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PROVA DINAMICA SU PALI IN ALTERNATIVA ALLA PROVA STATICA

Pile Dynamic Load test as alternative to Static Load test

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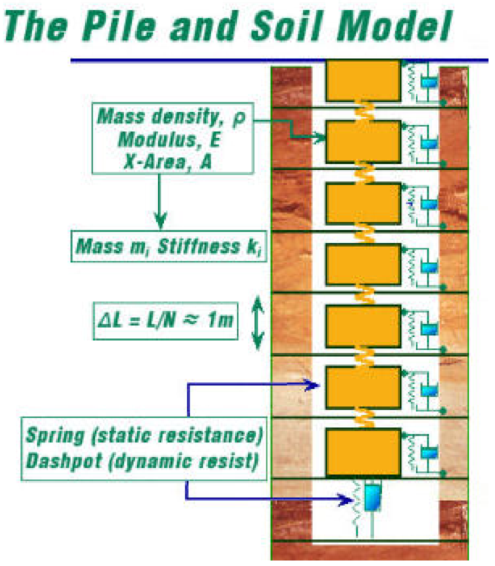
ABSTRACT
Pile Dynamic test is test to predict pile static capacity at the time of testing. Dynamic load test has its name because load on pile and soil is entered with hammer blow not with static load like in static load test. The simplest method to predict pile static capacity from field measured data is called Case Method. The Case Method is a closed form solution based on a few simplifying assumptions such as ideal plastic soil behavior and an ideally elastic and uniform pile. Case method capacity is in most cases highly dependent on selected damping which could be defined only on the basis of static load test or on the basis of CAPWAP analysis. In Eurocode CAPWAP is called signal matching procedure. Result of CAPWAP analysis is total pile static capacity and also simulation of static load test with skin friction distribution and pile toe capacity prediction.

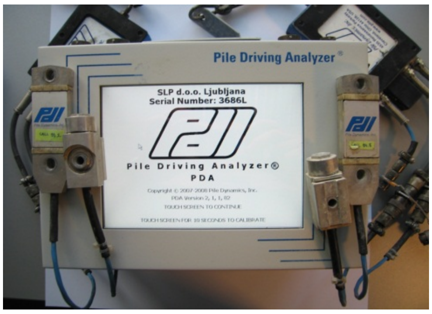
Pile Dynamic Testing history
In the 1950's, E.A. Smith of the Raymond Pile Driving Company developed a numerical analysis method to predict the capacity versus blow count relationship and to investigate pile driving stresses. The model mathematically represents the hammer and all its accessories (ram, cap, cap block), as well as the pile, as a series of lumped masses and springs in a one-dimensional analysis. The soil response for each pile segment was modeled as viscoelastic-plastic.



All components of the system are thus realistically modeled. The analysis begins with the hammer ram falling and attaining an initial velocity at impact. This method is the best technique for predicting the relationship of pile capacity and blow counts (or set per blow), and the only method available to predict driving stresses.
The wave equation approach is an excellent predictive tool for analysis of impact pile driving, but it has some limitations. These are mainly due to uncertainties in quantifying some of the required inputs, such as actual hammer performance and soil parameters.

Similar model is also the base of modern Wave Equation Analysis of Piles (GRLWEAP program) and also in signal matching process (CAPWAP program) as it will be explained later.

To overcome uncertainties in quantifying some actual hammer performance and soil parameters In 1972 first Pile Driving Analyzer® (PDA) and its associated software now known as CAPWAP® was produced in USA Cleveland company PDI Inc. Between 1980 to 1990 PDA was widely used in USA, UK and Sweden. In 1986 one PDA was used in Slovenia too.



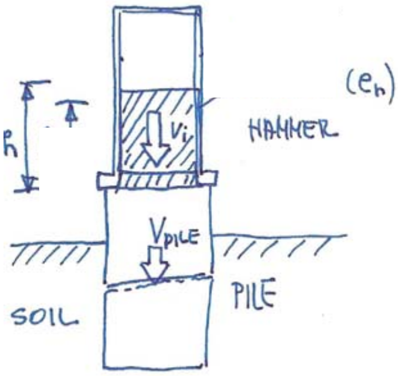
Pile Driving Analyser in 1980 and in PDA-PAX 2010 with wireless sensors

Introduction in to Pile Dynamic Testing

Basic theory

When a hammer or drop weight strikes the pile head, a compressive stress wave travels down the pile at a speed c (wave speed).

If hammer drop is fully free, hammer hit pile head with impact velocity (v_i). It is possible to assume that pile top velocity (v_{pile}) is approximately equal to hammer impact velocity (v_i).

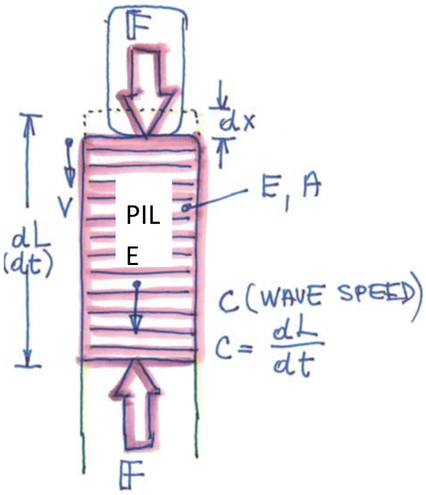


$$v_i = \sqrt{2\, g\, h\, e_h} \qquad (1)$$

$$v_{pile} \cong v_i$$

From well-known equations and sketch below, it is possible to find out connections between strain, stress, force, velocity, wave speed and pile characteristic (modulus of elasticity, mass density and cross section). Used symbols:

F = force in pile
v = velocity (pile movement velocity)
A = pile area
E = pile material modulus of elasticity
L = pile length; dL = compressed pile length
dx = pile deformation
ε = pile strain
c = wave speed
t = time



$$\epsilon = \frac{\sigma}{E} = \frac{F}{E\,A} \qquad c = \frac{dL}{dt}$$

$$\epsilon = \frac{dx}{dL} = \frac{F}{A\,E} \Rightarrow dx = \frac{F\,dL}{E\,A}$$

$$v = \frac{dx}{dt} = \frac{F\,dL}{A\,E\,dt} \qquad \boxed{F = v\,\frac{E\,A}{c} = v\,Z} \qquad (2)$$

$$\frac{F}{A} = \frac{v\,E}{c} = \sigma = \varepsilon\,E \qquad \boxed{\frac{\sigma}{E} = \epsilon = \frac{v}{c}}$$

$$\boxed{Z = \frac{E\,A}{c}\ (\,Impedance)} \qquad (3)$$

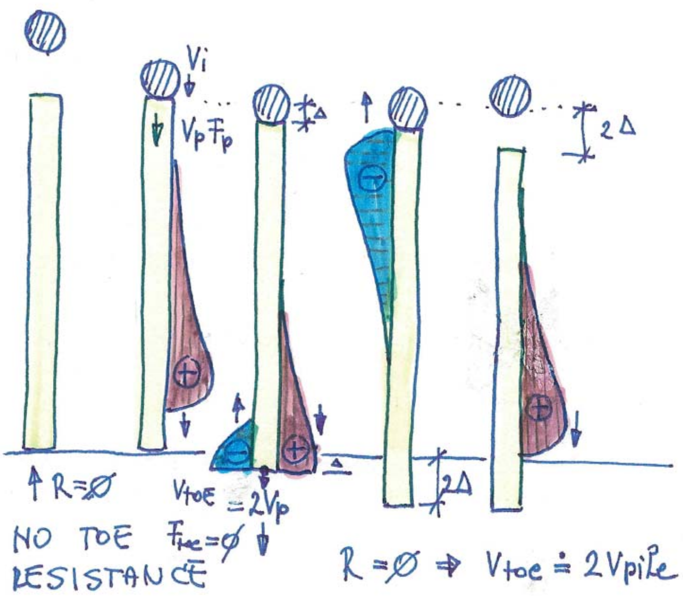
Wave speed (c) is a function of the pile elastic modulus E and mass density ρ.

