil layers: an upper 6 m thick layer of silty sand deposited on fine sand. The diagram below combines the soundings near Piles A with and without the q_t-stress averaged (by a geometric mean running over a 0.5 m sounding length). The analysis will address the two layers.

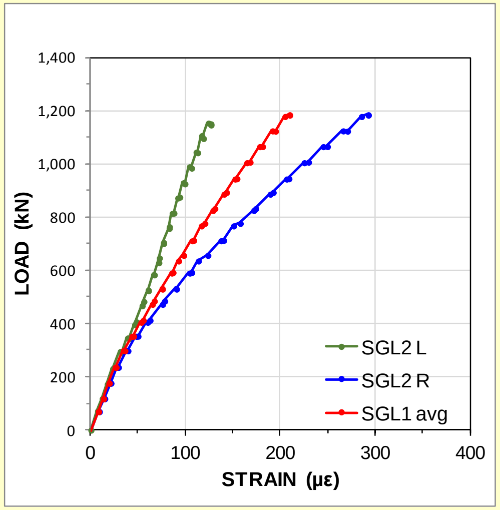
The groundwater table lies at a depth of about 0.5 m and can be assumed hydrostatically distributed. A phase -system calculation from the water contents measurements indicates soil total densities of 2,000 and 2,050 kN/m³, respectively.

