PILE MONITORING, TESTING, AND DATA PROCESSING:

NEW DEVELOPMENTS AND REMAINING ISSUES

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After scoping out the objectives of this general report, the report reviews the three assigned mains themes addressed by the papers submitted to the session: pile monitoring, testing, and data processing. It focuses on later developments and on issues requiring clarification, thereby identifying topics for potential discussion. Pile Monitoring does not bring much novelty, except for the integration of IT on construction sites. As far as testing, new developments focus on internal pile loading procedures while more confidence is being gained with dynamic and kinematic load tests. Significant advances are noted in the interpretation of data, where variability of results are coped with, loading rate effects are being better addressed, and more routine use of Finite element analyses are observed. Several many older problems remain while new issues emerge from more recent technologies and approaches.

INTRODUCTION

In its mission statement letter, the Technical Advisory Committee asked that the general report paid special attention to "what's new" and "questions to be solved". This request could be motivated by efficiency, such that the proud owner of the proceedings to this DFI conference would quickly know how to allocate his precious reading time. The report will thus cover the three mains themes of this session: Monitoring, Testing, and Data Processing, in accordance with that request.

Before embarking on a review of what the papers allocated to this session offer, it might worthwhile to reflect on novelty: What is new? What is new to one professional may already be know to another. What is new to an area of practice a may be "old hat" to another. One would therefore first agree on space and time scales to qualify the notion of "novelty".

As this is an international conference, are can easily agree that the world is the proper space scale. For time scale, a fraction of the lifetime of a technological innovation in the construction industry is suggested, say 20%. If the Franki Pile is taken as an aged reference product with a lifetime of 100 years, a 20 year look-back period should be the cut-off line. If a shorter period was adopted, this novelty focused report could be finished within a disappointing order.

In order to make a link between the state of the art and the presented papers, a more flexible perspective will be adopted, and allowance will be made to discuss changes in the daily practice resulting from past novelties. One could thus consider a novelty the fact that some of our behaviors have changed as a result of increased confidence towards a monitoring, testing or data processing system, which was treated earlier with reluctance because of too novel a character. For ease of identification, the liberty has been taken to list within and at the end of the present report references to this conference session in italics.

Finally, one should not solely focus on what's new (or what is presented as new), and be subjugated by the gimmicks and the flashy announcements: there still is a need for deep and sound understanding of the engineering principles behind some advanced systems and for keeping a cool head under the driving forces of the testing market.

PILE INSTALLATION MONITORING

Summary statement

Systems are now offered by many foundation specialty contractors to record parameters relevant to the assessment of the quality of the installed product. Examples of such systems are described by Bustamante (2003) for bored piles, Bottiau & Massarsch (1991) for auger cast piles, by Goble et al (1975) for driven piles.

Emerging: Real-time Information Technology (IT) on construction sites.

Scott (2006) presents the implementation of a wireless site data collection system (SHERPA) on piling sites, its benefits, and the problems it still has to overcome. Based on the fair statement that the distributed nature of the data contributing towards the quality of piles is at the source of many non-conformances, one should easily understand the benefits of digital data entry units distributed on a piling site funneling into an integrated central data base. A first system relying on stylus activated tablet computers fitted with a wireless network card presented problems with battery life and network coverage. A second system based on GPRS protocol, allowing data entry via mobile phones or PDA, avoids some of the maintenance hassles, but has to cope with limited network speed.

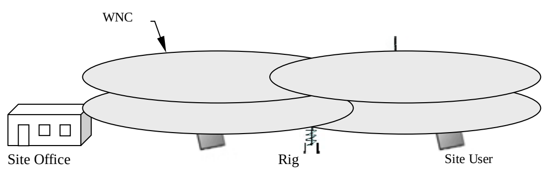

Fig. 1 – Piling site Wireless Network system *(Scott, 2006)*

Benefits of the networked piling site are identified as follows by the author: (1) reduction of non-conformances by 30%, leading to a reduction of remedial costs from an industry typical value of 1.9% to 0.25% of contract value; (2) promotion of a more autonomous site workforce while enforcing well established procedures, (3) establishment of a continuous time-based record, and (4) a more convivial and fluid reporting of delays. That latter aspect is a direct tool towards improvement of productivity.

Questions to be solved and perspectives: (a) relevance and completeness of monitored parameters, (b) validation of methods deriving shape and quality of pile from monitored parameters, (c) owner/engineer access to real-time information generated by specialty contractor, (d) integration of installation parameters with pre-installation information such as geotechnical model based on soil investigation and with post-installation information such as integrity tests, load tests, and monitoring results.

Other points of interest

One should note that no paper dealing with post-installation monitoring could be reviewed within the framework of Session 6. One borderline topic is pile capacity increase with time, or soil set-up: while monitoring implies passive recording of information without loading the pile, that capacity increase has been so far assessed on the basis of testing spread over the pile maturing period; sending thus that topic under the following section. It would be really worthwhile to develop a less cumbersome method of monitoring the increase of bearing capacity of a pile belonging to a built structure.

Another emerging trend is the monitoring of the pile vibratory installation process, emulating the benefits already accrued for the driven products with the Pile Driven Analyzer (PDA).

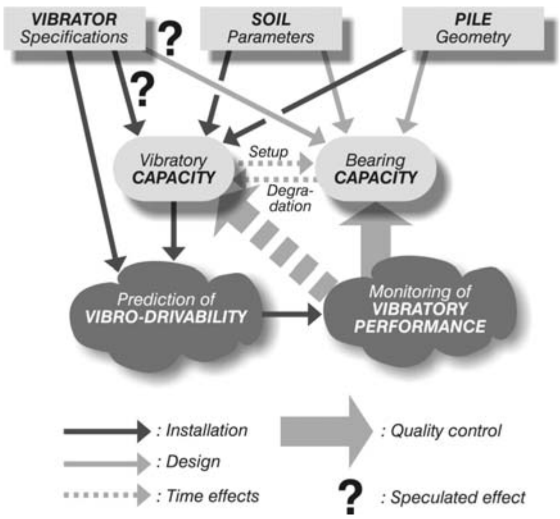

Fig. 2 – Monitoring of vibratory penetration (Holeyman et al, 2002)

PILE TESTING METHODS

Pile testing methods have been summarized on many occasions according to their common denominations, as in Table 1 (Holeyman, 1992). Two main classes can be distinguished within dynamic testing methods, based on the primary objective of the test: integrity or capacity, as summarized in Fig. 3.