$$a = \frac{dv}{\mathrm{dt}} = \frac{d}{\mathrm{dt}}\,\frac{F\,c}{\mathrm{E\,A}} \qquad F = m\,a = dL\,A\,\rho\,a$$

$$a = \frac{F}{dL\,A\,\rho} = \frac{d}{dt}\,\frac{F\,c}{E\,A} \Rightarrow \boxed{c^2 = \frac{E}{\rho}} \qquad (4)$$

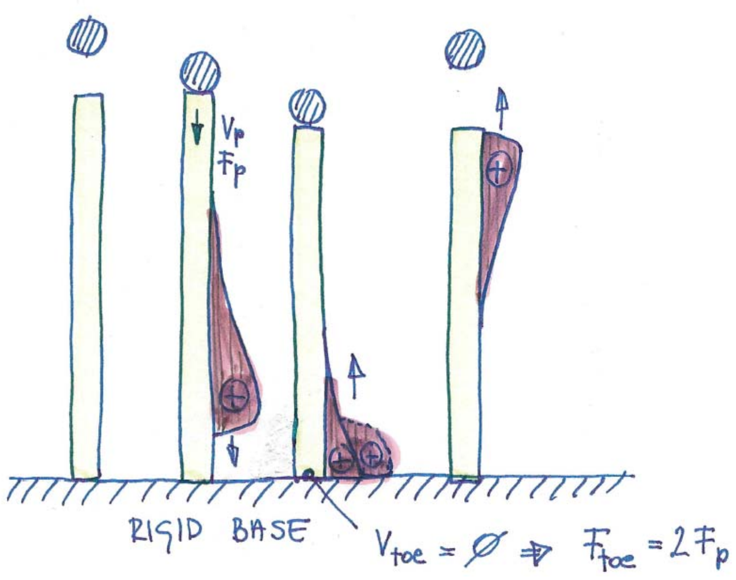
Impact at the pile head induces a force F and a particle velocity v in pile. <u>At pile driving there are two limit states at pile toe:</u>

1 / <u>Pile toe is free - no soil resistance</u>



It could be seen from sketch, that down traveling compression wave is returned after toe reflection as tension wave and velocity at the pile toe is doubled.

2 / Pile toe is on rigid soil which does not permit any pile toe movement.



It could be seen from sketch, that down traveling compression wave is returned after toe reflection as compression wave and force at the pile toe is doubled.

What is measured with the PDA during Pile Dynamic Test?

At pile head, acceleration a(t) and strain ε(t) are measured.

Strain is measured with strain transducers, acceleration is measured with accelerometers.

PDA integrates acceleration a(t) in pile velocity v(t) and calculate force in pile F(t) from measured strain ε(t).

a(t) measurements > $v(t) = \int a(t)dt$

$$F = v\frac{E\,A}{c} = vZ \quad (5)$$

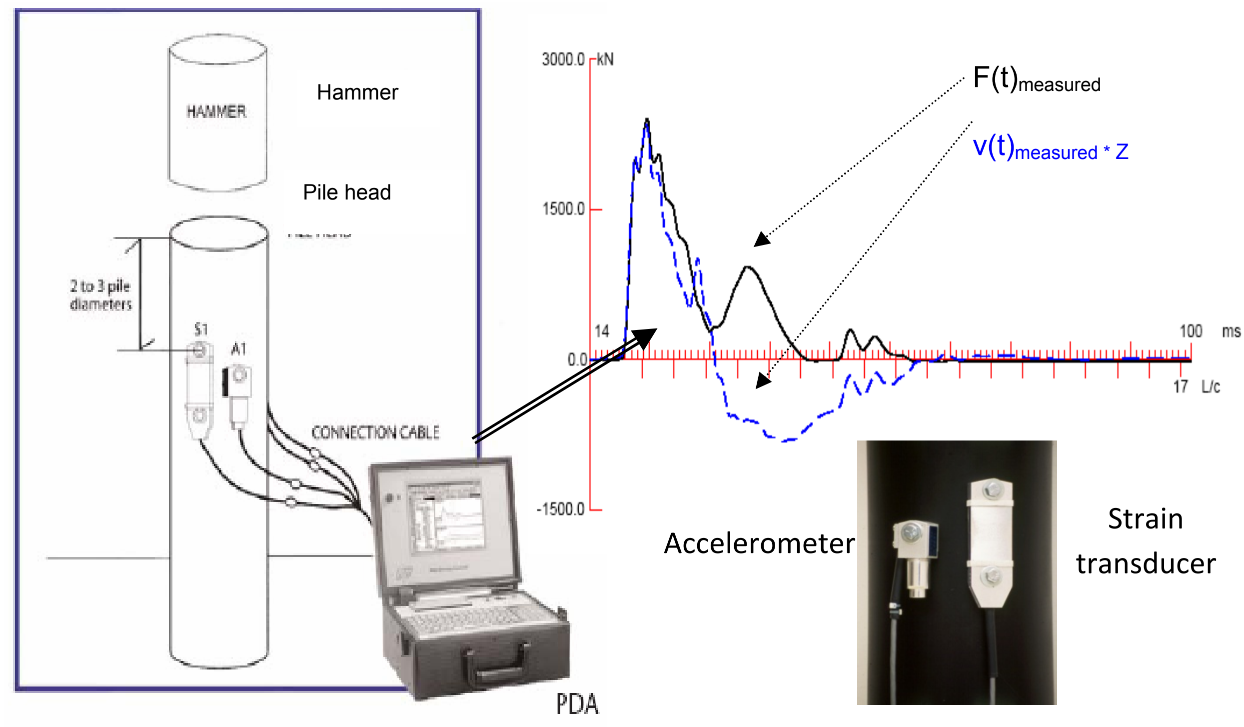
ε(t) measurements >

$$F = \varepsilon E\,A \quad (6)$$

Pile velocity v(t) is often also called particle velocity or pile movement velocity.

If just one point near the pile head is observed, than it could be seen, that force (F) and velocity (v) are changing with time, as stress wave travel along the observation point.

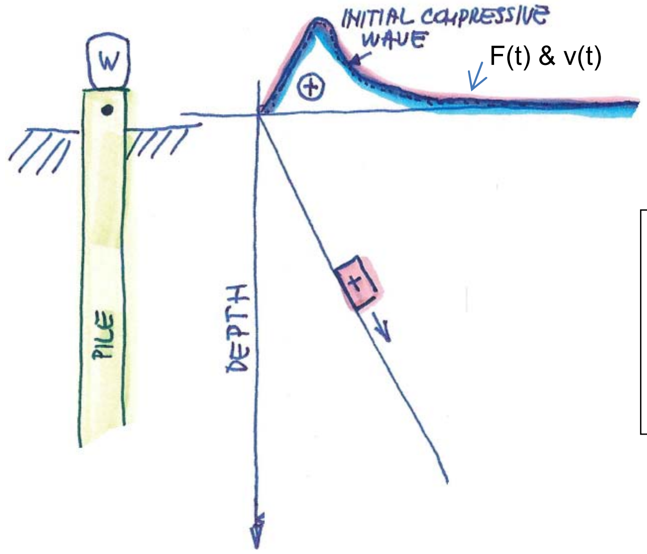
From both independent measurements it is possible to calculate force using equations (5) and (6).



Next drawings show measured force **F(t)**=ε*E*A and measured velocity multiplied with pile impedance **v(t)*Z** as could be observed at pile head for five typical situations.

