2° C.F.P.B.

CONGRESO INTERNACIONAL
DE FUNDACIONES PROFUNDAS DE BOLIVIA
del 12 al 15 de mayo de 2015
SANTA CRUZ - BOLIVIA

The Static Loading Test

Performance, Instrumentation, Interpretation

Bengt H. Fellenius

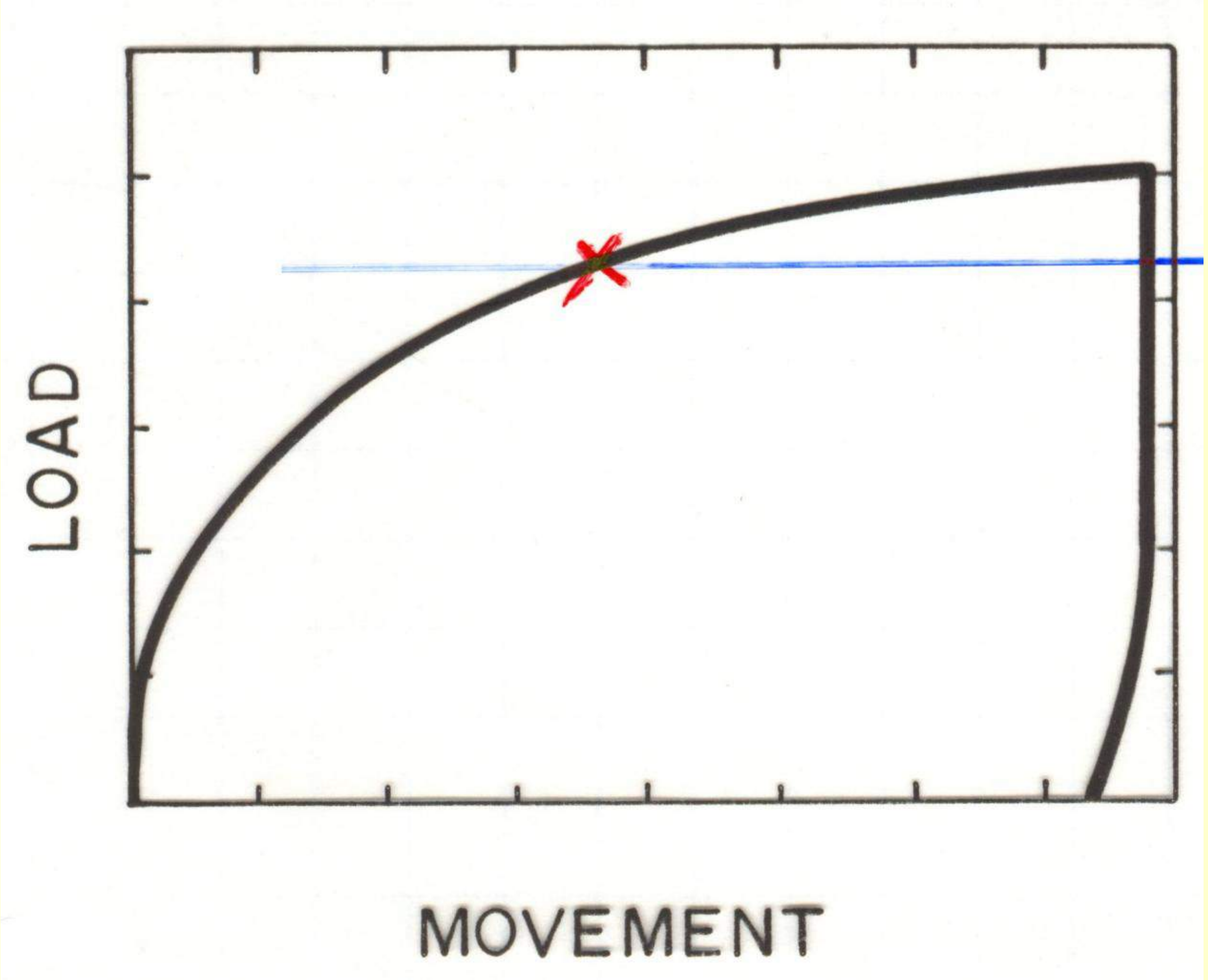
First K.R. Massarsch Lecture

Fellenius, B.H., 2015. The Static Loading Test. Segundo Congreso Internacional de Fundaciones
Profundas de Bolivia, First K.R. Massarsch Lecture, Santa Cruz May 12-15, 62 p

1

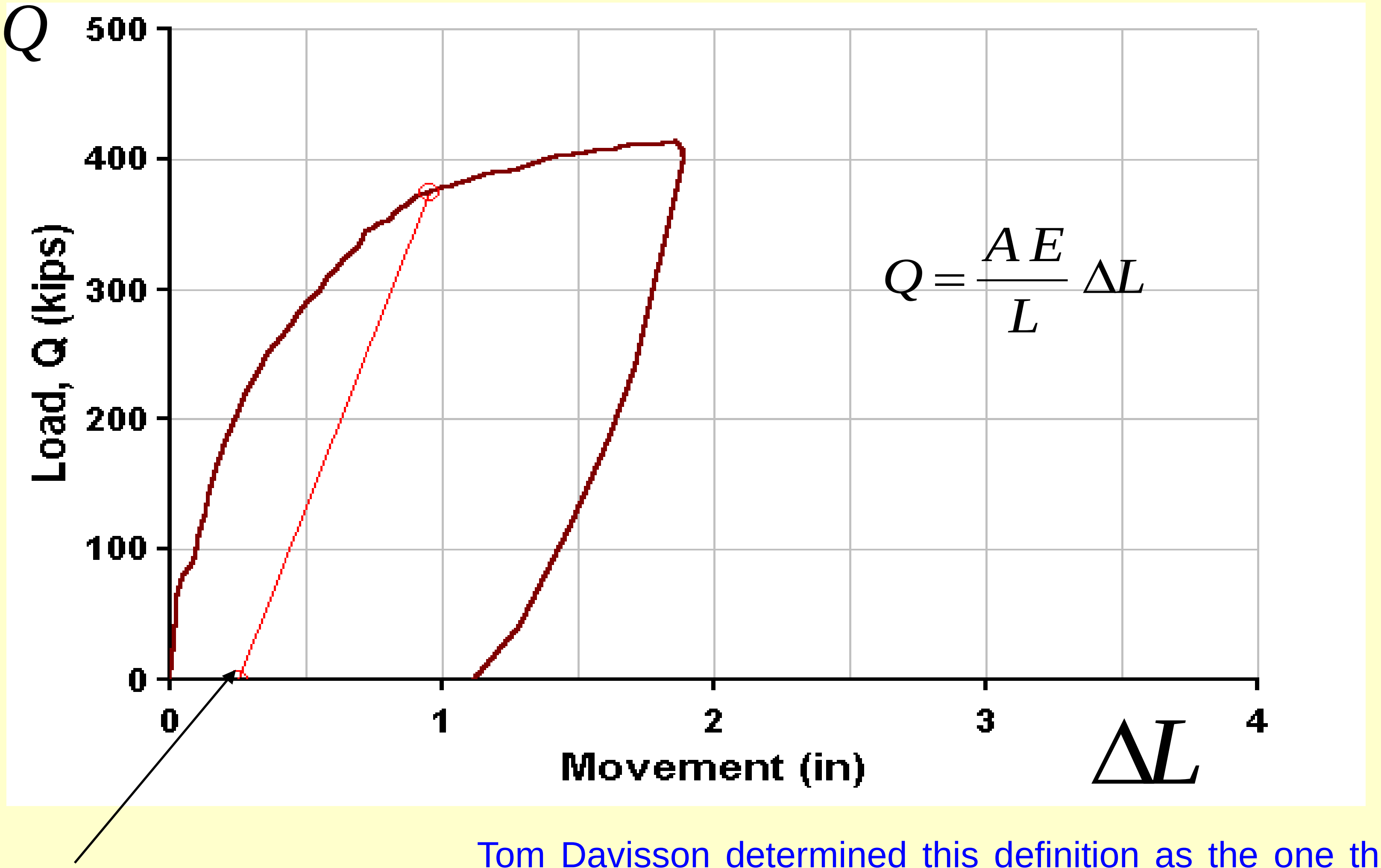
A routine static loading test provides the load-movement of the pile head...

and the pile capacity?



The Offset Limit Method

Davisson (1972)



$$Q = \frac{A\,E}{L}\,\Delta L$$

OFFSET (inches) = 0.15 + b/120

OFFSET (mm) = 4 + b/120

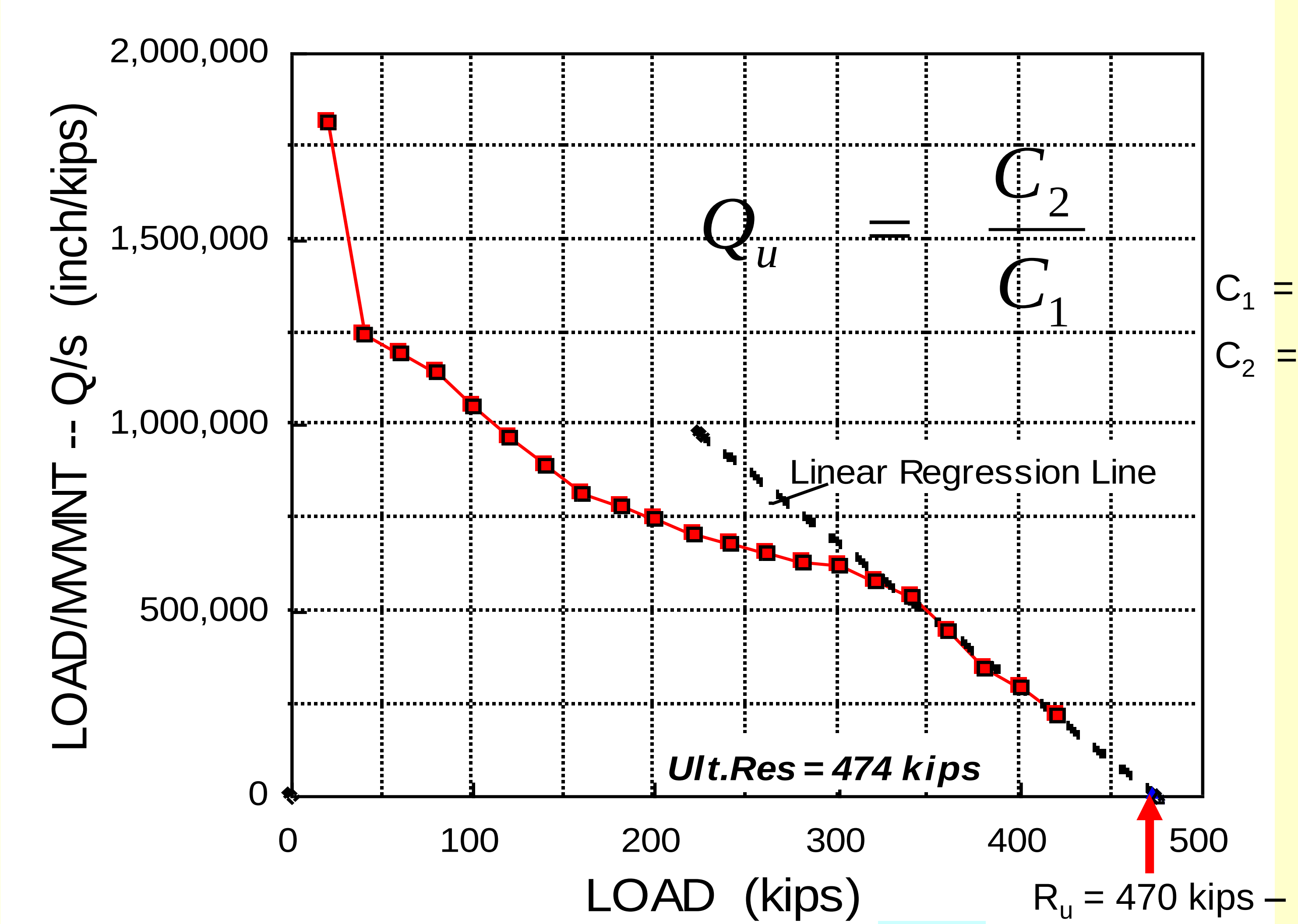
b = pile diameter

Tom Davisson determined this definition as the one that fitted best to the capacities he intuitively determined from a FWHA data base of loading tests on driven piles. The definition does not mean or prove the the pile diameter has anything to do with the interpretation of capacity from a load-movement curve.

The Decourt Extrapolation

Decourt (1999)

$$\frac{Q}{\delta}$$



$$Q_u = \frac{C_2}{C_1}$$

C_1 = Slope

C_2 = Y-intercept

R_u = 470 kips – 230 tons

$$Q$$

Other methods are:

The Load at Maximum Curvature

Mazurkiewicz Extrapolation

Chin-Kondner Extrapolation

DeBeer double-log intersection

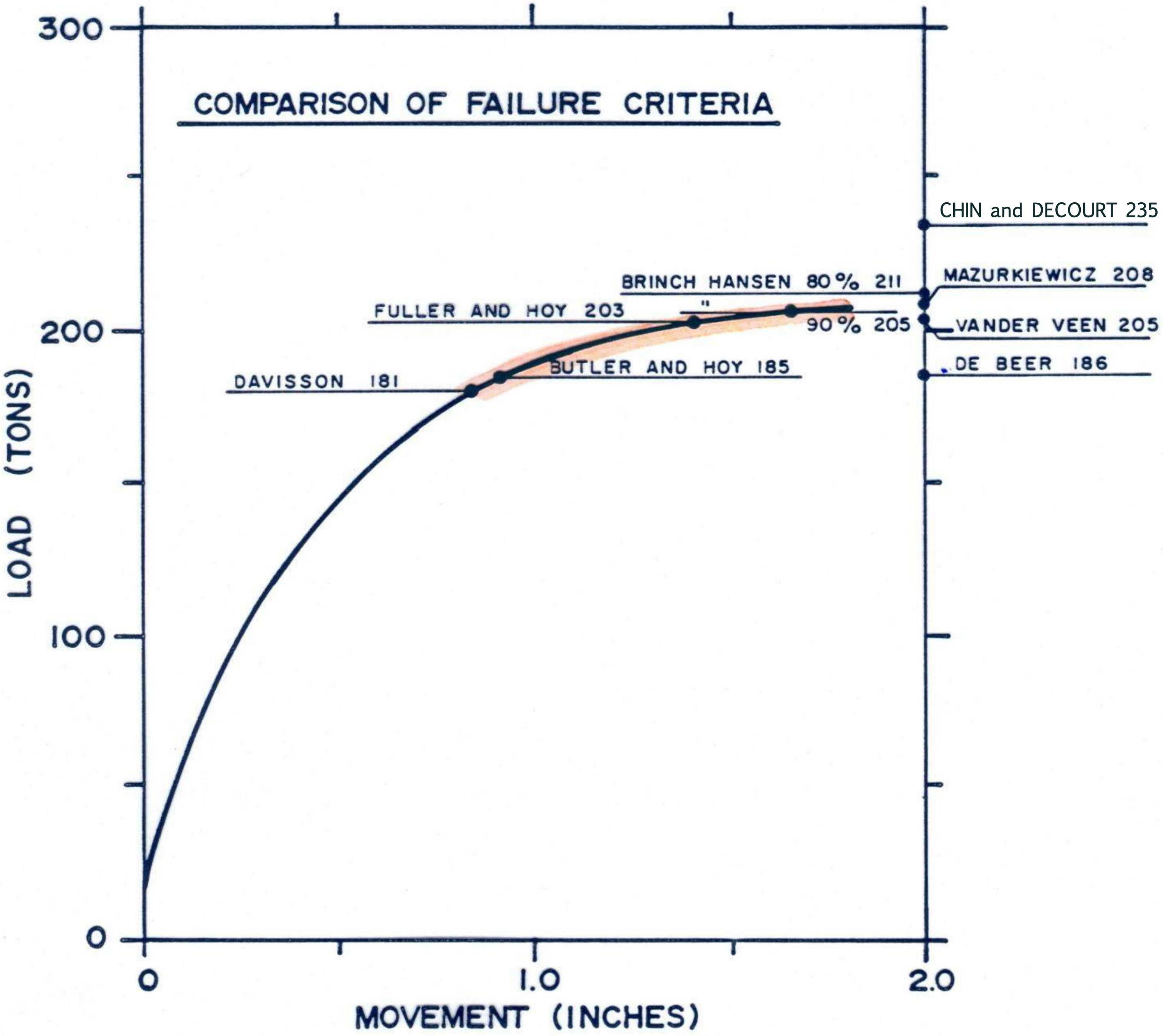
Fuller-Hoy Curve Slope

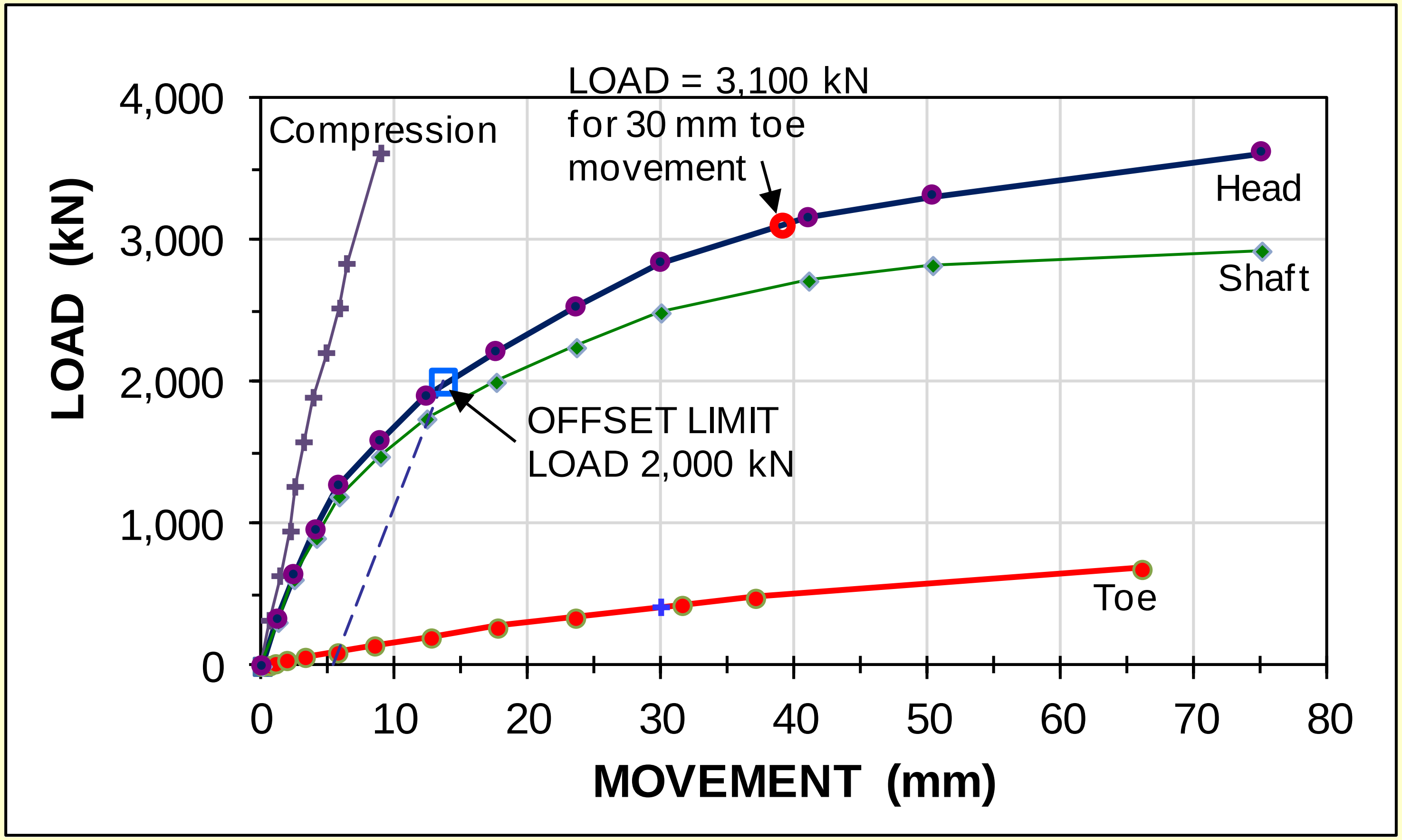
The Creep Method

Yield limit in a cyclic test

~~**Load 10 % of pile head diameter**~~

For details, see Fellenius (1975, 1980)


COMPARISON OF FAILURE CRITERIA
CHIN and DECOURT 235
BRINCH HANSEN 80% 211
MAZURKIEWICZ 208
FULLER AND HOY 203
"
90% 205
VANDER VEEN 205
DE BEER 186
BUTLER AND HOY 185
DAVISSON 181
300
200
100
0
LOAD (TONS)
0
1.0
2.0
MOVEMENT (INCHES)



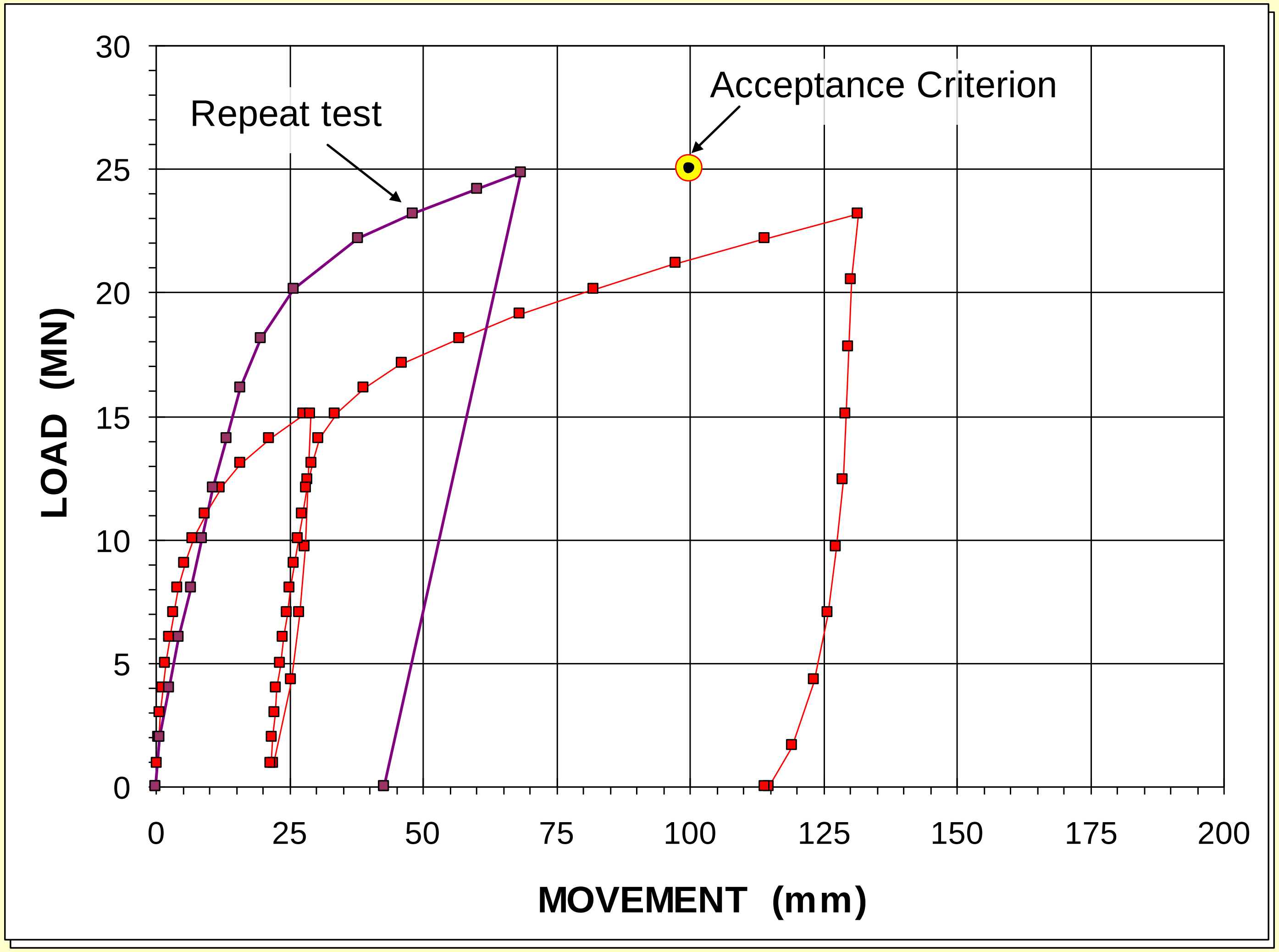
A rational, upper-limit definition to use for "capacity" is the load that caused a 30-mm pile toe movement.

Indeed, bringing the toe movement into the definition is the point. A "capacity" deduced from the movement of the pile head in a static loading test on a single pile has little relevance to the structure to be supported by the pile. The relevance is even less when considering pile group response.

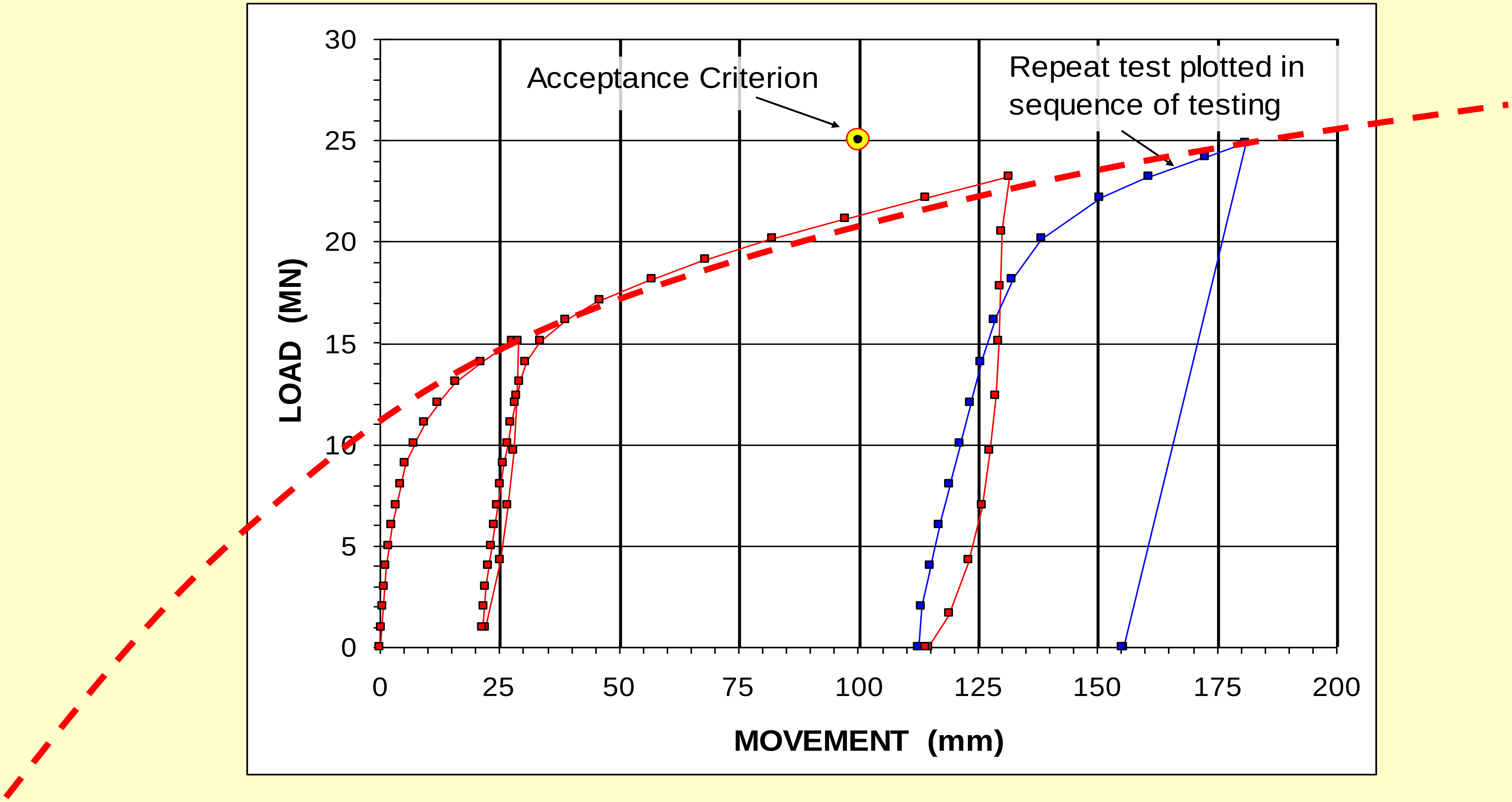
What really do we learn from unloading/reloading and what does unloading/reloading do to the gage records?