One key and general issue still deserving interest is how to translate in the design rules the increased level of confidence in the quality of the piles in terms of increased allowance of performance.

Table 1. Typical Key Attributes of Different Types of Pile Tests

	Integrity Testing	**High-Strain Dynamic Testing**	**Kinetic Testing**	**Static Testing**
Mass of Hammer	0.5 - 5 kg	2,000 – 10,000 kg	2,000 – 5,000 kg	N/A
Pile Peak Strain	2 – 10 µstr	500 - 1,000 µstr	1,000 µstr	1,000 µstr
Pile Peak Velocity	10 - 40 mm/s	2,000 - 4,000 mm/s	500 mm/s	10^{-3} mm/s
Peak Force	2 – 20 kN	2,000 - 10,000 kN	2,000 - 10,000 kN	2,000 - 10,000 kN
Force Duration	0.2 – 2 ms	5 - 20 ms	50 - 200 ms	10^{7} ms
Pile Acceleration	50 g	500 g	0.5 - 1 g	10^{-14} g
Pile Displacement	0.01 mm	10 - 30 mm	50 mm	> 20 mm
Relative Wave Length $\Lambda=\lambda/2L$	0.02 – 0.1	1.0	10	10^{8}

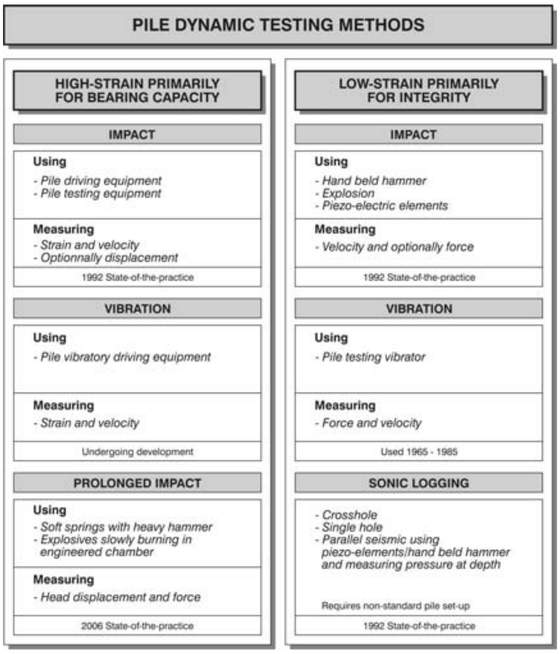

Fig. 3 – Pile dynamic testing methods

High-Strain and Capacity Testing

Piles are loaded under higher strains with a view to assess their load carrying behavior, under axial or transverse directions. Several loading techniques can be distinguished depending on the duration and location of the load: Static (Maintained Load), quasi-static (Constant Rate of Penetration), kinetic, and dynamic.

In general for dynamic testing, a shaper detail of the distribution of the shaft resistance versus depth (depth resolution) is gained by a sharp increase of the force pulse at the wave front and by a short length or duration of the original waveform. The sharpness of the wave relative to the pile characteristics can be used as a criterion to separate different types of "dynamic" pile tests.

Table 1 provides a summary of key attributes of several known pile test types. Of particular significance to this discussion is the relative wave length Λ, which represents the length of the force pulse in terms of the double length (2L) of the pile. It can be noted from Table 1 that integrity testing is typically characterized by a relative wave length of maximum 0.1, which provides for maximum depth resolution. The dynamic bearing capacity test is typically characterized by a relative wave length of 1, which still allows for depth resolution while providing high-strain testing.

Longer-duration impacts, such as generated by the Dynatest (Gonin et al., 1984) or the Statnamic® Test (Bermingham and Janes, 1989), are characterized by a relative wave length of 10 or higher and, therefore, do not allow for depth resolution. Although those tests resort to inertial actions on masses to generate their extended force pulse, the should be referred to as "kinetic tests", mainly because the inertial forces within the pile are small compared to the current force being applied and because the interpretation of these tests does not benefit from the wave equation framework. Fig. 4 provides a representation of the pile tests available in terms of relative wave length Λ and of strain

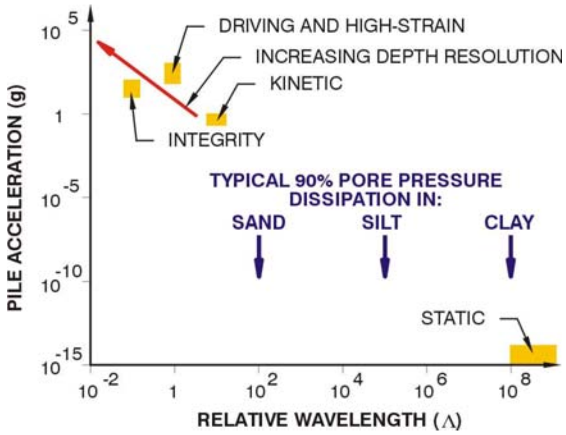

Fig. 4 – Sharpness and duration of force pulse for different pile tests

level. Fig. 4 also presents typical relative wave lengths required to reach 90% consolidation around a pile in sand, silt and clay. This diagram allows, in the writer's opinion, the separation between dynamic, kinetic, and static testing. Compared to static tests, one is faced with the difficulty in kinetic tests of sorting out the velocity dependency on the soil resistance, and in dynamic tests of resolving dynamic effects with, however, the advantage of depth resolution.

Low-Strain and Integrity Testing

Non-destructive integrity tests are routinely used in several (i.e. not all) parts of the world with a view to control the integrity of installed piles: sonic echo, impulse response, parallel seismic, gamma-gamma, and cross-hole sonic testing.

Recent developments worth noticing are the use of 3-D tomographic representations of cross-hole sonic logging profiles, and the more objective qualification of what constitutes an "anomaly". In that regard, the new French Norm (NF- P94-160-1) requests that the received wave energy be assessed on a comparative basis using on integration period covering the 10 first cycles of a reference signal.