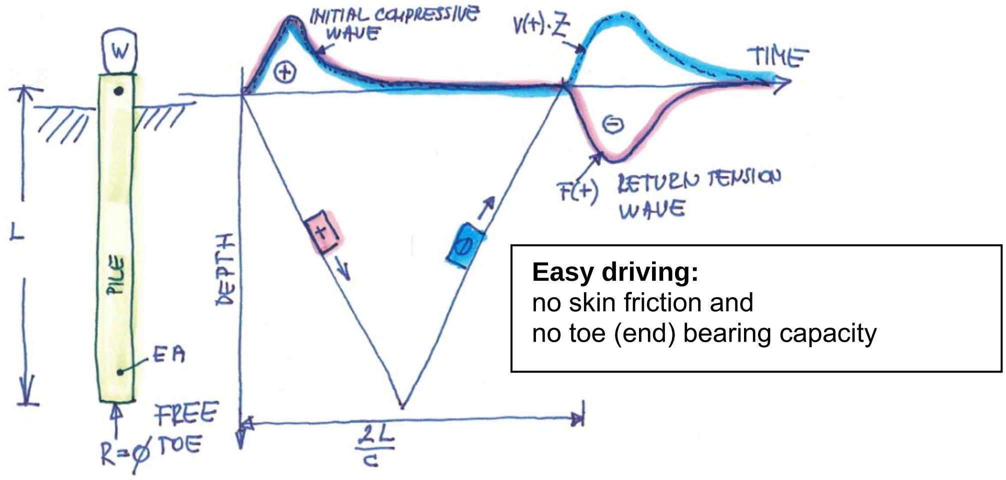
1 / uniform and **infinite long pile; no soil resistance**
2 / no skin friction and **no toe (end) bearing capacity**
3 / no skin friction and **very high toe (end) bearing capacity**
4 / **skin friction and no toe (end) bearing capacity**
5 / **skin friction and very high toe (end) bearing capacity**

1 / uniform and **infinite long pile; no soil resistance**

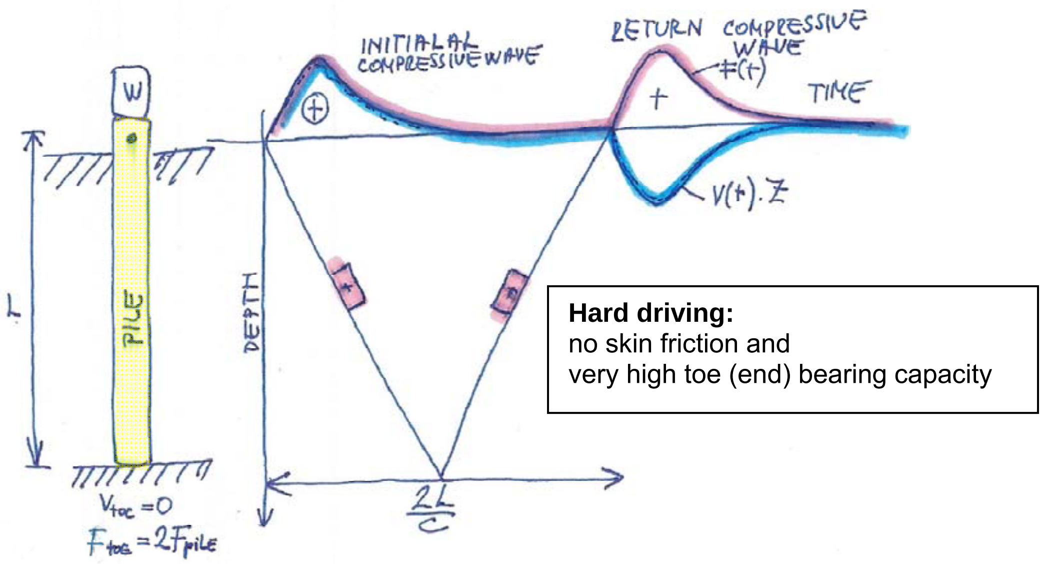


If pile is uniform and infinite long and there is no soil resistance, than measured force F(t)=ε*E*A and measured velocity multiplied with pile impedance F(t) = v(t)*Z are equal.

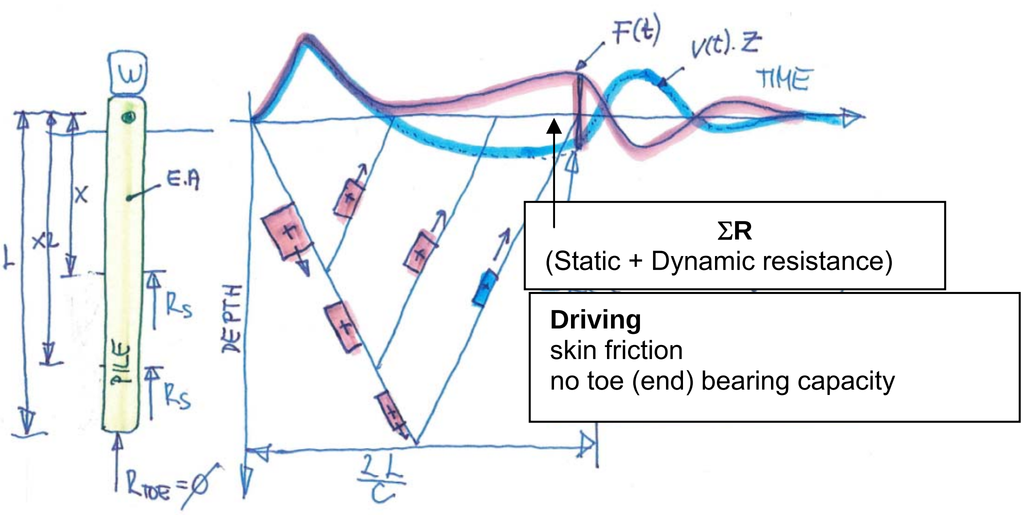
2 / no skin friction and **no toe (end) bearing capacity**



3 / no skin friction and **very high toe (end) bearing capacity**

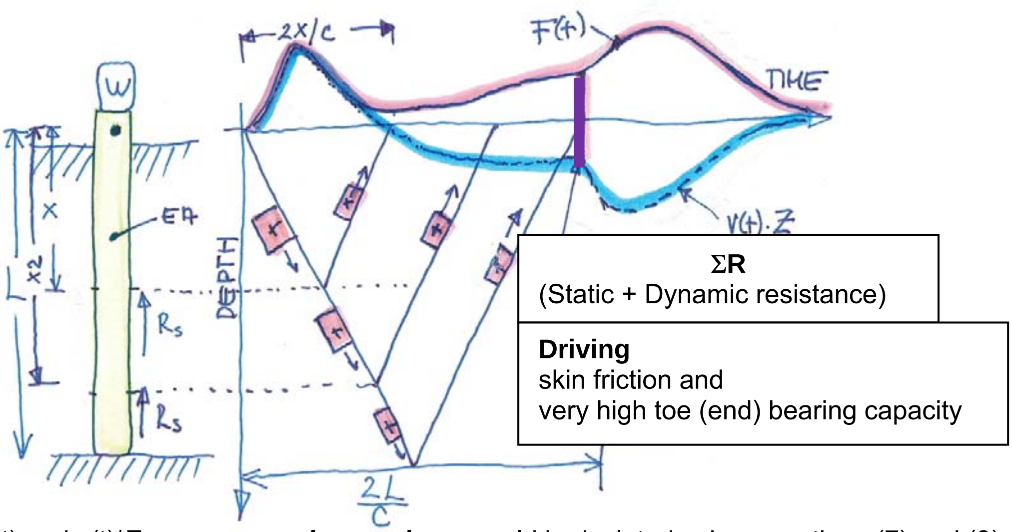


4 / **skin friction and no toe (end) bearing capacity**



Because of soil skin resistance part of down traveling wave is reflected back before time 2L/c and separates measured force and measured velocity. The magnitude of the reflected wave is proportional to the resistance at the soil.