Does unloading/reloading add anything of value to a test?

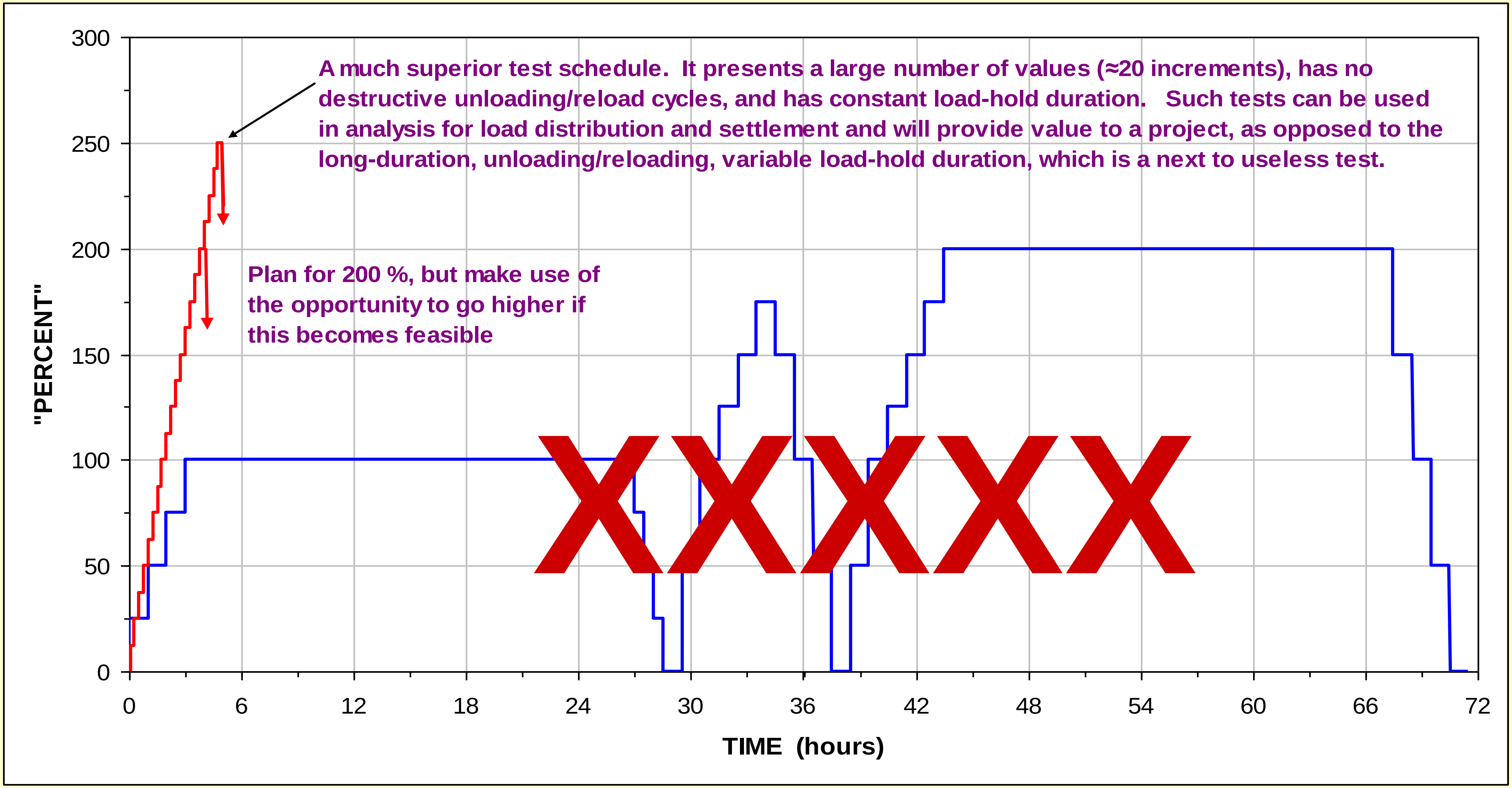
Result on a test on a 2.5 m diameter, 80 m long bored pile



Plotting the repeat test in proper sequence



The Testing Schedule



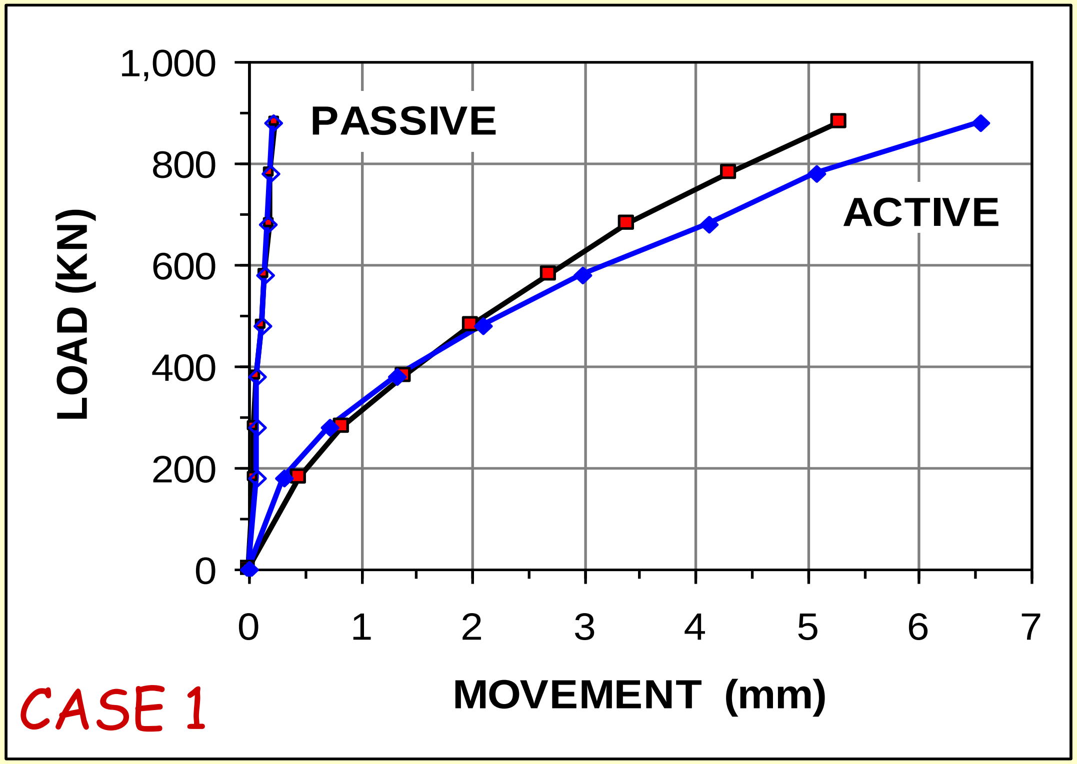
A much superior test schedule. It presents a large number of values (≈20 increments), has no destructive unloading/reload cycles, and has constant load-hold duration. Such tests can be used in analysis for load distribution and settlement and will provide value to a project, as opposed to the long-duration, unloading/reloading, variable load-hold duration, which is a next to useless test.

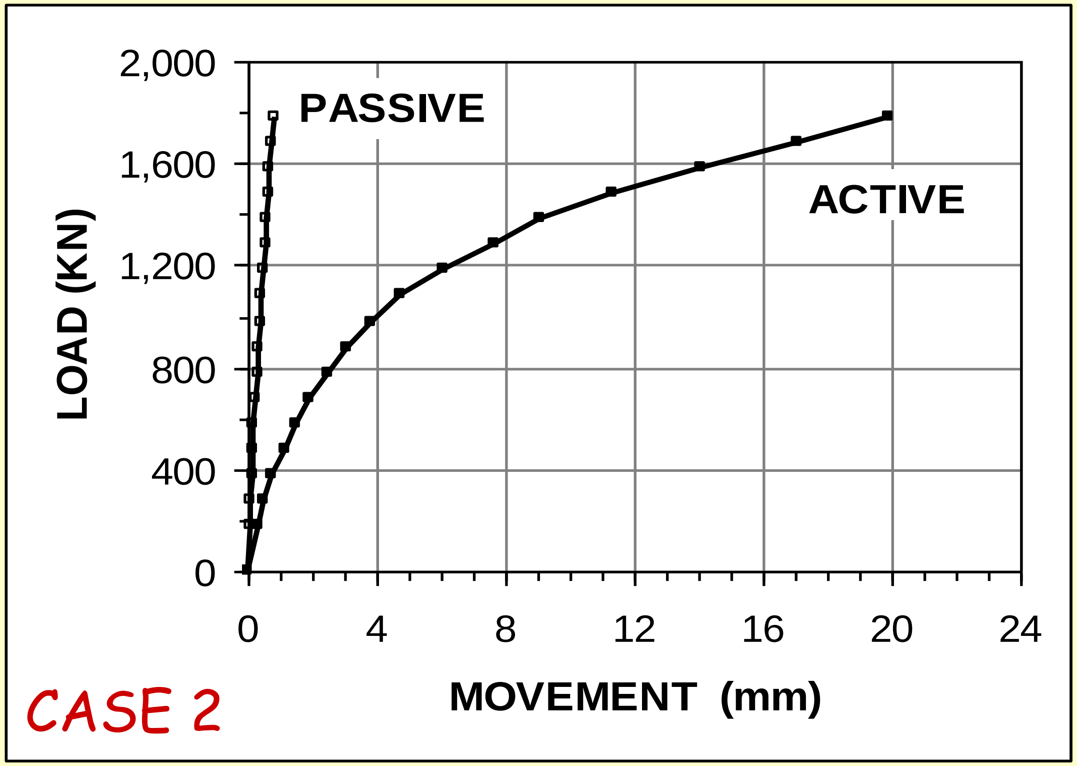
Plan for 200 %, but make use of the opportunity to go higher if this becomes feasible

The schedule in blue is typical for many standards. However, it is costly, time-consuming, and, most important, it is diminishes or eliminates reliable analysis of the test results.

3

Pile Interaction





Load-Movement curves from static loading tests on two "ACTIVE" piles (one at a time) and one "PASSIVE".

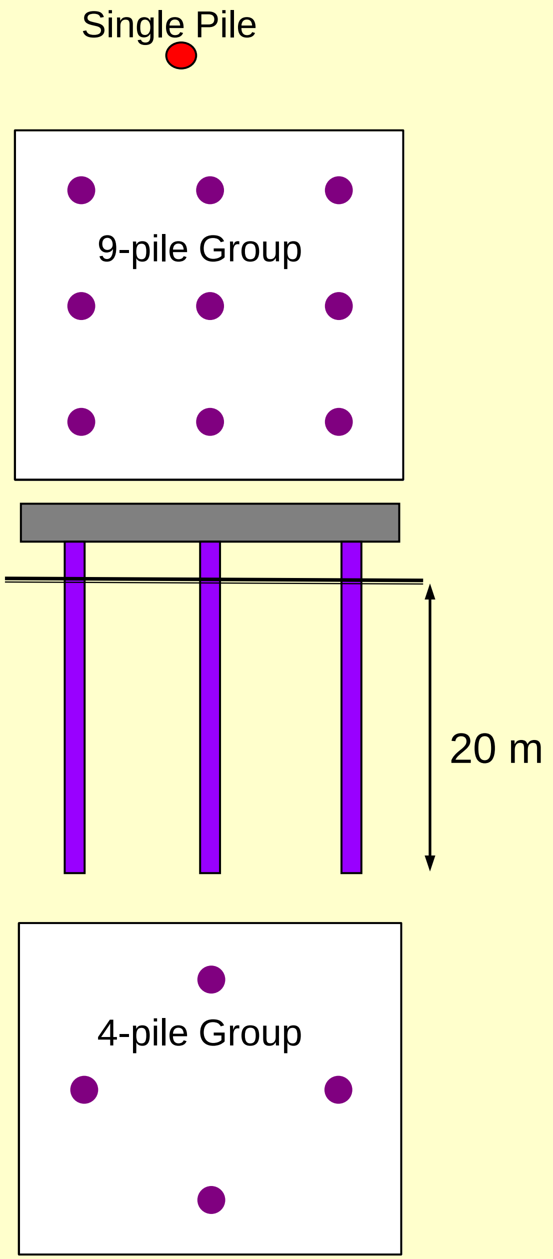
.

Diameter, b = 400 mm; Depths = 8.0 m and 8.6 m. The "PASSIVE" pile is 1.2 m and 1.6 m away from the "ACTIVE" (c/c = 3b and 4b).

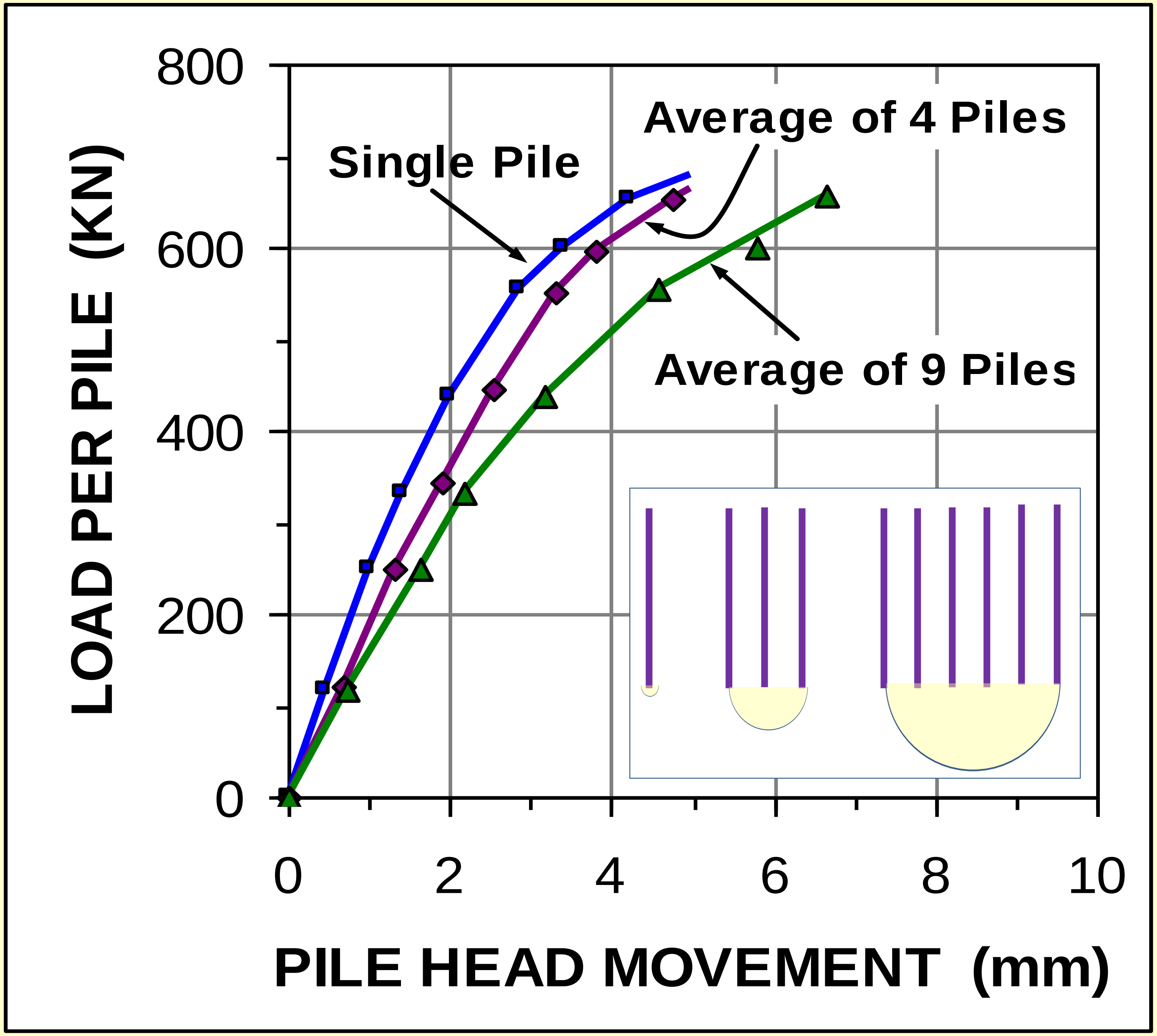
Load-Movement curves from static loading tests on one pile ("ACTIVE"). Diameter (b) = 500 mm; Depth = 20.6 m. "PASSIVE" pile is 3.5 m away (c/c = 7b).

Caputo and Viggiani (1984) with data from Lee and Xiao (2001).

Group Effect



Comparing tests on single pile, a 4-pile group, and a 9-pile group



O’Neill et al. (1982)

Instrumentation

and

Interpretation

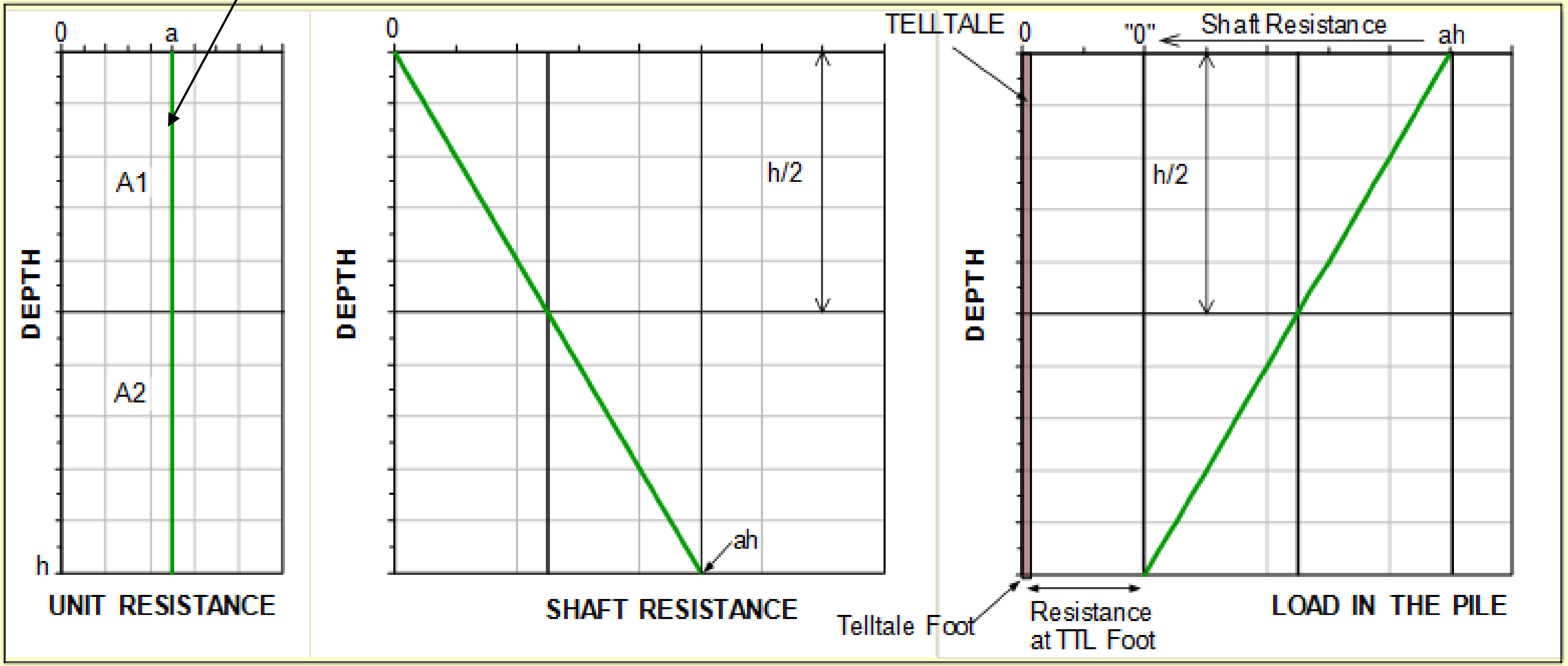
Telltales

- A telltale measures shortening of a pile and must never be arranged to measure movement.
- Let toe movement be the pile head movement minus the pile shortening.
- For a single telltale, the **shortening** divided by the distance between the pile head and the telltale toe is the **average strain** over that length.
- For two telltales, the distance to use is that between the telltale tips.
- The **strain** times the cross section area of the pile times the pile material E-modulus is the average **load** in the pile.

- **To plot a load distribution, where should the load value be plotted? Midway of the length or above or below?**

Load distribution for **constant** unit shaft resistance

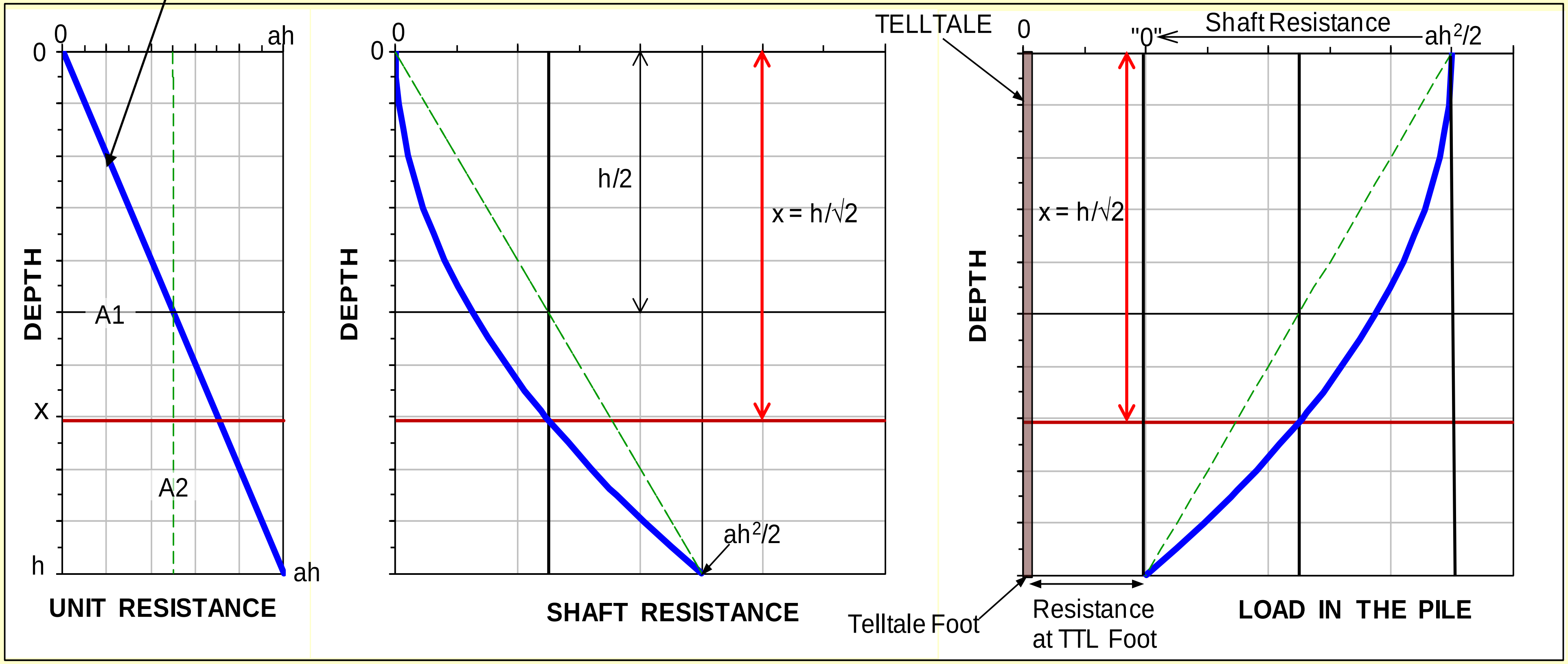
Unit shaft resistance
(constant with depth)



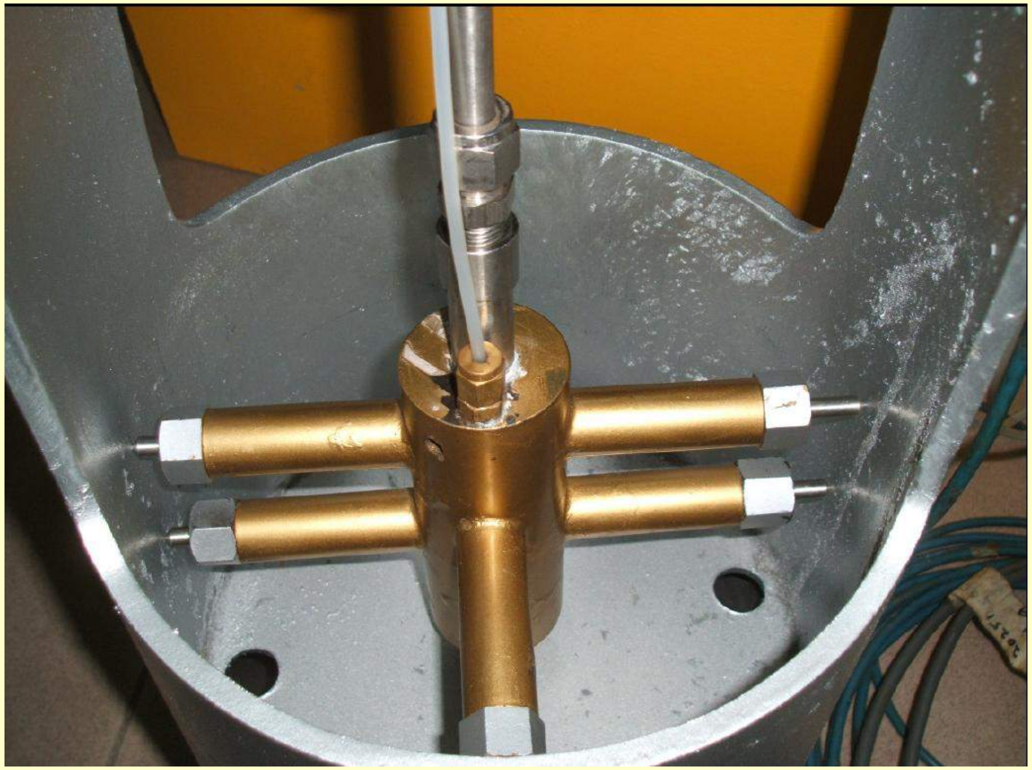
Linearly increasing unit shaft resistance and its load distribution

$$A1 = A2 \quad ===> \quad \frac{ax^2}{2} = 0.5\frac{ah^2}{2} \quad ===> \quad x = \frac{h}{\sqrt{2}}$$

Linearly increasing unit shaft resistance



Glostrext Retrievable Extensometer (Geokon 1300 & A9)