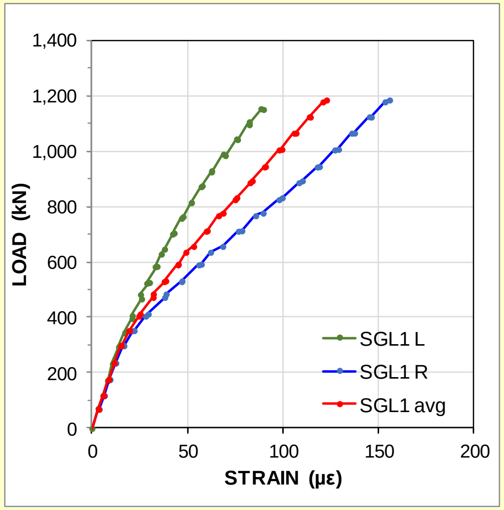


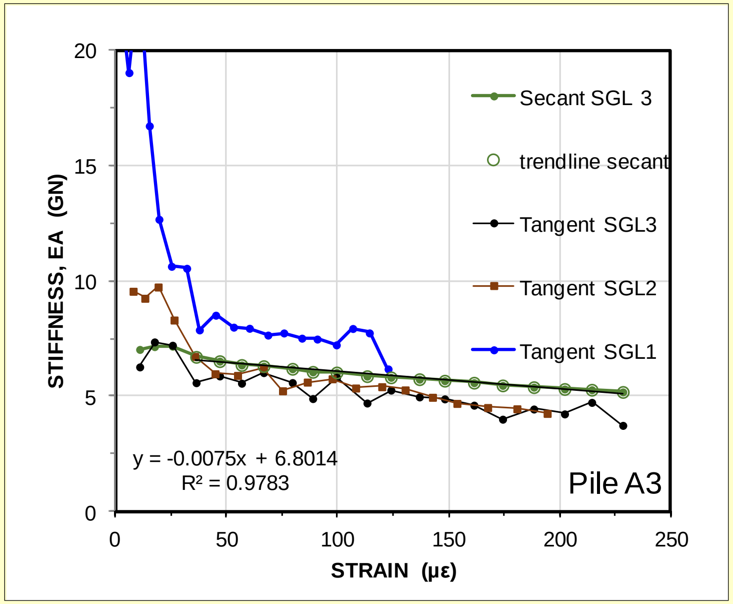
Now, the strain-gage measurements







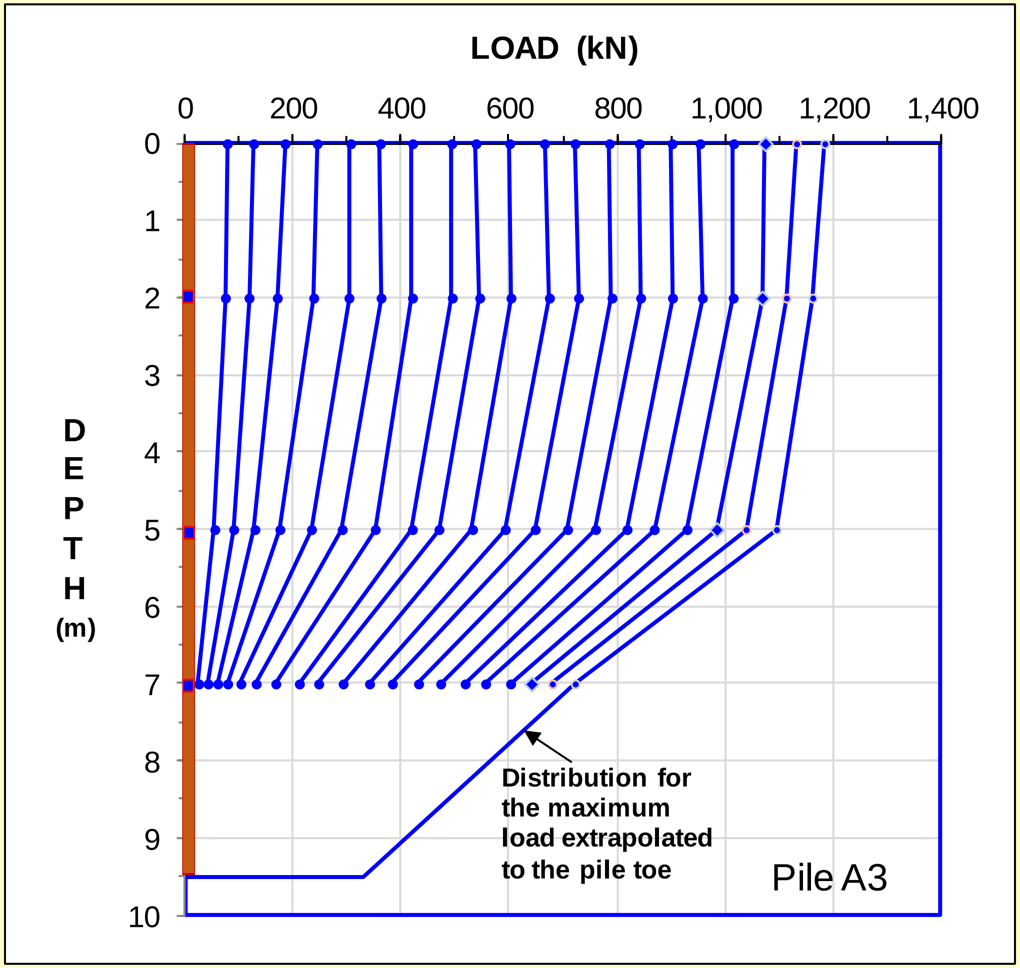




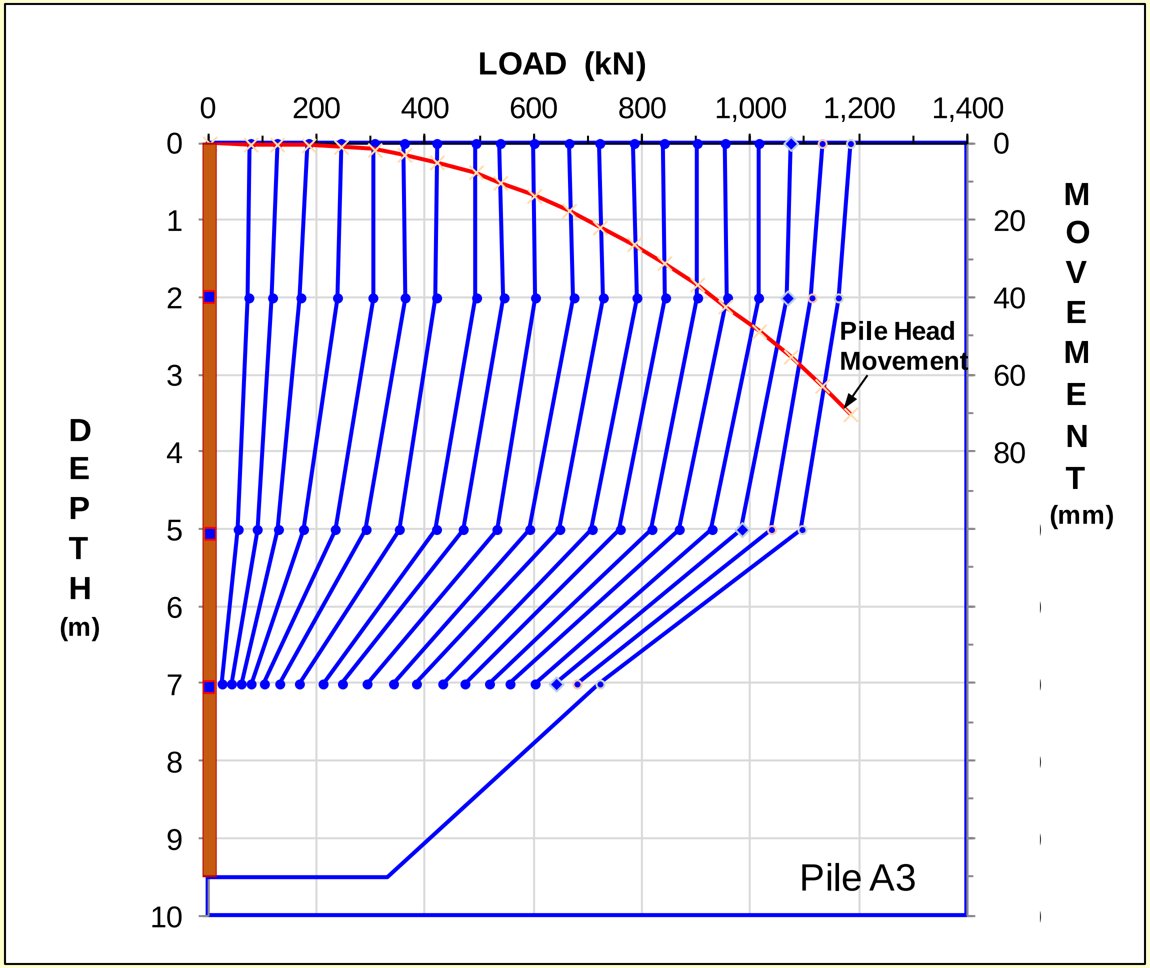
E_sA (GN) = 6.8 - 0.007 $\mu\epsilon$

N.B., we do not need to know the area (A). So, E_sA and the $\mu\epsilon$ will give us the loads at the gage locations for all loads applied to the pile head, *All **loads** calculated and plotted:*

