Design of Axially Loaded Piles – European Practice, De Cock & Legrand (eds)
© 1997 Balkema, Rotterdam, ISBN 90 5410 873 8

Pile dynamic testing, driving formulae, monitoring and quality control: Background for discussion

A. Holeyman
U.C.L., Louvain-la-Neuve, Belgium

ABSTRACT : Background information is provided for discussion on pile dynamic testing, driving formulae, monitoring and quality control as those practices relate to the design of piles. A general framework to classify pile dynamic testing is presented. Topics for discussion are suggested.

1. PILE DYNAMIC TESTING

Dynamic testing of piles has become part of many modern civil engineering projects as a result of the increased availability and performance of testing equipment and interpretation procedures (Holeyman, 1992). Two major classes of methods can be distinguished on the basis of energy level and intent, as presented in Figure 1 : high-strain dynamic testing methods primarily intended to provide bearing capacity information and low-strain dynamic testing methods primarily intended to provide information on pile integrity. Amongst the dynamic testing methods, the impact method is the most closely related to pile design considerations. The most common high-strain dynamic testing involves dropping a mass on the head of a pile and is addressed by ASTM Standard D-4945-89 (1989).

The load-bearing behaviour may be summarised by an allowable load or described by a complete load-settlement curve generally derived from distributed shaft and toe resistance terms. The interpretation following that procedure is based on the wave-equation theory and both force and velocity signals measured at the pile head during impact. The dynamic nature of the load and the time consumption for the shock wave to travel down and back up allows one to relate time to position down the pile and resolve soil reactions distributed along the shaft and at the toe.

Resolution of the shaft resistance terms versus depth (depth resolution) is afforded by the sharp increase of the force at the wave front and by the short length or duration of the original wave form. 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 characterised by a relative wave length of 0.1, which provides for the sharpest depth resolution available. The dynamic bearing capacity test is typically characterised 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 characterised by a relative wave length Λ of 10 or higher and, therefore, do not allow for depth resolution. It is suggested that, although those tests resort to inertial actions on masses to generate their extended force pulse, they 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 significantly benefit from the use of the wave equation framework.

PILE DYNAMIC TESTING METHODS

HIGH-STRAIN PRIMARILY FOR BEARING CAPACITY	LOW-STRAIN PRIMARILY FOR INTEGRITY
IMPACT	**IMPACT**
Using - Pile driving equipment - Pile testing equipment	*Using* - Hand held hammer - Explosion - Piezocrystals
Measuring - Strain and velocity	*Measuring* - Velocity and optionally force
1997 State-of-the-practice	*1997 State-of-the-practice*
VIBRATION	**VIBRATION**
Using - Pile vibratory driving equipment	*Using* - Pile testing vibrator
Measuring - Strain and velocity	*Measuring* - Force and velocity
Not presently developed	*Used 1965 - 1985*
PROLONGED IMPACT	**SONIC LOGGING**
Using - Soft springs with heavy hammer - Explosives slowly burning in engineered chamber	- Crosshole - Single hole - Parallel seismic using piezocrystals/hand held hammer and measuring pressure at depth
Measuring - Head displacement and force	
1997 State-of-the-art	*Requires non-standard pile set-up*

Fig. 1 - Pile dynamic testing methods

Figure 2 provides a representation of the pile tests available in terms of relative wave length Λ and of acceleration. Figure 2 also presents typical times expressed in terms of 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.

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	0.5 - 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 Λ	0.1	1.0	10	10^8

Primary difficulties and limitations associated with high-strain testing are the conversion of the dynamically mobilised resistance measured during the test into 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:

- Inertial and radiation-damping effects, which are frequency-dependent,
- Differences in the deformation pattern along the shaft and at the base between dynamic and static loading,
- Effect of pore-pressure generation and dissipation, and
- Dependence of the soil's modulus and shear strength on velocity.

