F. Rausche[1] *and G. G. Goble*[2]

Determination of Pile Damage by Top Measurements

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ABSTRACT: Measurements of force and acceleration at the pile top during driving can be used to detect the presence of damage at points along the pile below the ground surface. Analytical considerations based on one-dimensional wave mechanics are discussed, and a method is derived to place a quantitative measure on the degree of damage. Actual field measurements on damaged piles are presented.

KEY WORDS: field tests, foundations, inspection, pile driving

In the past few years, the capability has been developed to measure routinely force and acceleration at the top of a pile during driving. The primary reason for making these measurements has been to determine pile static capacity using the Case method [*1*][3] to verify hammer performance parameters, or to determine soil resistance characteristics by analysis with the Case Pile Wave Analysis Program (CAPWAP) [*2*]. With both force and acceleration time records available from the Case Method measurements, it is possible to detect discontinuities or reductions in cross section of the pile even though the point of disturbance is hidden below the ground surface. By one-dimensional wave propagation considerations, it is possible to reach quantitative conclusions regarding the degree of section reduction at the discontinuity.

In this paper, the basic mechanics will be presented for evaluation of pile damage. Some actual measurements on damaged piles will be shown and evaluated.

[1] President, Goble and Associates, Inc., Cleveland, Ohio 44106
[2] Chairman, Department of Civil, Environmental, and Architectural Engineering, University of Colorado, Boulder, Colo. 80309.
[3] The italic numbers in brackets refer to the list of references appended to this paper.

Fundamental One-Dimensional Wave Mechanics

When a suddenly applied axial load acts on a slender rod whose length is much greater than its diameter, the induced stress propagates away from the point of application. Pile driving is an example of this phenomenon. The variations of stresses in the rod have a wave-type appearance. In the case of the stress wave induced by impact, the more suddenly load application occurs, the better the applicability of stress wave mechanics.

The stress wave will propagate along the rod at a velocity c, and this velocity is a material property. Wave speeds in piles will be greater than 3000 m/s (10 000 f/s) for typical pile materials. The application of the suddenly applied force will induce velocities at the end of the rod that propagate with the stress wave. These particle velocities will have the same general magnitude as the velocity of the impacting ram and for pile driving typically range from 1.8 to 4.6 m/s (6 to 15 ft/s).

In addition to the forces induced by impact, there are also forces caused by passive effects such as soil resistance. When the stress wave propagates along the pile below the ground surface, the pile displaces downward. Due to the displacement, upward-acting soil resistance forces are generated that in turn induce stress waves in the pile that propagate away from the point of action and are superimposed on the impact wave. Other forces caused by passive effects are changes in cross section and reflections from the pile tip.

Development of Damage Detection Relations

It can be shown [*3*] that a proportionality exists between force and velocity at the pile top during and after impact so long as no return waves have reached the top. Thus, for a uniform cross section pile with no damage or soil resistance and having a length L, the measured force and velocity for a time after impact less than $2L/c$ are related by

$$F = v\,EA/c \qquad (1)$$

where F is the pile force, v is the particle velocity, E is the modulus of elasticity of the pile material, A is the pile cross-sectional area, and c is the velocity of stress wave propagation. The quantity EA/c is generally known as the impedance and will hereafter be designated as I.

Figure 1 shows measurements that were made on a very long steel pile. The measured acceleration has been integrated to obtain velocity, and that quantity multiplied by I is plotted together with the force. This pile was of uniform cross section and was driven inside an empty casing for all but the last 40 ft of its length. Thus, reflections from soil resistance or cross section changes were impossible until slightly before the first reflection from the

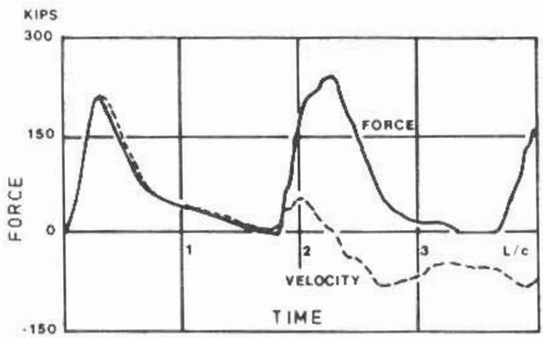

FIG. 1—*Measured force and velocity times* EA/C *for a pile with no side resistance except on the lower 40 ft.* L = *393 ft.* c = *16 800 ft/s.* EA/c = *44.7 kips/ft/s (1 ft = 0.3048 m. 1 ft/s = 0.3048 m/s. kips/ft/s = 14.59 kN/m/s).*