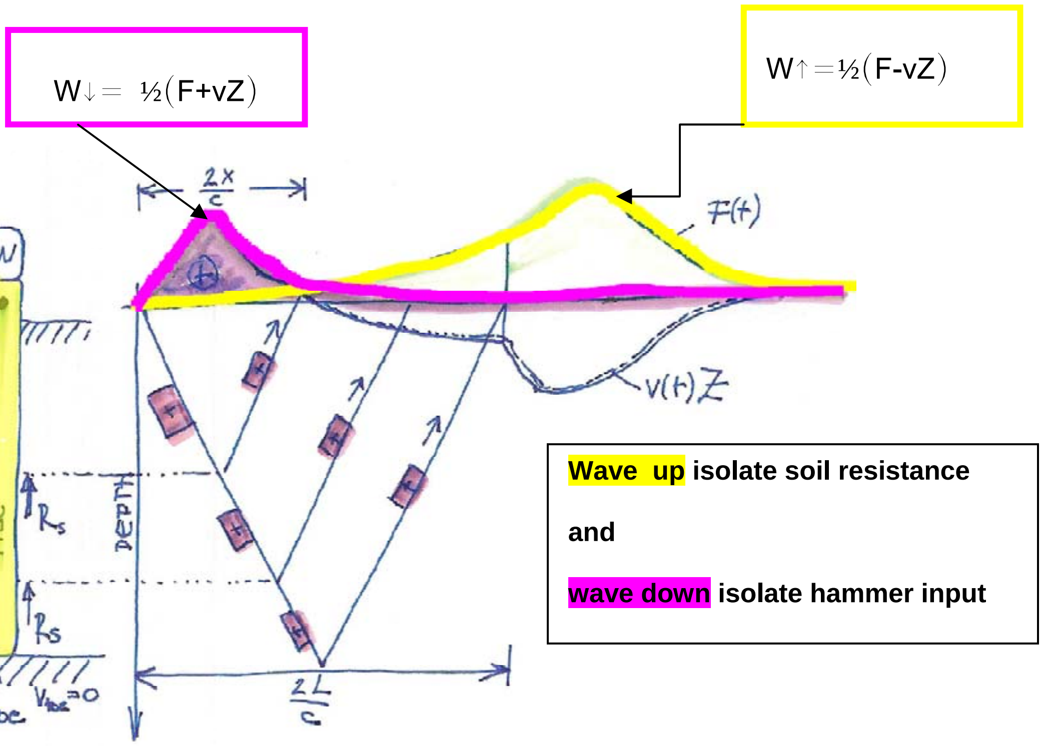
5 / **skin friction and very high toe (end) bearing capacity**



From F(t) and v(t)*Z, **wave up and wave down** could be isolated using equations (7) and (8).

Upward waves: $W\uparrow = ½(F-vZ)$ (7)

Downward waves: $W\downarrow = ½(F+vZ)$ (8)



The force at any location along the pile length could be determinate from superposition of the upward and downward traveling waves.

$$F = W\uparrow + W\downarrow \qquad (9)$$

So it is possible to determinate down traveling wave caused by the hammer and up traveling wave generated by the soil resistance (Total_soil_resistance = Dynamic_soil_resistance + static_soil_resistance).
For each hammer blow, force (from measured specific deformation) and velocity curve (from measured acceleration) over time and other results could be seen on the PDA (Pile Driving Analyzer model) screen.

Soil resistances at the pile skin and tip are passive. Pile movement is needed to activate soil resistance. Pile movement or displacement is produced with pile head load. Loading may be slow as in the case of static load test or very fast as in case of dynamic load test. Very quick load is hammer blow on the pile head.

Pile displacement has to be large enough to exceed soil elastic behavior and reach ultimate state to activate all pile skin and toe resistance. In such a case we can say that ultimate pile capacity at the time of testing is reached.

CASE pile static capacity is pile capacity approximation on the field for each hammer blow on the basis of PDA measurements and selected damping coefficient. Damping coefficient has to be selected on the basis of experiences. CASE method can be applied only for uniform piles.

Total (static and dynamic) resistance is :

$$R_{total} = W\downarrow 1 + W\uparrow 2 \qquad (10)$$

$W\downarrow 1$ is downward wave at time t1 and $W\uparrow 2$ is upward wave in time t2; $t2 = t1+2L/c$

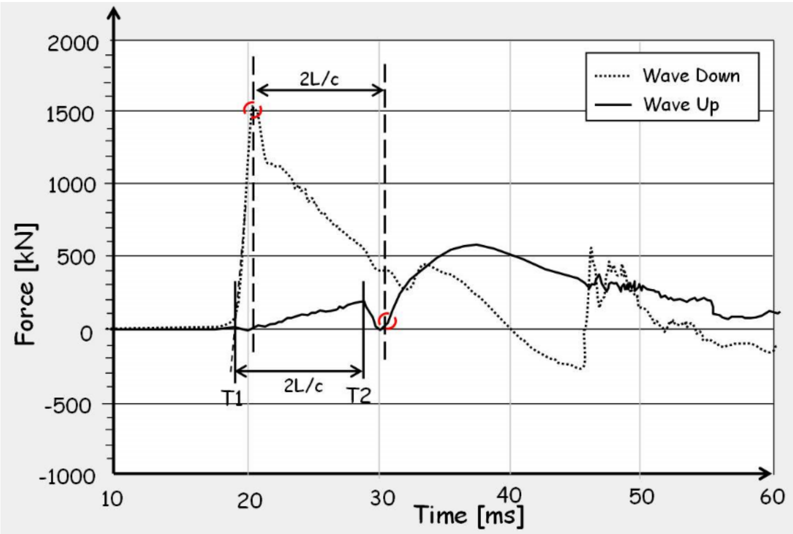
$$R_{total} = R_{static} + R_{dynamic}$$
$$R_{static} = R_{total} - R_{dynamic} \qquad (11)$$

$$R_{dynamic} = Jc * v * Z \qquad (12)$$

Jc is called case damping factor

$$R_{static} = (1-Jc)\, W\downarrow 1 + (1+Jc)\, W\uparrow 2 \qquad (13)$$

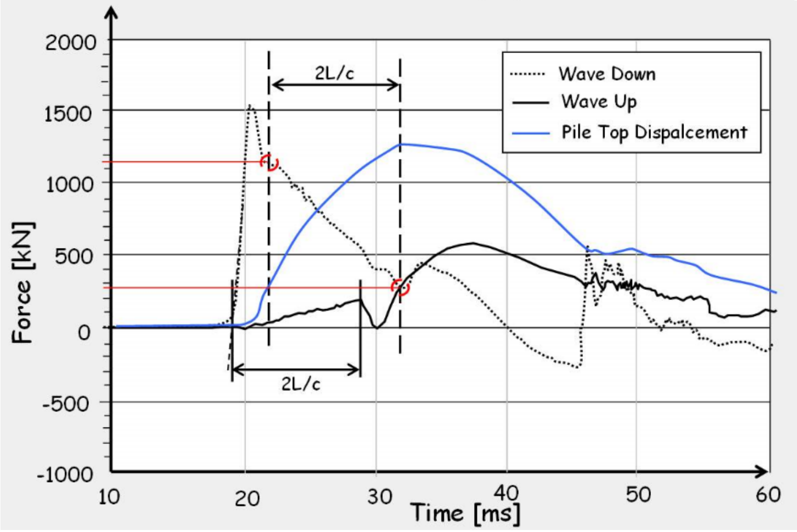
Static resistance is displacement dependent, while dynamic resistance is velocity dependent. The static soil resistance R_{static} calculated using equation (13) will vary depending on particular time period. Examples of Case static capacity calculations are presented below.