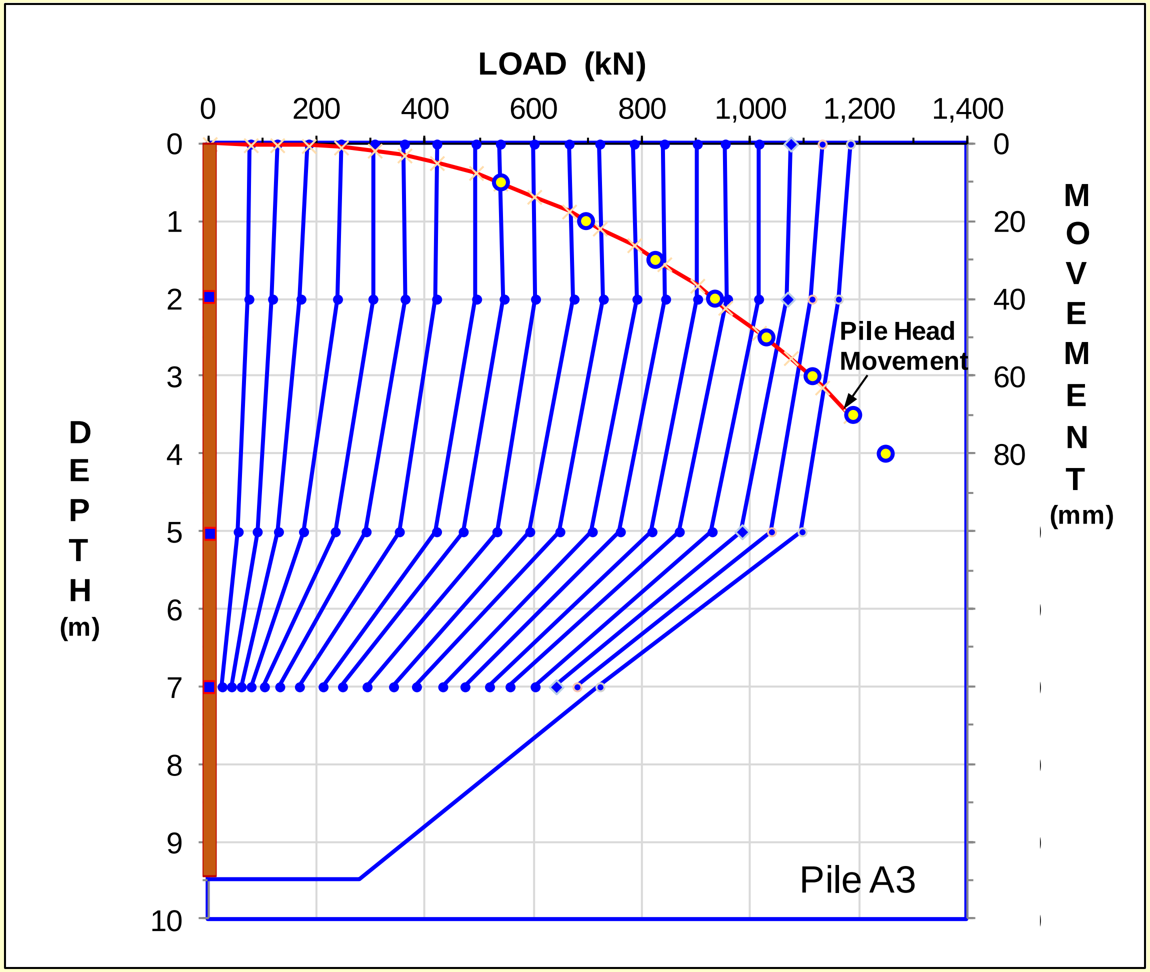
*Yes, but where are the **movements**?*



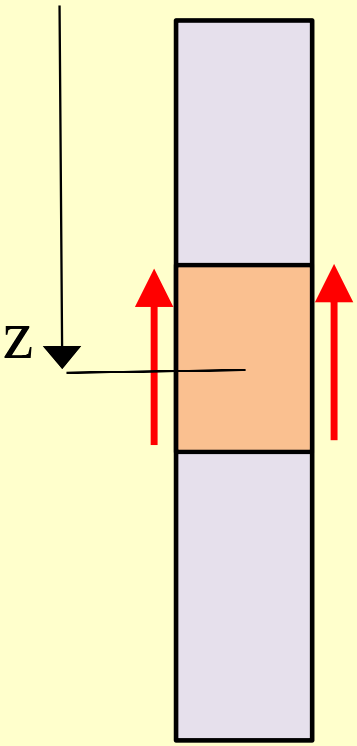
The pile head load-movement is here added to the graph. N.B., loads and movements go together. There is no more a single-point load-movement categorizing the pile response than there is a certain and specific "capacity".



Each of the dots added to the graph represents a different resistance at a pile element and a different movement of the element against the soil.



Fitting analysis to the results

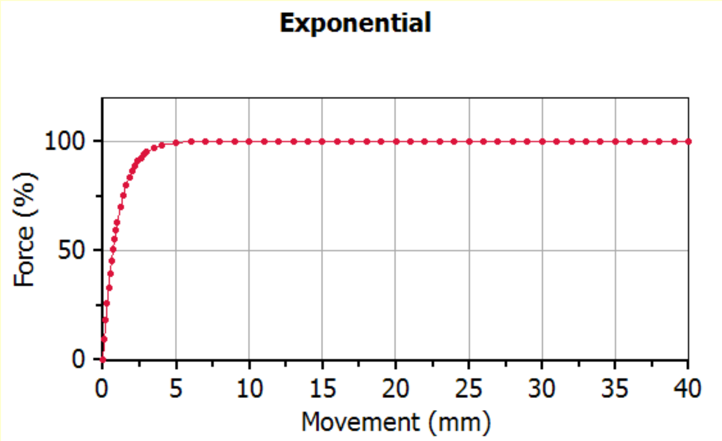


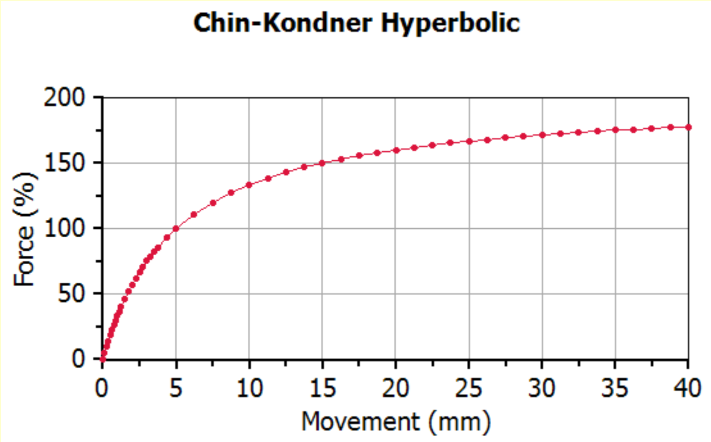
$$r_s = \beta\sigma'_z$$

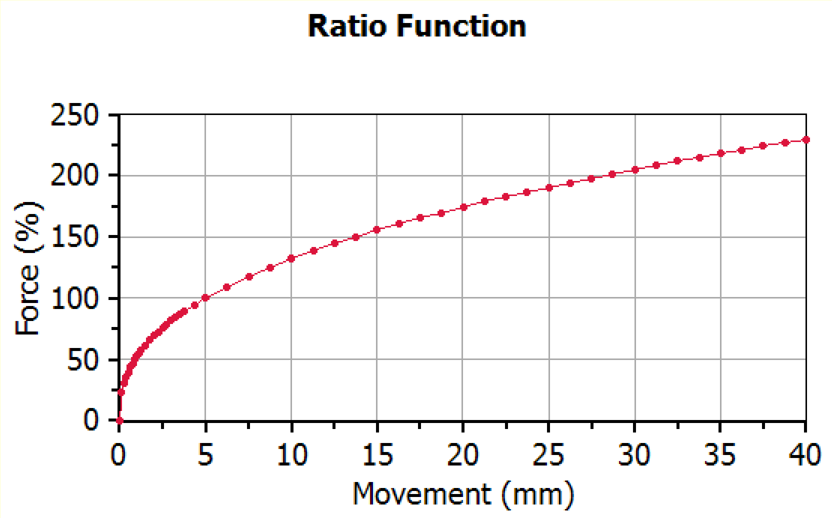
The pile is assumed made up of a series of short elements, each affected by soil resistance