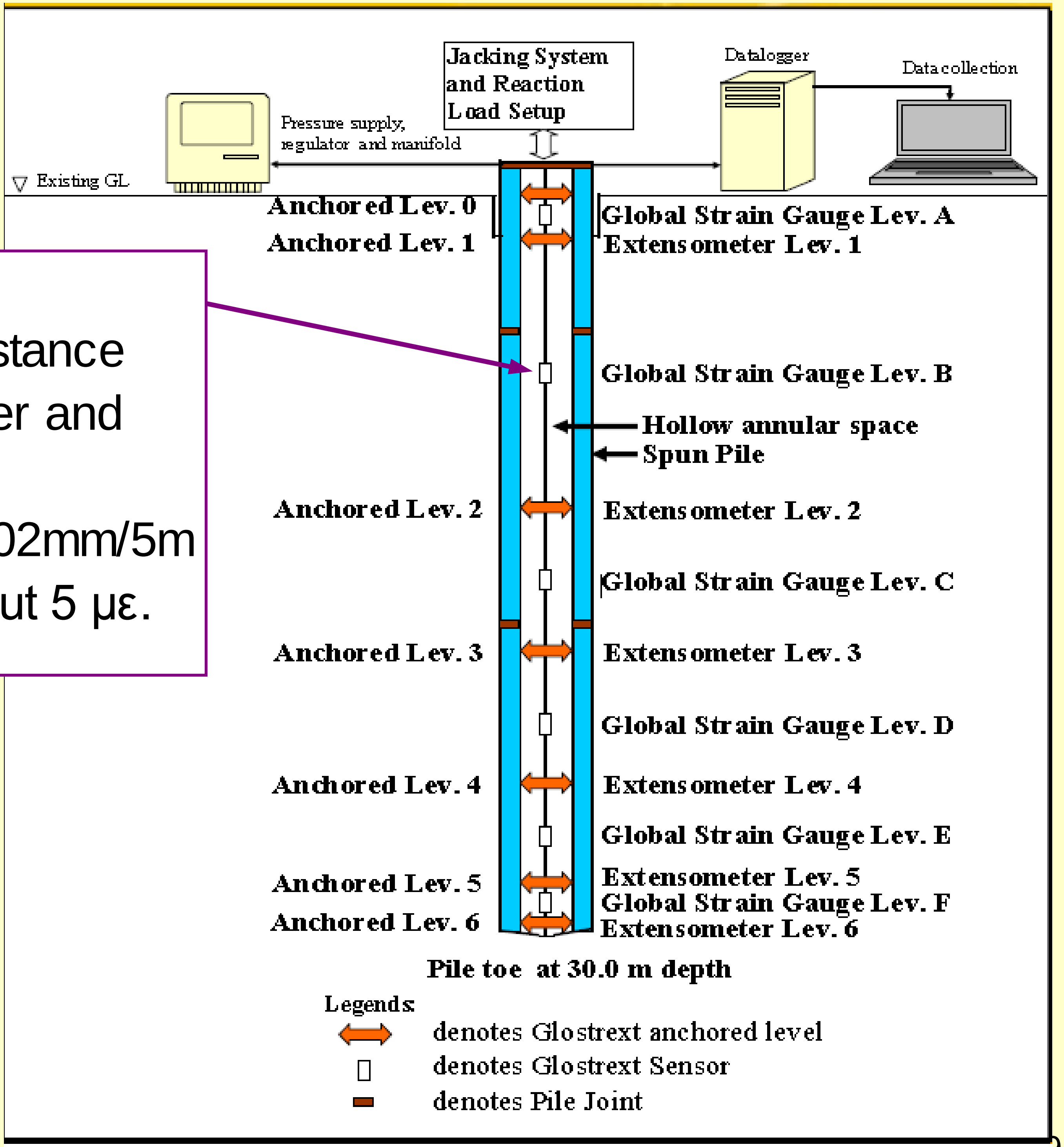


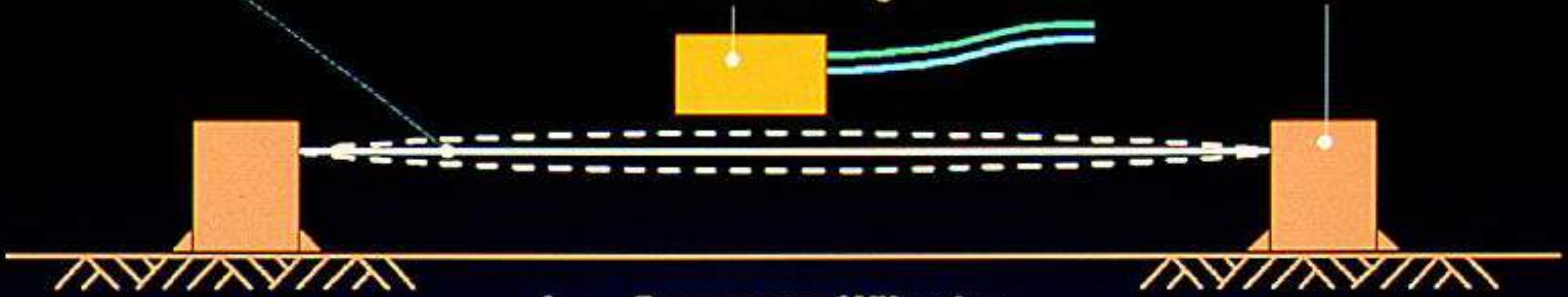
Anchor arrangement display

Hanifah, A.A. and Lee S.K. (2006)

Geokon borehole extensometer

Gage for measuring displacement, i.e., distance change between upper and lower extensometers. Accuracy is about 0.02mm/5m corresponding to about 5 με.





Vibrating, Tensioned, Steel Wire

Plucking Coil and Permanent Magnet

End Block Fixed to Surface Under Strain

f = Frequency of Vibration
L = Wire Length
T = Tension
m = Wire Mass per Unit Length

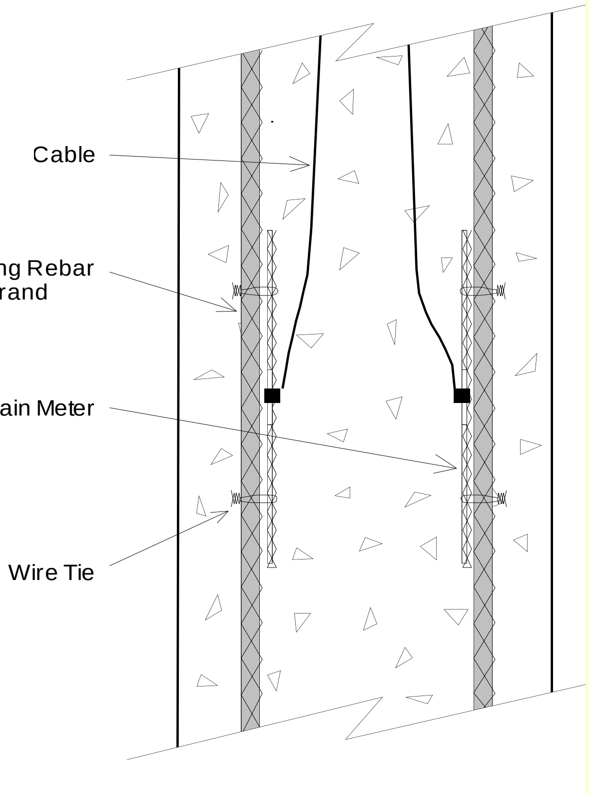
$$f = \frac{1}{2L}\sqrt{\frac{T}{m}} \quad \text{or } f = K_1\sqrt{\varepsilon} \quad \text{where } K_1 = \frac{1}{2L}\sqrt{\frac{AE}{m}}$$

$$\underline{\Delta\varepsilon = K_2\,(f^2 - f_0^2)}$$

Vibrating Wire Transducer

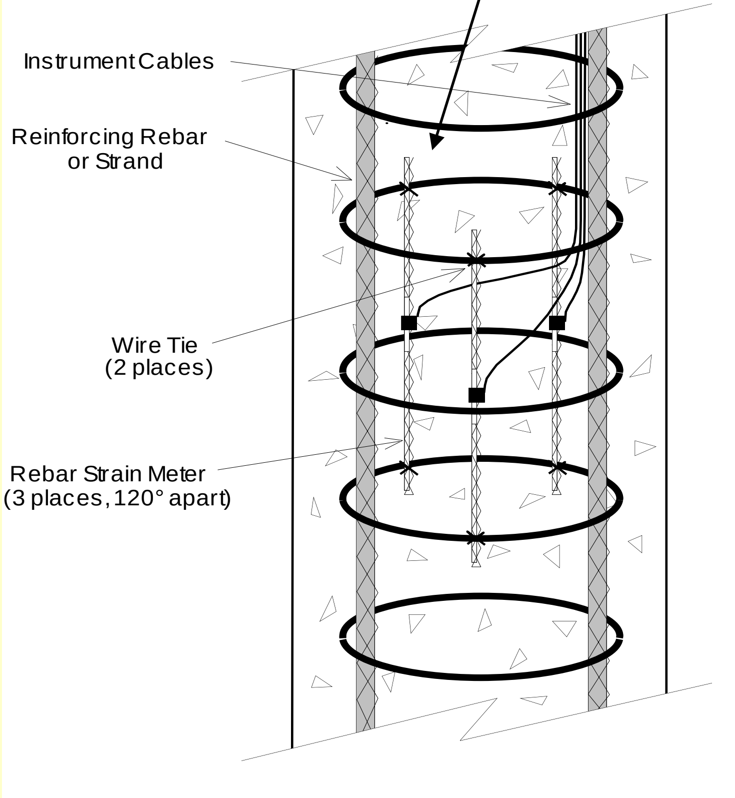
GEOKON
The World Leader in Vibrating Wire Technology

Rebar Strain Meter — “Sister Bar”



Tied to Reinforcing Rebar

Three bars?!

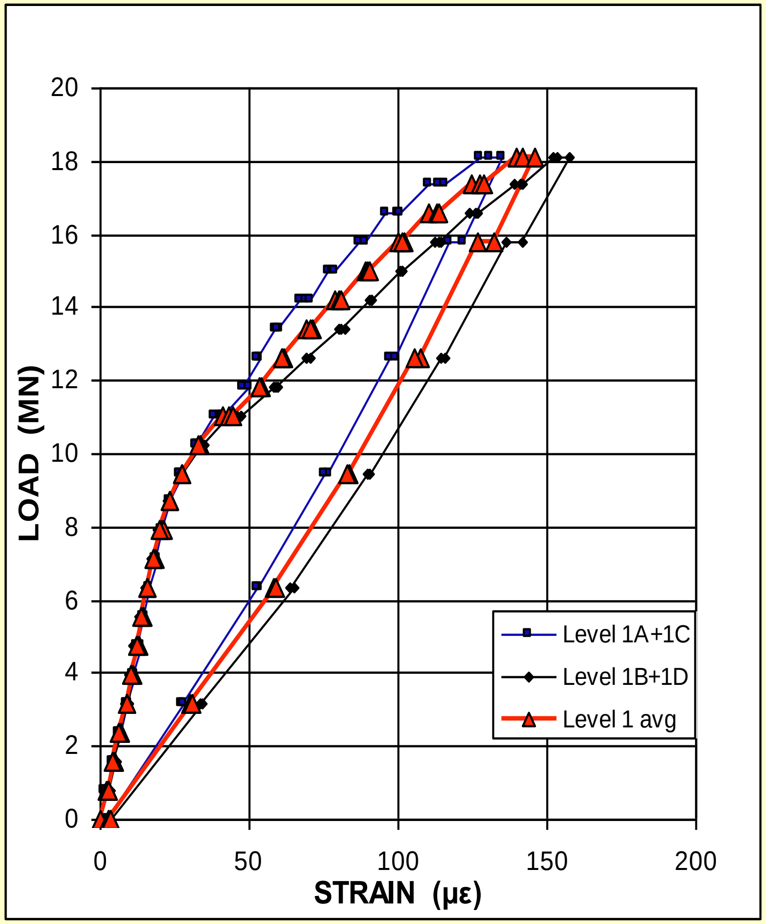


Tied to Reinforcing Rings

Hayes 2002

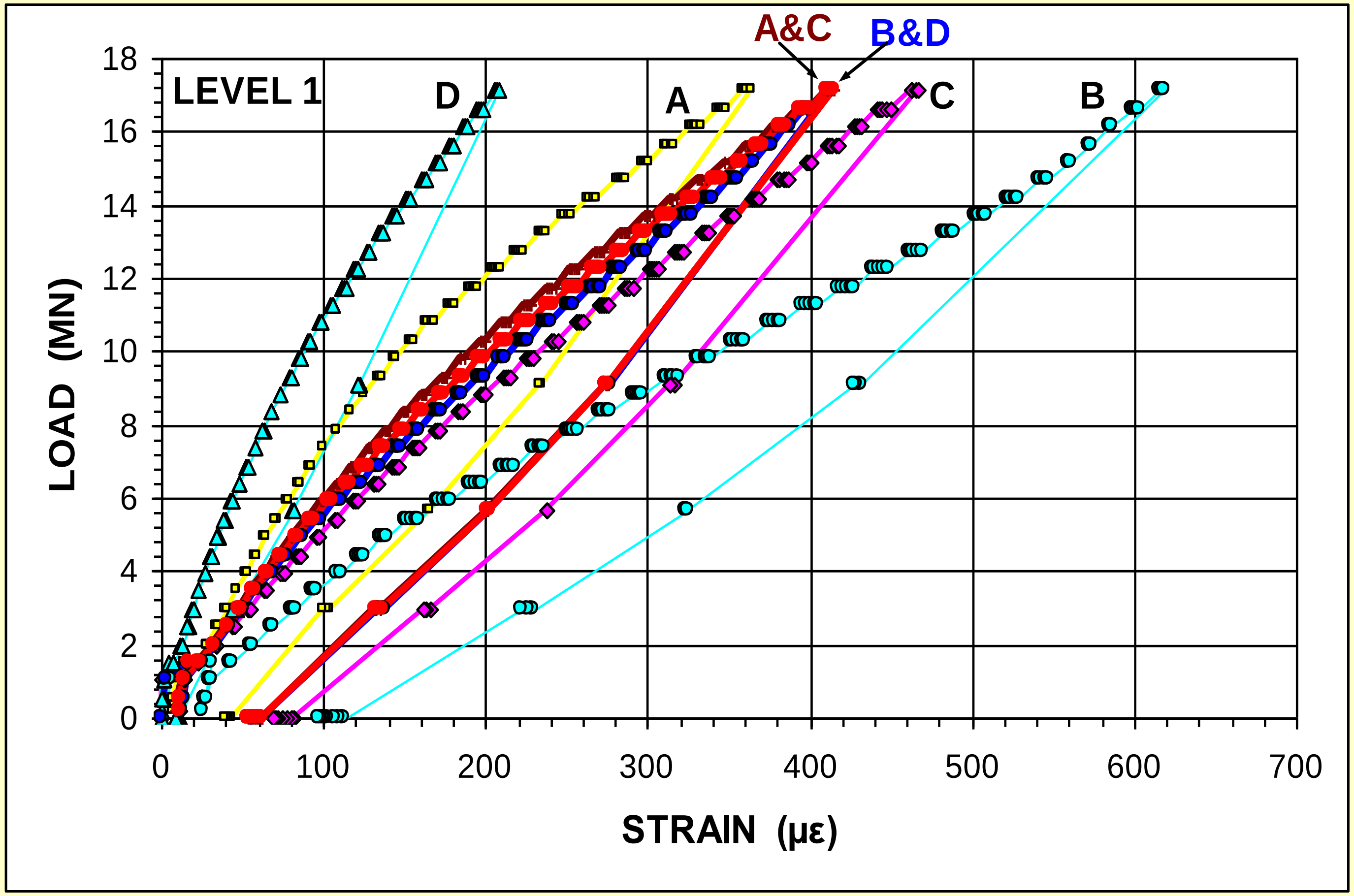
Load-strain of individual gages and of averages

PILE 1



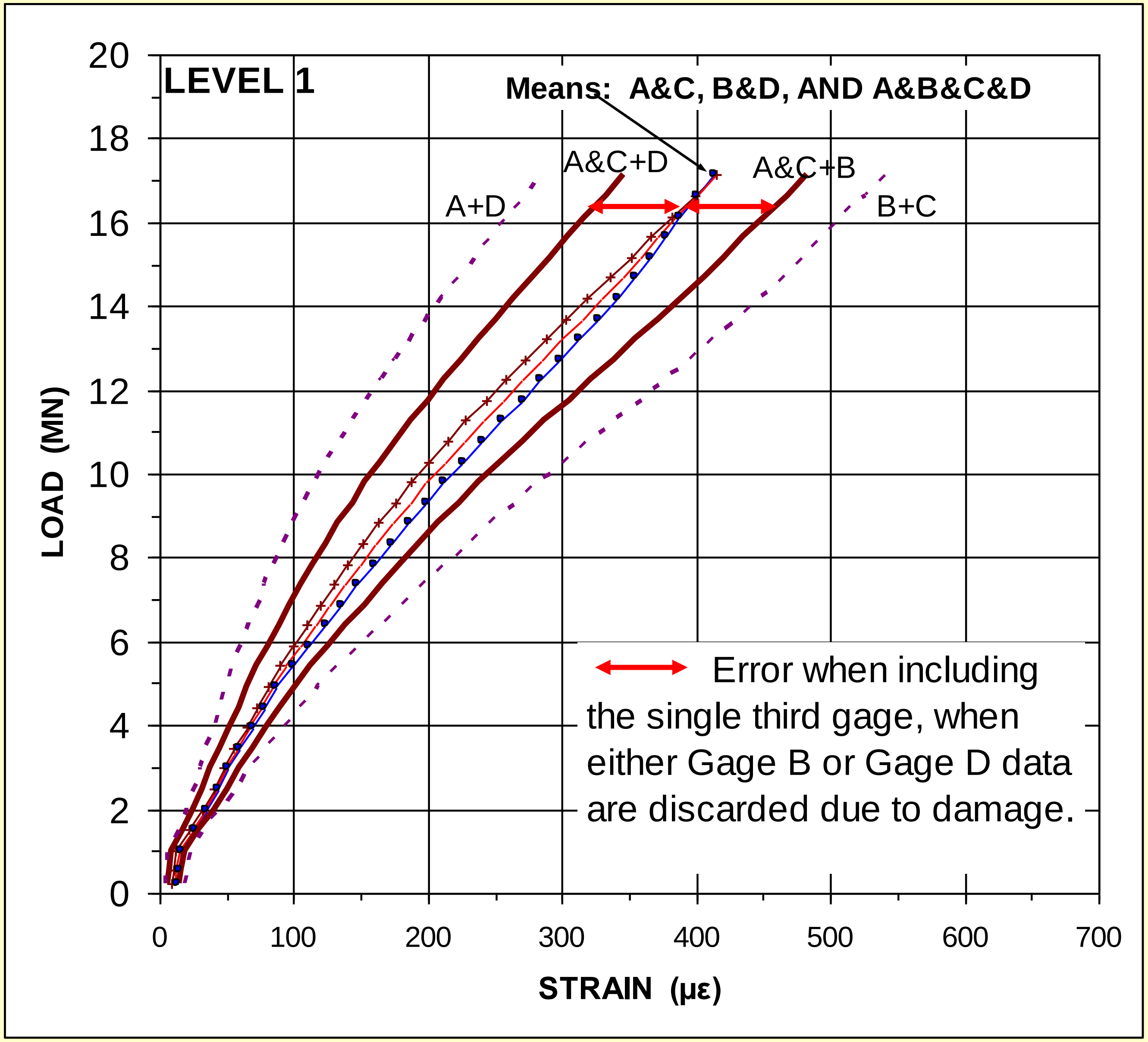
The curves are well together and no bending is discernible

PILE 2



Both pair of curves indicate bending; averages are very close; essentially the same for the two pairs

If one gage “dies”, the data of surviving single gage should be discarded. It must not be combined with the data of another intact pair. Data from two surviving single gages must not be combined.



↔ Error when including the single third gage, when either Gage B or Gage D data are discarded due to damage.

5

We have got the strain. How do we get the load?

- Load is stress times area
- Stress is Modulus (E) times strain

$$\sigma = E\,\varepsilon$$

- The modulus is the key

For a concrete pile or a concrete-filled bored pile, the modulus to use is the combined modulus of concrete, reinforcement, and steel casing

$$E_{comb} = \frac{E_s A_s + E_c A_c}{A_s + A_c}$$

E_{comb} = combined modulus

E_s = modulus for steel

A_s = area of steel

E_c = modulus for concrete

A_c = area of concrete

- **The modulus of steel is 200 GPa (207 GPa for those weak at heart)**
- **The modulus of concrete is. . . . ?**

Hard to answer. There is a sort of relation to the cylinder strength and the modulus usually appears as a value around 30 GPa, or perhaps 20 GPa or so, perhaps more.

This is not good enough answer but being vague is not necessary.

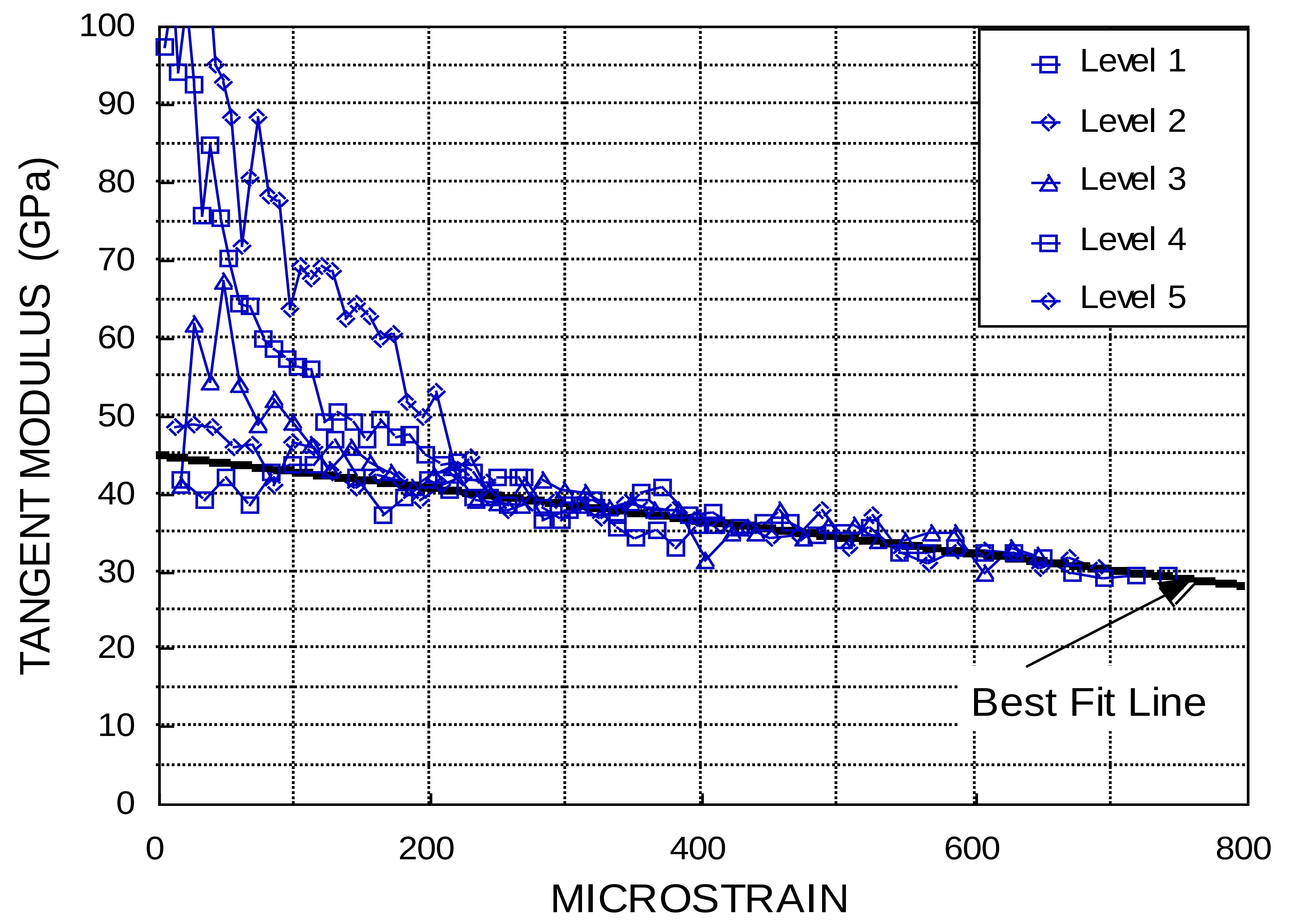
The modulus can be determined from the strain measurements.