Assumed damping factor is
Jc = 0.5

$R_{static} = (1-Jc)\, W_{\downarrow 1} + (1+Jc)\, W_{\uparrow 2}$

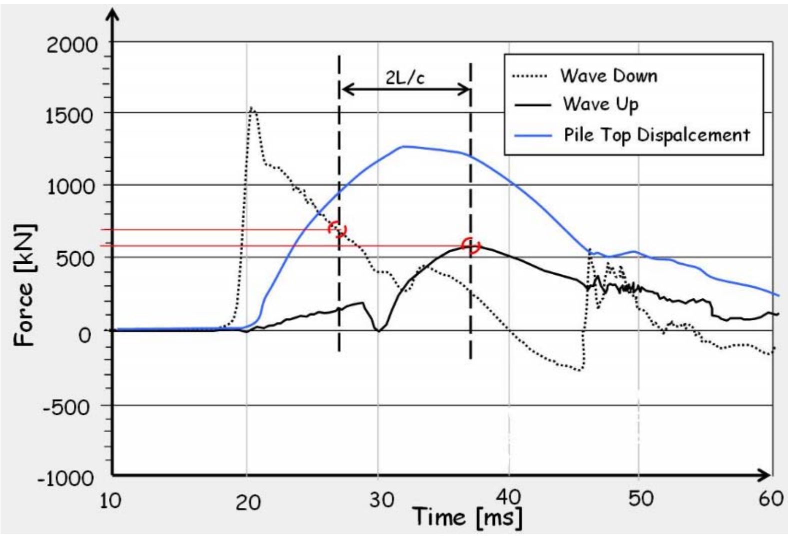
$R_{static} = 0.5*1500+1.5*25 = 787.5$ kN



Assumed damping factor is
Jc = 0.5

$R_{static} = (1-Jc)\, W_{\downarrow 1} + (1+Jc)\, W_{\uparrow 2}$

$R_{static} = 0.5*1150+1.5*275 = 987.5$ kN



Assumed damping factor is
Jc = 0.5

$R_{static} = (1-Jc)\, W_{\downarrow 1} + (1+Jc)\, W_{\uparrow 2}$

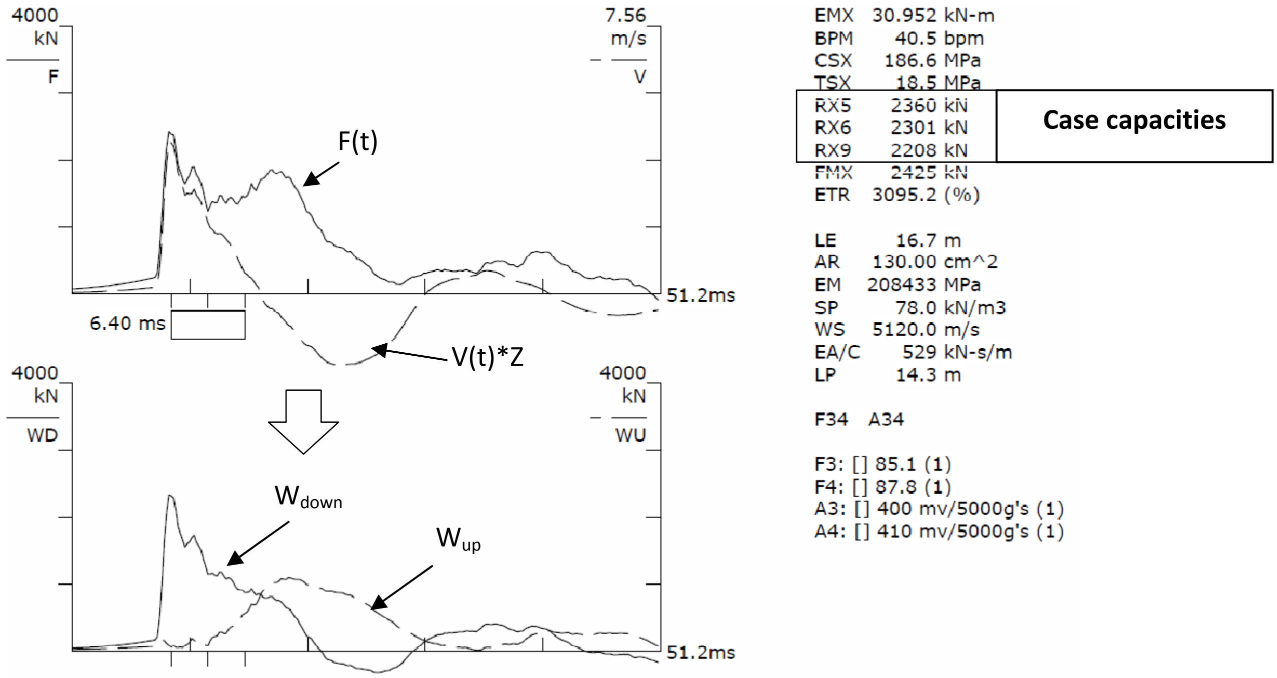
$R_{static} = 0.5*700+1.5*580 = 1220$ kN

A lot of information's which are important for the successful pile driving could be derived from F(t) and v(t) measurements:

- the maximum pile compression force during pile driving
- the maximum tensile stress during pile driving
- the maximum dynamic and permanent displacement on pile head
- hammer impact eccentricity
- energy transferred from the hammer to pile
- warnings and estimation of eventual pile damage and damage location.
- pile static capacity on the basis of approximate CASE method....

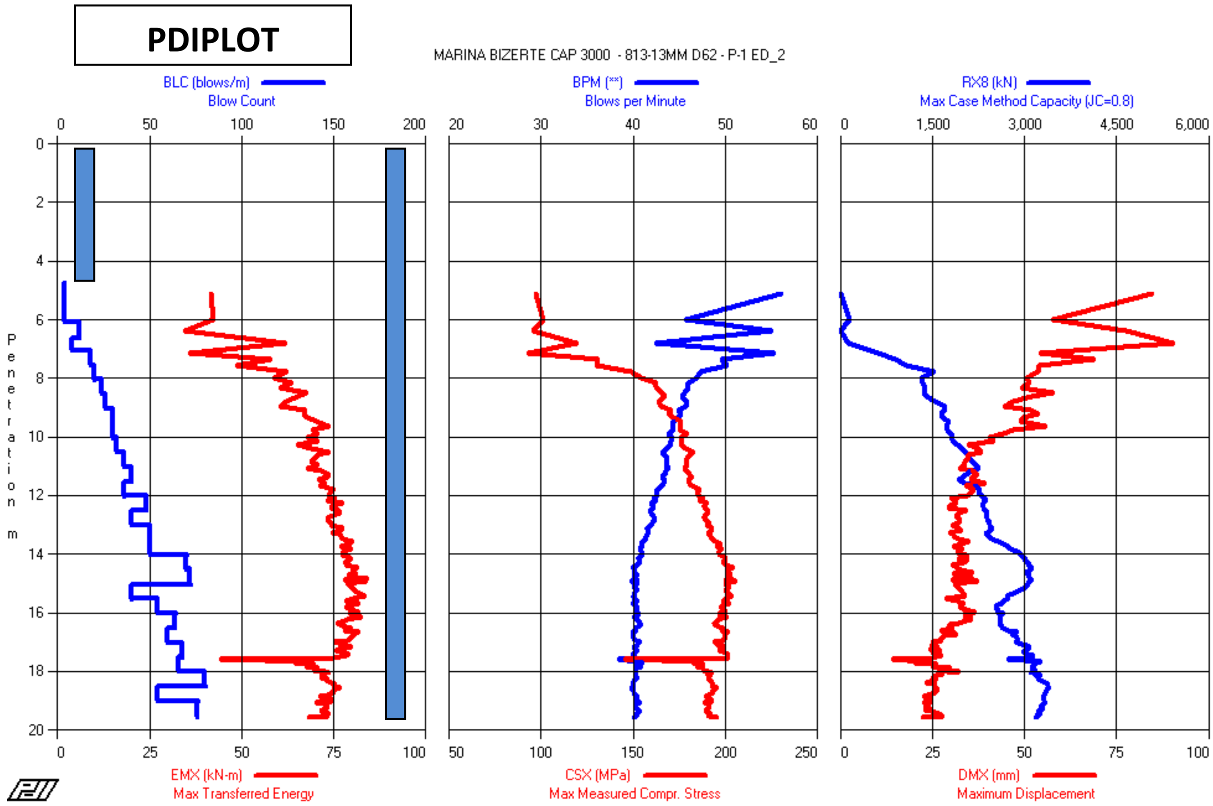
The maximum R_{static} over the time period is called RMX (RX5 = RMX with Jc =0.5).

From thousands of Pile Dynamic Tests all over the world, it was find out that RMX with Jc factor between 0.5 to 0.7 is the closest to the actual static capacity defined with static load test or CAPWAP Analyze (only for uniform piles).