Remaining difficulties and limitations associated with seismic and cross-hole sonic logging are: planning requirement and interference with construction process, control of casing positions, quality of mechanical contact between tube and concrete, defect must significantly separate receiver from source (i.e., defect boundary must ideally intercept casing to be detected), and still qualitative more than quantitative interpretation.

STATIC AND QUASI-STATIC LOADING TESTS

Many parts of the world have issued their standard methods, as reviewed for example by De Cock et al. (2003). This indicates that the procedures are mature, as codes are not deemed to reveal innovations. The opposite might reveal an effective lobby or an abusive dominance. The following will therefore focus on the emerging trends.

Emerging use of pile internal loading device (ILD).

Introduced in 1989 by J. Osterberg, the so-called "O-Cell®" represents one of the major breakthrough in static pile testing of the 20^{th} century. The principle is recalled on Fig. 5, showing how an inflating device embedded within the pile can mobilize soil resistances of two parts of the pile against each other. ILDs had been tried in the past by a few pioneers, but not to the readily available packaged service now offered by the operators of the O-Cell. Capacities in the range of 120 MN have been tried, leading to typical results shown on Fig. 6.

Questions to be solved and perspectives: (a) conversion of measured uplift friction into sought downward friction, (b) correction of measured base resistance to account for modified stress field around failure bulb, and (c) ILD for tubular piles.

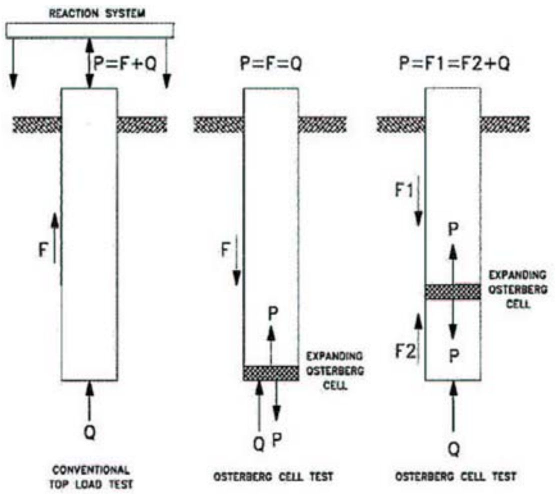

Fig. 5 – Comparison of Static Load tests *(England, 2006)*

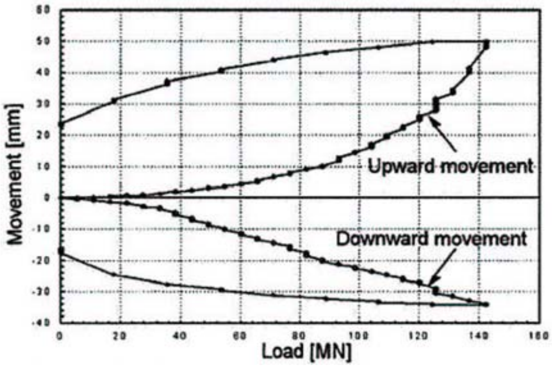

Fig. 6 - High Capacity Load-Movement Curves *(England, 2006)*

Emerging wider availability of retrievable extensometers for instrumented pile tests

Described in 1991 by Bustamante & Doix, the so-called retrievable extensometers have enabled the French LCPC to collect data regarding the progressive mobilization of soil resistance along several shaft segments. As shown on Fig.7, strains are measured over several successive segments of the pile shaft, separated by deployable anchors. Results provided by these "segmental" strains are typically represented for different load steps as profiles of the axial load versus depth (Fig. 8). It is thanks to that technology that massive documentation has been accrued over decades in France, especially on bored piles. The results of such insight has been consolidated into design rules widely used in Europe (DTU 13.2, Fascicule 62, etc.), and referred to in EuroCode 7.

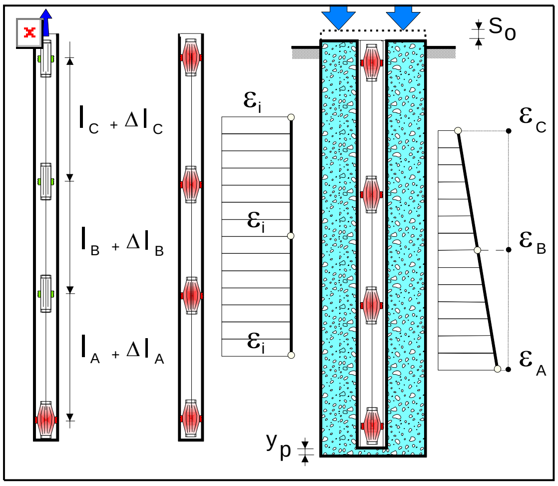

Fig. 7 – LCPC Extensometer Principle

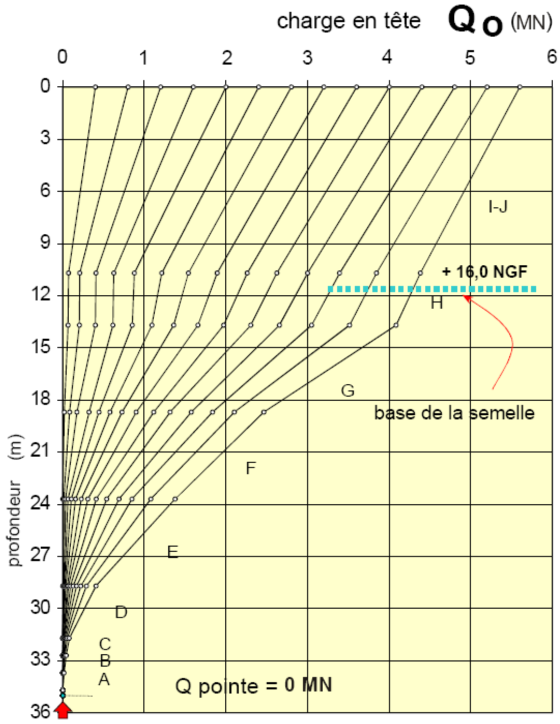

Fig. 8 – Typical results from LCPC extensometer instrumented pile test (Bustamante, 2005)

The technology is now more widely available as standard borehole extensometers have been adapted to fit access tubes concreted with the pile reinforcing cage. Displacement transducers record base lengths variations between anchor points using vibrating wire or Direct Current Differential transformers (DCDT). Great attention must be paid to the anchoring system as to achieve a reliable measuring base.

