When to Apply Dynamic Load Testing and Statnamic Testing

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ABSTRACT: Pile capacity testing by high strain dynamic loading methods is widely applied because of its economy and efficiency compared to static load testing methods (SLT). Frequently applied dynamic loading methods are dynamic load testing (DLT) and statnamic testing (STN). The paper will deal with the very often raised question in practice: When to apply DLT and STN when pile type and soil conditions are known. Special attention is given to DLT on cast in situ piles, and complicating factors like limited knowledge of concrete material properties and pile shape. The suitability of DLT and STN is discussed for cast in situ piles and driven precast piles by the evaluation of the accuracy, reliability, economy, mobilization of capacity and the chance on pile damage.

Introduction

Pile capacity testing by high strain dynamic loading methods is widely applied because of its economy and efficiency compared to static load testing methods (SLT). The most popular dynamic loading methods are dynamic load testing (DLT) by an impact hammer and statnamic testing (STN) by launching a reaction mass from the pile head. DLT introduces a short duration shock pulse into the pile. STN generates a relative long duration push load onto the pile head. Extensive descriptions of load testing methods and comparisons are published by Holeyman (1992) and Karkee et al (1997). However these papers do not deal with the very often raised question from practice: When to apply DLT and STN when pile type and soil conditions are known. The answer to this question will be treated in the next paragraphs.

Fig. 1 statnamic test on a cast in situ pile

Special attention is given to DLT on cast in situ piles, because the calculation of the pile load is based on signals from strain transducers mounted on the pile shaft. So for DLT the pile load calculation depends strongly on pile material and cross section properties and factors complicating the analysis like limited knowledge of concrete material properties and pile shape are discussed.

Finally the suitability of both DLT and STN will be evaluated by taking into account the following points:

- accuracy of the load measurements
- reliability
- economy
- mobilization of capacity
- chance on pile damage

The application of DLT and STN on cast in situ piles

Fig. 2. Dynamic load test on cast in situ pile

For cast in situ piles both DLT and STN are performed a certain period after pile production, to allow the piles to reach the required compressive strength to withstand the test loads. For DLT strain and acceleration transducers are mounted on the pile shaft near the pile head. The load displacement behavior is calculated by signal matching. For STN the load displacement behavior is calculated in most cases by the Unloading Point Method (UPM), however signal matching techniques are also applied.

Fig. 3. Statnamic piston with built in load cell placed on a cast in situ pile

Fig. 4. Strain transducer mounted on the shaft of a cast in situ pile

- *Accuracy in load measurement for STN*

With STN the load is accurately measured by a calibrated load cell placed on the pile head. The measured load is not dependent on the pile properties. The load measurement error is less than 0.1% of the maximum range of the load cell.

- *Material properties and accuracy in load measurement for DLT*

With dynamic load testing strain transducers are mounted on the shaft near the pile head. The load (F) on the pile head is calculated by multiplying the measured strain (ε) with the modulus of elasticity (E) of the concrete and the pile cross section (A).

$F = E.A.\varepsilon$ (1)

The accurate determination of the properties E and A for bored piles is difficult in many cases.

To calculate the force from the measured strain in a pile during DLT we need to know the cross section and the modulus of elasticity of the concrete at the measuring level. For piles with homogeneous material the stress wave velocity (c) is used to calculate the E-modulus with

$E = c^2.\,\rho$ (2)

$c = 2L/T$ (3)

Knowing or estimating the stress wave velocity c we can calculate the pile load at the measuring level with the formula

$F = c^2.\rho.A.$ (4)

So the derived stress wave velocity has a strong influence on the value of the load measured in the pile. An error in the measured load will result in an error for the pile capacity prediction.