Pile Driving Analyzer display during Dynamic Test for open end pipe pile with high capacity

If the measurements with PDA are performed during the pile penetration in the soil (Pile Dynamic Monitoring) it is possible to present results of the measurements in PDAPLOT diagrams which graphically show the changes of obtained information's (Case capacity, stresses in the pile, hammer energy,…) for different pile toe depths.



It is not possible to say that Pile Dynamic test together with Case capacity calculation is real alternative to Static load test.

But Pile Dynamic Load Test (DLT) together with CAPWAP Analyze is very good alternative to static load test (SLT).

The final result of DLT is pile static capacity of tested pile at the time of testing defined with CAPWAP analysis (signal matching). The result of CAPWAP analysis is toe and skin static capacity of the measured pile and simulation of static load test.

For piles in cohesive soils, DLT test should be performed at least 6 days after driving because of expected soil setup effect and increase of pile static capacity with time.

Pile Dynamic Test is composed from two main phases:

1. Site measurements with a PDA (Pile Driving Analyzer) during pile driving
2. Determination of pile static capacity with CAPWAP analysis

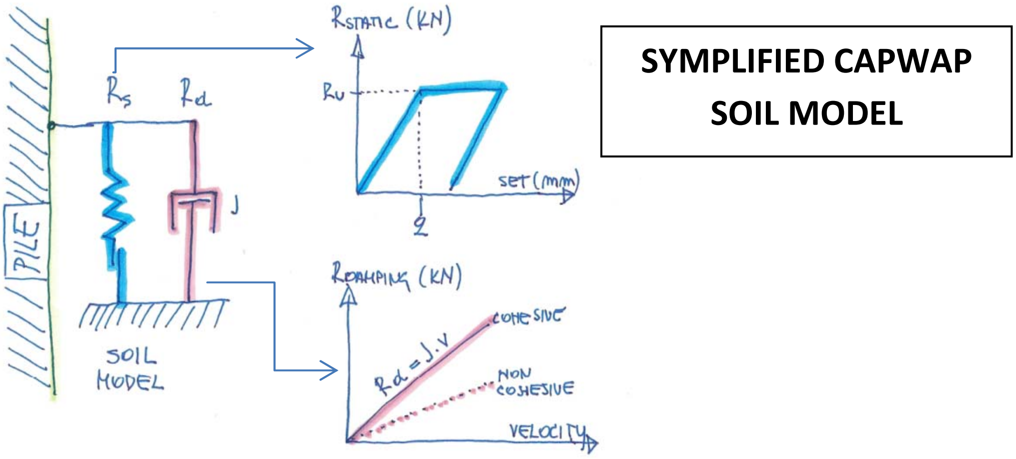
Execution of measurements during driving with a PDA (Pile Driving Analyzer)
On the tested pile a pair of accelerometers and at least a pair of strain transducers are attached at least two pile diameters below pile head. Sensors are connected to the Pile Driving Analyzer that internally performs all the necessary signal conditioning and processing to obtain output results during driving for each hammer blow and immediate screen display of measured force at the pile head ($F_{measured}$(t)) and pile head movement velocity ($v_{measured}$ (t)) both as a function of time. Also down and up traveling wave in the pile could be displayed in real time for each blow. Pile velocity is result of integration of measured pile acceleration. All data are recorded, so it could be re-analyzed.

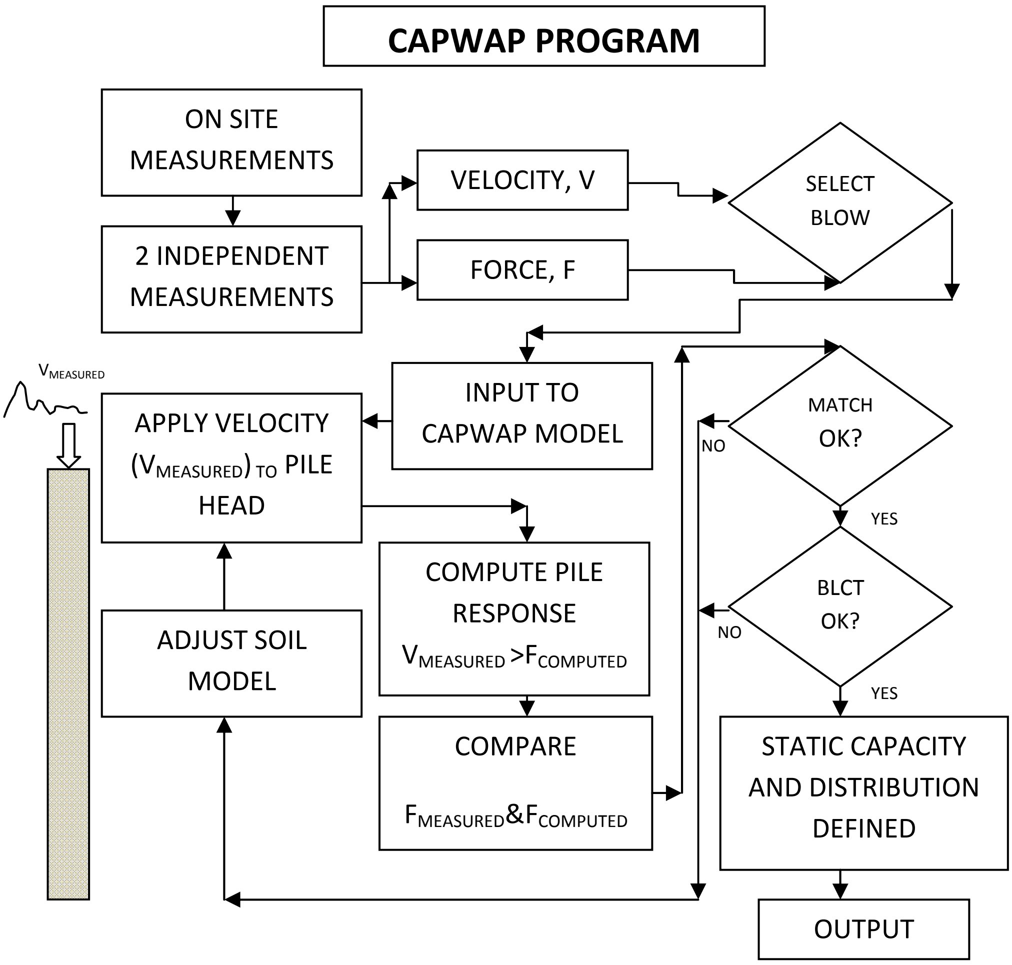
For accurate data interpretation pile material and cross section over all pile length has to be known.
Based on the measured force F(t) and velocity v(t) at the pile head during driving, pile capacity during driving and other information's could be obtained.

Sensors should be always above the waterline or ground level or special underwater sensors have to be used.

2. Determination of pile static load capacity with CAPWAP analysis

After the execution of field part of dynamic test, selected blow data (often one of the last blows) are analyzed in the computer program CAPWAP (Case Pile Wave Analysis Program), which is based on wave equation. Pile model and soil model, which is similar as is initiated with measured value of pile velocity ($v_{measured}(t)$). The result of CAPWAP analysis is calculated response ($F_{calculated}(t)$), which in the case of perfectly accurate pile and soil model data should be completely identical with the measured force curve.