These extensometers were for example applied by the BBRI to conduct a 72-pile testing program on displacement screw piles in the 1999-2003 period, as documented in Holeyman (2001) and Huybrechts and Maertens (2003). Fig. 9 shows the extensometers train being inserted into one of those test piles. The same approach has been recently used in Malaysia, as described by *Hanifah et al. (2006)* and *Krishnana et al. (2006)*. These authors label the strains as "global" and qualify the approach as "novel".

Fig.9 – Insertion of segmental extensometers in test pile (Huybrechts, 2001)

Typical accuracy is nominally 10 to 20 μstr, (approximately 0.3 to 0.6 MPa stress in concrete) to but actual accuracy will depend on quality of anchor points and temperature variations. Measured strains are converted into axial force by multiplying by the section modulus of the pile, which requires a reliable knowledge of the relevant material section and Young's modulus, which might only be straightforward for a driven steel pile.

For other pile types, a calibration factor has to be obtained using correlation of the strains measured over the upper section of the pile, ideally unrestrained, with back-up readings of a load cell placed atop the loaded pile. Cast-in-place concrete piles entail however additional uncertainties with respect to section and modulus variations. Gamma-gamma density readings of the concrete cast in bored piles have been measured to increase with depth, as shown on Fig.10. Residual loads may also have to be taken into account to get to the "true" mobilization curves, as discussed by *Wilkenson and Butterworth (2006)*.

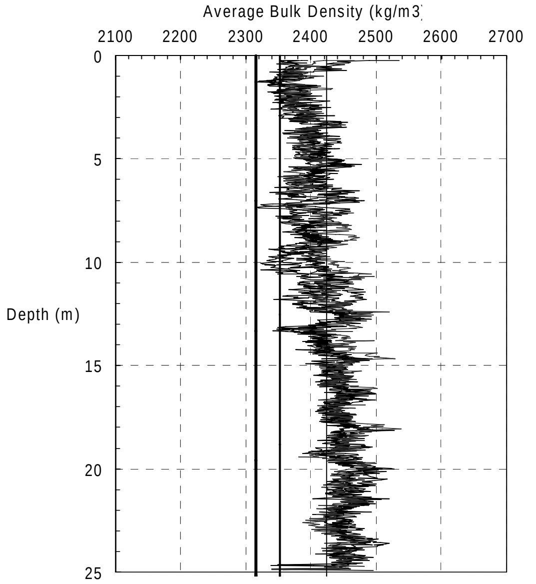

Fig. 10 - Gamma-gamma density profiles from 5 access tubes within 1.5 m diameter bored pile (Courtesy of EarthSpectives, 2006)

Fellenius (2001) has suggested a popular method to analyze measured strains (segmental or local) as a function of the applied load. *Kai et al. (2006)* present extensive data from in situ and laboratory tests that emphasize the variation of concrete modulus with concrete grade, pile type, and strain, clearly a recommendation that a site-specific calibration be ascertained before converting strains into axial loads.

Questions to be solved and perspectives: (a) reliable conversion of local or segmental strains into axial forces, (b) correction of mobilized resistance to account for "residual" stresses, and (c) number of strain profiles to obtain reliable axial and bending strain, (d) development of retrievable extensometers for dynamic load tests, and (e) interpretation of local skin friction in geotechnical layers of contrasted resistance.

Emerging variety of methods to actuate kinetic loading

Described in 1984 by Gonin et al., kinematic loading has now found variety in its implementation. While the Statnamic® system has innovated a loading principle by launching a mass initially resting atop the pile (Fig. 11), other available systems (Dutch Pseudo-Static® or Japanese Rapid Loading System) have used the initial principle of dropping a mass on top of a pile via spring of medium stiffness to prolong the load.

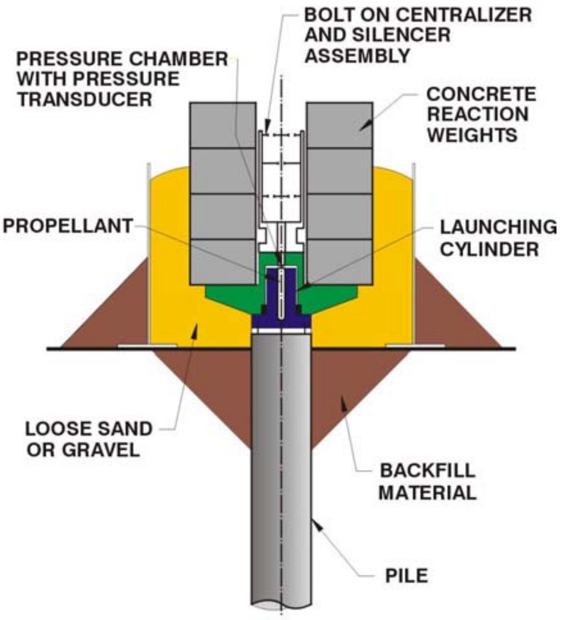

Fig. 11 – Original Statnamic Launching system (Bermingham & James, 1989)

Statnamic has been used in the horizontal direction, although the cost benefits relative to a static load test are less obvious than for vertical compression. Two contributions to this conference suggest that lateral dynamic testing can quickly provide useful information regarding pile behavior under earthquake triggered lateral loading. The system, developed by a Japanese research team (*Kitiyodom et al., (2006), Kojima et al., (2006)*) - used a horizontally traveling mass to hit tubular steel piles through a coil spring located 0.5 m above ground, shown on Fig. 12.