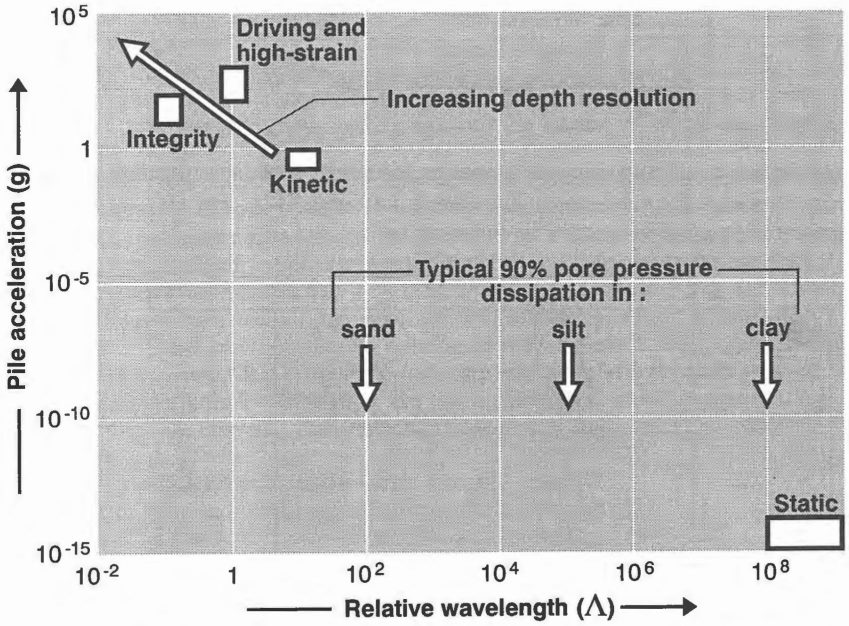

Fig. 2 - Sharpness and duration of force pulse for different pile tests

For driven piles monitored during driving, one must also contend with the effects of cyclic pore pressure generation and soil set-up (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 contented with. 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.

High-strain vibration, although easily implementable in practice, has not seen many applications. Vibrators are regularly used to install sheet piles; however, in that case, axial capacity is not usually a primary concern. Also, vibrations imply cyclic loading, which generates an additional difficulty in the interpretation because of pore-pressure generation and fatigue effects (Holeyman and Legrand, 1996).

2. DRIVING FORMULAE

Pile driving formulae can be viewed as a particular case of using installation monitoring to derive information on the performance of piles. Generally based on energy considerations, those formulae strive to provide a direct relationship between the set and the total downward ultimate bearing capacity (some say "driving resistance" or resistance during driving). Driving formulae usually take into account the rated or observed energy of the hammer, some loss of energy within the driving system, and an assumed or measured rebound of the pile.

Most driving formulae are a particular case of the following general expression :

$$\eta_i \; \eta_c \; Mgh = \frac{1}{2} Q_D \; s_{el} + Q_D \cdot s$$

in which
- η_i is the efficiency of impact
- η_c is the efficiency of drop
- M is the mass of the hammer
- g is gravity (9.81 m s^{-2})
- h is the stroke of the hammer
- Q_D is the pile driving resistance
- s_{el} is the transient displacement or "elastic" rebound.
- s is the set

Driving formulae still appearing in special provisions of some specifications include those of Eytelwein (or Dutch formula), Janbu (or Danish formula), Hiley and Delmag (after Crandall). Their parameters are summarised in the following table :

	η_i	η_c	s_{el}
Dutch	$\frac{1}{1+\mu}$	1	0
Danish	1	0.7 to 1	$\left(\frac{2\,\eta_c \; Mgh\,L}{A_p\,E}\right)^{1/2}$
Hiley	$\frac{1+e_r^2\,\mu}{1+\mu}$	0.75 to 1	$C_1 + \frac{Q_D\,L}{A_p\,E} + C_3$
Delmag	$\frac{1}{1+\mu}$	1	$0.6\ 10^{-3}$ L

with L = length of pile [m]
A_p = section of pile [m^2]
E = modulus of deformation of pile [Mpa]
M_p = mass of pile [Mkg]
μ = M_p/M
e_r = coefficient of restitution [-]
C_1 and C_3 = Hiley constants obtained from tables ($0 < C_1 + C_3 < 12\ 10^{-3}$ [m])

The large factors of safety typically used (4 to 12) to adopt the allowable value of the pile resistance form the interpreted driving ultimate resistance underline the low reliability of that approach as a design tool.

3. INSTALLATION MONITORING

Besides driven piles discussed above, it appears that little information is available to relate installation parameters to the bearing capacity of a pile. The writer anticipates that efforts pursued in that direction could provide, if not the bearing capacity, at least some confirmation of the installation dependent portion of the bearing capacity. More specifically, methods should be developed and promoted to reward and recognise increases in bearing capacity that depend on monitored processes and workmanship (e.g. lower soil relaxation around excavated piles).

Installation monitoring, as perceived by the writer, appears to be considered as a component of the quality control of the installation, more than a design related tool.

4. QUALITY CONTROL

The quality and resulting performance of piles can be controlled from "cradle to grave". Components of a quality control program relate to materials, installation and fabrication process, and the finished product. In present piling practice, materials are systematically controlled, installation and fabrication often controlled, and the finished product less often controlled. As shown in Fig. 1, low-strain dynamic testing can provide means to verify the integrity of the finished product.