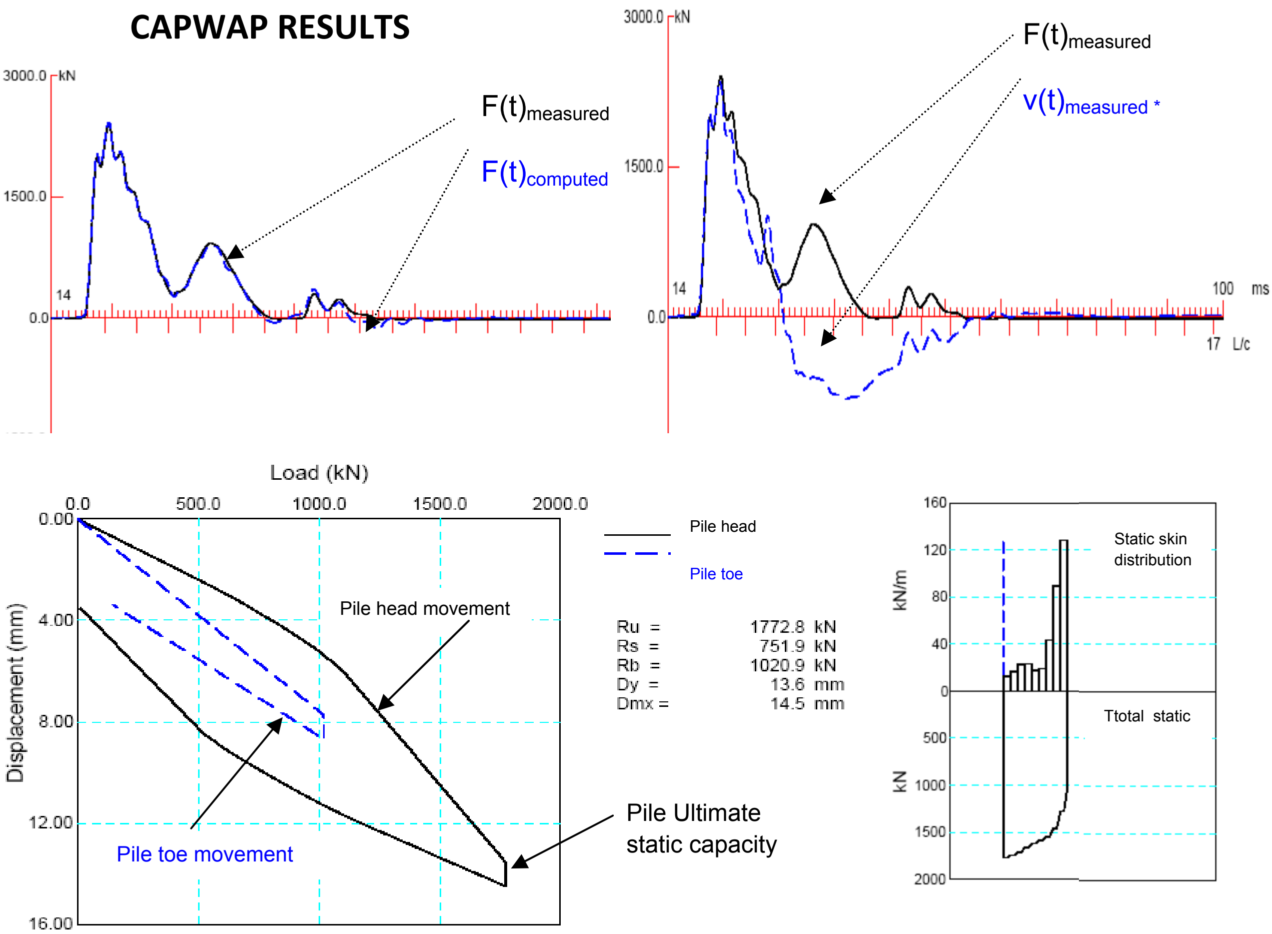




However, as we know in most cases a pile model but we don't know soil model, there is always difference between $F_{calculated}(t)$ and $F_{measured}(t)$. The difference in the first analysis is usually large, which means that our model at start is not correct. By repeatedly changing the model of the soil we are looking for the best approximation between the actual measured force ($F_{measured}$ (t)) and the calculated force ($F_{calculated}(t)$).

With satisfactory approximation of $F_{calculated}$ (t) and $F_{measured}(t)$, soil model properties (the static and dynamic) and also maximum activated static toe and skin capacity of tested pile is known. CAPWAP calculates these soil parameters based on the dynamic measurements.

With progressive loading of so defined pile/soil model, pile load-displacement graph is obtained. This graph is computer simulation of static load test defined with CAPWAP.



What is the basic difference between the dynamic load test (DLT) and static load test (SLT)?
If loading is slow (SLT) only static resistance R_{static} of soil is activated, while in fast loading (DLT) in addition to the static soil resistance also dynamic resistance $R_{dynamic}$ of the soil is activated:

$$R_{total} = R_{static} + R_{dynamic}$$

In order to separate static from the total resistance of the soil, CAPWAP analysis has to be used.

When ultimate or limit pile capacity can be defined using dynamic load test?
To activate limit or ultimate soil static resistance, used hammer has to transfer enough energy to produce permanent pile penetration or pile set more than 2.5mm for each blow. If pile set is smaller than 2.5 mm/blow only part of total and static soil resistance is activated.

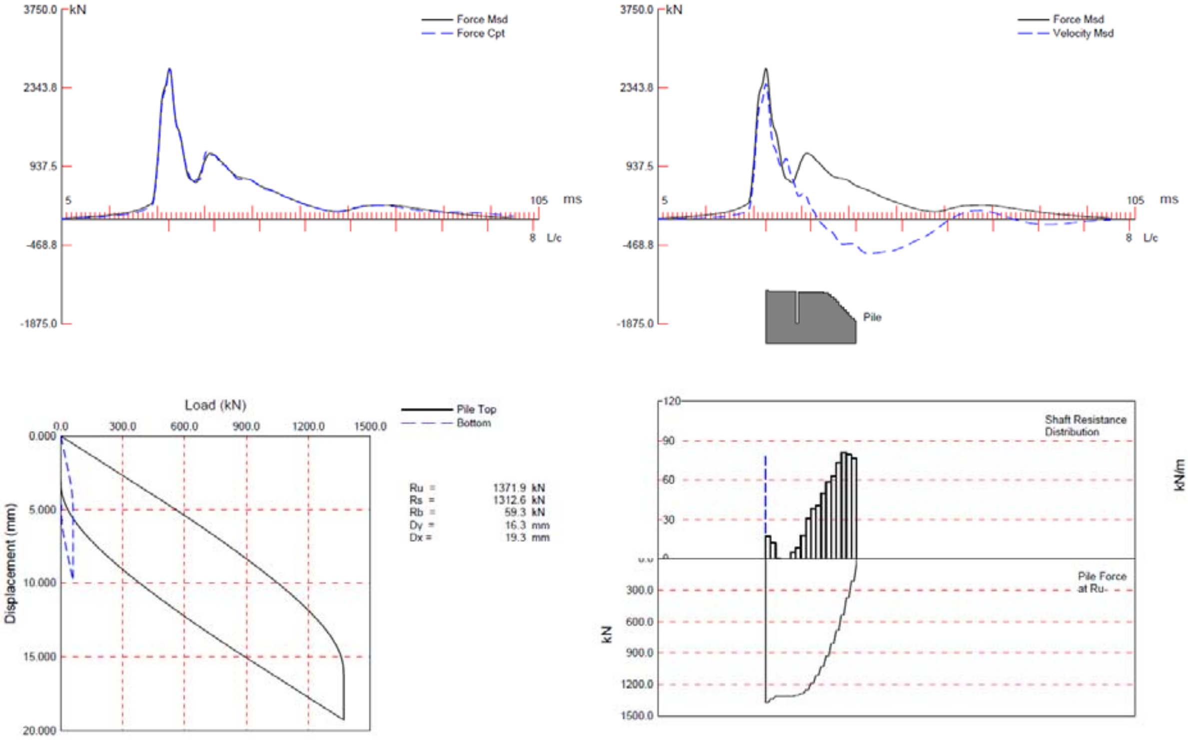
When static capacity defined with DLT (CAPWAP) is the approximately same as result of appropriate static load test (SLT)?