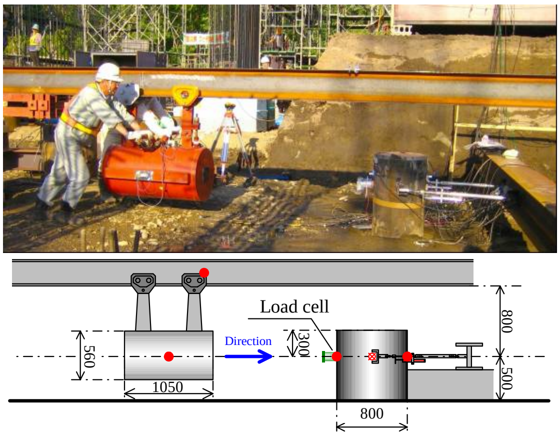

Fig. 12 – Manually actuated dynamic horizontal load test (*Kojima et al, 2006*)

The duration of the lateral impact is of the order of 40 ms. The results presented are quite preliminary and indicate that the inverse modeling used to derive the intrinsic lateral behavior parameters is not straightforward. The availability of static lateral load tests presented in a third paper by the same research team *(Tomisawa et al, 2006)* highlights the need for benchmarking the suggested "hybrid" model (beam element connected to lumped parameter soil models). The authors also stress the fundamentally non-linear lateral character of the lateral stiffness of the soil-pile interaction.

Questions to be solved and perspectives: (a) Differences in deformation pattern along the shaft and at the base between kinetic and static loading, (b) effects of pore-pressure generation and dissipation, (c) dependence of soil resistance on velocity, (d) reliable conversion of kinetic resistance to static resistance – see progress reported in Section on Data processing, (e) loss of time discrimination allowing depth related analysis, therefore, reliance on a single global measurement and (f) better availability of opto-level meter.

Emerging confidence in high-strain dynamic loading

Dynamic loading, pioneered by early wave-equation enthusiasts in the early 1980 with an attempt to replace static load testing, has had varied success, depending mainly on the local professional practice. It is widely accepted in the Americas and Asia, as well as in offshore piling projects, while it has been met with skepticism and reluctance in Europe, except in the Nordic countries.

When faced with the cost and time consuming perspective of a static load test, some reluctant engineers will still prefer no acceptance test at all to any dynamic load test. The same engineers will satisfy themselves with one single static load test on a site that contains hundreds of piles, even though they might (sub)consciously admit that the results will belong to a re-load event. That may specially occur if the contractor is nervous that the virgin pile test might not pass some very stringent settlement criteria. Is this a reasonable attitude?

Besides interpretation, the logistics of carrying a dynamic load test are still hampering development of acceptance dynamic tests on a routine basis, specially when a pile head has to be provided. That is why efforts are made to industrialize or professionalize the delivery of blows to piling sites. Amongst recent developments is worth mentioning the FonDyTest, illustrated on Fig. 13.

Fig. 13 – FonDyTest loading device

That piece of equipment developed at UCL has a mass of 4000 kg, a maximum drop height of 2.5 m, and can be accurately centered on the pile head thanks to a a set of computer-controlled inflatable jacks. It is equipped with internal hydraulic and pneumatic systems allowing to lift and release the drop mass with minimal crane demand. This feature is needed in Europe where free-fall winches are prohibited on cranes for safety reasons.

A widening consensus is now emerging within pile load testers to conduct some kind of SIMBAT procedure. Introduced by Paquet in the late 1980s, that procedure involves multiple blows in a sequence combining increasing drop heights with some reduced drop heights. That procedure thus involves several evaluations at different transient displacements, and mainly at different pile peak velocities to grasp some experimental handle on the notorious damping effects. The benefits of that procedure are recalled by *Williams et al (2006)*.

Primary difficulties and limitations generally raised against high-strain testing are the decoding of dynamically mobilized resistance measured during the test in terms of static resistance and the limited transient displacement enforced by the impact. Conversion of dynamic resistance into static resistance is rendered difficult in part because of the following effects: (1) inertial and radiation-damping effects, which are frequency-dependent, (2) differences in the deformation pattern along the shaft and at the base between dynamic and static loading, (3) effect of pore-pressure generation and dissipation, and (4) dependence of the soil's modulus and shear strength on velocity. For driven piles monitored during driving, one must also contend with the effects of cyclic pore pressure generation and soil setup (or relaxation). Also, and less often mentioned, reliability problems of measurements, especially of the force for cast-in-place piles, and velocity and displacement in general must be accomodated. Finally, the development, commercial success, and persistence of early simplistic models, which still represent the bulk of the practice, have deterred most end users from addressing the complexity of the phenomena at hand.

DATA PROCESSING

Dynamic Testing

Processing of the collected signals, using simple operations such as the addition and subtraction of simultaneous or phase-delayed signals, is a quick and powerful method of interpretation. In the case of high-strain testing, signal processing may lead to the evaluation of shaft, toe, and total resistance, as illustrated in Fig. 14. In the case of low-strain testing, signal processing may lead to the impedance profile of the shaft. The various processing approaches discussed below result from the direct application of the stress-wave theory to piles and the formulation of certain hypotheses regarding soil resistance mobilization. The ultimate "static" shaft resistance may be derived from the dynamic resistance using a signal matching procedure based on inverse modeling such as that illustrated on Fig. 15.

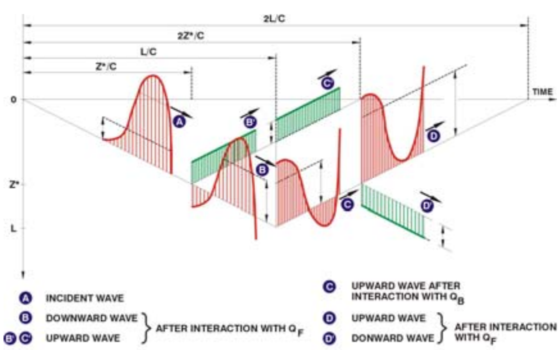

Fig. 14 – Wave generation and reflections in dynamically loaded pile.