$$r_s = f(\text{movement})$$

Movement = function of E-modulus







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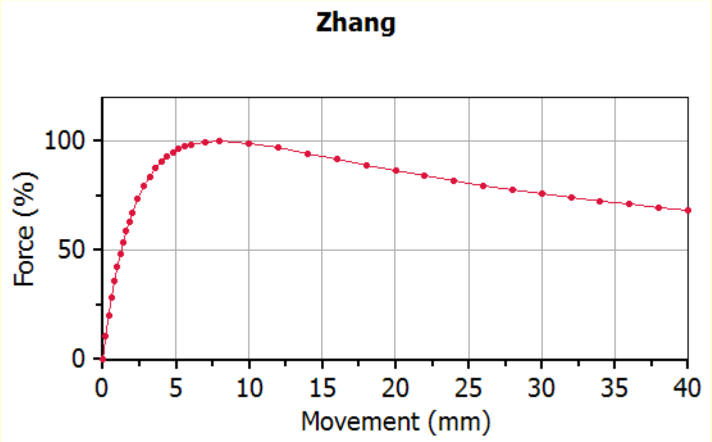
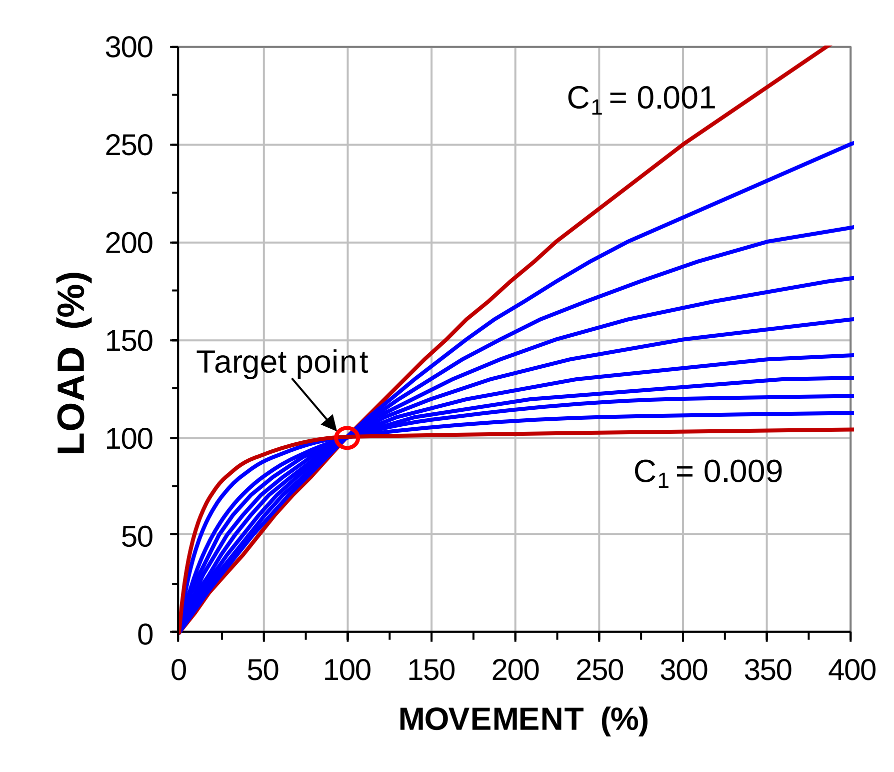
WHICH TO USE AND HOW TO MODIFY?



The load-movement of a pile element can be expressed by several functions, called "t-z functions" for the response of shaft shear and "q-z functions" for toe stress response. First, three strain-hardening functions: The Hyperbolic, Ratio, and Vander Veen Functions.



*To normalize, the loads are shown in percent of the **target load** (100 %) and the movements are in percent of the specific **target movement** (100 %). Then, the chosen function **parameter** determines the function curve from start to end.*

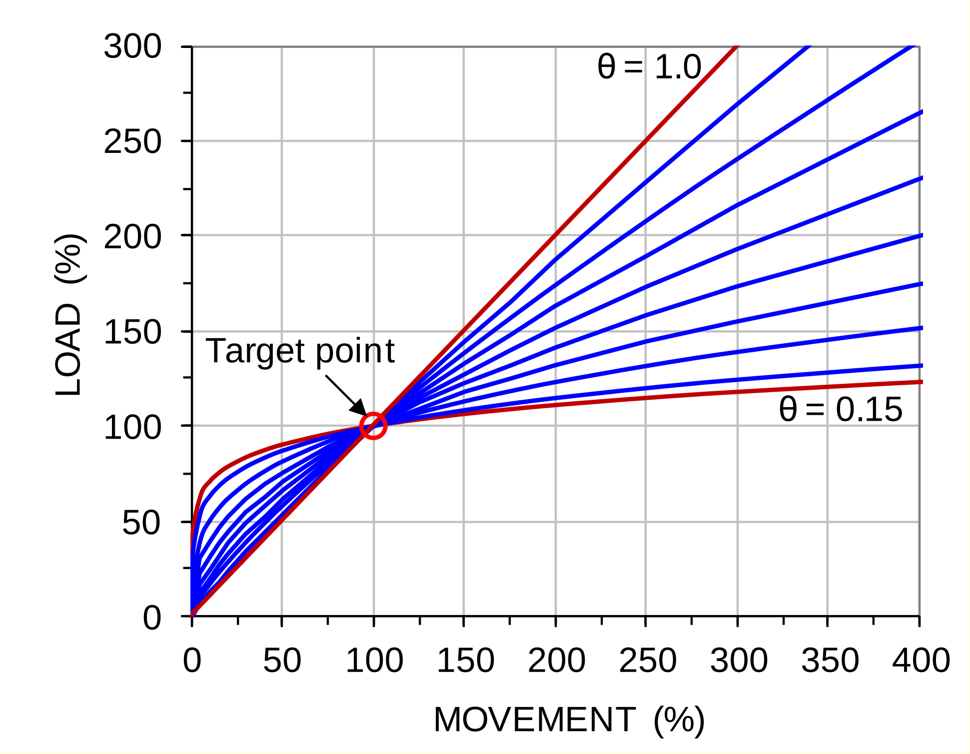
The Hyperbolic function (Chin-Kondner)

$$\delta = \frac{QC_2}{1 - QC_1}$$

$$Q = \frac{\delta}{C_1\delta + C_2}$$

$$C_2 = \delta\left(\frac{1}{Q} - \frac{1}{Q_u}\right)$$

Q = any applied load
δ = the movement associated with Load Q
Q_u = peak load or ultimate load; can be considered = Q_{trg} = **target load**
δ_u = movement at the peak load; can be considered = δ_{trg} = **target movement**
C_1 = slope of the straight line in the $\sqrt{\delta}/Q$ versus δ diagram—**function parameter**
C_2 = y-intercept of the straight line in the $\sqrt{\delta}/Q$ versus δ diagram

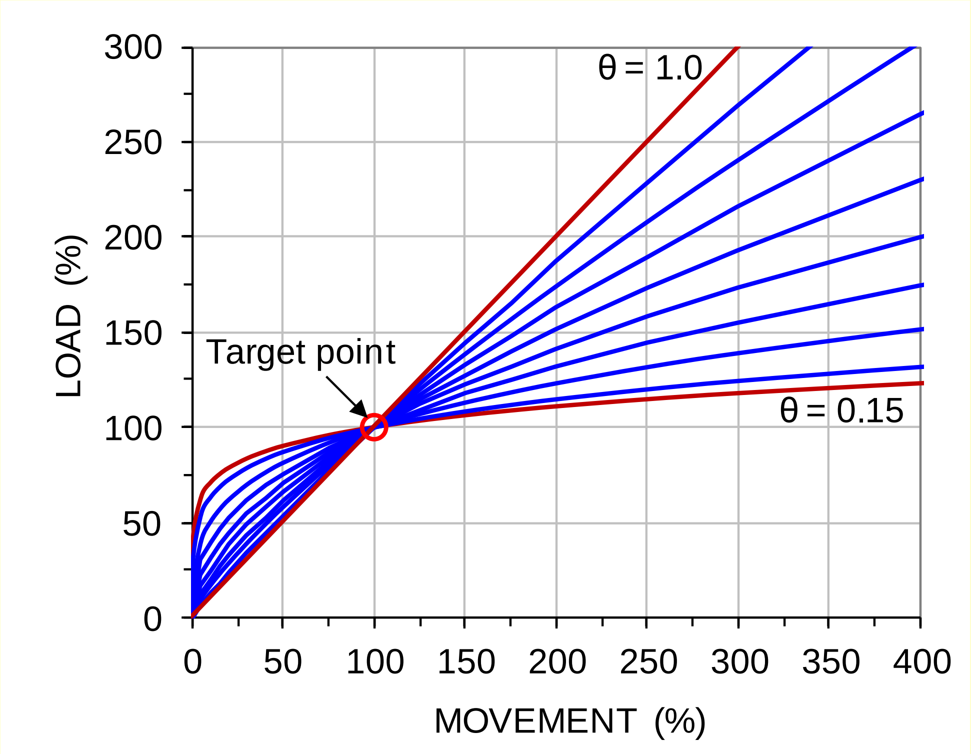


The Ratio function

$$Q_n = Q_{trg}\left(\frac{\delta_n}{\delta_{trg}}\right)^{\theta}$$

Q_{trg} = Target Load
δ_{trg} = Target Movement
Θ = Function Parameter, an exponent; $0 \leq \Theta \leq 1$