There are few important conditions:

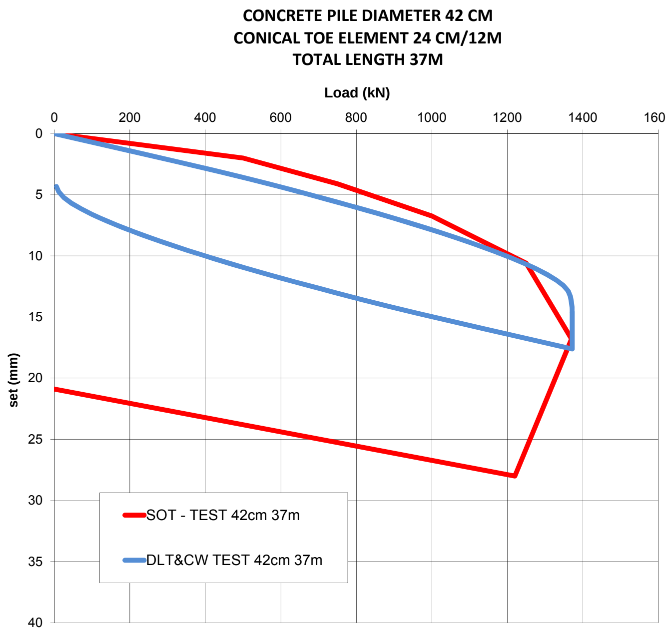
- Both tests should be performed in approximate the same time after pile installation
- Both tests should activated total or ultimate pile capacity
- Collected data during both tests have to be high quality
- DLT (CAPWAP) data interpretation has to be performed by qualified engineer with Foundation QA Certificate

Site testing example

Concrete hollow pile with diameter 45 cm and total length 37m.
Dynamic test was performed 45 days after end of driving (ED) and 12 days after static load test.



CAPWAP results with static load test graph simulation



Wireless sensors on pile

Static and Dynamic test correlation on the same site

Dynamic load test and Eurocode

Use of *Dynamic load test* is defined in chapter »(7.6.2.4) Compressive resistance from dynamic impact tests«

Eurocode requires that Dynamic load test has to be calibrated with previous Static load test on the same pile type of similar length and cross-section and in similar ground conditions, but not necessary on the same site.

Rck (ultimate characteristic bearing resistance) and Rcd (design bearing resistance) are calculated using partial factors ξ and γ_t,

For static load test

$$R_{c;k} = \mathrm{Min}\left\{\frac{(R_{c;m})_{mean}}{\xi_1};\frac{(R_{c;m})_{min}}{\xi_2}\right\}$$

For dynamic load

$$R_{c;k} = \mathrm{Min}\left\{\frac{(R_{c;m})_{mean}}{\xi_5};\frac{(R_{c;m})_{min}}{\xi_6}\right\}$$

$$R_{c;d} = R_{c;k}/\gamma_t$$

Correlation factors for Static load tests			**Correlation factors for Dynamic load test + CAPWAP**		
n(SLT)	ξ1 (m) on mean	ξ2 (s) on minimum	n(DLT)	ξ5 - on mean	ξ6 - on minimum
1	1,4	1,4	2	1,36	1,28
2	1,3	1,2	5	1,28	1,15
3	1,2	1,05	10	1,23	1,11
4	1,1	1	15	1,21	1,06
5	1	1	20	1,19	1,06

Where ξ1 , ξ2 , ξ5 and ξ6 are correlation factors related to the number of piles tested (n) and are applied to the mean $(Rc;m)_{mean}$ and the lowest $(Rc;m)_{min}$ value. Factor γ_t=1.1.

Example below shows, that higher design bearing capacity could be used, if two calibrated Dynamic load tests are performed instead of one Static load test. The same situation is also with two Static load tests and five Dynamic load tests.

Minimum SLT&DLT value Rc,min =			1490 kN	
Medium SLT&DLT value Rc,mean =			1580 kN	
Static load test		Dynamic load test		
No.test	Rcd(SLT)	No.test	Rcd(DLT)	DLT/SLT
1	968	2	1056	109%
2	1105	5	1127	102%
3	1197	10	1165	97%
4	1306	15	1309	100%
5	1355	20	1328	98%

If we know common practice, where a lot of Static load tests are performed just to check design loads and not to reach pile ultimate capacity, than advantage to use Dynamic load test is even higher.

Dynamic tests on non-driven piles, with very high capacities are common. For such tests free fall hammers with weight up to 50 tons were constructed in USA and Asia.

For successive DLT on non-driven pile at least three blows with high enough energy have to be performed.

Dynamic load tests are even more economical for piles with high capacity.

Dynamic Load Test on non-driven piles with 4 ton and 11 ton free fall hammer

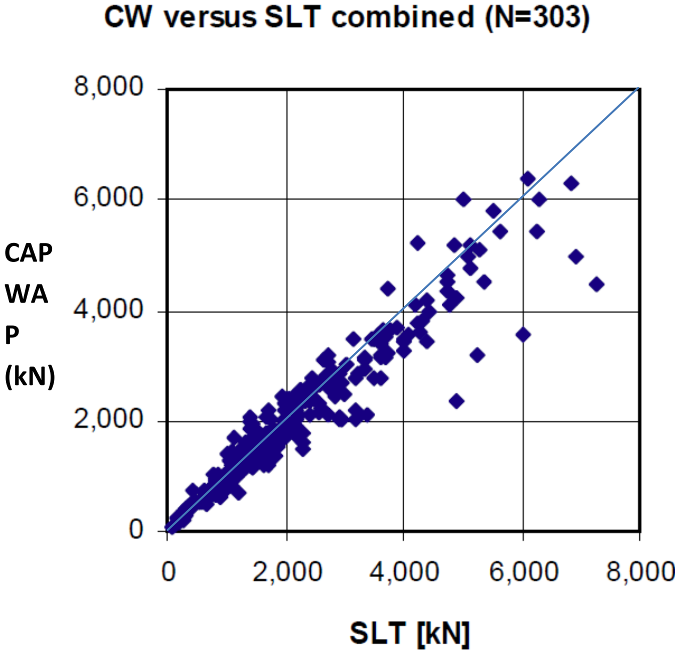
Correlation of Dynamic Load test & CAPWAP with Static Load tests

Differences between CAPWAP and SLT results are generally well within the range of SLT failure loads by different evaluation methods, and are comparable to the statistics of different static tests on the same piles. For the 303 cases in the combined database, the average CAPWAP/SLT ratio was 0.98 with coefficient of variation COV of 0.169. Since the average CAPWAP to SLT ratio is less than 1, and the often used Davisson evaluation is less than the average failure definition, CAPWAP is statistically generally conservative (on the safe side).

Less than 9% of the cases result in a ratio of CAPWAP to the maximum applied static load exceeding a ratio of 110%. Thus, CAPWAP is usually a conservative result compared to the reserve strength of the pile.

Accuracy of prediction by CAPWAP of long-term service load is improved by requiring dynamic test at least 6 days after installation to allow soil strength to stabilize with time.

CORRELATION OF CAPWAP WITH STATIC LOAD TESTS, Garland Likins and Frank Rausche, SW2004



Conclusions

The method and procedure of measurement is standardized by the standard ASTM D4945-89 and defined and in the recommendation of the EU7.

Dynamic Load Testing is a fast, reliable and cost effective method of assessing foundation bearing capacity. Dynamic Load Testing is performed on driven piles, drilled shafts and other cast in place foundations, and usually conducts several tests in one single day.
In addition to bearing capacity, Dynamic Load Testing gives information on resistance distribution (shaft resistance and end bearing) and evaluates the shape and integrity of the foundation element.

Advantages of dynamic load test

- Quick and less expensive
- More piles can be tested
- Construction quality control tool of:
  - hammer performance
  - pile stresses
  - pile damages….
- With free fall weights also non driven piles could be tested
- Very good correlation with Static Load test

Disadvantages of dynamic load test

- Static capacity is interpreted and not directly measured
- Requires expert knowledge for correct analysis - CAPWAP analyses shall be performed by an engineer who has achieved Advanced Level or better on the Foundation QA Examination for Providers of PDA Testing Services.

Today Pile Dynamic test is part of UK, German, USA, China, Thailand, Australia, Scandinavia, Canada, Mexico, Brazil, Argentina and Euro code regulations.