Calculate first the *change of strain for a change of load* **and plot the values against the strain.**

$$E_t = \frac{\Delta\sigma}{\Delta\varepsilon}$$

Values are known

Example of “Tangent Modulus Plot”



In the stress range of the static loading test, modulus of concrete is not constant, but a more or less linear relation to the strain

$$E_t = \left(\frac{d\sigma}{d\varepsilon}\right) = a\varepsilon + b$$

Which can be integrated to:

$$\sigma = \left(\frac{a}{2}\right)\varepsilon^2 + b\varepsilon$$

But stress is also a function of secant modulus and strain:

$$\sigma = E_s\ \varepsilon$$

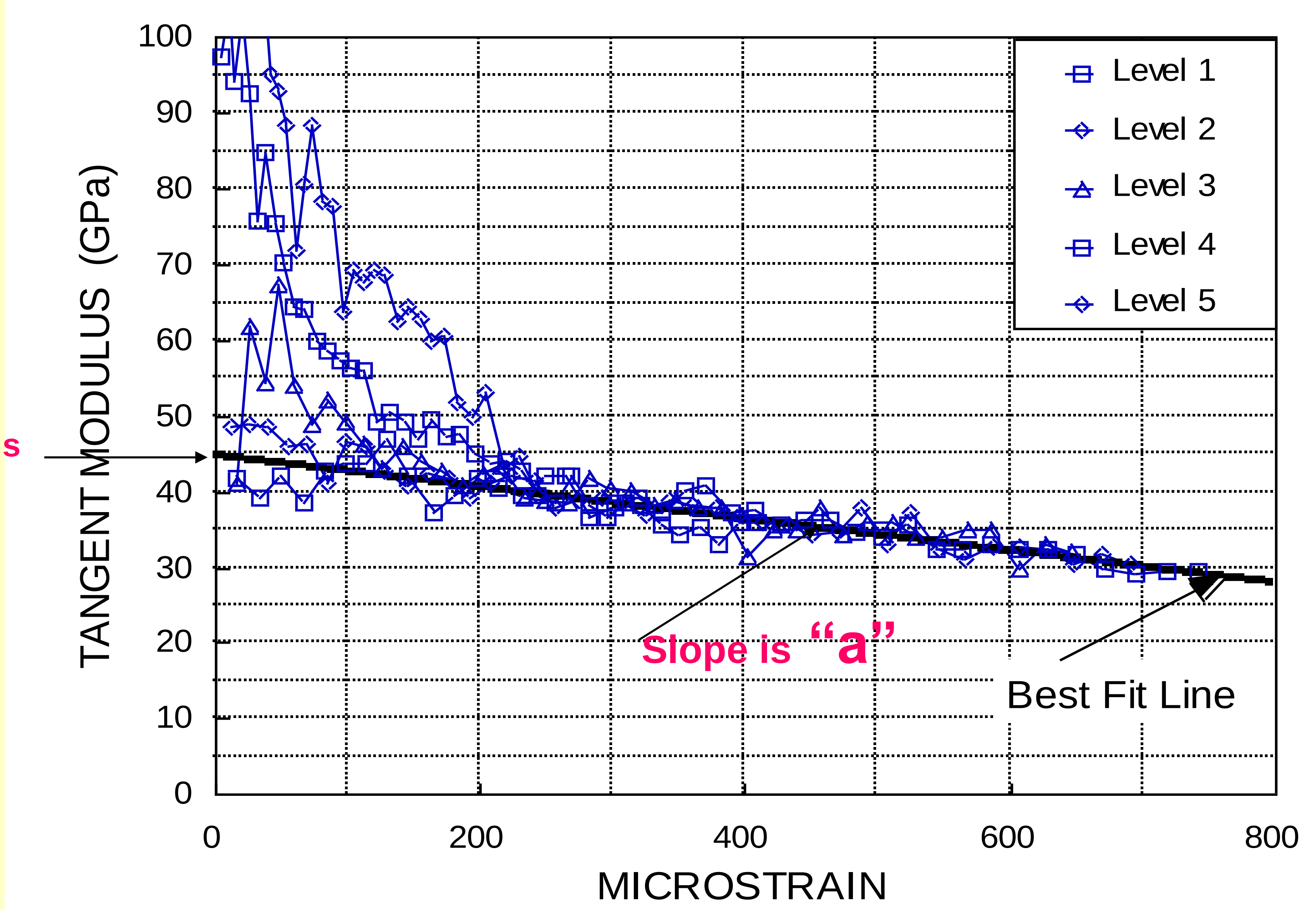
Combined, we get a useful relation:

$$E_s = 0.5a\,\varepsilon + b$$

and

$$\mathrm{Q = A\ E_s\ \varepsilon}$$

Example of “Tangent Modulus Plot”



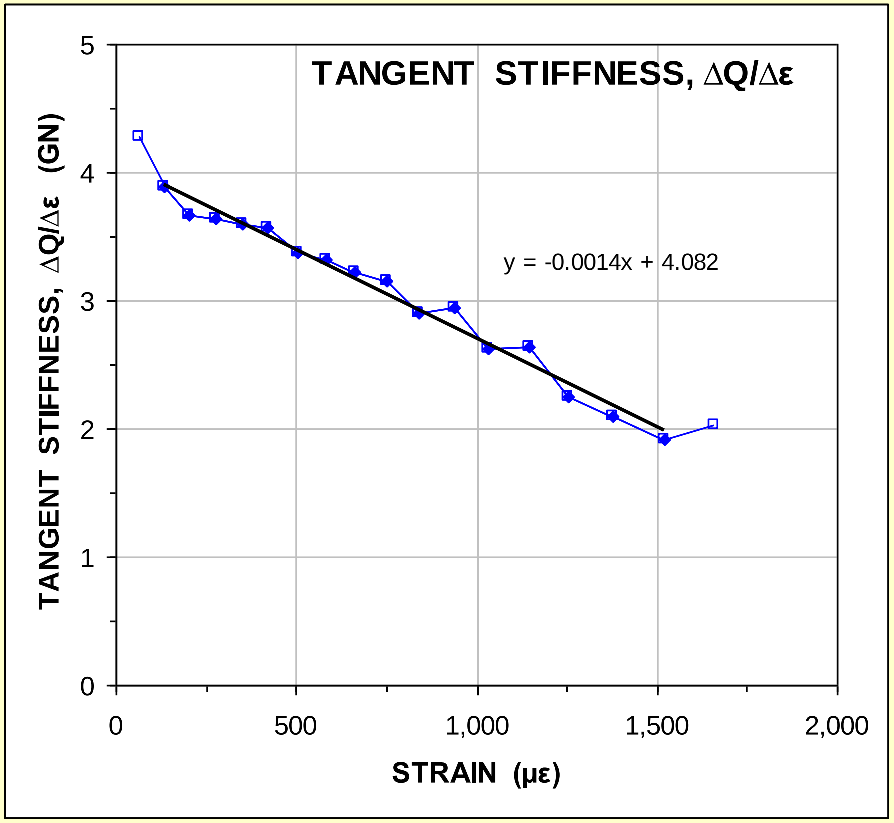
Intercept is ”b”

Slope is “a”

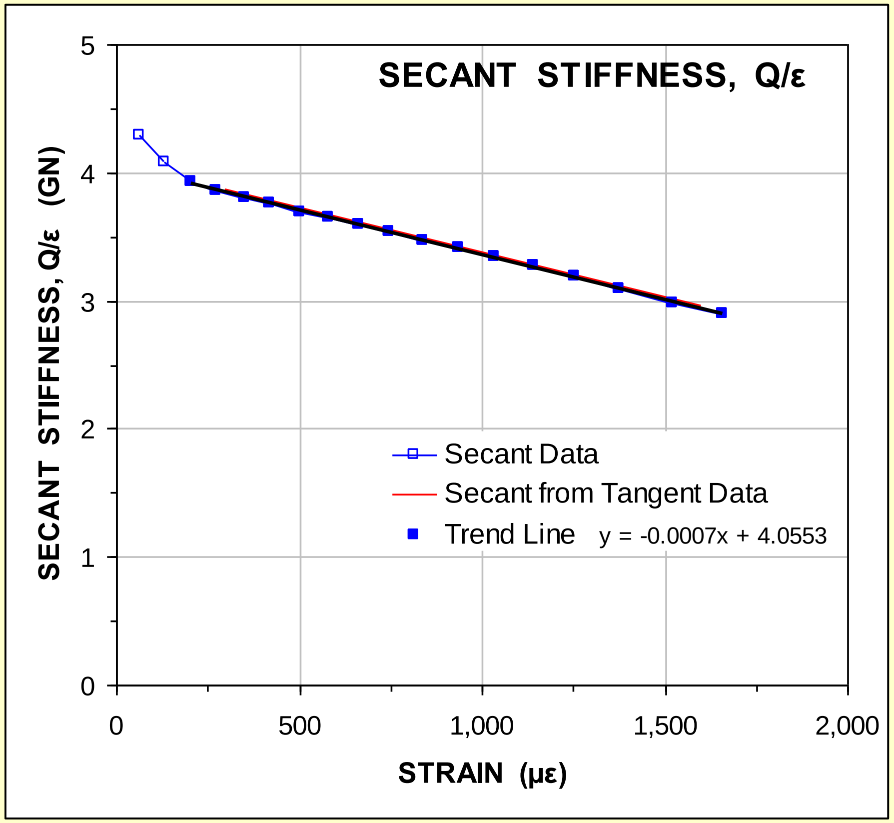
Best Fit Line

Field Testing and Foundation Report, Interstate H-1, Keehi Interchange, Hawaii, Project I-H1-1(85), PBHA 1979.

Strain-gage instrumented, 16.5-inch octagonal prestressed concrete pile driven to 60 m depth through coral clay and sand. Modulus relations as obtained from uppermost gage (1.5 m below head, i.e., 3.6b).

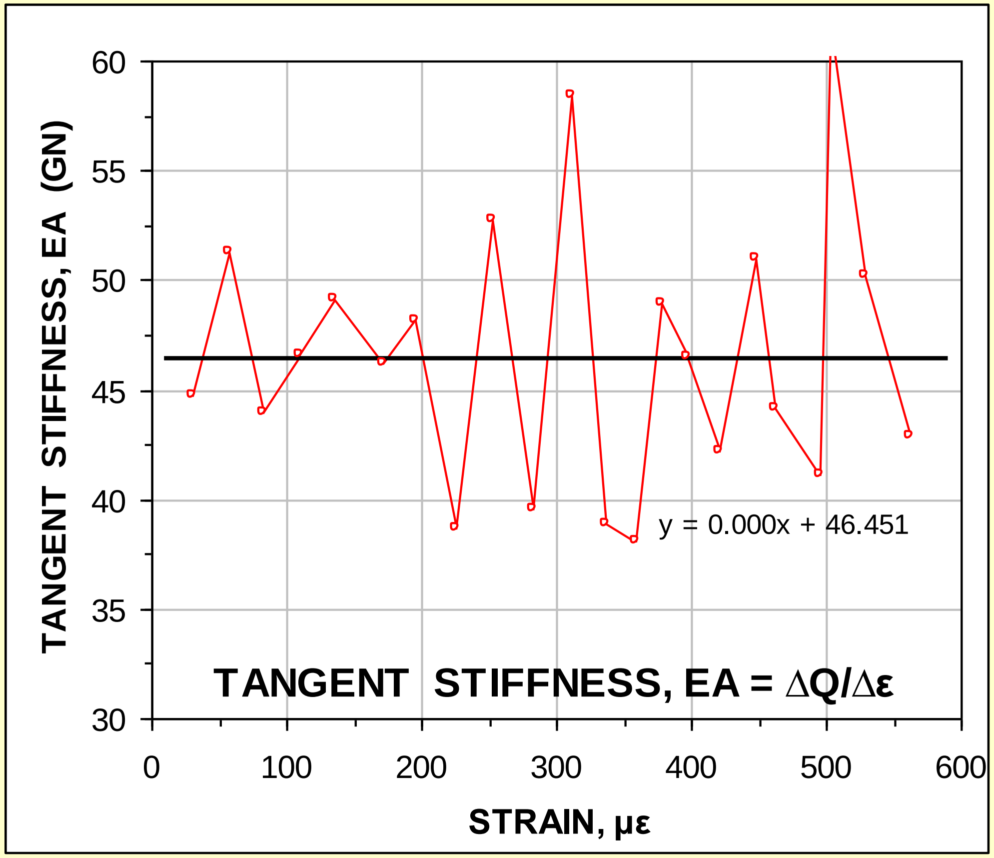


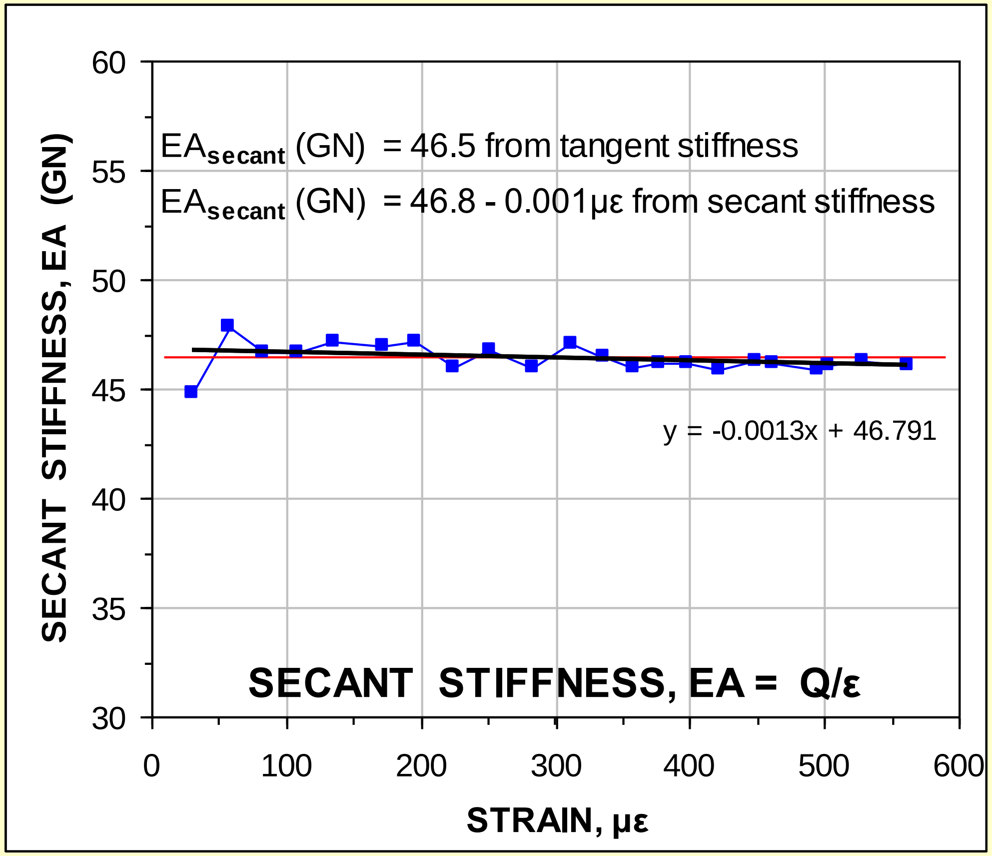
The tangent stiffness approach can be applied to all gage levels. The differentiation eliminates influence of past shear forces and residual load. Non-equal load increment duration will adversely affect the results.



The secant stiffness approach can only be applied to the gage level immediately below the pile head (must be uninfluenced by shaft resistance), provided the strains are uninfluenced by residual load.

Unlike steel, the modulus of concrete varies and depends on curing, proportioning, mineral, etc. and it is strain dependent. However, the cross sectional area of steel in an instrumented steel pile is sometimes not that well known.

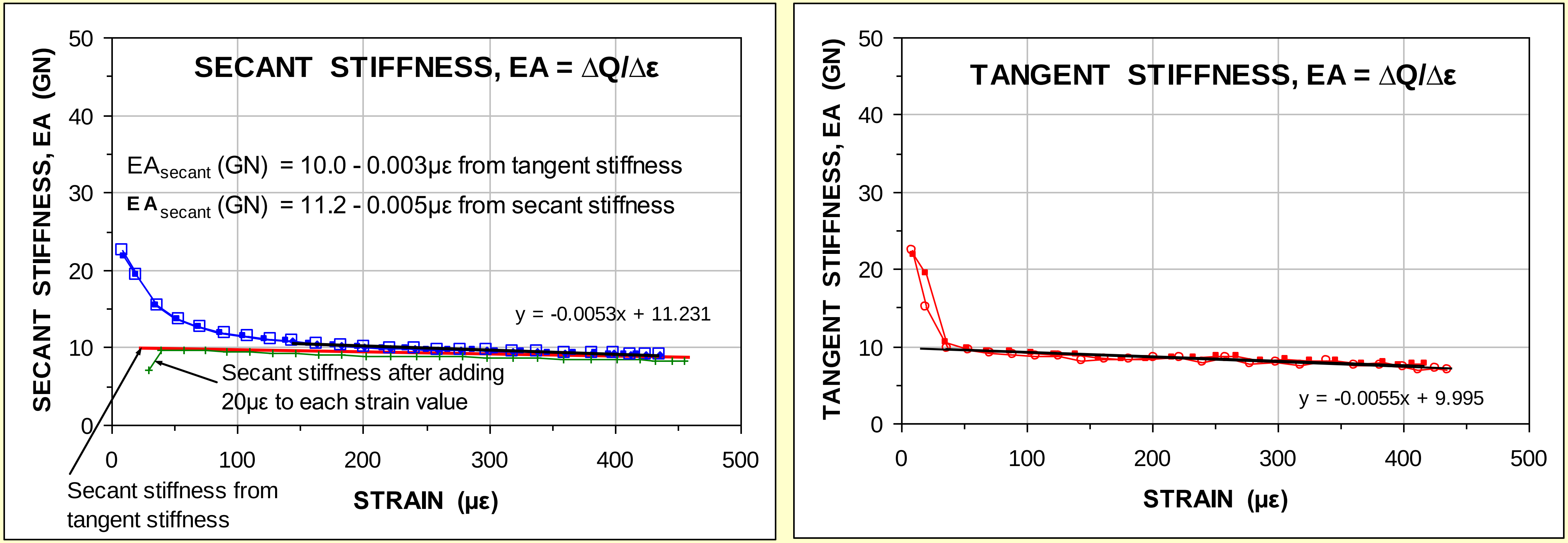




Pile stiffness for a 1.83 m diameter steel pile; open-toe pipe pile.
Strain-gage pair placed 1.8 m below the pile head.

(Data from Bradshaw et al. 2012)

The initial "hyperbolic" trend can here be removed by adding a mere 20 με to the strain data, "correcting the zero" reading, it seems.



EA_{secant} (GN) = 10.0 - 0.003με from tangent stiffness

EA_{secant} (GN) = 11.2 - 0.005με from secant stiffness

Secant stiffness after adding 20με to each strain value

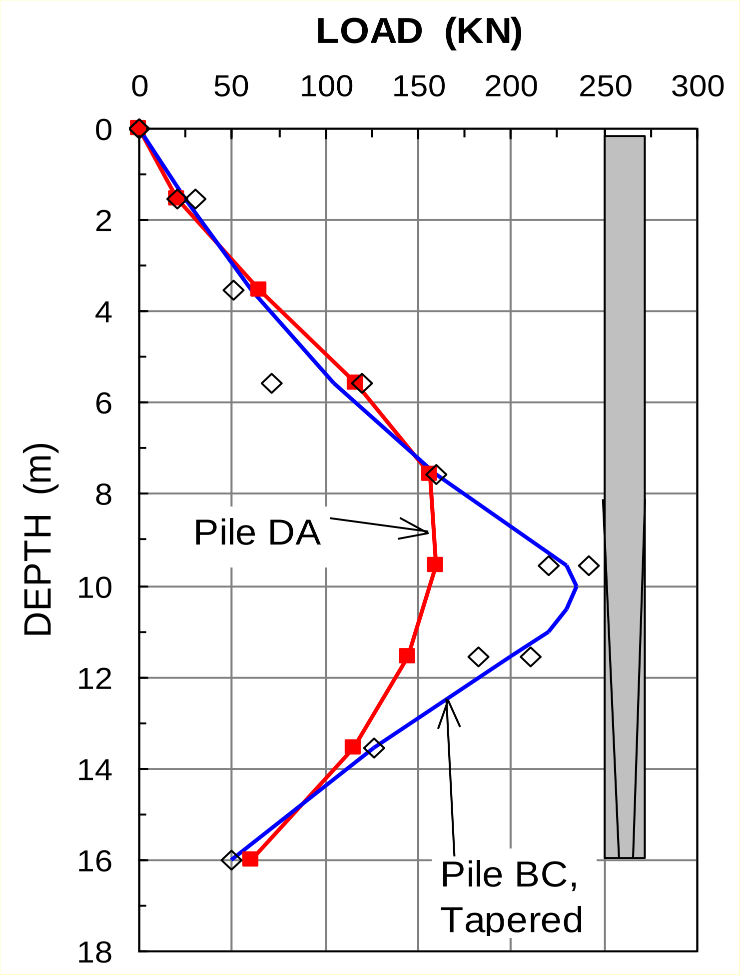
Secant stiffness from tangent stiffness

Pile stiffness for a 600-mm diameter prestressed pile.
The gage level was 1.5 m (2.5b) below pile the head.

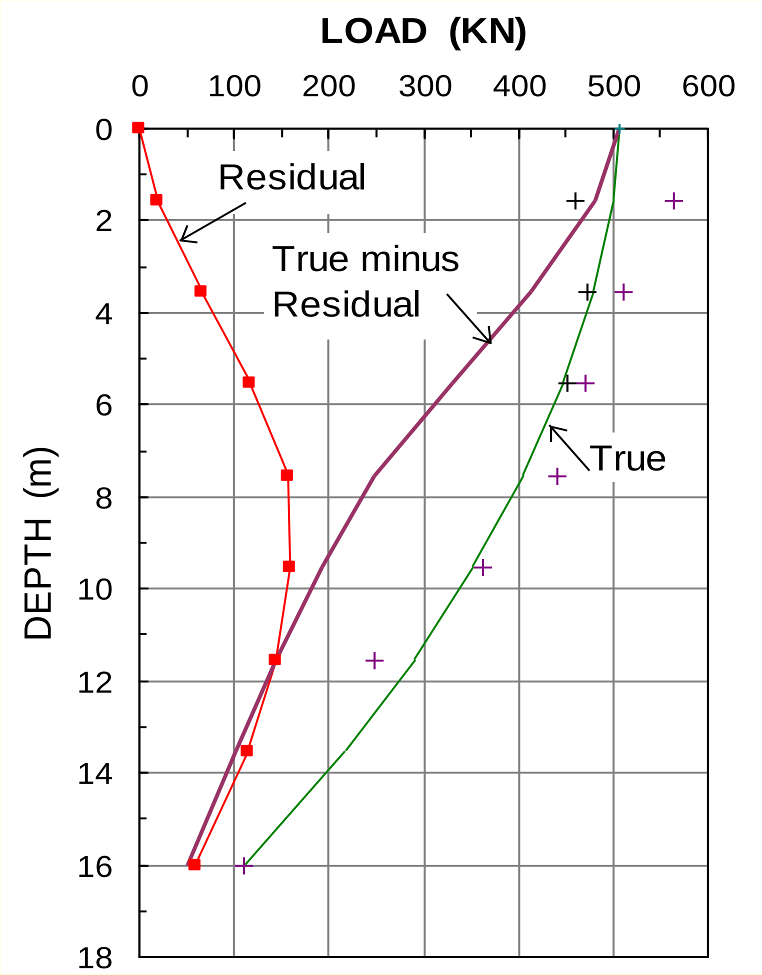
Data from CH2M Hill 1995

- We often assume – somewhat optimistically or naively – that the reading before the start of the test represents the “no-load” condition.
- However, at the time of the start of the loading test, loads do exist in the pile and they are often large.
- For a grouted pipe pile or a concrete cylinder pile, these loads are to a part the effect of the temperature generated during the curing of the grout.
- Then, the re-consolidation (set-up) of the soil after the driving or construction of the pile will impose additional loads on the pile.

Example from Gregersen et al., 1973



A. Distribution of residual load in DA and BC before start of the loading test

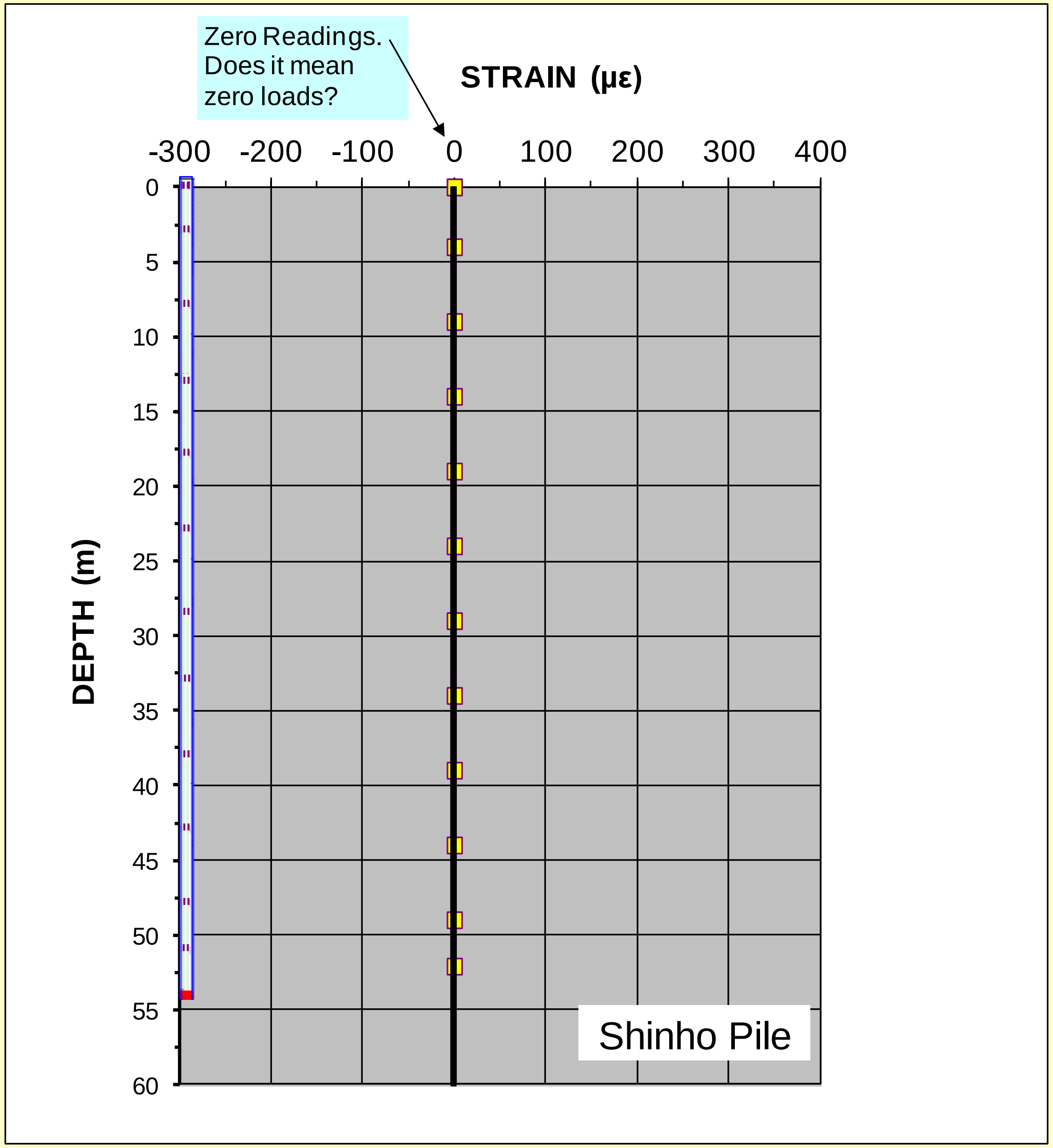


B. Load and resistance in DA for the maximum test load

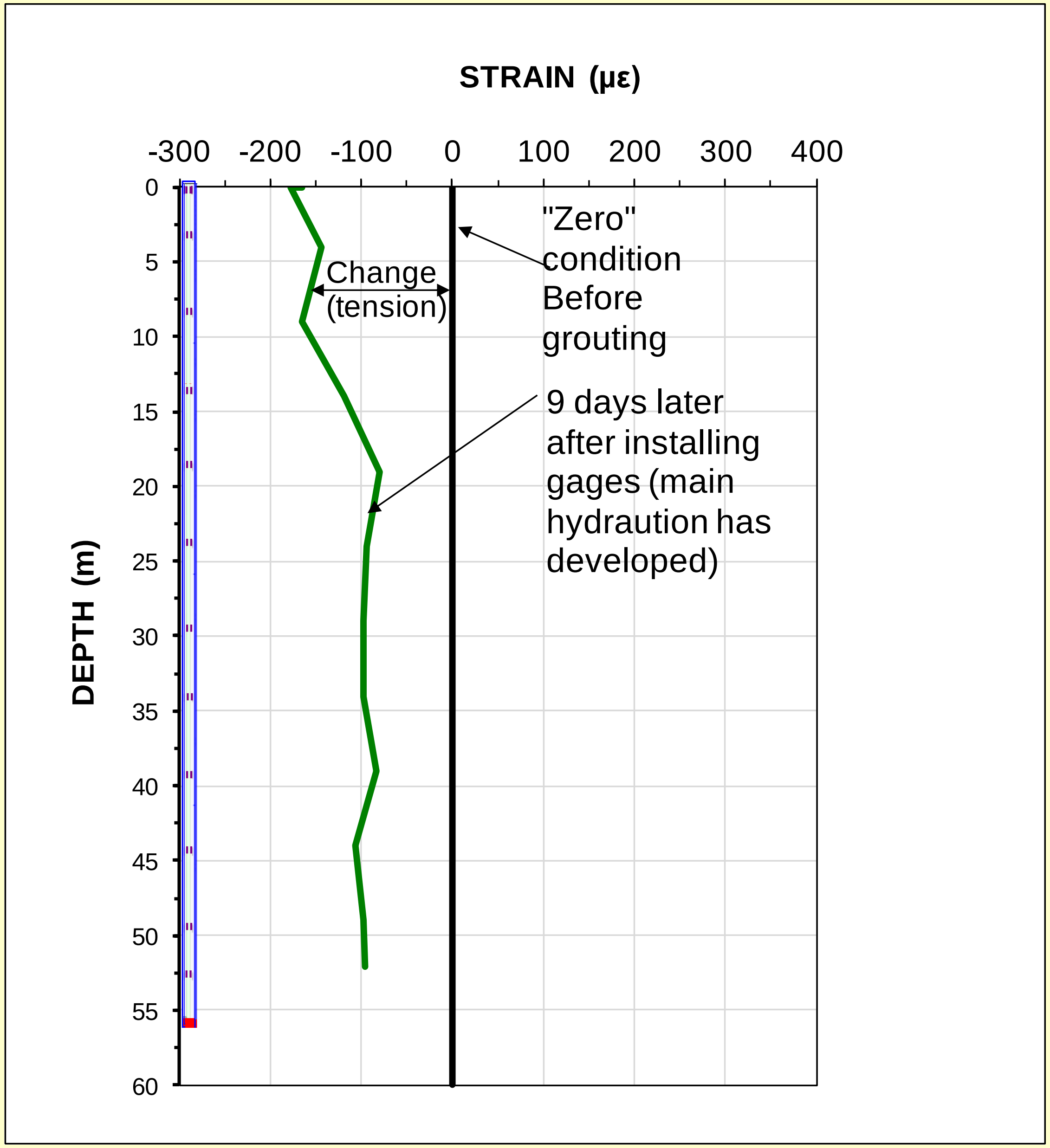
Immediately before the test, all gages must be checked and "Zero Readings" must be taken.