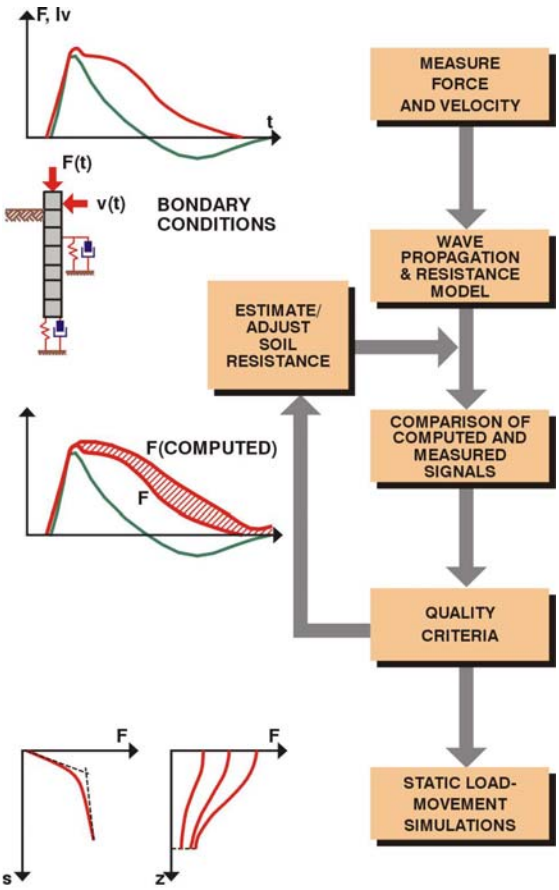

Fig. 15 – High-strain Inverse modeling to assess static load-settlement curve

Emerging improved assessment of soil "damping" to interpret load tests

Damping was introduced as a first approximation by Smith (1960) to account for some velocity dependency of the mobilized soil resistance during dynamic loading (see Fig. 16). For nearly half a century, an overwhelming majority dealing with dynamic load tests have been published without questioning the validity of that framework. While offering the benefit of simplicity and conceptual ease of understanding, correlations with soil type remained unconvincing, specially in finer grained materials to the point that site specific calibration of dynamic test has been requested in many circumstances by the skeptics.

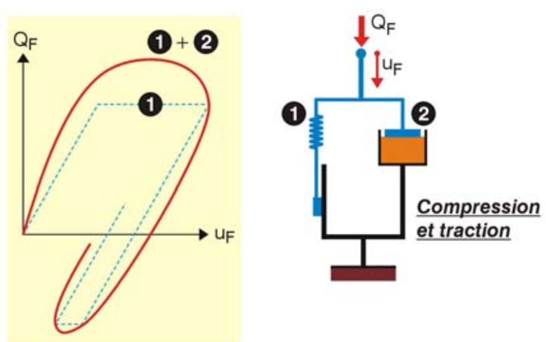

Fig. 16 – Basic from of damping (of the Smith, 1960)

Various definitions of damping have added to the confusion: Smith-type (original), Smith viscous, and Case dampings, just to name the three main ones. Then came more mathematically involved, definitions of damping such as Gibson (1968), and Rausche et al. (1994).

Clarification of what constitutes damping has been progressively developed by few researchers (e.g. Holeyman, 1984, Paquet, 1988, El Naggar & Novack, 1994, Randolph & Deeks, 1992, as summarized in Figs. 17, 18 and 19). It has now been established that energy losses result from geometric damping, from soil intrinsic damping, and that steady-state resistance depends upon failure rate.

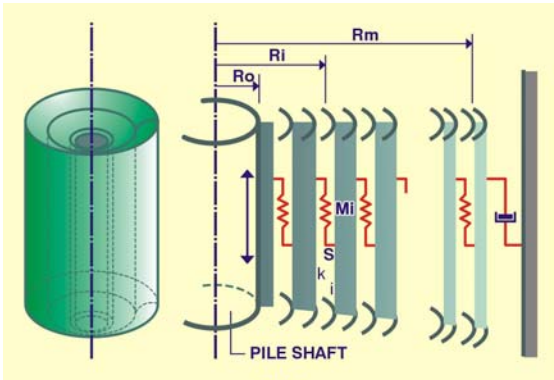

Fig. 17 – Skin friction radial modeling (Holeyman, 1984)

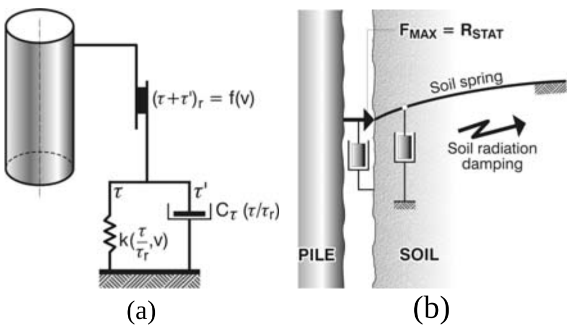

Fig. 18 – Simplified soil-Pile dynamic interaction Models (a) Holeyman, 1984, (b) Paquet, 1988

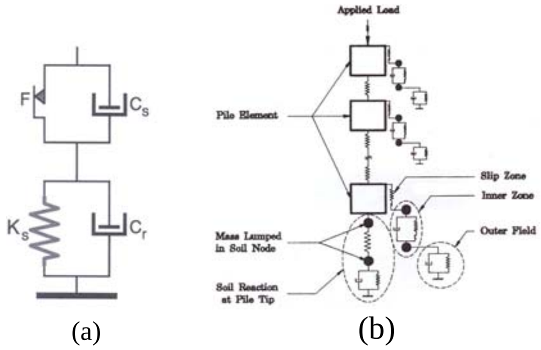

Fig. 19 - Soil-Pile dynamic interaction Models (a) Randolph & Deeks, 1992, (b) El Naggar & Novak, 1994

Geometric damping accounts for energy dissipation into the elastic medium surrounding the pile. The intrinsic damping itself account for energy losses due to viscosity at low strains and due to non-recoverable behavior (hysteretic damping) at higher strains. Finally, the term "failure damping" is suggested here as a simplified term to describe the velocity dependence of the steady-state resistance. In spite of the now available conceptual and physically based developments, simplicity of the all encompassing damping has been preferred by the vast majority of the practicing testers.

On the other hand, research at the University of Sheffield has recently produced results from laboratory tests conducted in a calibration chamber that clarify the velocity dependence of the steady-state (or CRP) resistance of a model pile jacked at different penetration rates into clay beds as shown in Fig. 20. *Brown (2006) and Anderson et al. (2006)* present variations of a progressively activated damping, the ultimate value of which follows a power-type function as initially suggested by Gibson:

$$\frac{\tau_d}{\tau_s} = 1 + \alpha\left(\frac{\tau_d}{\tau_{d(ultimate)}}\right)\left(\frac{v_d}{v_s}\right)^{0.2}$$

where τ_d is the dynamic shear resistance, τ_s is the assumed static shear resistance determined at a pile velocity of 0.01mm/s, $\tau_{d(ultimate)}$ is the ultimate dynamic shear resistance, v_d is the pile velocity, v_s is the assumed static pile velocity which is 0.01mm/s in that study.