*To normalize, the loads are shown in percent of the **target load** (100 %) and the movements are in percent of the specific **target movement** (100 %). Then, the chosen function **parameter** determines the function curve from start to end.*



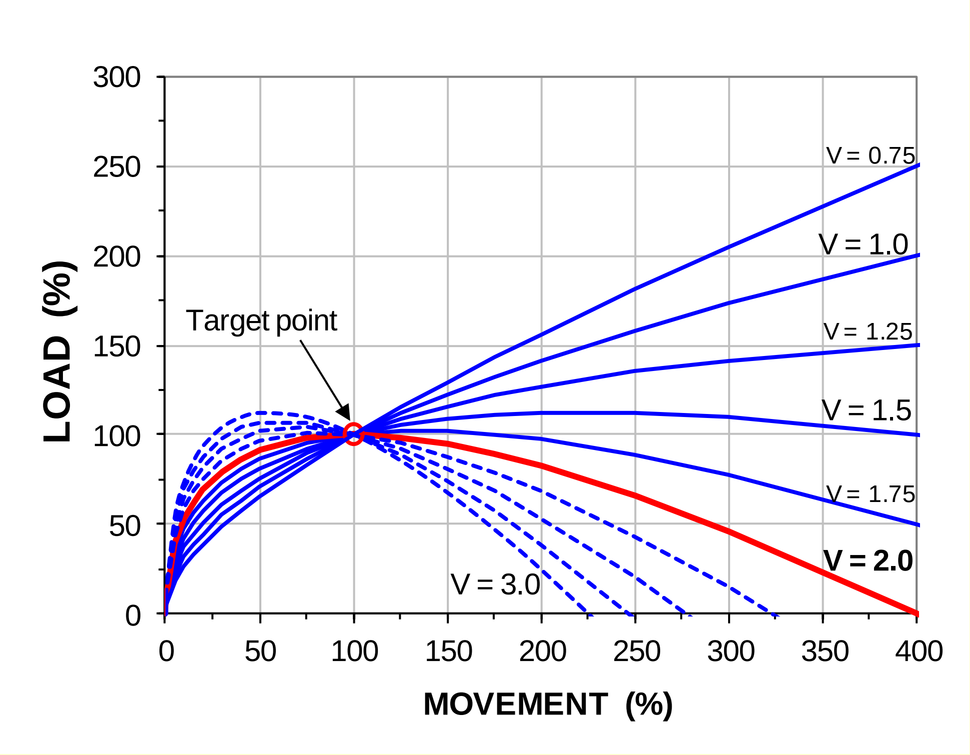
The Van Der Veen function ("exponential")

$$Q_n = \quad Q_{trg}\,(1 - e^{-b\delta_n})$$

Q_n = Load or Resistance "n"
Q_{trg} = Load or Resistance at target
δ_n = movement mobilized at Q_n
b = an exponent; > 0

To normalize, the loads are shown in percent of the ***target load*** *(100 %) and the movements are in percent of the specific* ***target movement*** *(100 %). Then, the chosen function* ***parameter*** *determines the function curve from start to end.*

Here are three strain-softening functions: The Vijayvergyia, Hansen, and Zhang Functions.

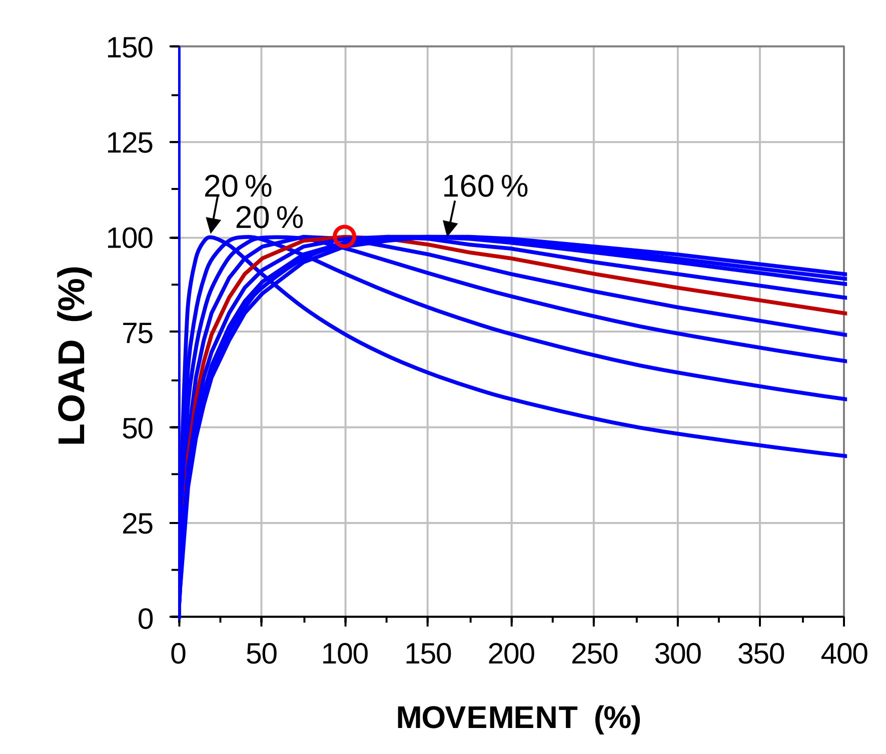


The Vijayvergiya function

$$Q / Q_{trg} = V \sqrt{\frac{\delta}{\delta_{trg}}} - (N-1)\frac{\delta}{\delta_{trg}}$$

Q = any applied load
δ = the movement associated with Load Q
V = the function coefficient; > 0
Q_{trg} = target load
δ_{trg} = target movement (associated with Q_{trg})

*To normalize, the loads are shown in percent of the **target load** (100 %) and the movements are in percent of the specific **target movement** (100 %). Then, the chosen function **parameter** determines the function curve from start to end.*