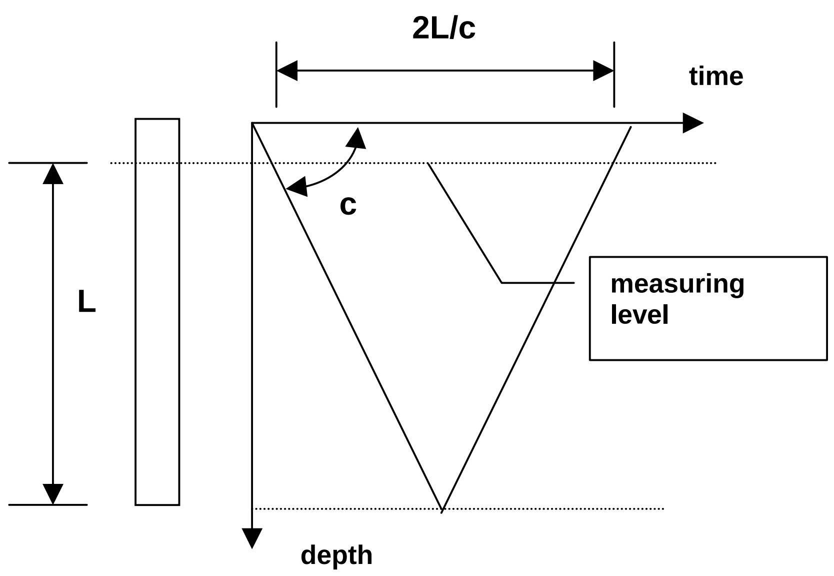

Fig.5 Calculation of stress wave velocity c from toe reflection

The stress wave velocity is calculated from the time (T) it takes for a stress wave to travel over the pile length (L) from the pile head to the pile toe and back to the pile head (Fig. 5). For this method it is required that the reflection coming from the pile toe is clearly visible in the signals. In Fig. 6 the force and velocity times impedance signals of two dynamic load test are presented. The first case shows a clear toe reflection and the stress wave velocity can be calculated accurately. If the toe reflection is not visible one has to estimate the toe reflection time. However an error in the estimated toe reflection time (T) and stress wave velocity (c) will result in a considerable error in the calculation of the E-modulus. For example a

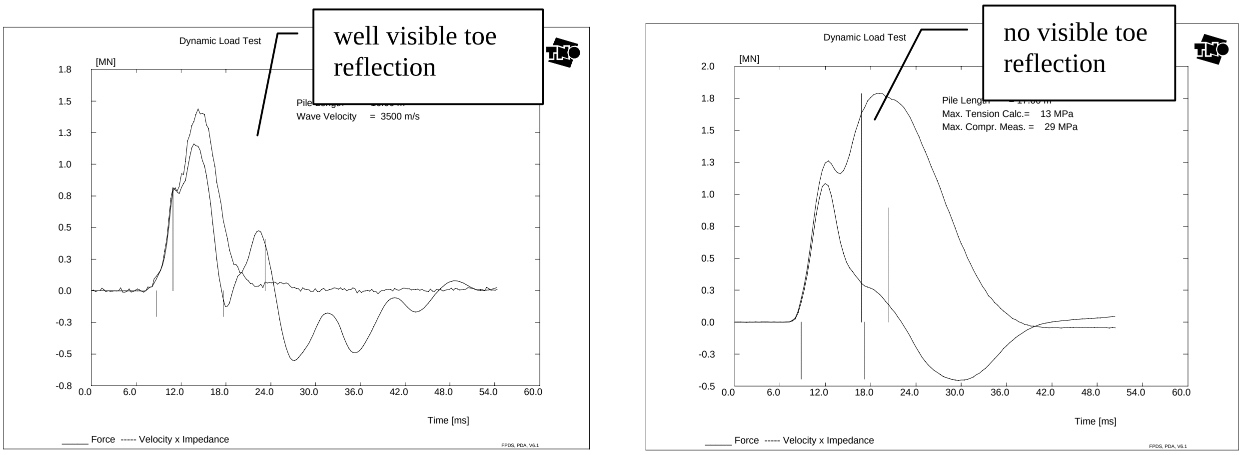

Fig. 6 Well visible and no visible toe reflection.

5% error in the stress wave velocity will result in a 10% error for the E-modulus and corresponding load in the pile. Another option in this case is to rely on an estimate for the E-modulus from the pile material properties.

Making an estimate on the E-modulus is difficult because it is not a constant value but depends on the age and the quality of the concrete (Franklin, 1971)(Fig. 7), the loading rate (Sparks et all, 1973), and even the temperature of the concrete (Abbasi 1990). For example, for static load testing the modulus of elasticity for concrete is in the range of 28 GPa to 32 GPa while for dynamic load testing it is in the range of 32 GPa to 52 GPa