One should however note that the diameter ratio chamber to pile is only of the order of 11, which is small enough to raise boundary

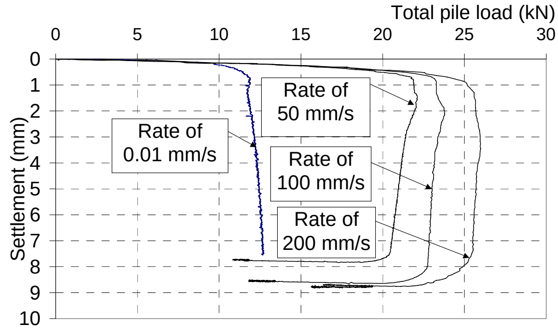

Fig. 20 – Model Pile Load-settlement curves at different penetration rates *(Anderson et al, 2006)*

conditions issues in both the quasi-static and the dynamic domain.

These recent results should however be confronted to experimental and numerical results produced by Randolph and co-workers (2005) pertaining to the penetration of cones or T-bars, newly developed for offshore geotechnical exploration of soft clays. According to those researchers, the monotonic increase of the resistance can only be observed under an undrained assumption for the soil behavior, shown on Fig. 22. If on the contrary, allowance is made for consolidation, the resistance increases again at lower penetration rates. This implies that a lower bound penetration resistance can be found at intermediate penetration rates, as shown on Fig. 23.

These latter results may well question the validity of the quest for the "true" or "unique" load-settlement curve advocated by Fleming (1992) and England (1993). That noteworthy development is indeed based on fitting hyperbolic functions to settlement data measured during a 2 to 6 hours accurately maintained load.

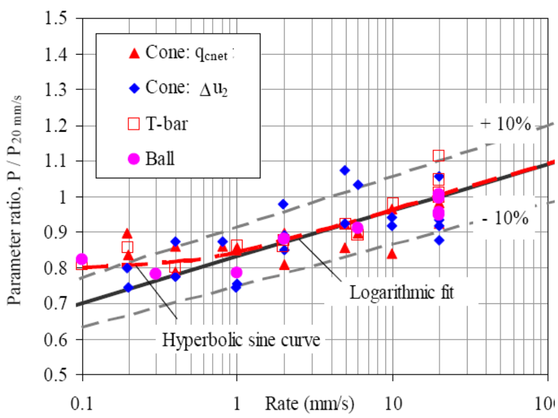

Fig. 22 – Effect of penetration rate on undrained resistance (Randolph, 2004)

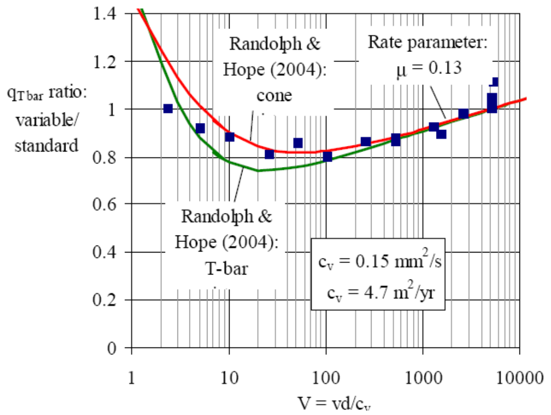

Fig. 23 - Penetration resistance from T-bar "twitch" tests (Randolph, 2005)

Questions to be solved and perspectives: (a) What is an acceptable approximation in the static load-settlement curve derived from a dynamic load test, how much better should it be than a prediction established without the results of the load test (i.e. what is the added value of a dynamic load test) (b) Conditions allowing an acceptance dynamic load test without the need to correlate its parameters with at least one static load test performed at the same site, and (c) development of a loading procedure that removes the need for casting a loading head atop the pile.

<u>Emerging site-specific statistical treatment of high and low-strain dynamic tests results</u>

Thanks to the speed and reduced costs associated with high-strain pile dynamic and kinetic testing, tens of tests can be nowadays secured on a single site in a mater of days. *Matsumoto et al (2006)* present the results of 180 loading events actuated on 25 steel piles in Japan. Such a data base allows them to identify variations not addressed by the initial soil investigation. They also observe that the performance of non driven piles can be improved by systematic dynamic testing.

Primary difficulties associated with low-strain integrity testing have been noted: test repeatability (improved to some degree by signal averaging), elimination of spurious vibrations (in hammer and Rayleigh wave effects), discrimination between soil resistance and shaft impedance effects, difficulty in identifying gradual changes in shaft section, masking of potential necking below bulb. These have led to overall historical distrust of engineering community towards results, and fuelled by the absence of a simple quantitative and rational interpretation method.

The systematic low-strain testing of all piles on a given site now enables the development of a site-specific data base that allows one to identify effective anomalies with more reliability. *Middendorp et al (2006)* present their views on the state-of-the-art of pile integrity testing in the Netherlands. Key results from a 30-year experience of testing in that country are: (1) concrete wave speed has to be calibrated, (2) 0.5 m wave length hammer must be used to identify pile head defects, (3) anomalous signals need to be ascertained against a reliably established site-pile signature, and (4) inverse modeling of anomalies requires an inverse model to be calibrated against the site-pile characteristic signature, as illustrated in Fig. 24.