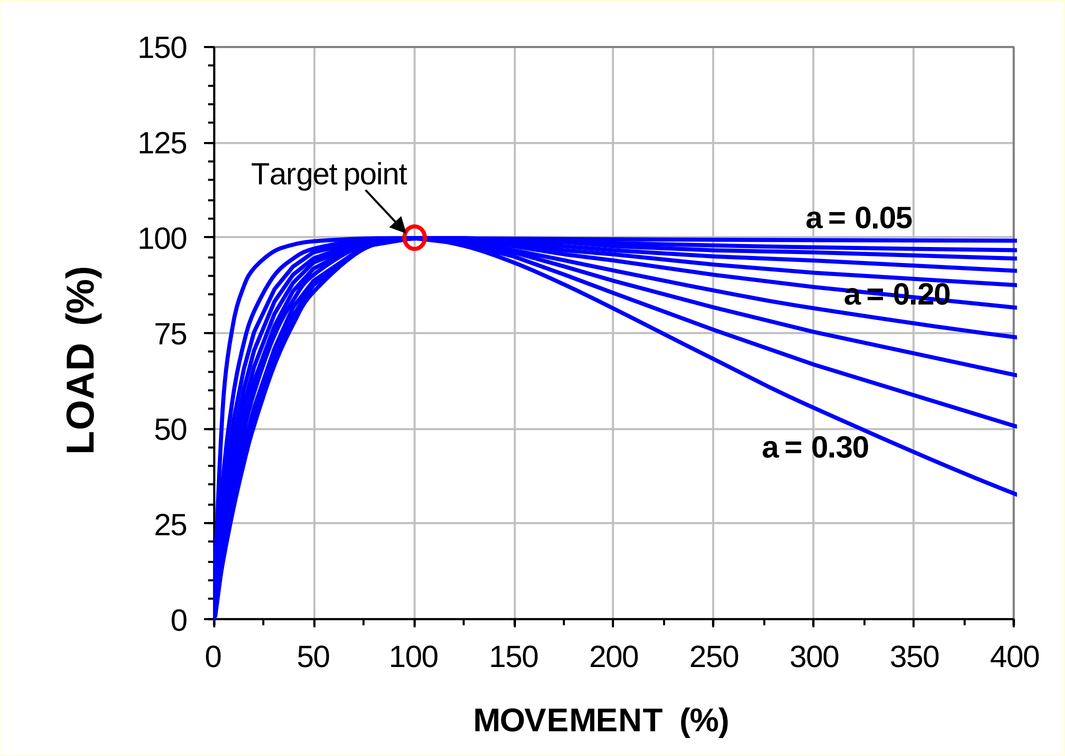
The Hansen 80-% function

$$Q = \frac{\sqrt{\delta}}{C_1\delta + C_2}$$

$$C_2 = \frac{\sqrt{\delta}}{Q} - C_1\delta$$

$$Q_{trg} = \frac{1}{2\sqrt{C_1 C_2}}$$

Q = any applied load
δ = the movement associated with Load Q
Q_u = peak load or ultimate load; can be considered = Q_{trg}
δ_u = movement at the peak load; can be considered = δ_{trg}
C_1 = slope of the straight line in the $\sqrt{\delta}/Q$ versus δ diagram
C_2 = y-intercept of the straight line in the $\sqrt{\delta}/Q$ versus δ diagram



The Zhang function

$$r = \frac{\delta(a + c\delta)}{(a + b\delta)^2}$$

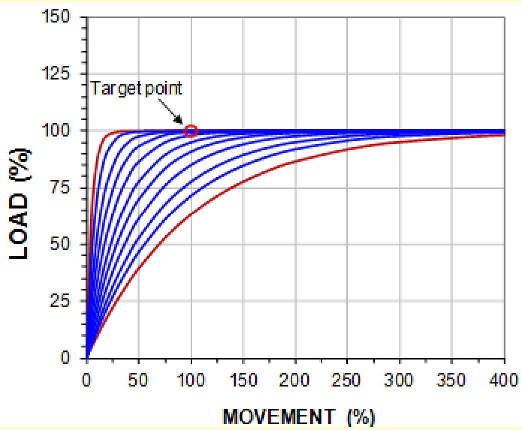
$$r_u = \frac{1}{4(b - c)}$$

$$\delta_u = \frac{a}{b - 2c}$$

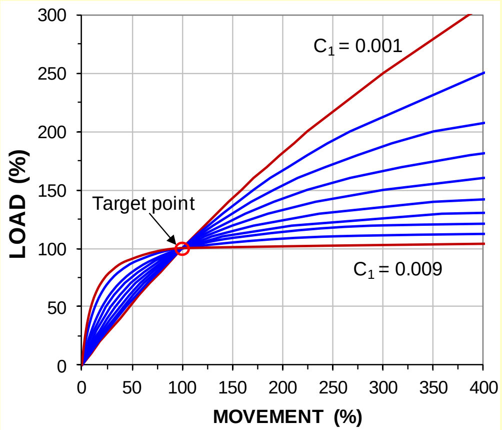
r_n = Resistance

r_u = Resistance at Peak
δ_1 = movement mobilized at Q_n or δ_{trg}
δ_u = movement mobilized at Peak force
a = main parameter
b and c are functions of "a"

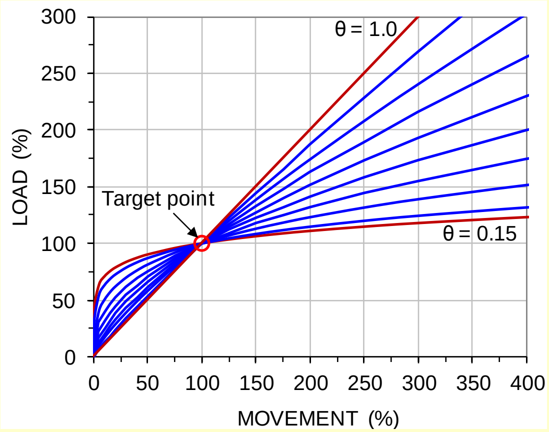
The shapes can be very diverging



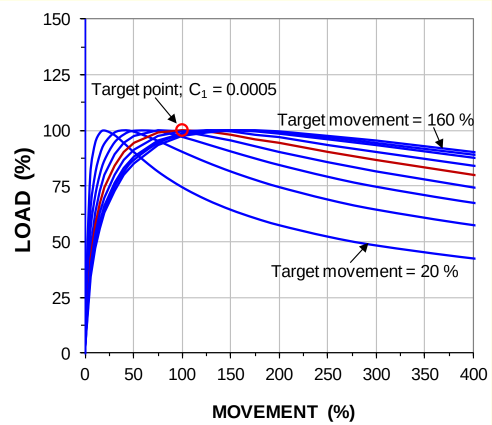
VanderVeen



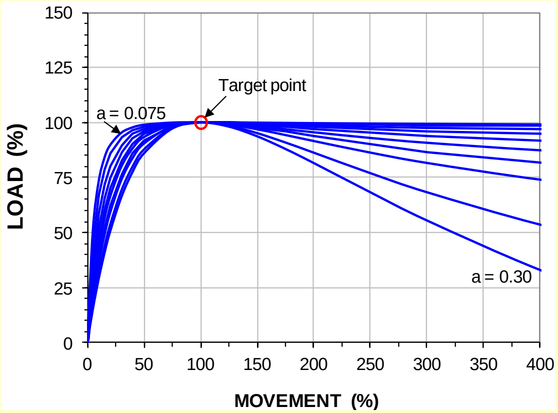
Chin (hyperbolic)