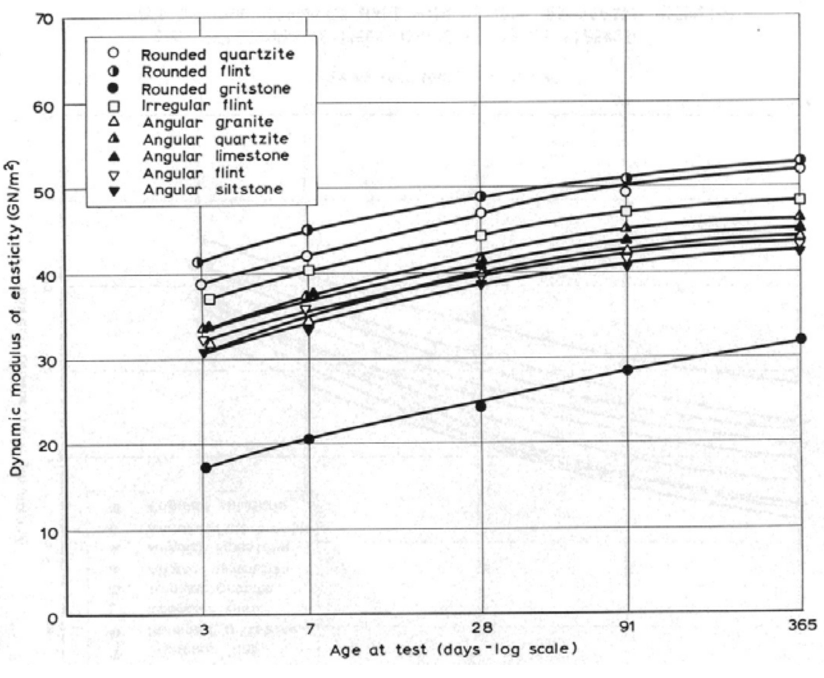

Fig. 7 Relations between dynamic modulus of elasticity and age for concretes made with various aggregates

Another complicating factor in determing the stress wave velocity c for cast in situ piles is the fact that the concrete is not homogeneous. The concrete quality will vary over the cross section and over the pile axis. The concrete in contact with the soil will be of lesser quality than the concrete in the center of the pile and the shaft area that has been in contact with the soil might be the location where the strain transducers are mounted. The concrete quality difference over the pile length is caused by the pouring procedure and the difference in concrete pressure during construction. The quality of the concrete near the toe will in general be better than the quality of the concrete near the pile head. This also means that the stress wave velocity will vary with the pile length. So the stress wave velocity calculated with c=2L/T is a mean value for the whole pile. The modulus of elasticity calculated from it represents a mean value for the pile and there can be a considerable difference with the modulus of elasticity at measuring level.

- *Influence of pile cross section variations on DLT capacity prediction*

Fig 8. Cast in situ pile with bulb

To predict capacity from DLT results, signal matching techniques are the most frequent applied methods, (TNOWAVE, CAPWAP™). Based on a wave equation computer program calculated signals are matched with measured signals by adjusting the computer soil model and pile model in an iterative way. When signals match it is assumed that the computer soil model represents the real soil behavior and the static pile capacity is calculated from it.

Pile discontinuities like necking, bulbs, and material changes introduce stress wave reflections which can influence the calculated signals strongly. Reflections from bulbs yield an almost similar wave equation result as a local stiff soil layer and a necking similarly results as a local soft layer. When pile discontinuities are not properly taken into account, either a proper match cannot be obtained or the capacity prediction will not be reliable. Soil properties can be confused with pile discontinuities.

- *Reliability for testing on cast in situ piles*

Because of the many unknowns that have to be solved to perform a proper DLT signal matching analysis on cast in situ piles, there is considerable chance of errors in pile capacity predictions.

The load measurement for STN is similar as for static load testing and unknown pile properties of cast in situ piles will not influence the load measurement results. During STN the load duration is long enough that the all pile parts move in the same velocity range. Under these conditions the pile can be considered to act as one mass with a pile rigidity behavior similar to static load testing (Middendorp 1995) For this reason pile behavior during STN is closer to static load testing than DLT.

- *Economy*

For DLT on cast in situ piles a drop hammer with a guiding system has to be mobilized. The required ram mass is as rule of thumb 2% of the maximum load that has to be applied. A crane is required to move the drop hammer over the building site. The pile head has to be prepared to prevent damage from impact loading. An epoxy or grout cement is used to smooth the pile head surface to prevent stress concentrations during impact loading. The location of the transducers has to be at least 2 pile diameters from the pile head. When the pile head is loacated at ground level this requires an extension of the pile head for a similar length or the excavation of the pile head. For small capacity piles multiple piles can be tested in one day. For loads above 10MN the testing rate is normally in the range of 2 piles per day.