The most common low-strain dynamic testing involves hitting the pile head using a hand-held hammer and monitoring the pile head to obtain its transient velocity, and optionally the impact force. This test is well documented, but is not, to the writer's knowledge, the object of a national standard. The primary objective of the low-strain dynamic test is to assess the integrity of the pile as a structural member. Anomalies that impair the integrity of a pile and that are expected to be identified by integrity tests include the presence of material of poorer quality than expected (locally and overall) and variations in the cross section of the shaft (e.g., crack, necking, and bulb). Additionally, some idea of the pile and soil behaviour at low-strain may be inferred. Because the primary information offered by the test is the manner in which waves travel and are reflected within the pile material, pile material strain during those integrity tests has a typical maximum of only 2 to 10 µstr.

Primary difficulties associated with low-strain integrity testing are:

- 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,
- Historical distrust of engineering community towards results stemmed from early days, and
- Lack of one simple, quantitative, and rational interpretation method.

Other low-strain methods are used to investigate the integrity of piles, although not exclusively relying on the transmission of longitudinal waves. These are the Parallel Seismic Testing, Crosshole Sonic Logging, and Single hole Sonic Logging (Stain, 1982). These three methods require the provision of casings outside or within the pile shaft.

Parallel Seismic Testing is typically used when the pile head is not accessible. A bore-hole is drilled immediately adjacent and parallel to the pile, and a slotted tube is installed. The boring is usually drilled to within 1 m of the shaft and at least 3 to 5 m deeper than the presumed pile depth. The cased hole is filled with water, and a hydrophone is lowered down the hole to monitor, at regular depth intervals (typically 0.5 m), the water pressure wave resulting from the impacts imparted on a structural element directly connected to the pile head. Wave arrival time delays are plotted versus depth in order to identify the deep foundation bottom.

Crosshole and single-hole sonic logging are typically used to evaluate the concrete condition of drilled shafts and slurry walls. Casing within the pile generally consists of water-filled tubes attached to the reinforcement cage before the casting of concrete. Ultrasonic pulses are generated by a piezoelectric motion generator (source), and the resulting water pressure waves are recorded by a hydrophone (receiver). Pulses have a typical duration of 50 microseconds (μs) and result in a concrete strain on the order of 0.1 μstr. Crosshole logging is performed by simultaneously lowering source and receiver into separate tubes; single hole logging is performed by lowering a source/receiver assembly, separated by a fixed depth interval, into a single hole. Wave arrival time delays and amplitudes are interpreted with a view to identifying zones with poor quality concrete, voids, intrusions, and breaks.

Difficulties and present limitations associated with seismic and sonic logging are:

- Planning requirement and interference with construction process,
- Control of casing positions,
- Quality of mechanical contact between tube and concrete,
- Defect must fully separate receiver from source (i.e., defect boundary must ideally intercept casing to be detected), and
- Qualitative more than quantitative interpretation.

5. SUGGESTIONS FOR DISCUSSION

As a preliminary approach to be adjusted based on a more complete review of questions raised at the Seminar, the following topics are suggested for discussion :

5.1 Pile dynamic testing

- Dependence of mobilised load on energy level
- Need for correlation with static loading tests
- Use for non driven piles
- European standard.

5.2 Pile Driving Formulae

- Standard for set measurement upon retap
- Soil set up factors
- Use of complete driving history versus last blows to assess bearing capacity
- Automatic set recording systems

5.3 Installation monitoring

- Availability of monitoring systems for various pile types (e.g. screwed, continuous flight auger (CFA), grouting, ...)
- Correlation between installation parameters and bearing capacity
- Case histories documenting different performance of a given pile type resulting from different installation records

5.4 Quality control

- Limitations of integrity tests
- Characterisation of anomalies in term of nature, volume, shape
- Addressing identified anomalies (repair, discount of capacity, etc...)
- European standards for low-strain dynamic tests

6. REFERENCES

ASTM D4945-89. 1984. Standard Test Method for High-Strain Dynamic Testing of Piles, Annual Book of American Society for Testing and Materials, Volume 4.08 (7p.)

Bermingham, P., and Janes, M. 1989. An Innovative Approach to Load Testing of High Capacity Piles, Proc. of the International Conf. on Piling and Deep Foundations, London, May, pp. 409-413

Gonin, H., Coelus, G. & Leonard, M. 1984. Theory and Performance of a New Dynamic Method of Pile Testing, Proc. 2nd Int. Conf. Application of Stress-Wave Theory to Piles, Stockholm, pp. 403-410

Holeyman, A. 1992. Technology of Pile Dynamic Testing, Keynote lecture, Proc. of the 4th International Conference on the Application of Stress wave theory to piles, The Hague, September 21-24, pp. 195-215

Holeyman, A. and Legrand, C., 1996, A Method to Predict the Drivability of Vibratory Driven Piles, Proceedings of the 5th International Conference on the Application of Stress-Wave Theory to Piles, Orlando, September, pp. 1101-1112.

Stain, R.T. 1982. Integrity Testing, Civil Engineering (London), April, pp. 53-59 & May, pp. 71-73.