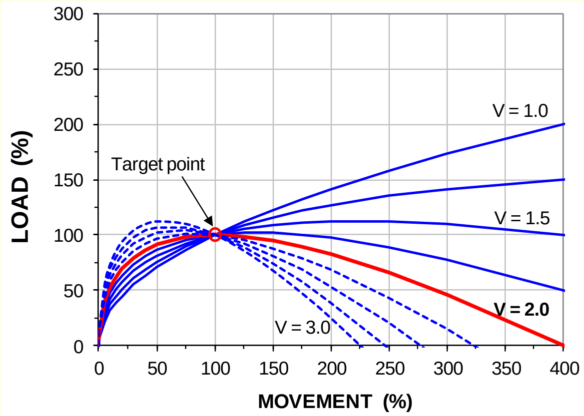
Ratio



Hansen



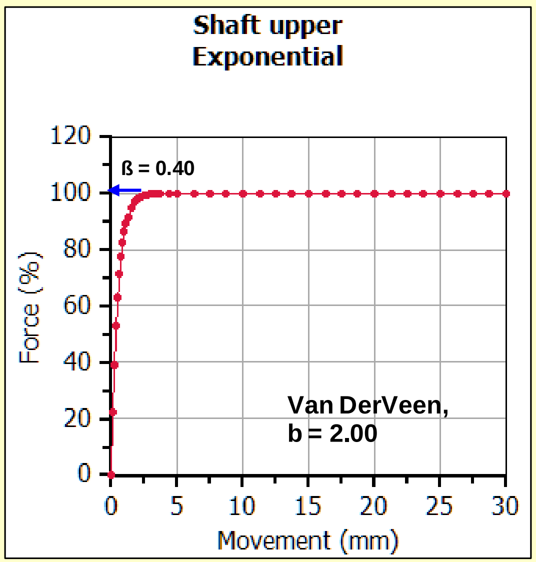
Zhang

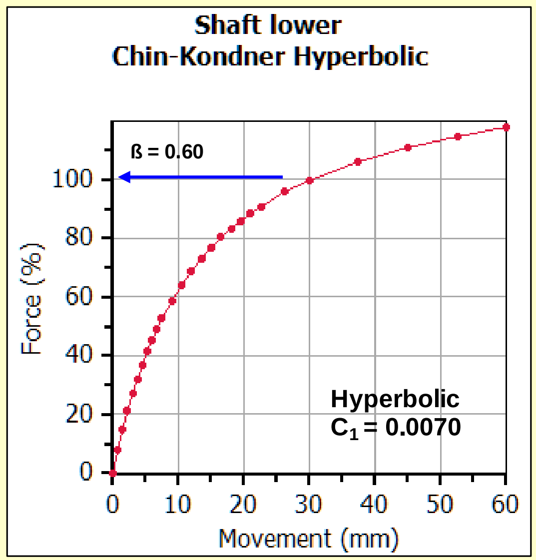


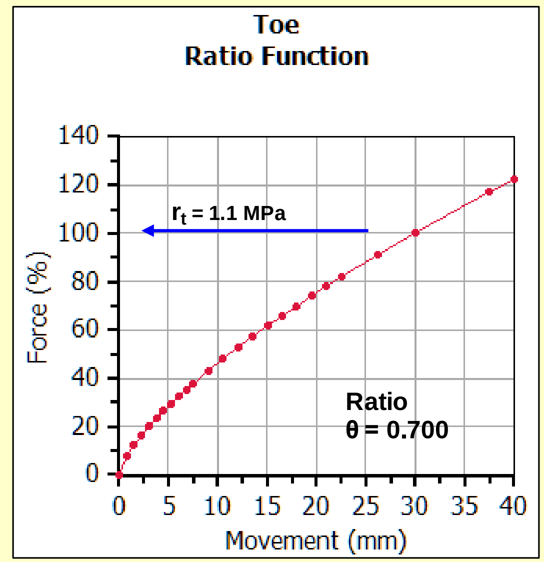
Vijayvergiya

All t-z/q-z functions are determined by the coordinates of the target point combined with a single parameter (coefficient or exponent).

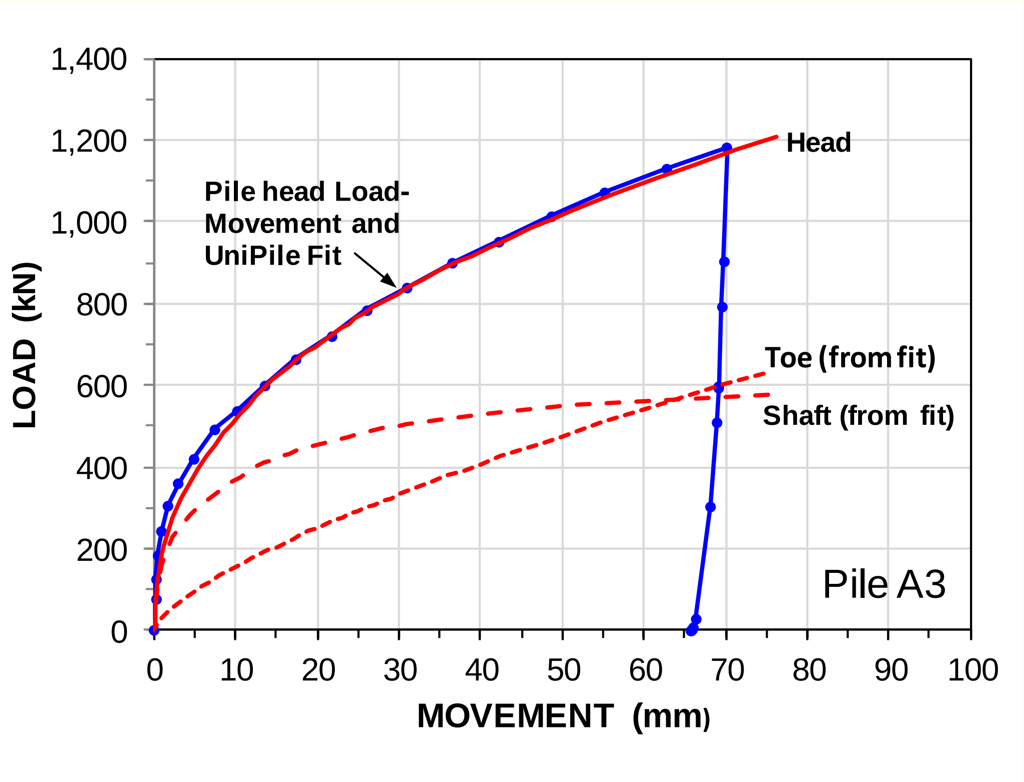
The load-movement plot for the pile head and gage measurements will serve as a first indication of what actual t-z and q-z functions to apply in fitting a theoretical calculation to the measured load-movement curve. In my first tries to obtain a fit for Pile A3 at the B.E.S.T. site, I found the following functions to provide a good fit.