Answer to the question in the graph:

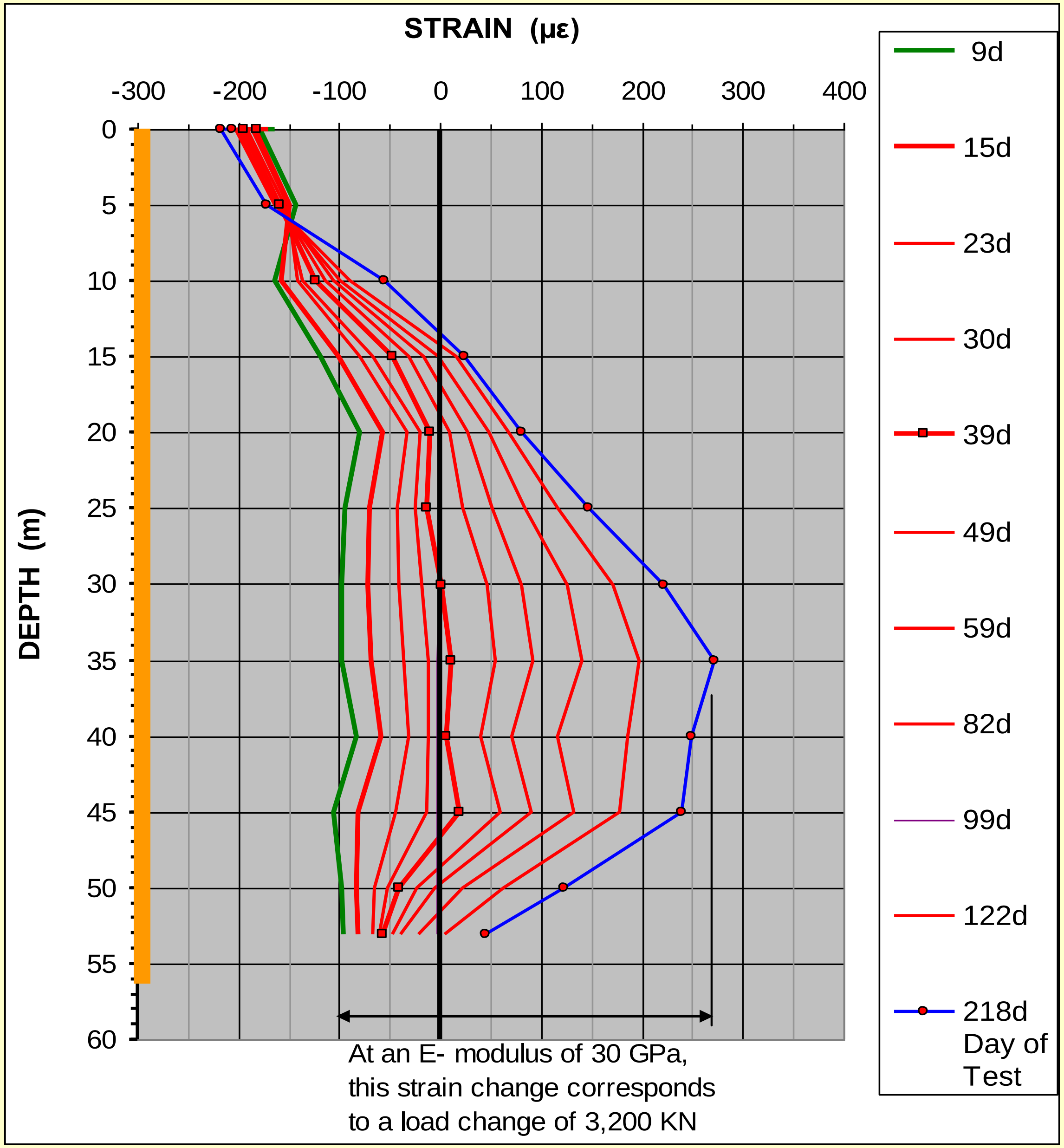
No, there's always residual load in a test pile.



Gages were read after they had been installed in the pile (= “zero” condition) and then 9 days later (= green line) after the pile had been concreted and most of the hydration effect had developed.

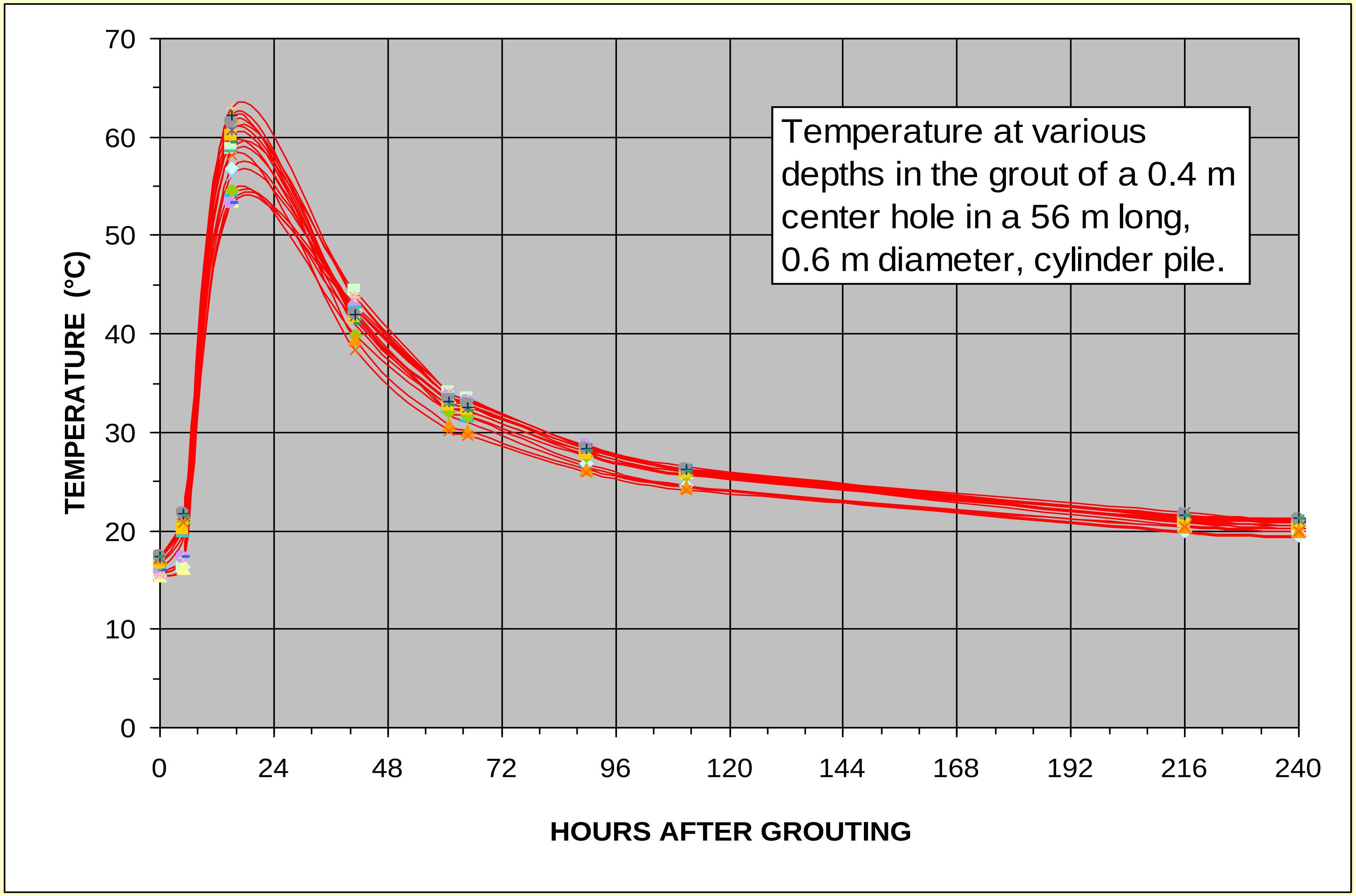


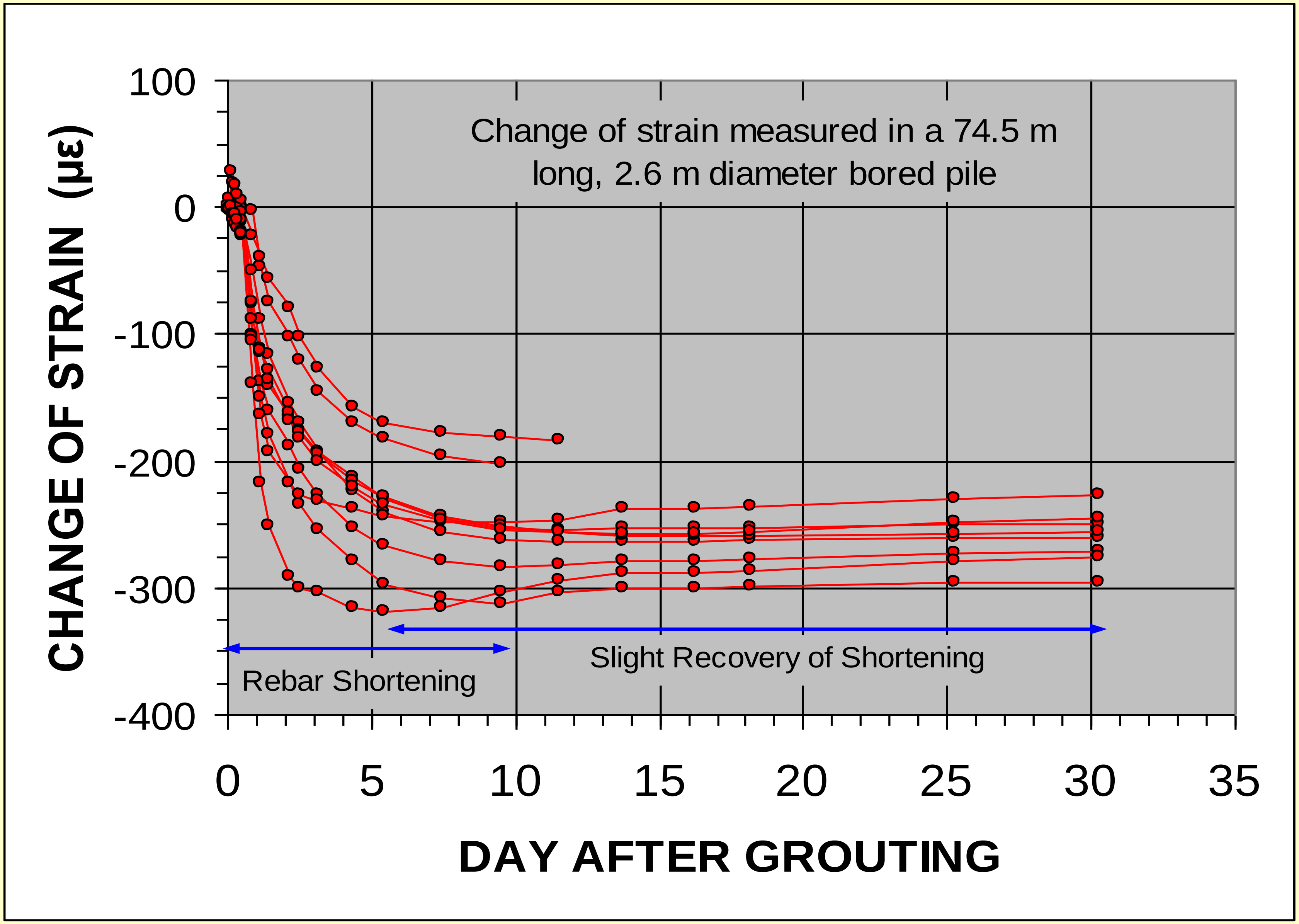
Strains measured during the following additional 209-day wait-period.



At an E- modulus of 30 GPa, this strain change corresponds to a load change of 3,200 KN

Concrete hydration temperature measured in a grouted concrete cylinder pile

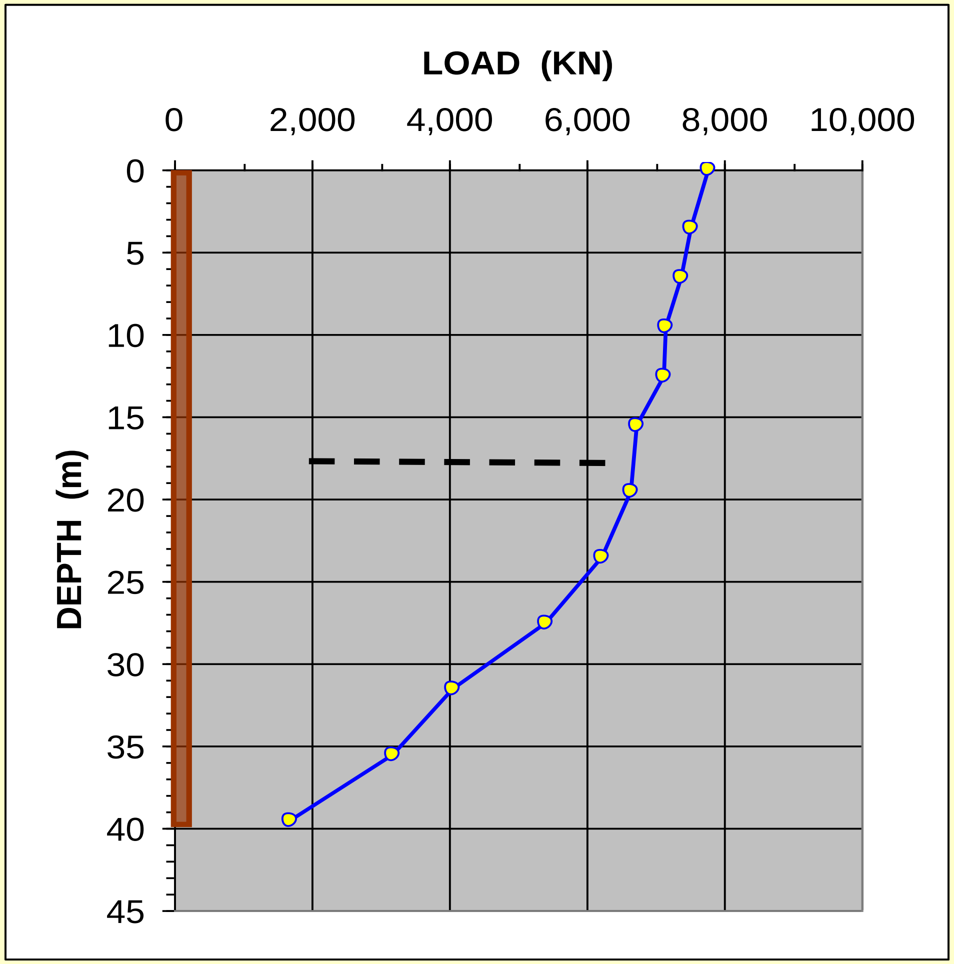


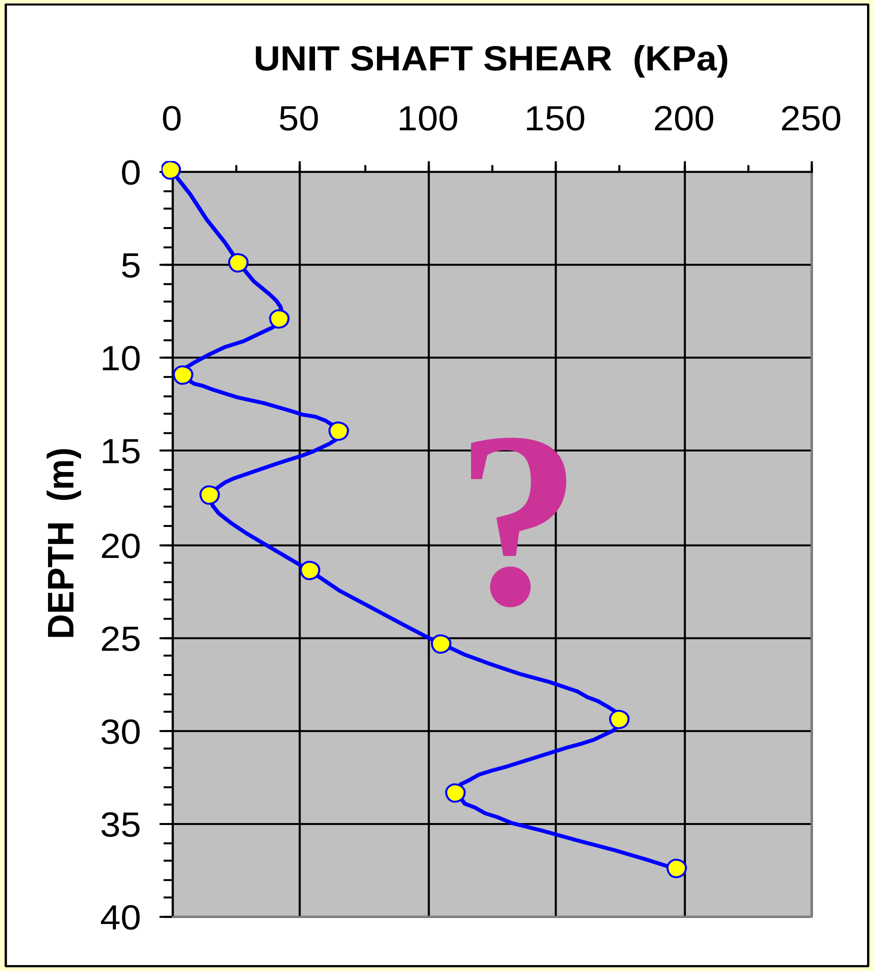


Change of strain during the hydration of the grout in the Golden Ears Bridge test pile

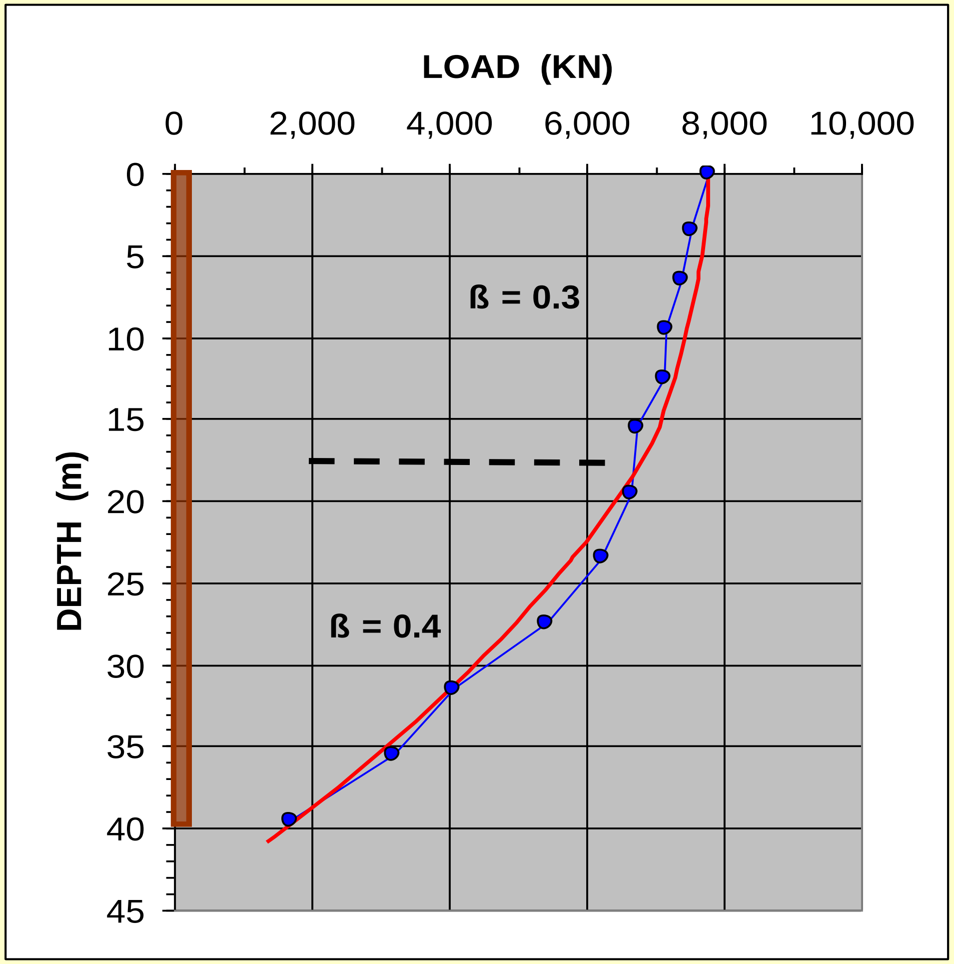
8

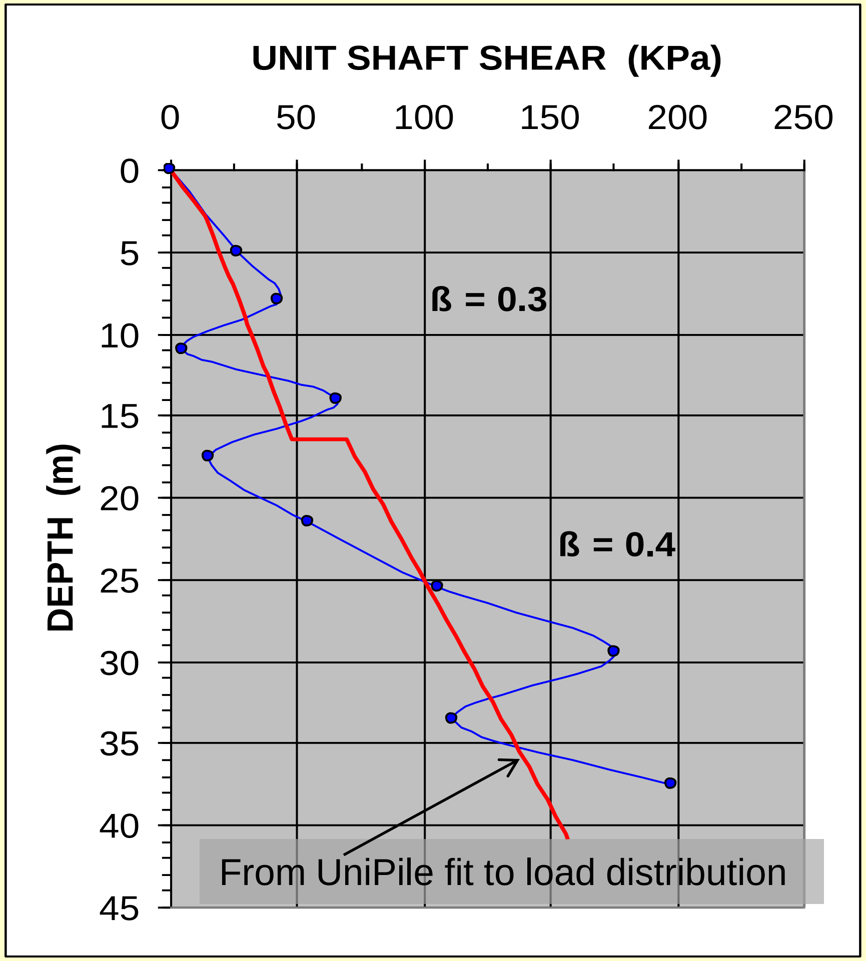
Results of static loading tests on a 40 m long, jacked-in, instrumented steel pile in a saprolite soil





A more thoughtful analysis of the data

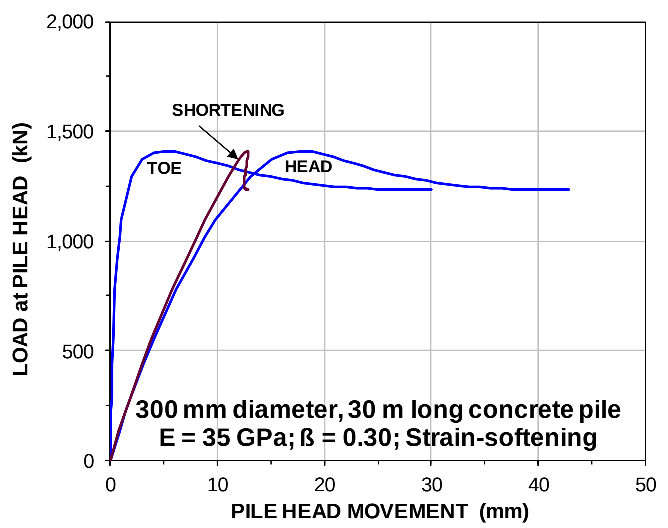




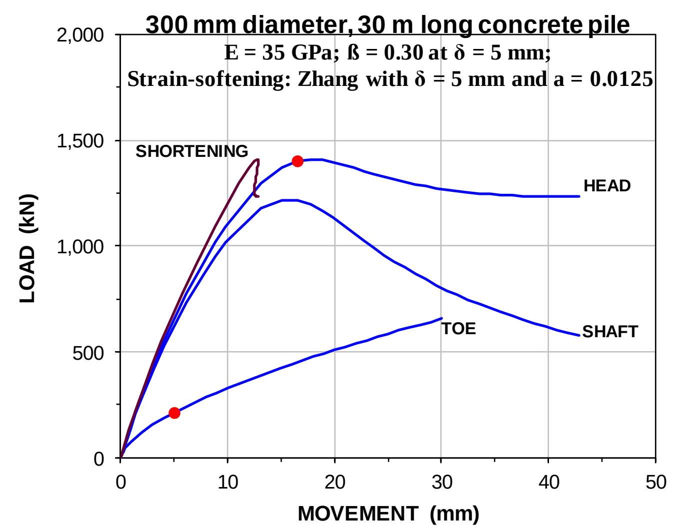
From UniPile fit to load distribution

~~The butler~~ The differentiation did it

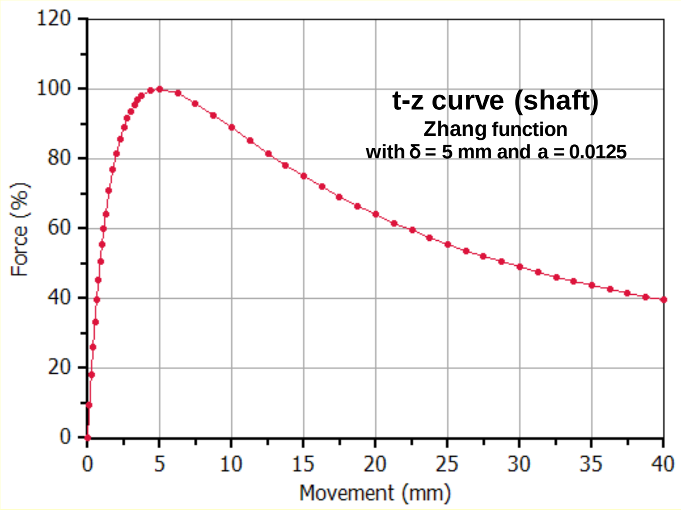
A static loading test with a toe telltale to measure toe movement—typical records