For STN a loading device with a reaction mass catching system has to be mobilized. The required reaction mass is as rule of thumb 5% of the maximum load that has to be applied. A crane or a crawler system is required to move the STN device over the building site. For loads up to 4MN a STN device with a hydraulic catch mechanism can be applied. For higher loads STN requires a gravel catch system. Testing can take between 0.5 and 2 days per pile depending on the pile capacity. However for piles with a capacity less than 4 MN, a loading device with hydraulic catch mechanism can be applied and the number of piles tested in one day are in the same range as with DLT. STN can be even more efficient when the loading device and hydraulic catch mechanism are placed on crawlers. An epoxy or grout cement is used to smoothen the pile head surface to prevent stress concentrations during push loading.

Table 1. Preferences for DLT or STN with respect to economy for cast in situ piles

Cast in situ piles			
Capacity	DLT with drop hammer	STN device with gravel catch mechanism	STN device with hydraulic catch mechanism
Up to 4 MN	****	***	****
4 MN to 10MN	****	***	not applicable
10MN to 30MN	****	***	not applicable
more than 30MN	****	***	not applicable

***** = economic
* = not economic

- *Chance of pile damage*

With DLT the load on the pile head is introduced by an impacting ram. When the ram is not properly guided and hits the pile in an eccentric way, bending stresses will occur and result in excessive compression and/or tension stresses which can damage the pile.
Most cast in situ piles need considerably more displacement to mobilize the ultimate capacity than driven piles. This softer response will easily generate tension waves. Cast in situ piles are not designed to withstand high tension stresses. As soon as allowable tension stress levels are reached the impact energy has to be reduced to prevent pile damage. As a result, DLT has to be stopped at a stage where full capacity has not yet been mobilized.

With STN the duration of the loading is long enough to keep the pile is under constant compression and tension stresses will not occur. To prevent bending stresses the piston of the statnamic device is installed exactly on or near the center of the pile head cross section. The launching of the reaction mass, and the resulting push load start from the center of the pile.

Fig 9. Dynamic load test on a precast pile

The application of DLT and STN on precast driven piles

For precast driven piles both DLT and STN are performed after a setup period after pile installation. This allows the soil to recover from driving induced disturbances like pore water pressure. In most cases the soil will regain strength during the setup period.

For DLT strain and acceleration transducers are mounted on the pile shaft near the pile head. The load displacement behavior is calculated by signal matching.

For STN the load displacement behavior is calculated in most cases by the Unloading Point Method, however signal matching techniques are also applied.

- *Accuracy*

With DLT on precast driven piles, the load in pile is measured by strain transducers mounted on the pile shaft. Precast piles are considered to be of homogenous material and with the method described in section 2.2 and based on the determination of the stress wave the E-modulus can be determined accurately. The toe reflection will be visible at several stages of driving and the stress wave velocity can be determined easily. Only when the pile head is heavily reinforced will the E-modulus at the pile head be different from the E-modulus calculated by the stress wave velocity.

With STN the load is accurately measured by a calibrated load cell placed on the pile head. The measured load is not dependent on the pile properties. The load measurement error is less than 0.1% of the maximum range of the load cell.

- *Reliability*

The capacity of driven piles is mobilized at relative small displacements.

Both DLT and STN are performed after a set up period. For DLT the pile load displacement behavior is calculated by a signal matching technique (CAPWAP™, TNOWAVE) in most cases.

For STN the pile load displacement behavior is determined by a direct method, the Unloading Point Method (UPM) and in some cases by signal matching.

- *Economy*

DLT has the advantage that the pile driving hammer used for pile installation can also be used for redriving the piles after a set-up period. However, when the pile driving hammer has to be used for constant production, an additional pile driving hammer or drop hammer has to be mobilized. When the mobilization of the full pile capacity is requested, the production hammer might not be sufficient to mobilize pile capacity after the set up period and an additional heavier hammer has to be mobilized.

For STN the same economical conditions are applicable as mentioned in paragraph 2.5.

Table 1. Preferences for DLT or STN with respect to economy for driven piles

Driven piles			
Capacity	DLT with pile driving hammer	STN device with gravel catch mechanism	STN device with hydraulic catch mechanism
Up to 4 MN	*****	***	*****
4 MN to 30 MN	*****	***	not applicable
more than 30MN	*****	***	not applicable

***** = economic
* = not economic

- *Mobilization of capacity*

Set up phenomena can increase the soil resistance considerably. The pile driving hammer used for pile installation might not be able to mobilize the full pile capacity in such a case.
Another reason that capacity can not be mobilized with DLT is that the load cannot be increased because compression or tension stresses becoming too high.

