High-Strain Kinetic Testing of Deep Foundations

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Abstract

High-strain kinetic testing involves the upward decelerating or accelerating of a mass and using its inertial force to generate an axial prolonged pulse at the head of a pile. Currently available high-strain kinetic loading methods are reviewed. Present difficulties and limitations associated with the interpretation of kinetic testing of piles based on recorded force and movement at the pile head are discussed. Insight into the merits and limitations of high-strain kinetic testing of piles can be gained from applying existing soil models to simulate test results obtained from a case history.

Introduction

Because of the recent greater availability and higher performance of pile testing and monitoring equipment, pile dynamic testing has become part of many present day civil engineering projects. One of the most recently developed pile loading techniques involves the upward decelerating and/or accelerating of a mass and using its inertial force to generate an axial fast push (or a prolonged pulse) at the head of a pile. Pile-head force and movement are typically monitored during the event. The duration of the force pulse is on the order of 100 to 200 milliseconds (ms) and thus long enough for the waves to travel back and forth several times (typically 10 to 20) within the pile.

Because several kinetic tests up to maximum loads on the order of 10 to 20 MN can be administered in a single day, they are at an economical advantage when compared to static tests. However, they are generally more expensive than pile dynamic tests administered using a pile driving rig and hammer. As a result of the progressivity and duration of the force pulse, inertial effects on the pile and surrounding soil are regarded as minimal by promoters of this type of testing (Gonin et al., 1984,

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Bermingham and Janes, 1989). This is why this testing method has been referred to as "kinetic", rather than dynamic testing (Holeyman, 1992).

Pile load test results are interpreted based on recorded force and movement at the pile head. Because of the many potential inertial and rate effects, a single and simple derivation of the static loading curve from the recorded kinetic loading curve has not yet emerged. The present paper attempts to clarify the contents of what is generally and globally referred to as "damping" and provide some estimates of the magnitude of its various components.

Available technologies

A soft cushion can be engineered to lengthen the duration of the force pulse resulting from a pile impact. Gonin et al. (1984) have developed a system in France called "Dynatest" that uses soft coil springs for that purpose. The loading equipment is installed on a small tracked vehicle, with a ram weight of 15,000 kg (see Figure 1). After surfacing the top of the pile with quick-setting concrete, the ram weight is raised by two jacks to a height that can vary from 0.1 to 1.4 m. The ram falls freely onto the springs placed on the pile head, rebounds, and is picked up by an automatic system. The force pulse is rated at 4 MN maximum and typically lasts 100 to 150 ms (see Figure 1). Reported pile load testresults indicate a maximum load of approximately 3 MN for a maximum pile load movement of 20 mm. The Dynatest was developed with a view to quickly check a large proportion of the piles installed at a given site.

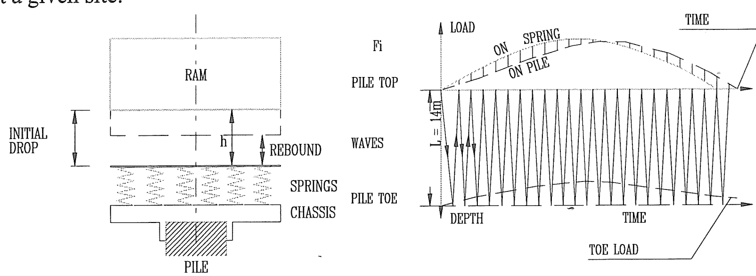

Figure 1. "Dynatest" Apparatus and Load Diagram (Gonin et al., 1984)

A similar system known as PSPLT, for Pseudo Static Pile Load Tester, is currently offered by Fundex. A 25,000 kg mass is handled (lift, drop, and catch at apex of rebound) by a hydraulic system mounted on a 60-ton pile driving rig undercarriage on tracks. Several tests can be conducted on the same pile by releasing the mass from various heights. A drop height of 3.5 m is reported to generate a load pulse with a peak of approximately 4 MN and a duration of approximately 200 ms (Fundex, 1992).

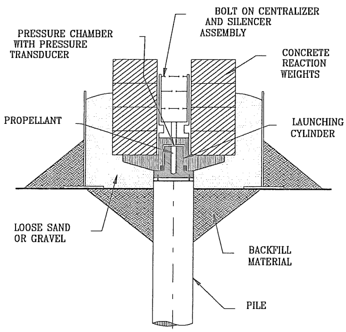

Figure 2. "Statnamic" Apparatus (Bermingham and Janes, 1989)

The controlled combustion of fuel within a pressure chamber is another feasible way to generate a long force pulse. Bermingham and Janes (1989) have developed a system in Canada called "Statnamic", which uses rapidly expanding gases as a soft cushion to transfer forces to the pile head. The Statnamic apparatus consists of a reactive mass placed over a pressure chamber atop a pile to be tested (see Figure 2). Fuel is burned within the pressure chamber, creating large pressures that drive the reaction mass upward at high velocity and push the pile downwards. The total height to which the reaction mass is propelled can reach 2 m. A pressure transducer located in the pressure chamber of known diameter is used to monitor the force pulse while pile head movement is monitored by use of a laser level. The force-time history (shape and length of the pulse) can be modulated by varying the following parameters:

- Reaction weight (typically 5% of test load),
- Amount of fuel, and
- Physical characteristics of pressure chamber (diameter and stroke before gas freely escapes) and venting system.

Test results reported to date indicate a maximum load of 3.1 MN, using a 15,000 kg-reaction mass, for a maximum pile movement of 50 mm. A typical duration of the force pulse is 100 ms, which is progressive enough to keep acceleration levels within the pile below 1 g. A 30-ton crane is required to set up the equipment atop a pile. Piles with a batter of 1 in 6 have been tested.