pile tip at $2L/c$ after impact. The records start to diverge when soil resistance forces have their effect at the pile top. Note that both force and velocity turn upward together at about $1.8L/c$. Since the pile is of uniform cross section, it can be concluded that this increase is due to an input force from the driving system. This input came when the hammer assembly impacted with the helmet, a fact that can be verified by examination of the acceleration record (not given here). Very shortly after assembly impact, the reflection from the tip soil resistance arrived causing force and velocity records to diverge. The difference

$$R_{\Delta} = F - vI \tag{2}$$

at a time t_x after impact is caused by resistance forces that at a distance

$$x = ct_x/2 \tag{3}$$

from the pile top. The resistance forces R_{Δ} may be either concentrated or distributed.

If a pile changes cross section at a depth x, then at the time $2x/c$ after impact, a wave effect can be observed at the pile top in both force and velocity records. If the upper pile section has an impedance I_1 and the lower one an impedance I_2, then the pile top force will change by

$$F_{\Delta} = -2F_1 \frac{I_1 - I_2}{I_1 + I_2} \tag{4}$$

if the pile top is fixed [*4*].

In Eq 4, F_i is the force at impact. Similarly, a change of velocity can be observed at a free pile top

$$v_\Delta = 2v_i \frac{I_1 - I_2}{I_1 + I_2} \tag{5}$$

with v_i being the velocity at impact. Thus, the change between force and velocity from either consideration at the pile top due to a cross-sectional change is

$$u_\Delta = 2F_i \frac{I_1 - I_2}{I_1 + I_2} \tag{6}$$

This is true as long as the total force at the pile top does not reach zero (separation) and for times less than $2L/c$ after impact.

In general, the impact wave is reduced by the effect of soil resistance at the time it gets to the point of cross-section change. In fact, it will have decreased by $R/2$ for only elastoplastic resistance forces. More realistically, however, it should be assumed that F_i has decreased by R_Δ, since damping wave effects are not additive. Thus, Eq 6 becomes

$$u_\Delta = 2(F_i - R_\Delta) \frac{I_1 - I_2}{I_1 + I_2} \tag{7}$$

A relative lower cross section

$$B = \frac{I_2}{I_1} = \frac{A_2}{A_1} \tag{8}$$

will be introduced that is valid for piles of only one material. Thus, subsituting Eq 8 in 7 and solving for B leads to

$$B = \frac{2 - \mu_\Delta/(F_i - R_\Delta)}{2 + \mu_\Delta/(F_i - R_\Delta)} \tag{9}$$

which can be further reduced when defining

$$\alpha = \frac{u_\Delta}{2(F_i - R_\Delta)} \tag{10}$$

which is a relative pile top wave effect. Thus,

$$B = \frac{1 - \alpha}{1 + \alpha} \tag{11}$$

Example of Damage Determination

Consider Fig. 2, which is a record taken on a broken concrete pile. The early force and velocity behavior shows the typical force–velocity proportionality. At a time of 8.6 ms after impact, the velocity shows an increase relative to the force. This increase can only be explained by a small pile mass and stiffness approximately 16.5 m (54 ft) below the pile top [$x = \frac{1}{2}ct_x = (54 \text{ ft})$]. Before the relative velocity increase became noticeable, the proportional velocity had already dropped by an amount $R_\Delta = 925$ kN (208 kips) relative to the force. The relative increase of this velocity at the point of damage effect was $u_\Delta = 1352$ kN (304 kips) and the impact force was $F_i = 2304$ kN (518 kips). Therefore

$$\alpha = \frac{u_\Delta}{2(F_i - R_\Delta)} = \frac{304}{2(581 - 208)} = 0.49$$