To mobilize the pile capacity a STN device will be sent to the building site with at least a corresponding loading capacity. Only when the piles are overdesigned will the full bearing capacity not be mobilized.

Table . Preferences with respect to set up phenomena and mobilization of capacity

Driven piles			
Soil set up	DLT	STN	Preferred method
low to medium	*****	*****	DLT/STN
medium to high	**	*****	STN

***** = capacity fully mobilized
* = capacity not mobilized

- *Chance of pile damage*

For DLT the are some cases with a chance of pile damage. In the case of low friction and a soft toe response tension waves will be generated during DLT. When the maximum allowable tension stresses are reached the load on the pile cannot be increased because this will generate higher tension stresses and the pile will experience damage. In the case of a pile with a hard toe response, for example pile toe on rock, the compressive stresses at the pile toe can theoretically be two times higher than the maximum compression stress at the pile head. This is caused by the superposition of compression stress waves at the pile toe. So, if during DLT the compression stresses at the pile head are higher than half the compressive strength of the pile material, collapse of the pile material at the pile toe will occur. In this case piles can only be tested up to half the compressive strength of the pile material, which may not correspond with the capacity of the pile.

For STN the pile is kept under constant compression and tension waves are suppressed. Superposition of compression waves at the pile will not occur. As with SLT piles can be tested near to the compressive strength of the shaft.

Preferences with respect to soil resistance and pile material stresses

Driven piles						
Soil resistance		Tension stresses		Compression stresses		
shaft friction	toe resistance	DLT	STN	DLT	STN	Preferred method
low to medium	soft	xxxxx	x	***	***	STN
medium to stiff	soft	xxxx	x	***	***	STN
low to medium	medium	xx	x	***	***	DLT/STN
medium to stiff	medium	xxx	x	***	***	DLT/STN
low to medium	high	xxx	x	*****	***	DLT/STN
medium to stiff	high	xxxxx	x	*****	***	STN

xxxxx - high tension stresses ***** - medium compression stresses
x - no tension stresses * - high compression stresses

Conclusions

For bored concrete piles, auger piles and caissons the dynamic load testing method is less suitable and statnamic load testing is the preferred method. The most important reasons for the preference of statnamic load testing in the case of cast in situ piles are:

1. **Accuracy in load measurement**
   STN is not dependent on pile material and cross section properties
2. **No influence of cross sectional variations**STN results are not influenced by cross sectional variations over the pile length
3. **No tension during compressive testing**
   STN long duration loading will keep pile under constant compressive pressure
4. **Concentric loading**
   Easy placement of STN loading device in center of the pile
5. **Pile and soil response closer to static**
   With STN the pile moves as one unit, similar to static load tests.
   Stress wave phenomena can be neglected resulting in a simple method of analysis

For driven piles both DLT and STN methods can be applied reliably and each has its advantages and disadvantages. A big economic advantage for DLT can be the use of the production rig for testing. A big advantage for STN is the fact that maximum available energy can be used to mobilize capacity and that that testing does not have to be stopped when tensional stresses become too high like with DLT.

References

Static and Dynamic Tests for Evaluation of the Vertical Load Bearing Capacity of Piles.
Madan B. Karkee, Takashi Horiguchi, Hideaki Kishida, pp199-213

Holeyman, A.E., 1992. Keynote Lecture: Technology of Pile Dynamic Testing. Proceedings of the Fourth International Conference on the Application of Stress-wave Theory to Piles, The Hague, F.B.J. Barends, Editor, A.A. Balkema Publishers, pp195-215.

Abbasi, A.F., Al-Tayyib,1990. Effect of hot weather on pulse velocity and modulus of elasticity of concrete. Materials and Structures, 1990, 23, pp334-340

Franklin, R.E., King, T.M.J. 1971, Relations between compressive and indirect-tensile strength of concrete, Road Research Laboratory, RRL Report LR 412
Sparks, P.R., Menzies, J.B., 1973. The effect of rate of loading upon the static and fatique strength of plain concrete in compression. Magazine of Concrete Research, Vol 25/ 1973, No. 83, pp 73-80.