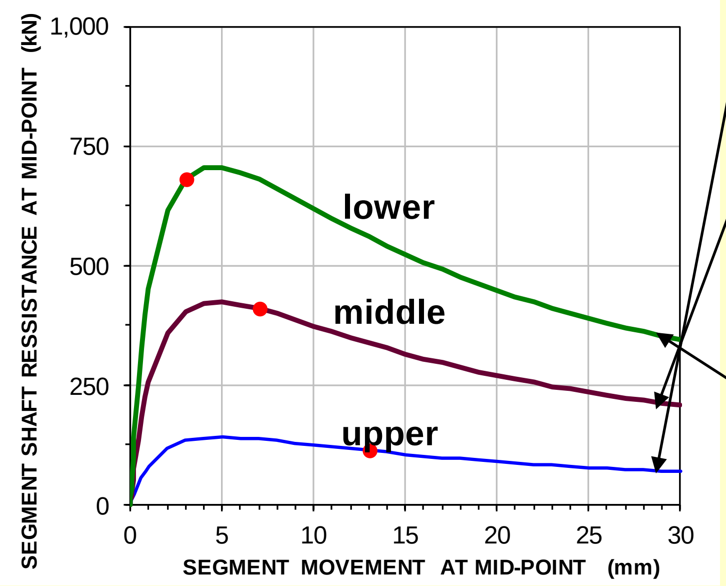


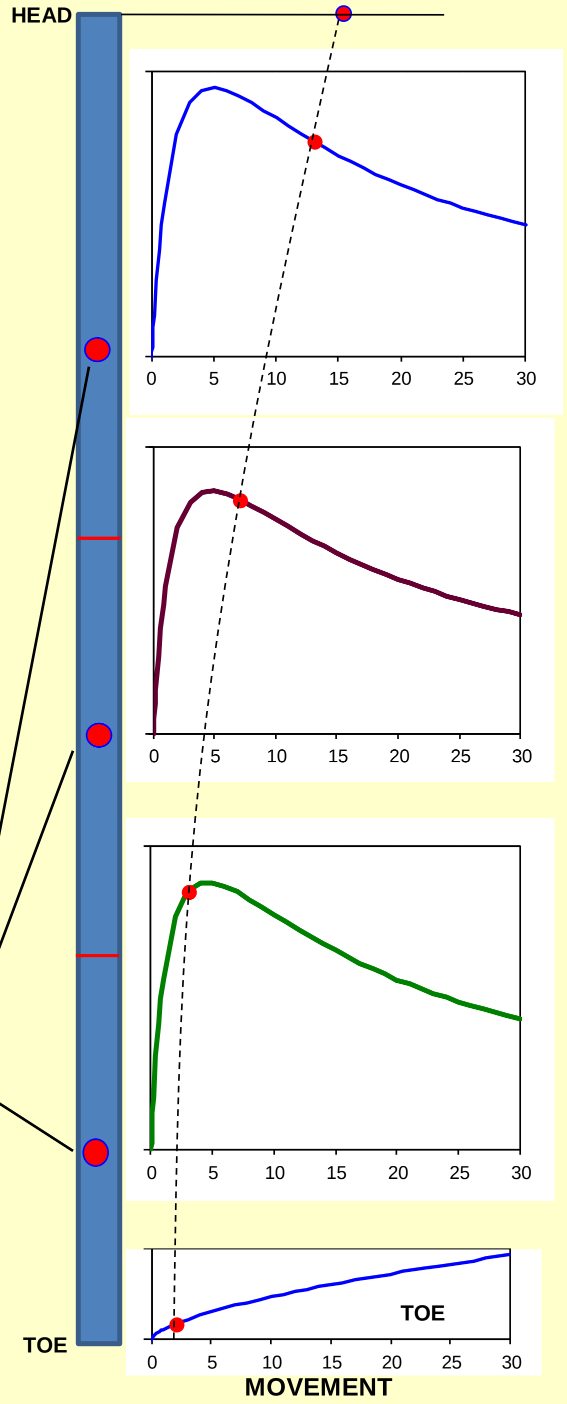
Now with instrumentation to separate shaft and toe resistances



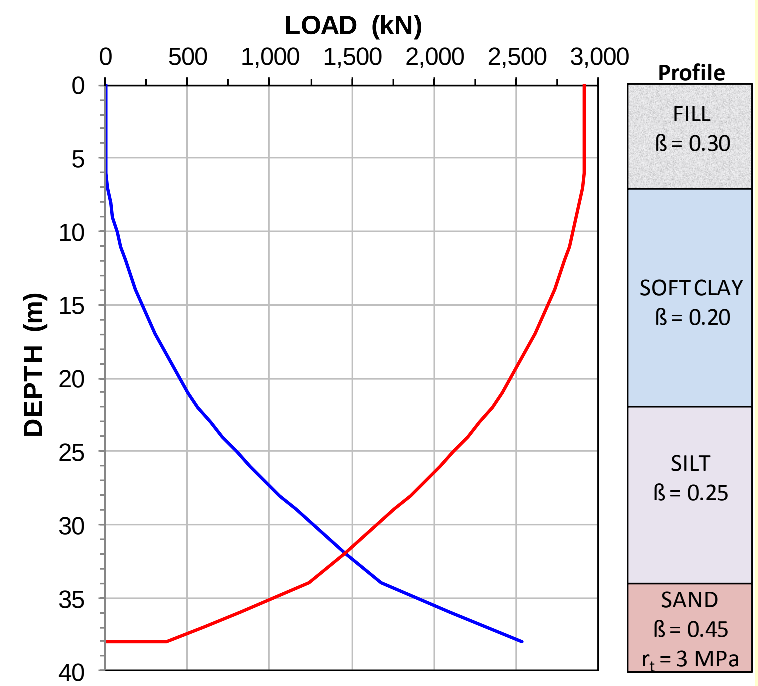
Shaft resistance load-movement curve (t-z function) —typical

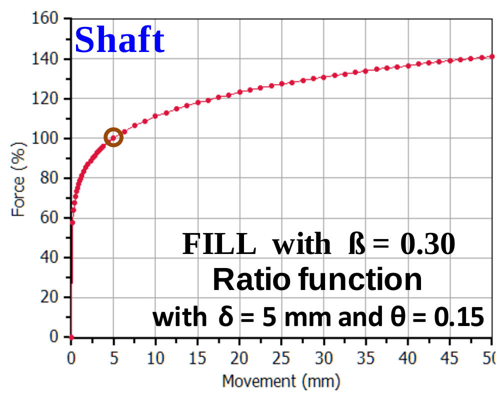


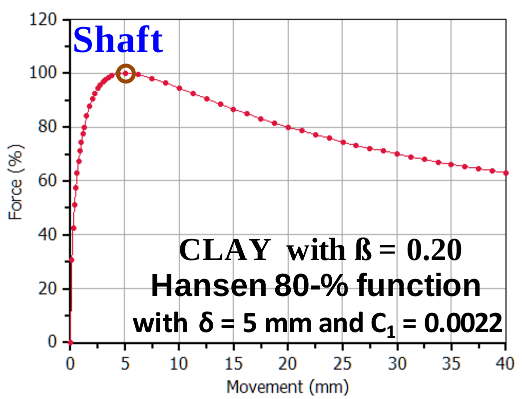


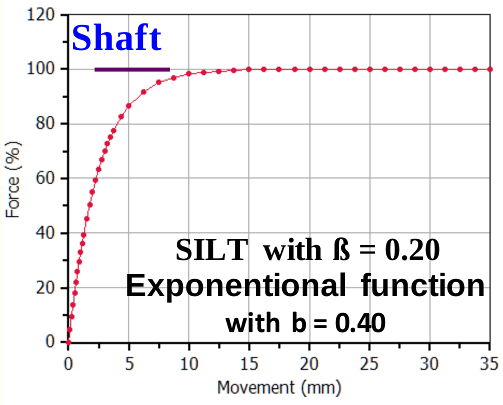


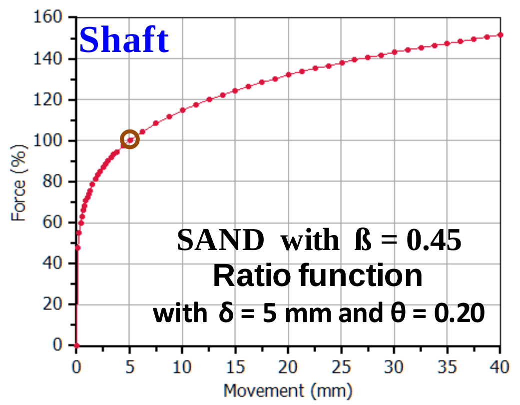
400 mm diameter, 38 m long, phictitious concrete pile

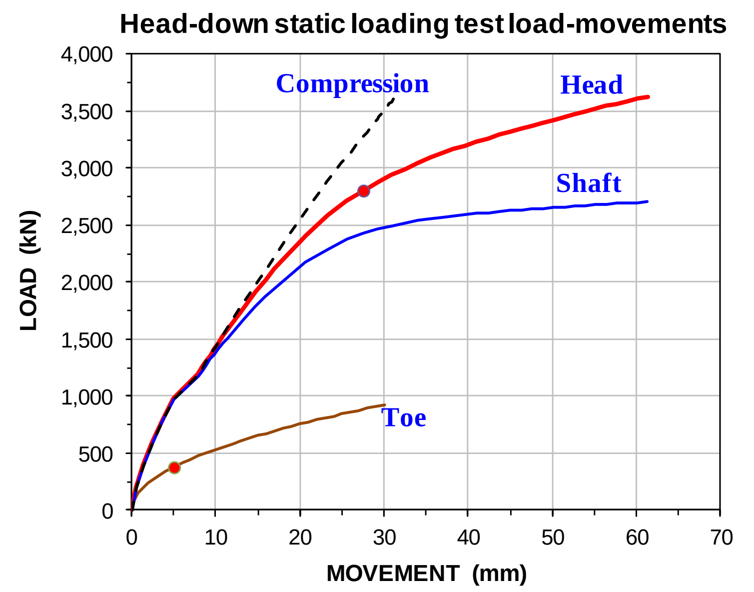


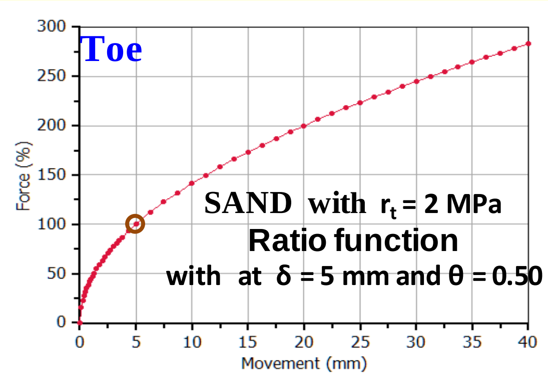












The simulations are made using UniPile Version 5

The bi-directional test

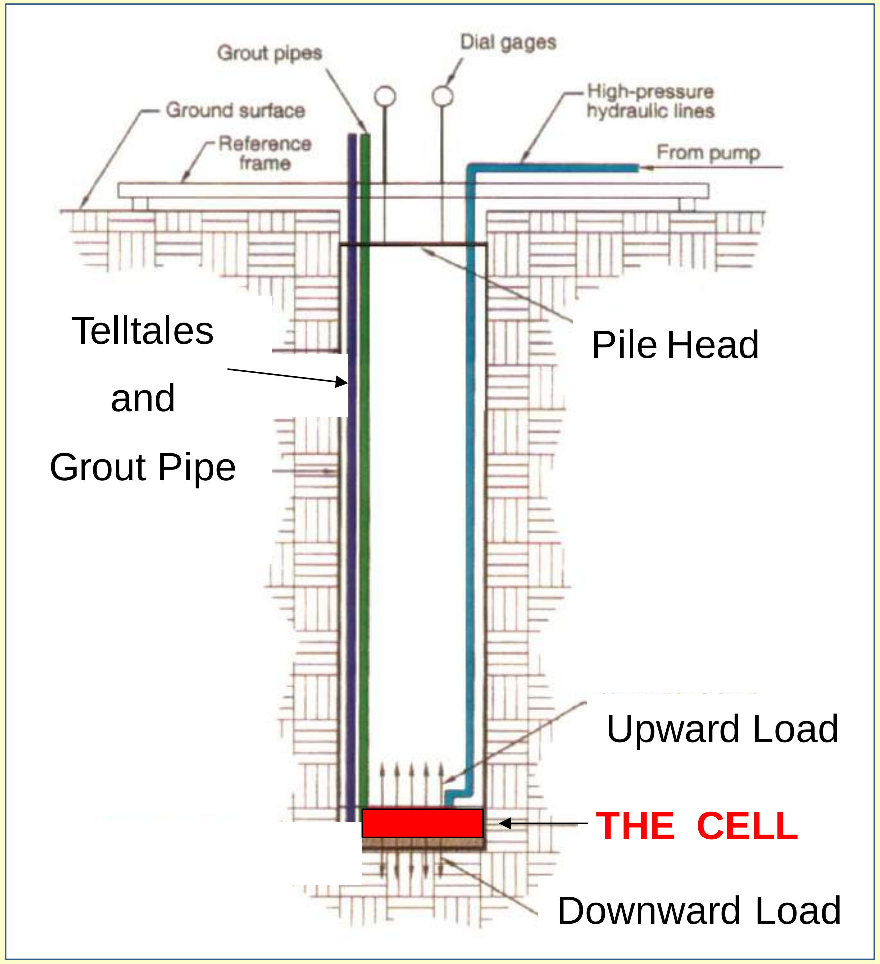
Arcos Egenharia de Solos
Bidirectional test at
Rio Negro Ponte
Manaus—Iranduba, Brazil

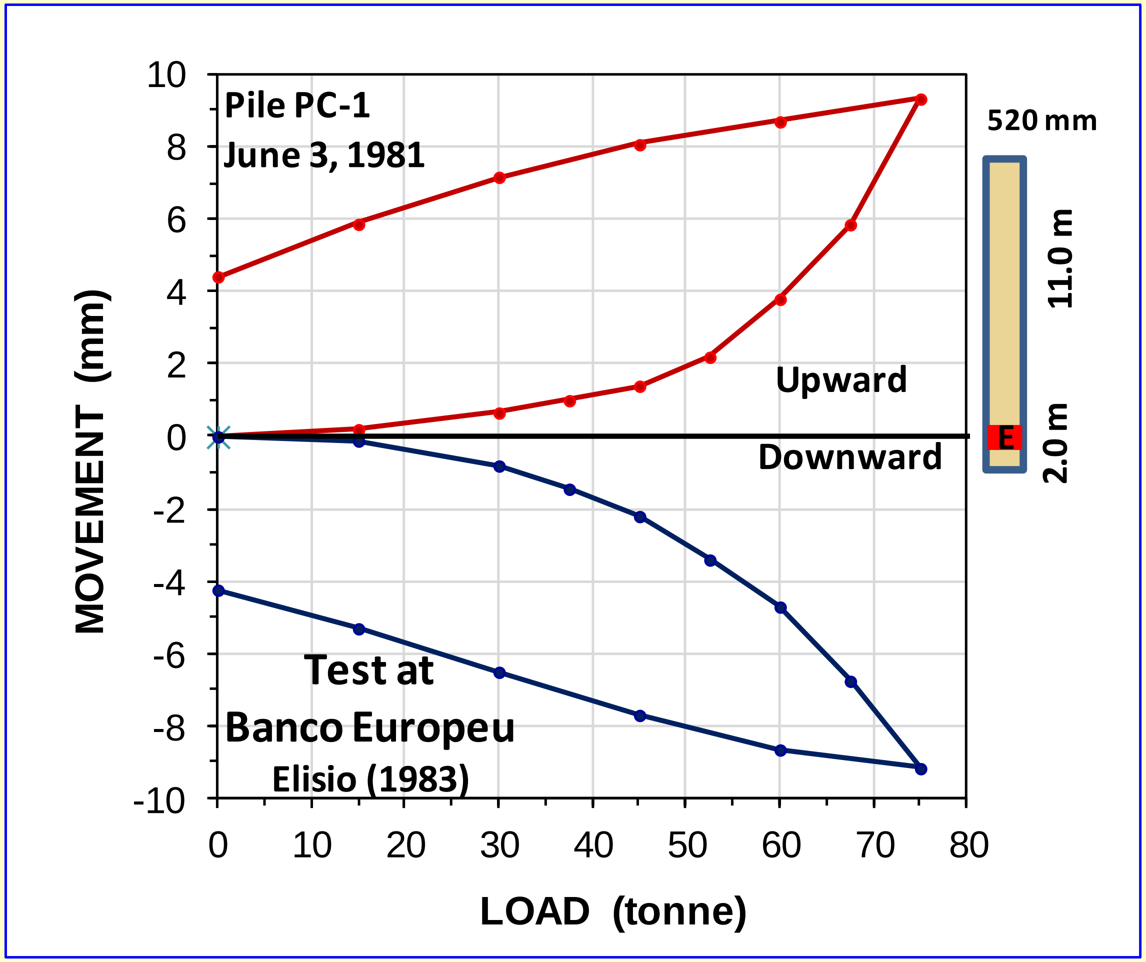
Schematics of the bidirectional test

(Meyer and Schade 1995)

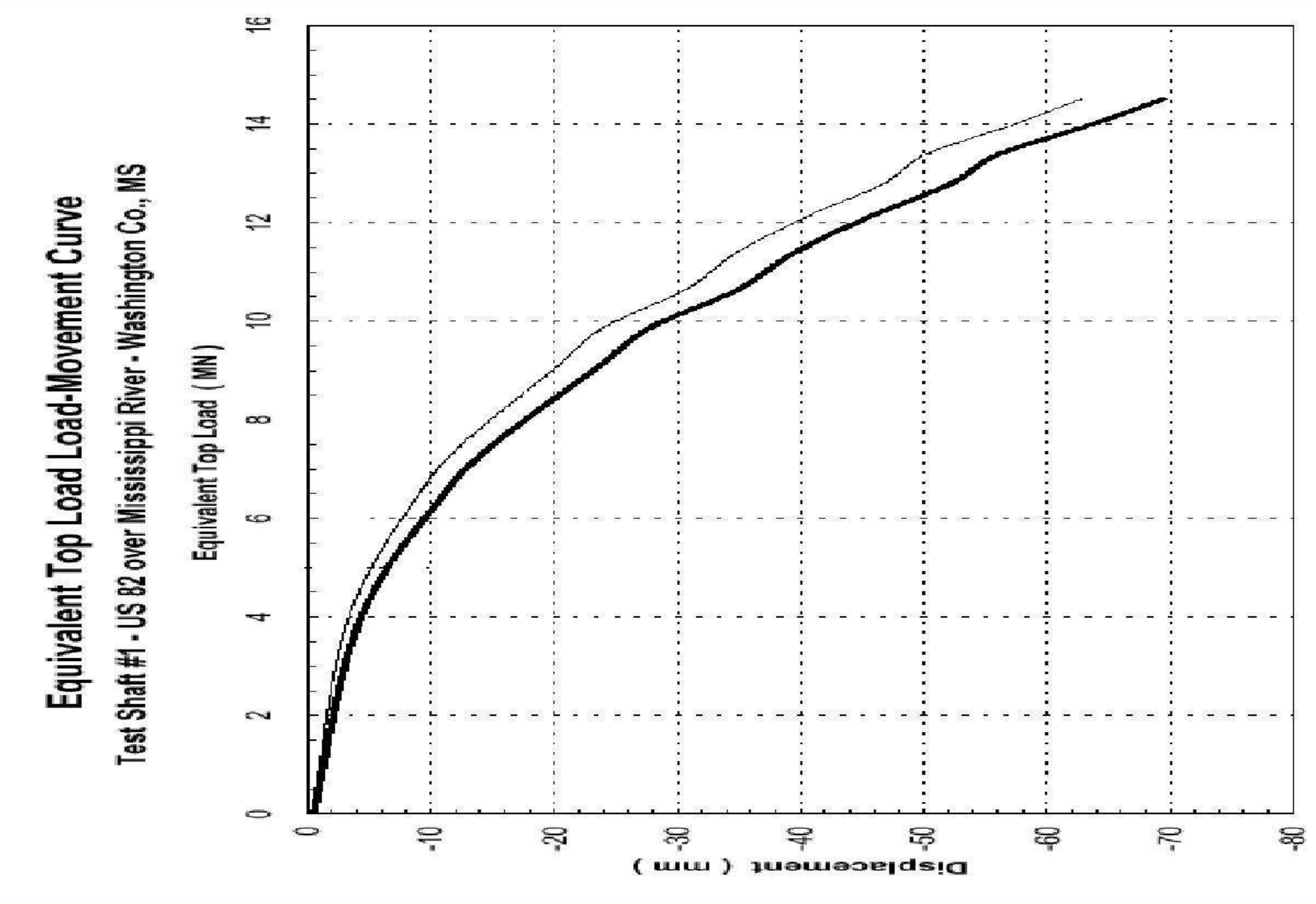
Typical Test Results

(Data from Eliso 1983)

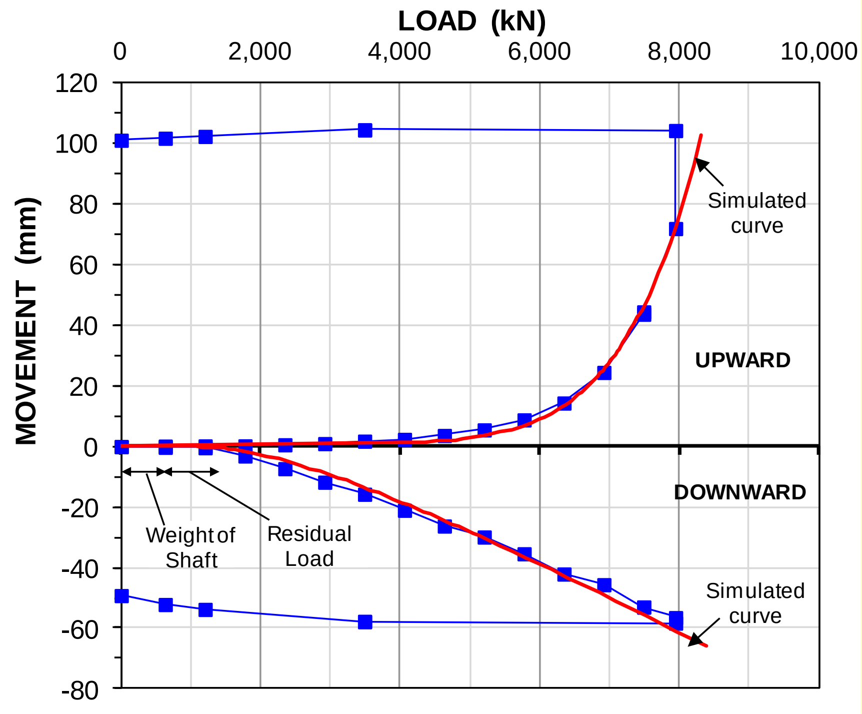




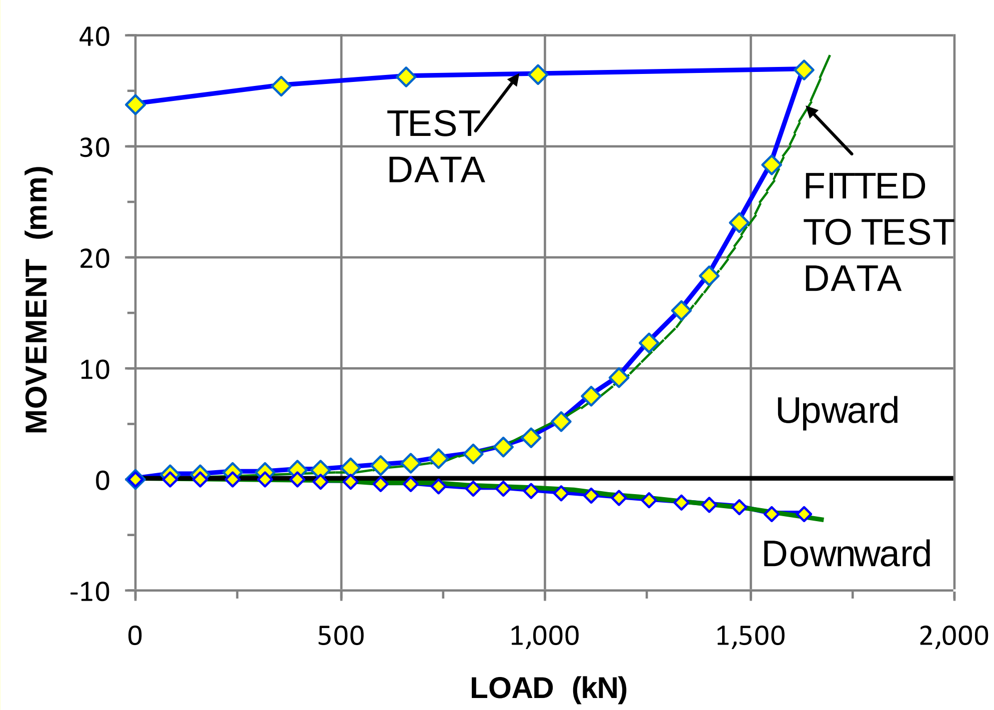
From the upward and downward results, one can produce the equivalent head-down load-movement curve that one would have obtained in a routine “Head-Down Test”



Example 1



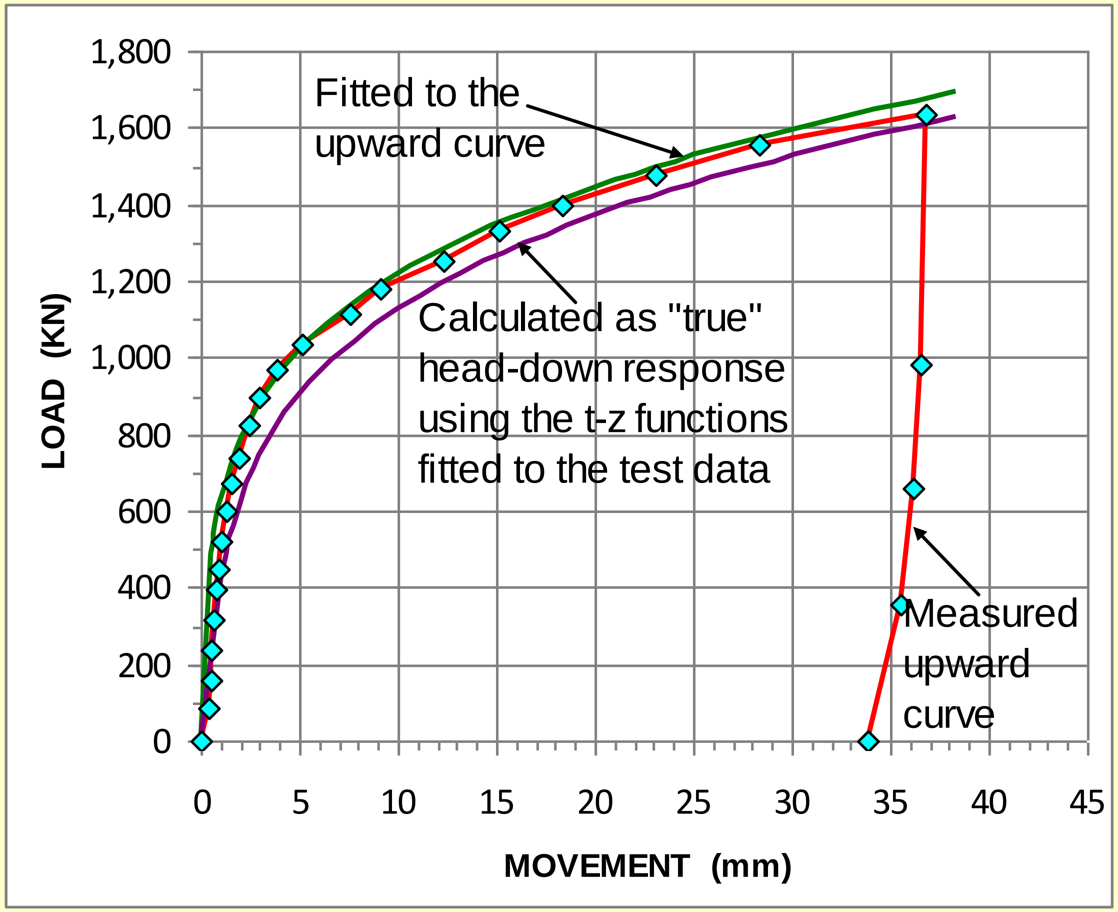
Example 2



Upward and downward curves fitted to measured curves

UniPile5 analysis using the t-z and q-z curves fitted to the load-movement curves at the gage levels in an effective-stress simulation of the test