and

$$B = \frac{1 - \alpha}{1 + \alpha} = 0.34$$

Damage Classification

There is no experimental proof available justifying the following classi-

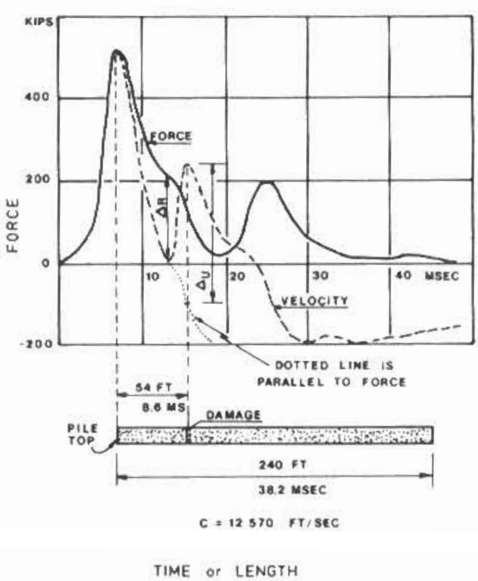

FIG. 2—*Example of a force and velocity measurement on a broken pile.*

fication. It was set up under the presumption that B actually indicates how much pile cross section is left. The following classification assumes that the soil resistance immediately below the point of breakage is negligible.

B	Severity of Damage
1.0	undamaged
0.8–1.0	slight damage
0.6–0.8	damage
Below 0.6	broken

Cracks and Slacks

Slacks, as they often occur between spliced pile sections, can well be discovered in easy driving. One important distinction between a crack/slack and a damage is that the latter becomes worse while a crack diminishes as driving becomes harder.

Once it is established that a reflection is due to a slack rather than to damage, its gap width can be determined in an approximate manner. This determination is based on an integration of the relative velocity change (measured from the force as a zero line). Thus,

$$\delta = \frac{1}{2} \int_{t_1}^{t_2} \left(v - \frac{F - R_\Delta}{I} \right) dt \tag{12}$$

where t_1 and t_2 refer to the beginning and end of the slack effect and R_Δ is the difference between force and proportional velocity at time t_1. Figure 3 shows a sample calculation in which the shaded area corresponds to the integral of Eq 12.

The slack of 1.12 mm (0.044 in.) determined in Fig. 3 is probably a lower bound, since precompression effects had already closed the gap to a certain degree. It is also possible that the gap was not uniform (gap closed on one side, open on the other side). In this case, it would take a certain force to reduce the slack distance. Note that the slack reduced the speed of wave transmission to the lower section and the pile tip reaction occurs later than expected. The time of the wave return indicates a slack at 17 m (56 ft) below the top, a point that is very close to a pile splice. A greater accuracy in distance determination cannot be expected. The splice was of a mechanical type and had a design slack of about 0.79 mm (0.032 in.).

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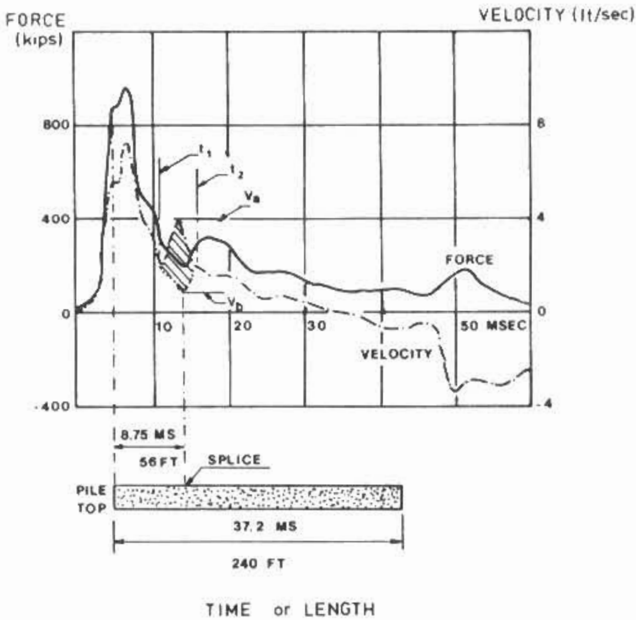

FIG. 3—*Example of force and velocity records for a pile containing a slack.* c= *12 900 ft/s.* V_a = *4 ft/s.* V_b = *0.9 ft/s.* t_1 = *11.3 ms.* t_2 = *16.0 ms. slack* = *½ (4.0 − 0.9) (16.0 − 11.3) (12/1000)* = *0.044 in.* (*1 ft/s* = *0.3048 m/s. 1 in.* = *25.4 mm*).

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