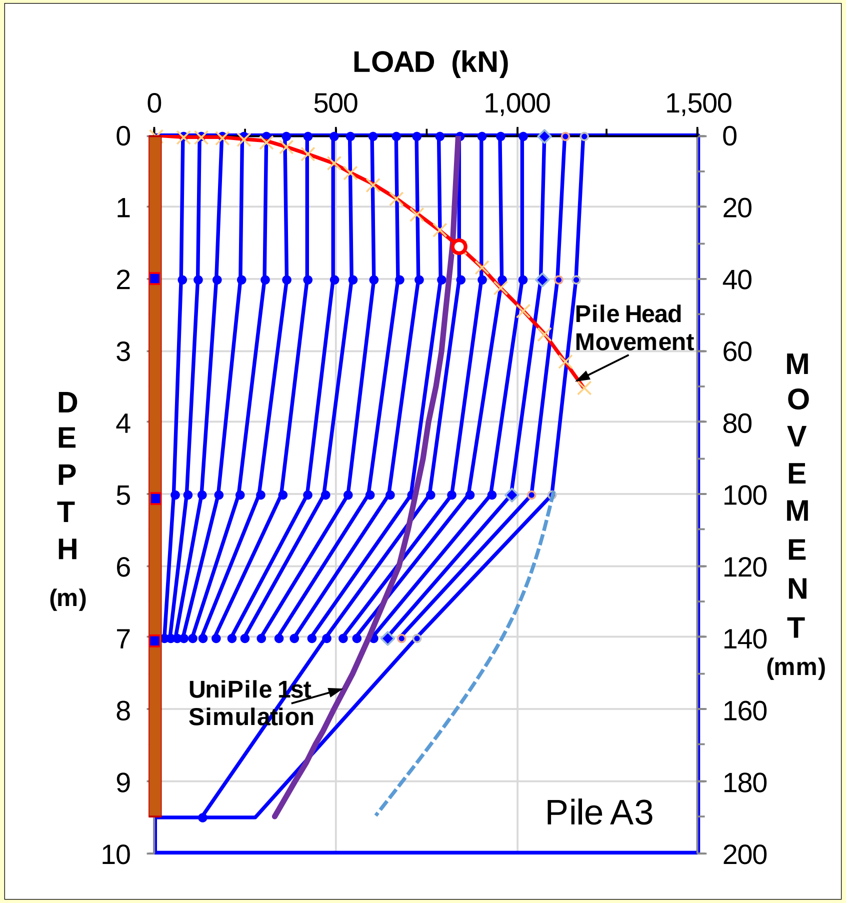




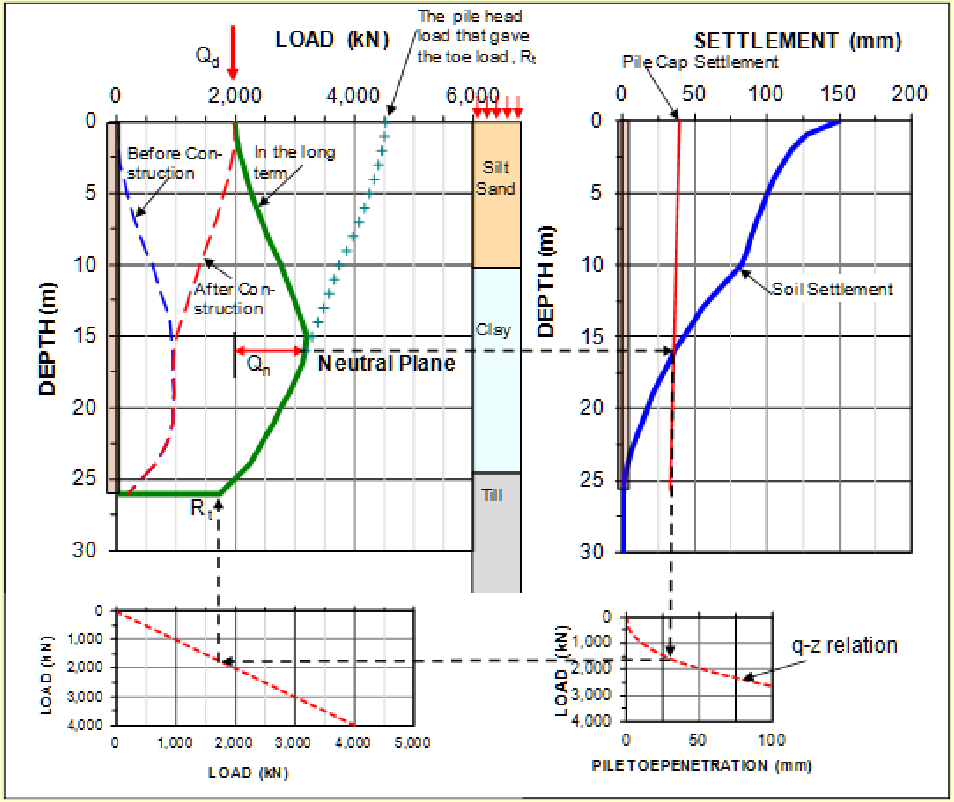
The measured and fitted pile-head load-movement curves. I have used the UniPile5 (UnisoftGS.com) software for the calculations.



The measured and calculated load-distributions. The figure includes the UniPile simulation of the load distribution for the 32 mm movement, close to the 30-mm target movement for the pile element. The agreement is good in the upper half of the soil profile. The discrepancy below may be due to the effect of residual load that gives a tendency for the analysis of the strain-gage records to overestimate the loads. When the results of the additional tests and, in particular, from the combined bidirectional and head-down tests, are available, I will revisit the UniPile simulations.



The B.E.S.T. tests involve no foundation design. But, if there was a design, how would the design analyses work have proceeded? We have not determined a "capacity" and we do not need such make-believe values for the design analysis. The below figure shows the next step as it was for an industrial project involving a series of narrow piled foundations in the US. Because the pile groups are narrow (involving just a few piles), the design could was made for single piles. The intended working load (unfactored) on the piles was 2,000 kN. The figure shows how in the long-run the load will increase due to the drag force induced by general subsidence at the site and that an equilibrium will develop with regard to both forces and settlements. The well-established (series of instrumented pile tests) pile response was used to determine the piles will settle less than 50 mm, which was considered acceptable for the foundations and the structure.



Establishing the unified pile design loop for determining settlement (Fellenius and Ochoa 2009, Fellenius 2016c).

Thank you very much for your attention