"Damping" Factors

Damping is a general term that attempts to isolate the energy dissipating features of the loading history of a pile during dynamic or kinetic loading. Damping is responsible in particular for bringing the pile to rest when vibrating freely after impact or load pulse. It is also responsible for increasing the mobilized soil resistance during the rapid movement of the pile associated with dynamic or kinetic loading.

Within the development of stress wave theory applied to pile driving, damping was introduced by Smith (1960) with a view to incorporate all soil effects that would produce resistance beyond that mobilized during static loading. In the early model proposed by Smith, the soil damping was assumed by a dash pot placed in parallel with the static resistance components. It was thus implied that resistance mobilized in excess of static would solely depend on the current velocity of the pile element considered.

Other damping factors have been introduced since then, some related to the soil ultimate resistance or to the pile impedance (Goble et al., 1975), with the same intent to capture the velocity dependent terms of the soil resistance in a single parameter, to be evaluated empirically. Fundamental laboratory and model studies have also been undertaken to study the velocity dependence of the soil resistance ideally under uniform and well controlled loading conditions. However, different laws (linear viscosity, logarithmic law, power law, ...) were shown to result from different test conditions such as strain rate range, strain tensor, strain uniformity, and model geometry.

Physical components of damping

When attempting to transpose a kinetic loading curve into a static loading curve, we suggest that a distinction be made between the several following components of "damping":

- inertial effects of pile mass,
- strain rate effects on concrete compressibility,
- inertial effects of surrounding soil,
- strain rate effect on soil deformability, and
- strain rate effect on soil ultimate resistance.

These components can be tracked individually in a wave equation analysis that incorporates soil reaction models where wave energy transfer can be evaluated. The model shown in Figure 3 (Holeyman, 1984) follows the development of

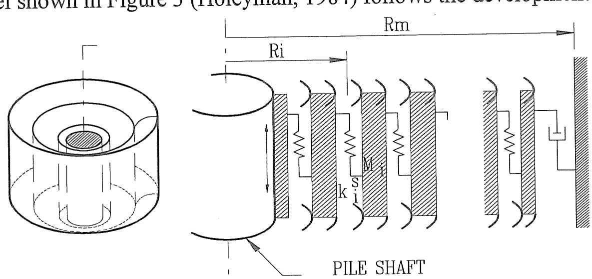

Figure 3. Radial Wave Equation Model for Skin Friction (Holeyman, 1985)

cylindrical shear waves originating from the pile shaft and embodies within its geometry the inertial effects of the soil surrounding the pile; these effects are sometimes referred to as "geometric" or "radiation" damping. It should be noted that radiation damping merely expresses the outward transfer of energy from the pile to the surrounding infinite medium and is acting even under the assumption of a purely elastic soil.

The shear stress-strain behavior used to calculate the relative movement between successive concentric cylinders of the model can incorporate the following terms encompassing the soil intrinsic energy dissipation:

- hysteretic damping, result of irrecoverable energy during cyclic loading,
- viscous damping, result of strain rate at low and medium strains, and
- failure damping, result of strain rate at very large strains.

The model allows one to attribute components of damping to specific physical phenomena, characterized by physical parameters that can be assessed by other independent means: density, shear modulus, shear strength, shear wave velocity, cyclic shear tests damping, and critical state shear resistance at various strain rates. The model was used to simulate a Statnamic load test, as described below.

Case History and Conclusions

A series of three full scale Statnamic tests with increasing amplitudes was performed on June 6, 14, and 15 1990 on the same pile installed in the Berminghammer yard, located in Hamilton, Ontario, Canada. The pile consisted of a 31 m long, 324 mm diameter steel pipe with a 10 mm thick wall that had been driven closed end and filled with concrete. Soil conditions were reported to consist of 3 m of granular fill and 27 m of soft to very soft silty clay (bay mud) overlying weathered shale. The weathered shale where the pile was tipped had an estimated compressive strength of 350 kPa (50 psi).

Figure 4 provides on the same graph the measured and the calculated loading curve corresponding to the highest amplitude. The curve calculated using the model described above was obtained by imposing the recorded pulse at the pile head and adjusting soil parameters until the calculated displacement reasonably matched the measured one. Although it is understood that such a procedure does not lead to a uniquely perfect solution, it can be noted that the model captures the stiffness of the early part of the loading history, the strong hysteresis, and the oscillations of the pile towards the later free damped vibrations of the pile.

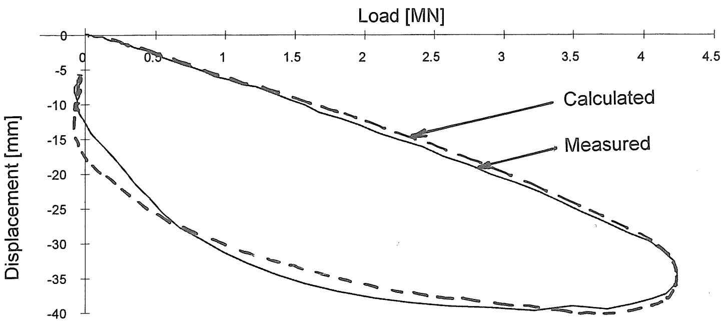

Figure 4. Measured and Calculated Loading Curves

In the process of analyzing the measured Statnamic records, we came across the following observations:

- the inertia of the pile mass accounted for less than 2% of the force,
- the deformation modulus of concrete during kinetic testing was assumed to be 32,000 MPa, i.e. intermediate between dynamic (40,000 MPa) and static (28,000 MPa) values,
- the period and damping of the pile free vibrations after the loading pulse can be used to confirm stiffness and radiation damping, and
- attention must be paid to the fact that soil Rayleigh waves may reach the laser used to measure the pile displacement some 80 ms after the pile is affected.

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