Example 2 Upward curve only



Fitted to the upward curve

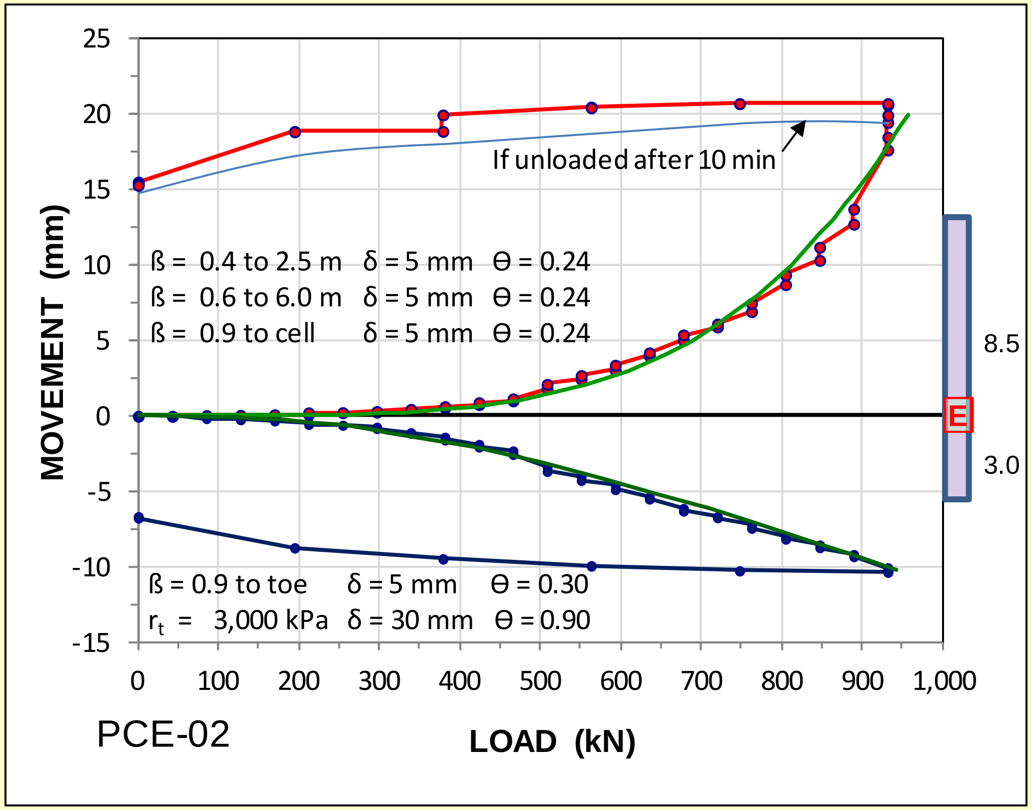
Calculated as "true" head-down response using the t-z functions fitted to the test data

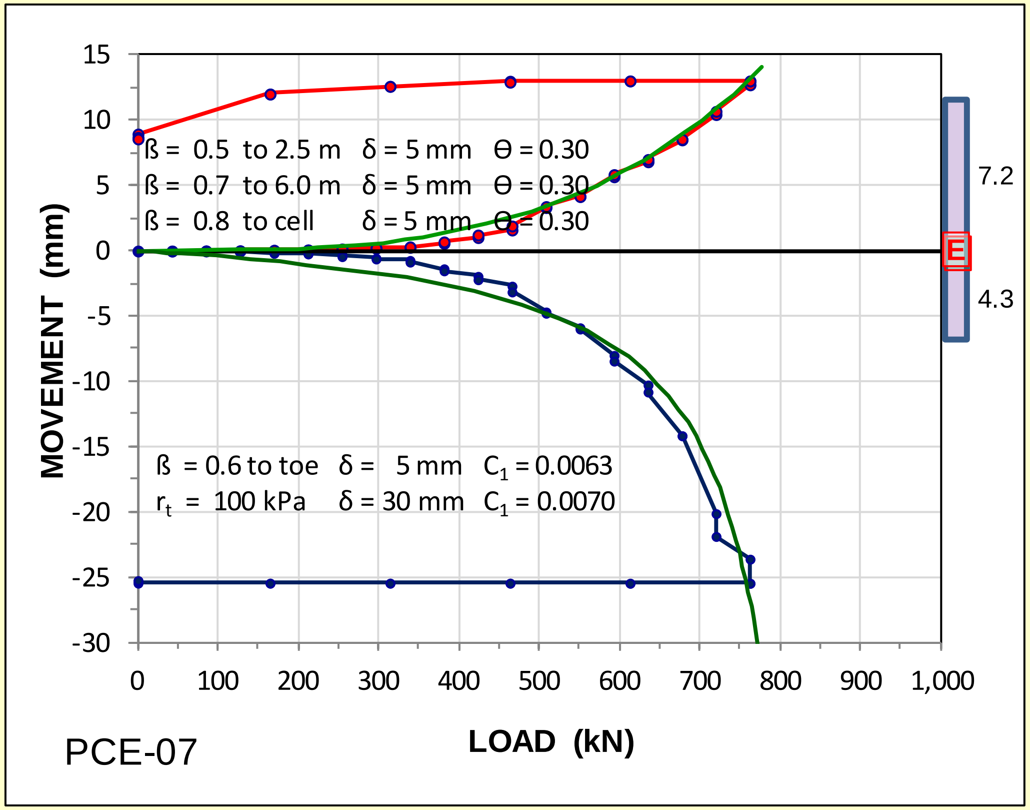
Measured upward curve

Head-down combining upward and downward curves

The difference shown above between the upward BD cell-plate and the head-down load-movement curves is due to the fact that the upward cell engages the lower soil first, whereas the head-down test jack engages the upper soils first, which are less stiff than the lower soils.

A CASE HISTORY Bidirectional tests performed at a site in Brazil on two Omega Piles (Drilled Displacement Piles, DDP, also called Full Displacement Piles, FDP) both with 700 mm diameter and embedment 11.5 m. Pile PCE-02 was provided with a bidirectional cell level at 7.3 m depth and Pile PCE-07 at 8.5 m depth.

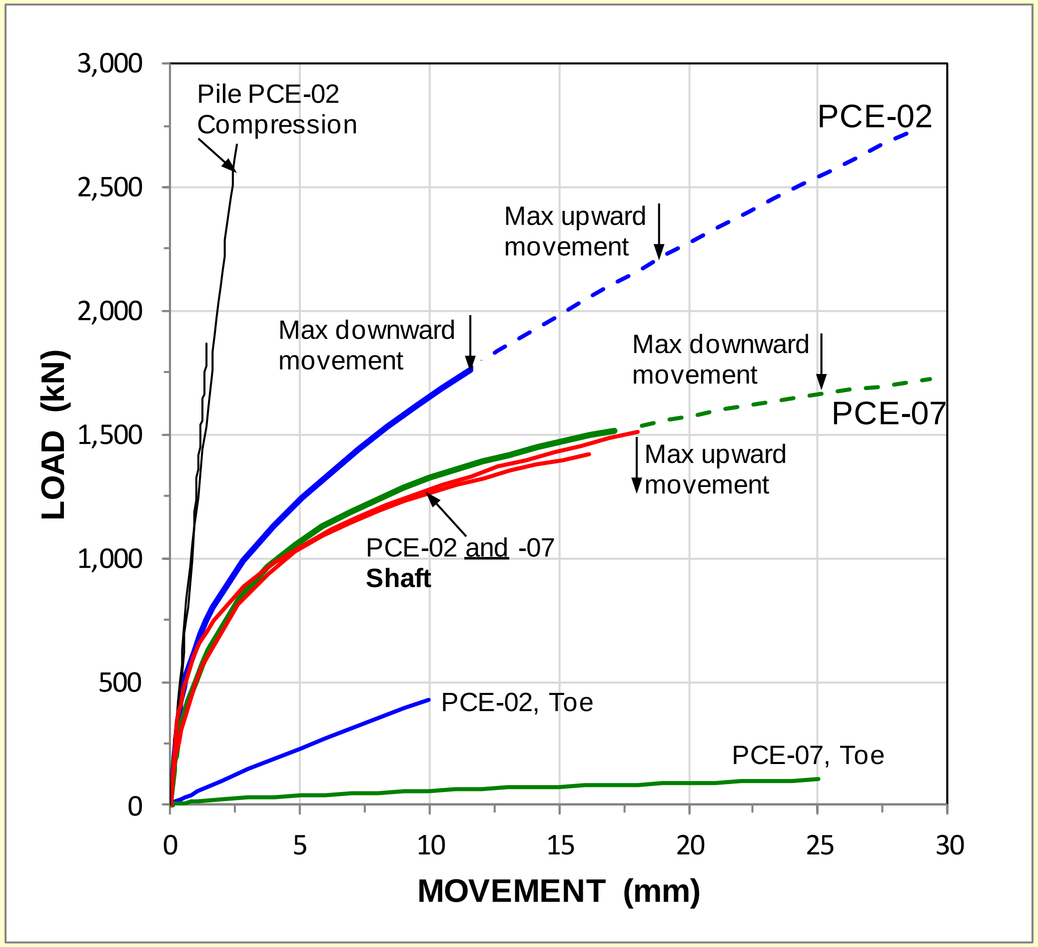




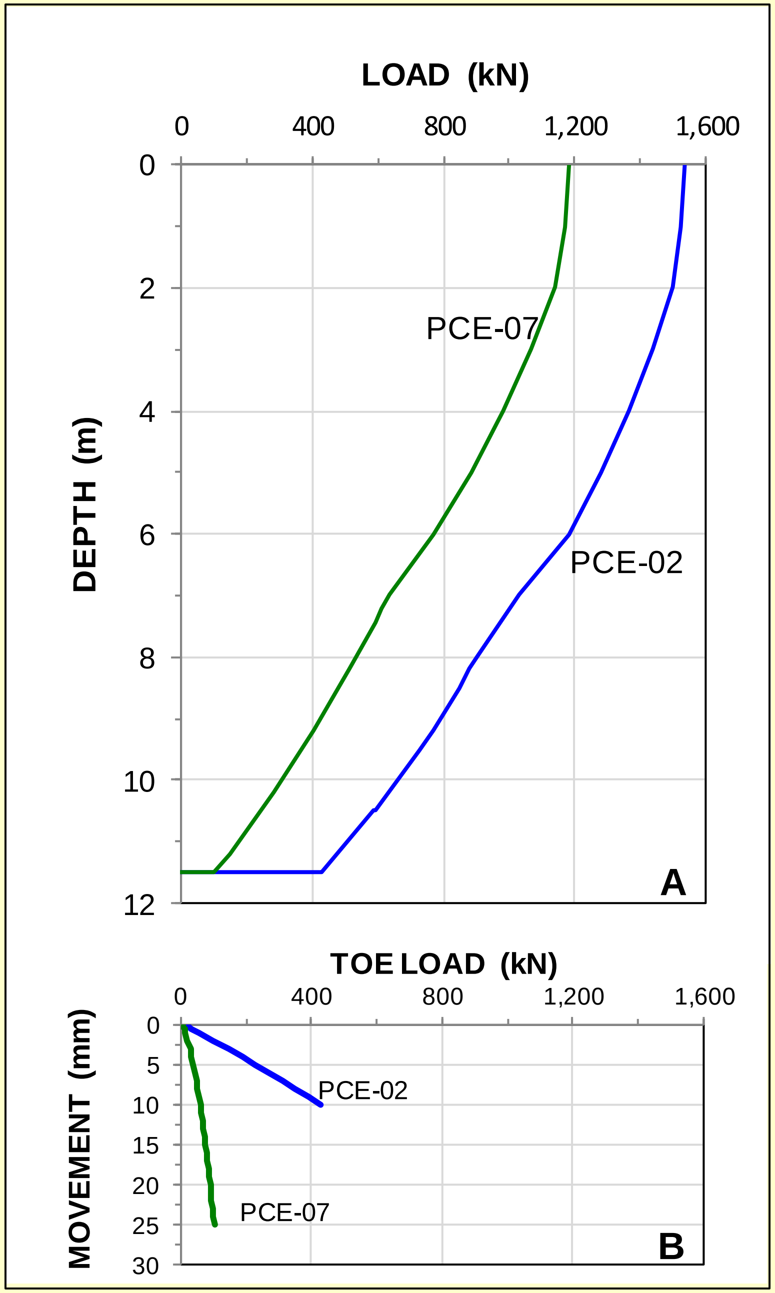
Acknowledgment: The bidirectional test are courtesy of
Arcos Egenharia de Solos Ltda., Belo Horizonte, Brazil.

After data reduction and processing

Equivalent Head-down
Load-movements

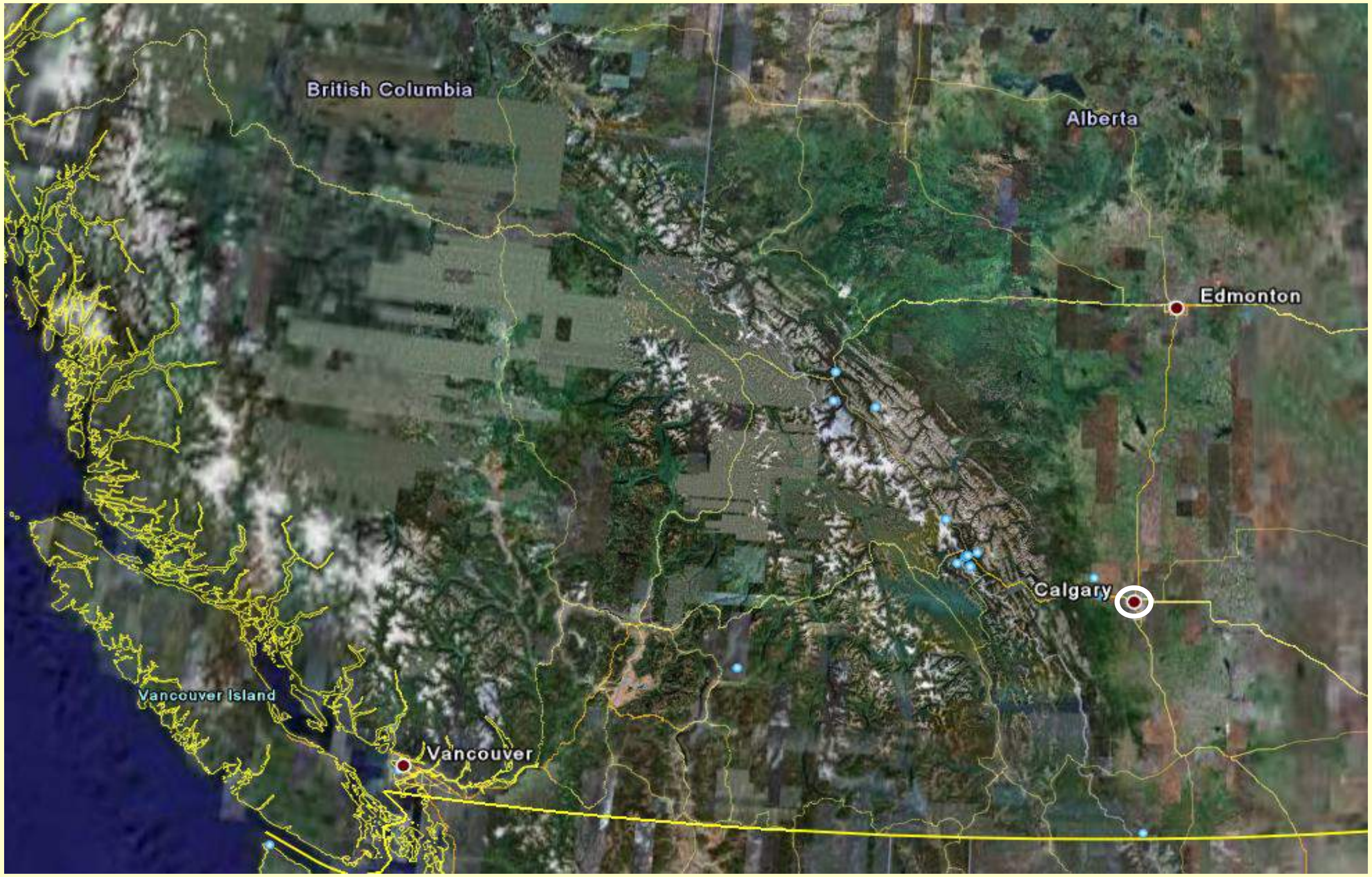


Equivalent Head-down
Load-distributions



A conventional head-down test would not
have provided the reason for the lower
“capacity” of Pile PCE-02

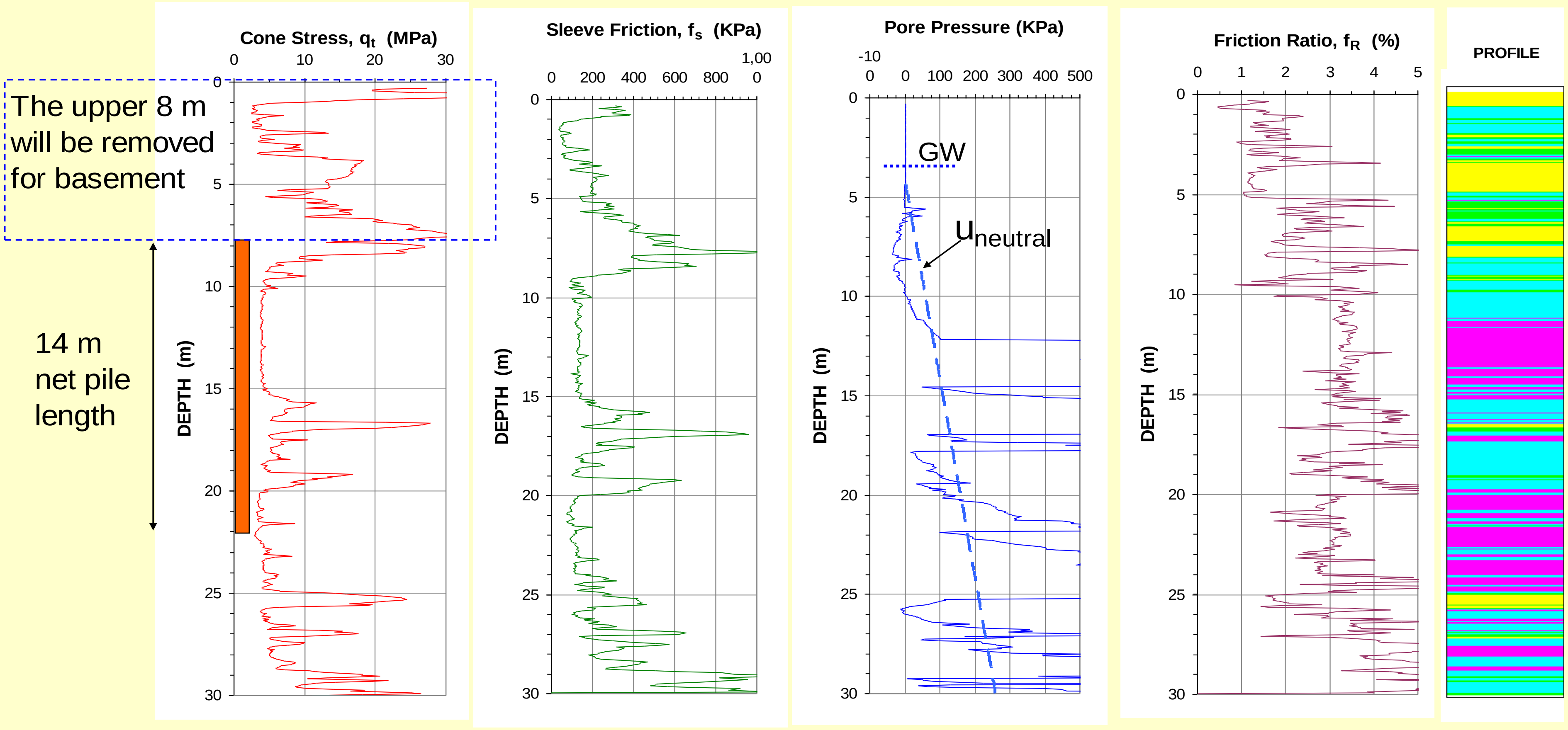
Bidirectional Tests on a 1.4 m diameter bored pile in North-West Calgary constructed in silty glacial clay till



A study of Toe and Shaft Resistance Response to Loading and correlation to CPTU calculation of capacity

cnt.

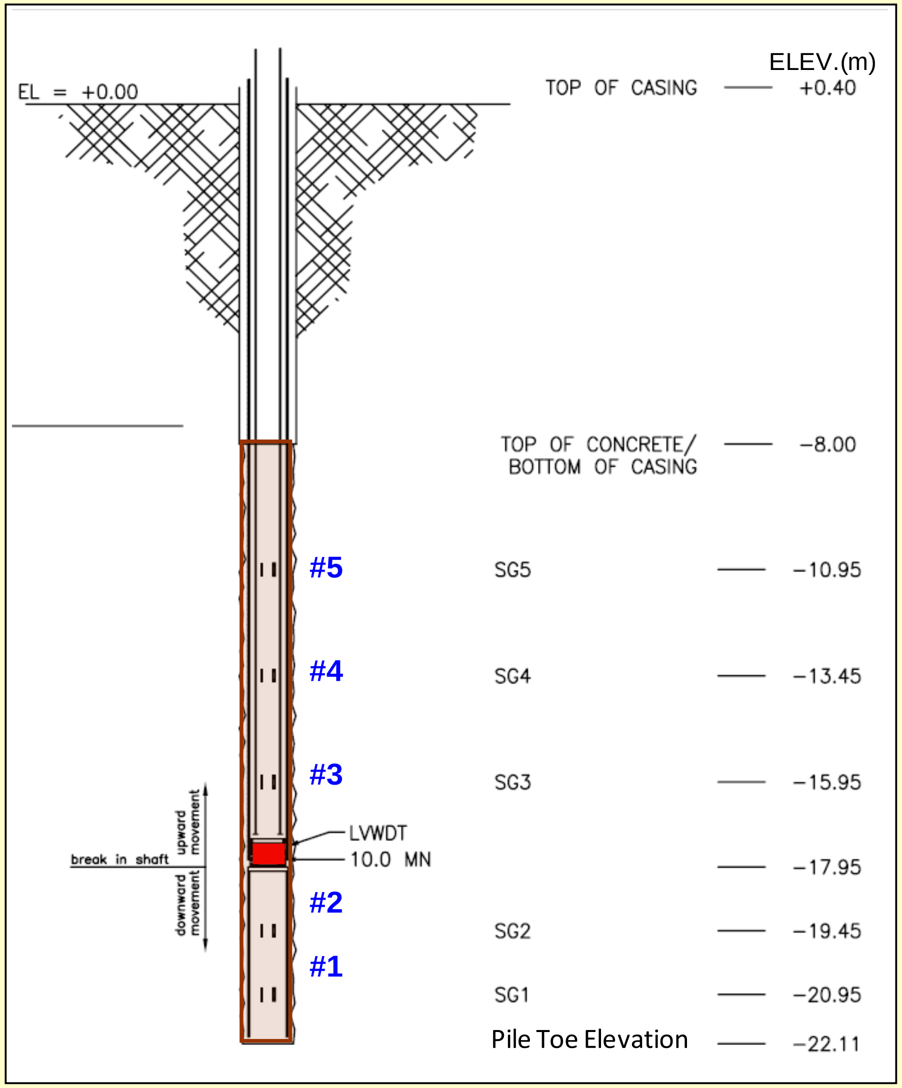
Cone Penetration Test with Location of Test Pile


The upper 8 m will be removed for basement

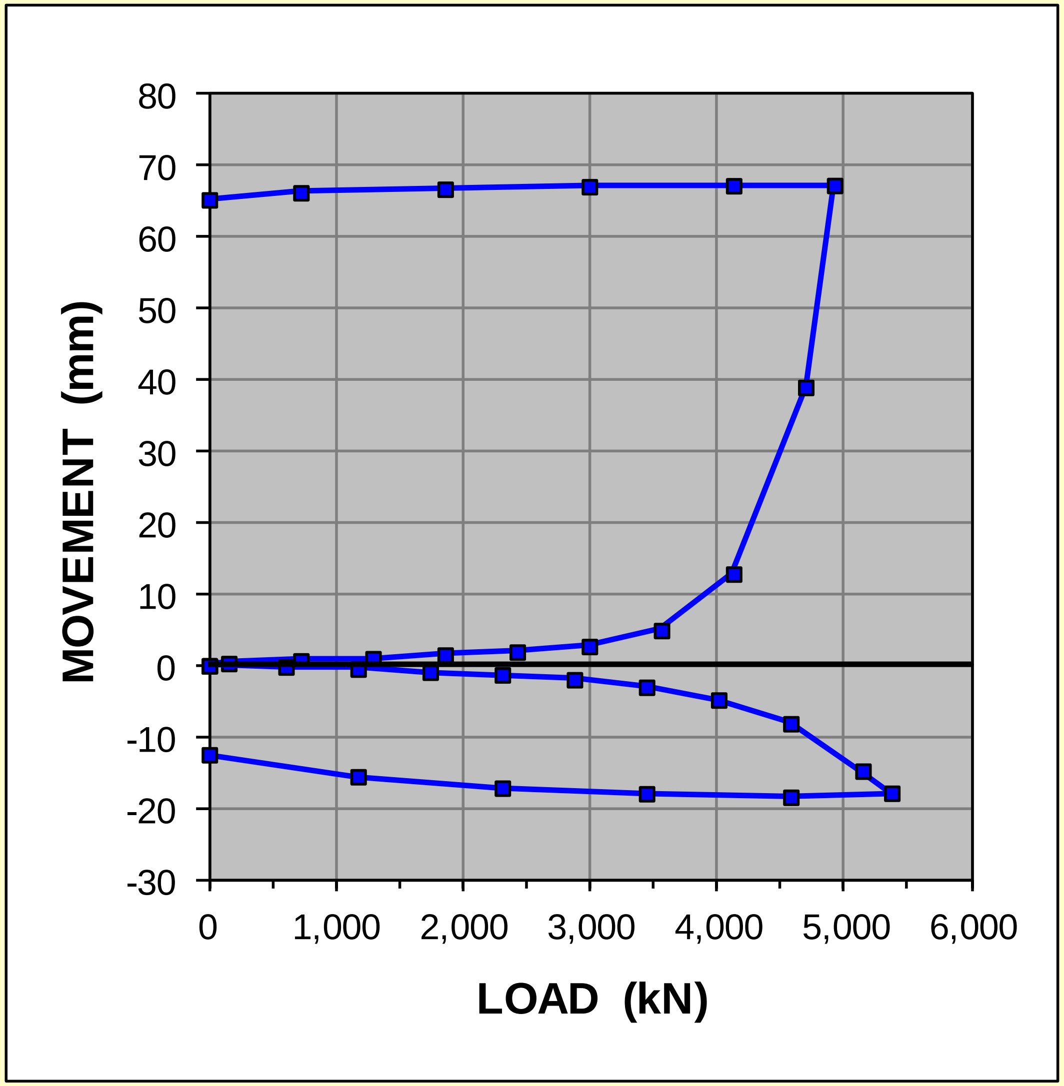
14 m net pile length

cnt.