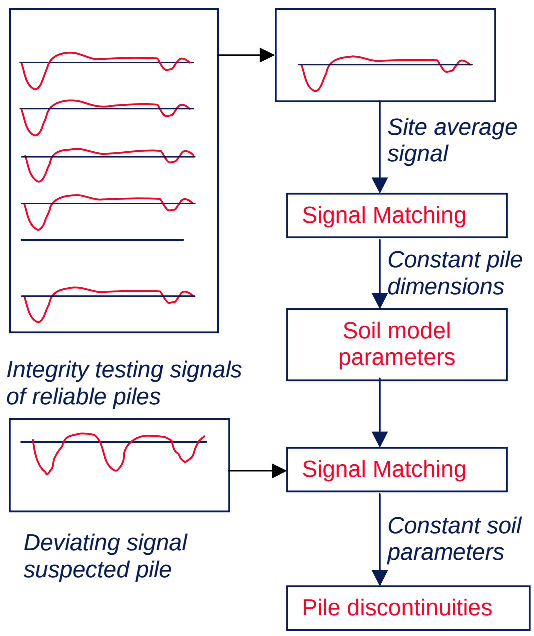

Fig. 24 – integrity testing signal matching procedure *(Middendorp et al., 2006)*

Taking another angle at integrity testing, *Williams and Jones (2006)* confirm an emerging trend in the U.K. of combining several NDE and even high-strain methods. Such a combination is required to shed some light on the challenging problem of assessing old deep foundations for their re-use or upgrade within the framework of re-development projects, as summarized in Table 2. A real challenge arises from the fact that deep foundations have to be assessed while remaining connected to the existing superstructure, which seriously complicates or even exclude resorting to wave reflection methods.

Table 2: Guidance on NDE Test Methods (Williams & Jones, 2006)

Test Method	Measurements	Access	Limitations
Low Strain Seismic	Pile length and depth to major anomalies.	Direct access to pile head required – preferably not in contact with structure	Max depth 30 diameters in cohesive soils. Suitable for pre-cast piles.
Low Strain TDR	Pile length, depth to major anomalies, dynamic stiffness and mobility. Indication of concrete quality and section.	Direct access to pile head required – preferably not in contact with structure	Max depth 30 diameters in cohesive soils. Suitable for pre-cast and cast-in-place piles.
Impedance Profile	Impedance versus depth gives discrete assessment of concrete quality/section	As TDR	As TDR
Parallel Seismic	Pile Continuity only	50mm diameter tube needs to be installed within 400mm of pile side and grouted in place with access to pile head or cap	Limited to depth tube can be installed. Can be influenced by rock interfaces.
Electro-magnetic	Depth of sheet piling, permanent casing and or reinforcement	90mm diameter tube needs to be installed within 200mm of pile. Access to pile head.	Limited to depth tube can be installed. Can be influenced by other ferrous materials in soil.
High Strain Simbat	Load capacity, pile continuity, distribution of forces on pile shaft and at toe.	Pile cap needs to be constructed on pile head and separated from pile cap/structure.	Unable to predict effect of creep. Need to mobilize base of pile to predict ultimate capacity.

Emerging routine use of Finite Element Modeling (FEM) to interpret pile installation and test results

Introduced in the late 1960, FEM has been regarded by the majority of the piling actors as an exotic black box where only the programmer knew what was going on. Now, with the readily availability of soil mechanics capable computer packages, almost every piling engineer can solve specific problems using that powerful tool. Actually, now the danger lies more with the overuse of overly user-friendly geotechnical packages by non geotechnical engineers. One can also fear that future engineers may first jump on their computer before they take a look back allowing them to conceptually analyze the problem they have to solve. Mathematical and drafting talents are being less and less emphasized in civil engineering curricula, leaving room to heavier reliance on numerical packages. Still, *Yang and Liang (2006)* show that old-fashioned analytical tools, such as Laplace transform of the wave equation, can help with the casting an elegant stepped deduction of the skin friction and toe resistance from high-strain tests measurements.

FEM approaches are presented in three papers allocated to Session 6, drawing on commercially available geotechnically oriented or capable packages: Plaxis®, Flac®, and Abaqus®. Of particular interest is the attempt by *König and Grabe (2006)* to model the installation of a displacement pile through the simulation of monotonic jacking (Fig. 25), pore pressures generation, and final blows. Post-installation mechanisms are also part of their concern, as they also present results of dynamic tests conducted at various times after installation to document set-up effects of precast concrete piles driven in Hamburg.

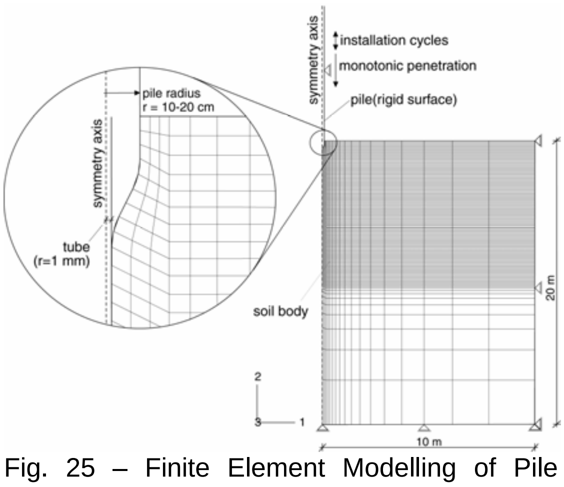

Fig. 25 – Finite Element Modelling of Pile Installation Process *(König & Grabe, 2006)*

Questions to be solved and perspectives: (a) from cradle to grave modeling of pile fabrication, testing, setup, and monitoring during superstructure load buid up, and ageing (b) Modelling residual stresses resulting from concrete setting and curing, and (c) chemio-physical modeling of pile set up.

CONCLUSIONS

Pile monitoring, testing, and data processing advance on multiple fronts in terms of relevance, sophistication, interpretation, and commercial availability. The ability to measure relevant data and interpret it into meaningful engineering terms a vital ingredient in the improvement of the industry. Digital data collection, transfer, and processing are contributing to the acceleration of that improvement process. It is hoped that reluctance towards sharing relevant information and improved processes will further dim. Based on a 20-years look-backing period, more specific emerging trends have been identified, and linked to the papers allocated to Session 6 of the DFI conference:

- real-time Information Technology (IT) on construction sites
- use of pile internal loading device (ILD)
- wider availability of retrievable extensometers for instrumented pile tests
- increased variety of methods to actuate kinetic loading
- increased confidence in high-strain dynamic loading
- more physically based assessment of soil “damping” or viscosity to interpret pile load tests (dynamic, kinetic, and static)
- Site-specific statistical treatment of the results of high and low-strain dynamic tests
- routine use of Finite Element Modelling (FEM) to interpret pile installation and test results.

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