Pile Profile and Cell Location

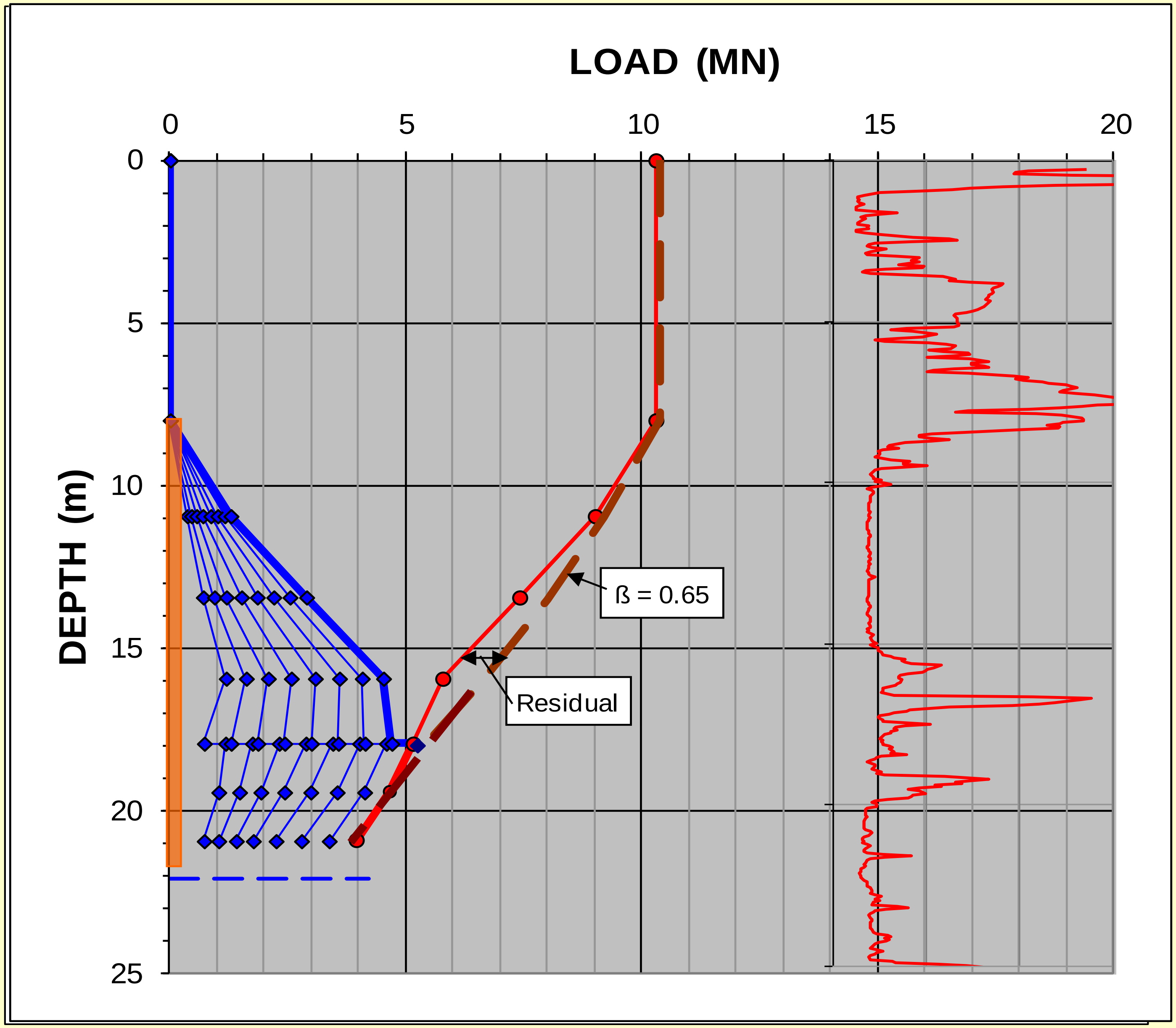


Cell Load-movement Up and Down

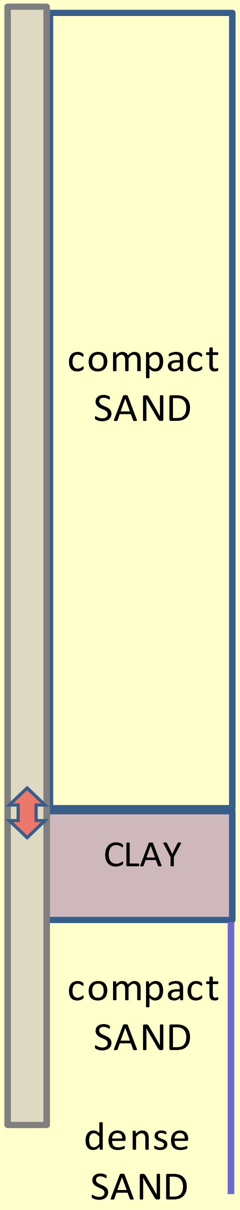


cnt.

Load Distribution



Analysis of the results of a bidirectional test on a 21 m long bored pile

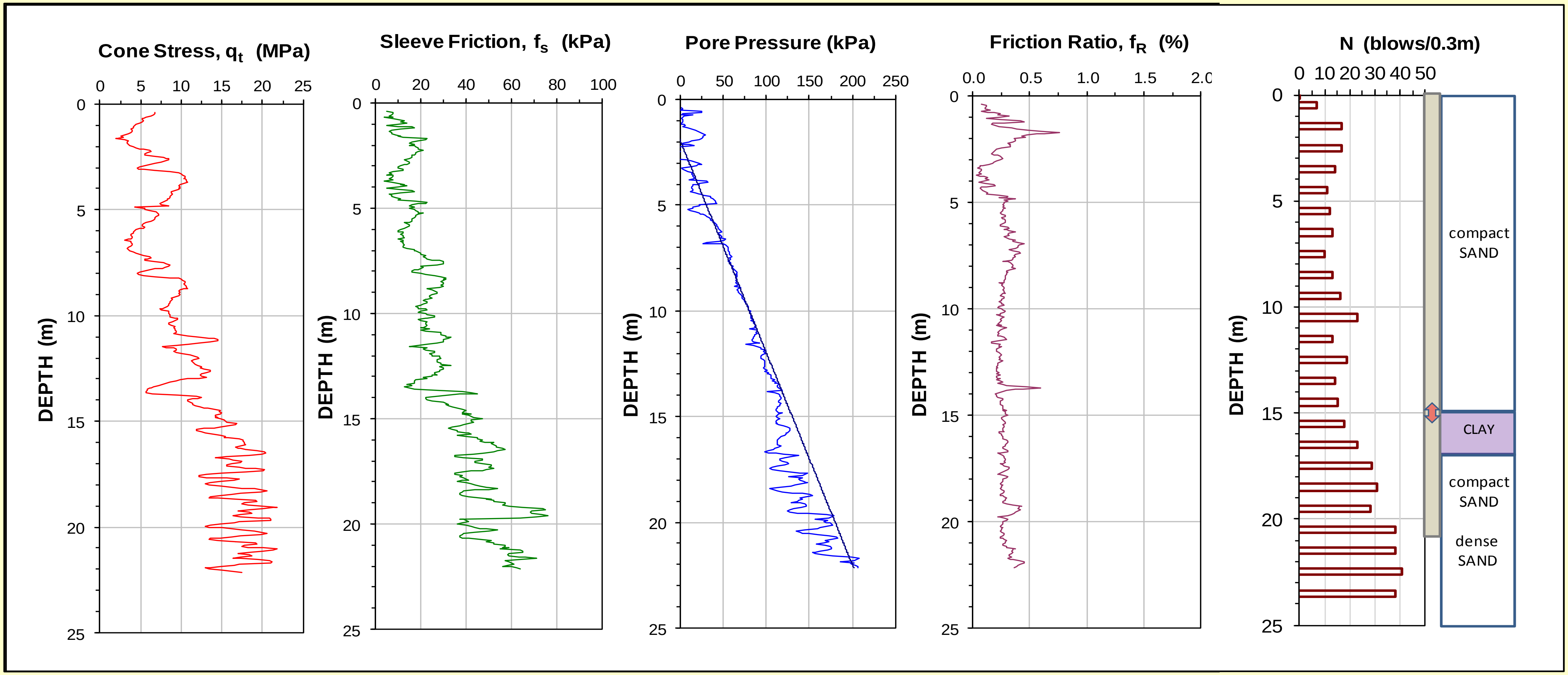


The sand becomes very dense at about 25 m depth

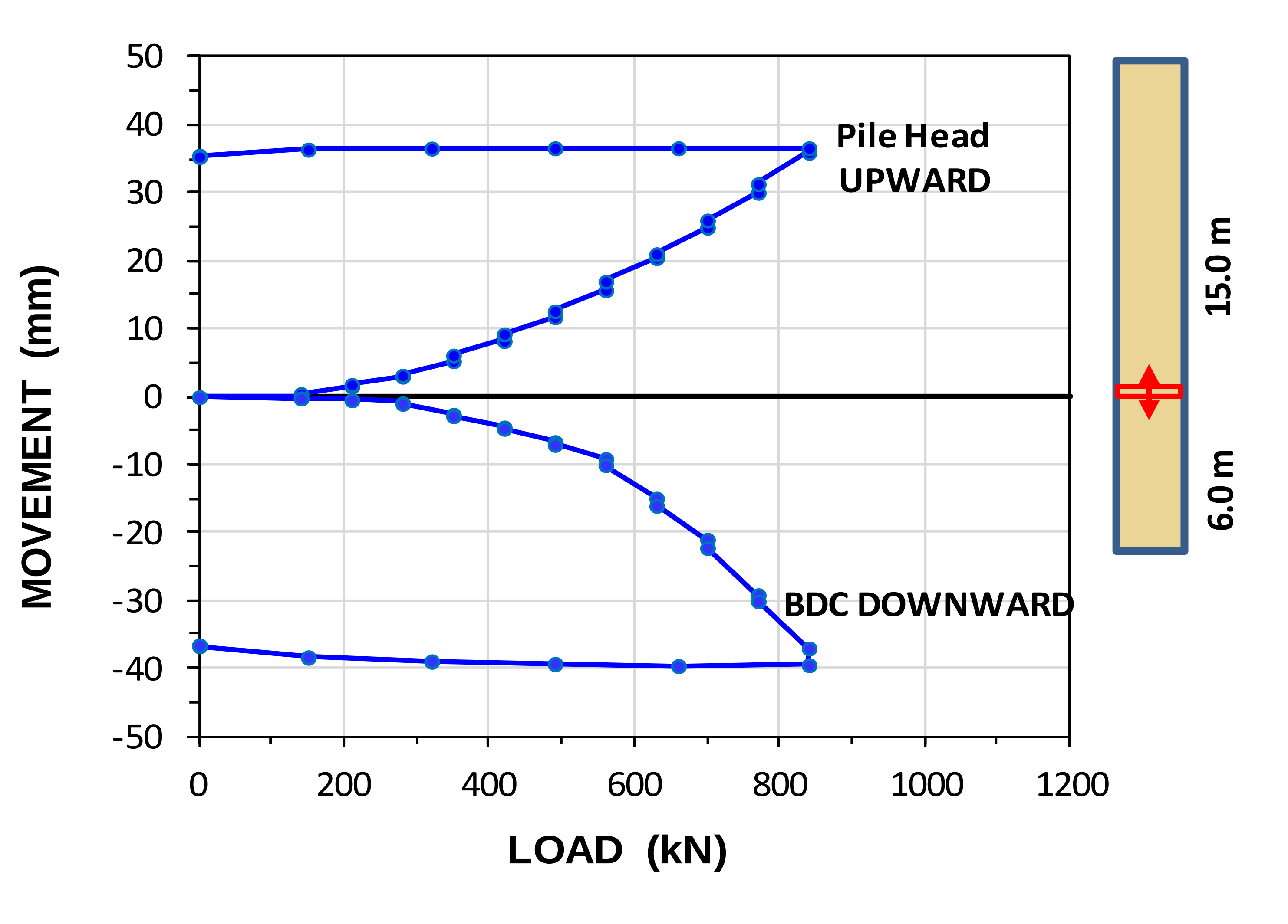
A bidirectional test was performed on a 500-mm diameter, 21 m long, bored pile constructed through compact to dense sand by driving a steel-pipe to full depth, cleaning out the pipe, while keeping the pipe filled with betonite slurry, withdrawing the pipe, and, finally, tremie-replacing the slurry with concrete. The bidirectional cell (BDC) was attached to the reinforcing cage inserted into the fresh concrete. The BDC was placed at 15 m depth below the ground surface.

The pile will be one a group of 16 piles (4 rows by 4 columns) installed at a 4-diameter center-to-center distance. Each pile is assigned a working load of 1,000 kN.

The soil profile determined by CPTU and SPT

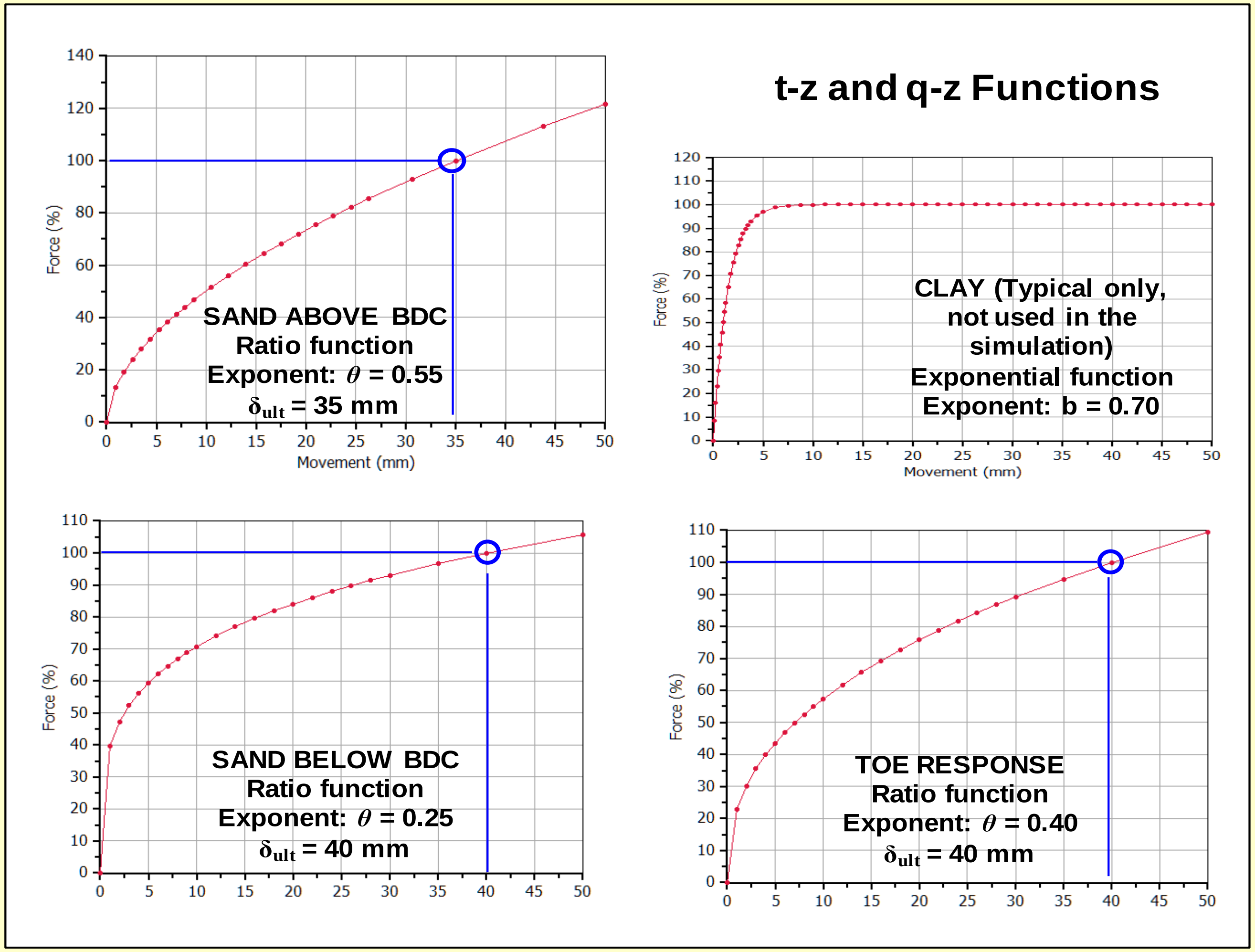


The results of the bidirectional test



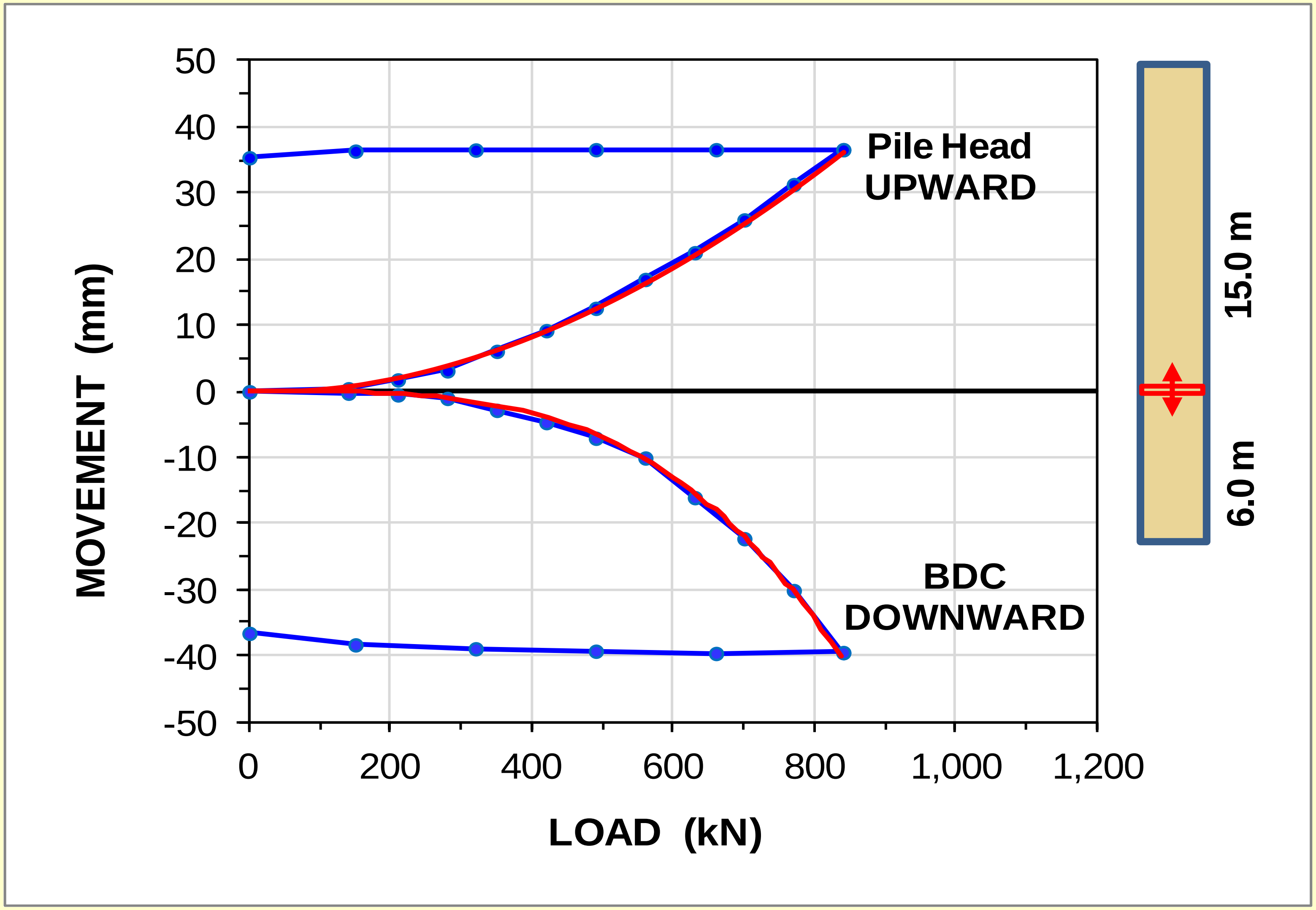
Acknowledgment: The bidirectional test data are courtesy
of Arcos Egenharia de Solos Ltda., Belo Horizonte, Brazil.

To fit a simulation of the test to the results, first input is the effective stress parameter (ß) that returns the maximum measured upward load (840 kN), which was measured at the maximum upward movement (35 mm). Then, “promising” t-z curves are tried until one is obtained that, for a specific coefficient returns a fit to the measured upward curve. Then, for the downward fit, t-z and q-z curves have to be tried until a fit of the downward load (840 kN) and the downward movement (40 mm) is obtained.

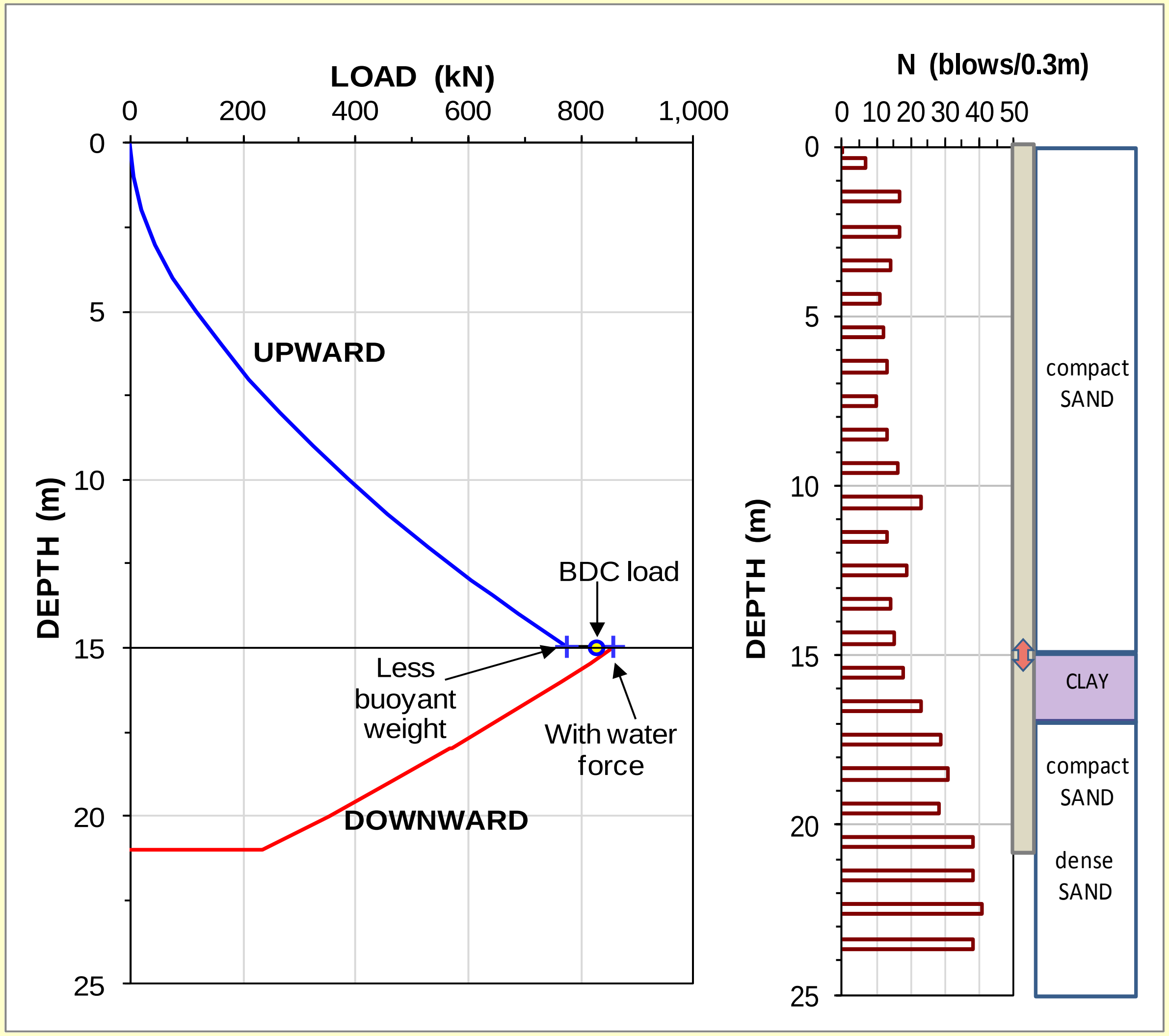


Usually for large movements, as in the example case, the t-z functions show a elastic-plastic response. However, for the example case , no such assumption fitted the results. In fact, the best fit was obtained with the Ratio Function for the entire length of the pile shaft.

The final fit of simulated curves to the measured

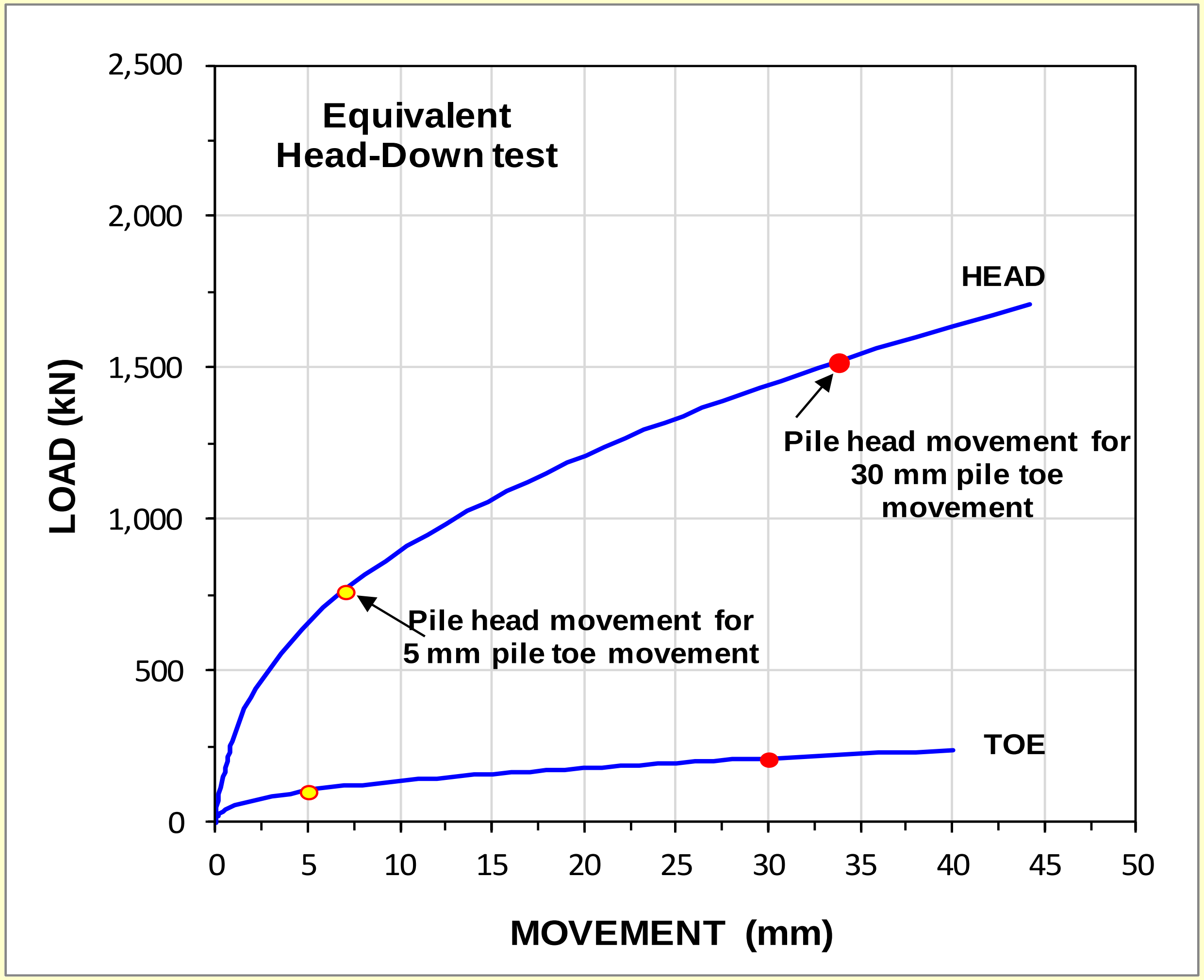


The test pile was not instrumented. Had it been, the load distribution of the bidirectional test as determined from the gage records, would have served to further detail the evaluation results. Note the below adjustment of the BDC load for the buoyant weight (upward) of the pile and the added water force (downward).



The analysis results appear to suggest that the pile is affected by a filter cake along the shaft and probably also a reduced toe resistance due to debris having collected at the pile toe between final cleaning and the placing of the concrete.

The final fit establishes the soil response and allows the equivalent head-down loading- test to be calculated



When there is no obvious point on the pile-head load-movement curve, the “capacity” of the pile has to be determined by one definition or other—there are dozens of such around. The first author prefers to define it as the pile-head load that resulted in a 30-mm pile toe movement. As to what safe working load to assign to a test, it often fits quite well to the pile head load that resulted in a 5-mm toe movement.

The most important aspect for a safe design is not the “capacity” found from the test data, but what the settlement of the structure supported by the pile(s) might be. How to calculate the settlement of a piled foundation is addressed a few slides down.

Thank you for your attention