Pile driveability assessment by waveform analyses

L'évaluation de la possibilité de foncer les pieux par l'analyse de la forme des ondes

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SYNOPSIS This paper is concerned with the assessment of pile drivability from recorded strain wave forms. The field performance of an offshore, large-diameter, steel pipe pile driven with a diesel hammer is discussed, with emphasis on evaluating the energy transmitted to the pile. For this purpose, the method of two-point strain measurements is successfully applied. It is shown that this procedure totally resolves the hitherto most uncertain aspect of the diesel hammer performance. It is also pointed out that Hiley's formula coupled with the actually identified efficiency of driving yields a reasonable estimate for the bearing capacity of that particular pile driven in a Quaternary deposit.

INTRODUCTION

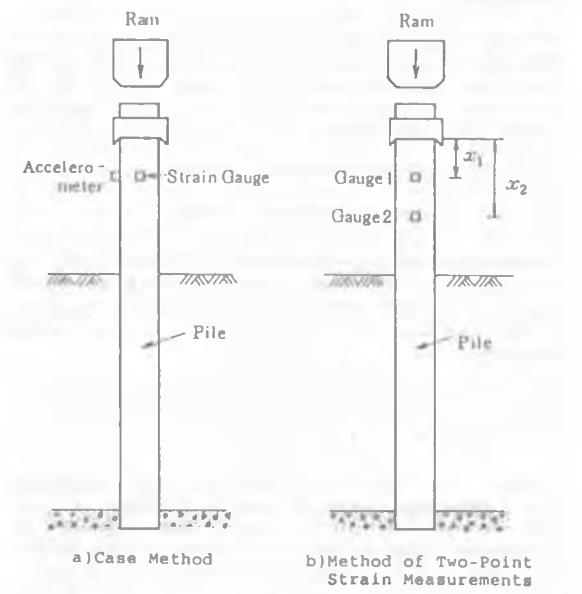
The measurement of stress waves in a pile during driving has had increasing attention, with respect to the drivability or penetrability or even bearing capacity of the pile.

Most of the related analysis procedures including the Case method (Rausche et al., 1985) premise the measurement of acceleration and strain waveforms at the same section of a pile during driving, as schematically shown in Fig. 1(a). Note, however, that the (hybrid) analysis procedure has inconvenience from a practical point of view. Namely, the impact or highly transient nature of pile driving requires a sophisticated precaution for making the recorded accelerogram meaningful and tractable.

The situation is greatly improved if we can resort to strain gauges only, in view of their wide range of frequency responses as well as their facility of handling. Indeed, the method of two-point strain measurements (Lundberg and Henchoz, 1977) enables us to determine strain, particle velocity and energy transmission at an arbitrary section of a pile from the measurement of strains at two different sections of the pile (Fig. 1(b)). The key idea is to make use of the phase difference between the two gauge points and to separate the effects of the downward- and upward-travelling waves that may be present at the two sections.

In what follows, the theoretical basis of the method of two-point strain measurements will be outlined first. Then, the field performance of an offshore large-diameter steel pipe pile driven with a diesel hammer will be discussed, with emphasis on evaluating the energy transmitted to the pile.

Compressive stress and compressive strain are taken as positive throughout the paper.



a)Case Method b)Method of Two-Point Strain Measurements

Fig. 1 Hybrid Analysis Procedures for Pile Driving

THEORETICAL BASIS

The behaviour of an elastic pile during driving may be treated within the framework of the following wave equation:

$$\partial^2 u/\partial t^2 = c^2 \partial^2 u/\partial x^2 \tag{1}$$

Here, u is the longitudinal displacement, t is the time, x is the co-ordinate taken downward from the pile head, and c is the bar wave velocity given by

$$c=\sqrt{E/\rho} \quad (2)$$

in which E is Young's modulus and ρ is the mass density of the pile material.

The general solution to Eq. (1) takes the following form:

$$u(x,\ t)=u_d(x-ct)+u_u(x+ct) \quad (3)$$

Hereafter the subscripts d and u denote the physical quantities associated with the downward- and upward-travelling waves in the pile, respectively.

Let v and σ be the particle velocity and the axial stress, respectively. It then follows that

$$v=\partial u/\partial t=(c/E)\cdot(\sigma_d-\sigma_u) \quad (4)$$

The above relation means that when the amplitudes of the stress waves are known at an arbitrary section of a pile, the particle velocity at that section can readily be evaluated.

Let the stress waveform be measured at two different sections ($x=x_1$ and $x=x_2$) of a pile above the ground surface, and let T be the travelling time between the two sections. It then follows that

$$\sigma_d(x_2,\ t)=\sigma_d(x_1,\ t-T) \quad (5)$$

$$\sigma_u(x_2,\ t)=\sigma_u(x_1,\ t+T) \quad (6)$$

By considering the above relations along with the principle of superposition with respect to stress, we have the following basic equations for the method of two-point strain (or stress) measurements:

$$\sigma_d(x_1,\ t)=\sigma(x_1,\ t)-\sigma(x_2,\ t-T)+\sigma_d(x_1,\ t-2T) \quad (7)$$

$$\sigma_u(x_1,\ t)=\sigma(x_1,\ t)-\sigma_d(x_1,\ t) \quad (8)$$

In Eq. (7) the first term on the right-hand side represents the stress recorded at gauge point 1 at time t, and the second term represents the stress recorded at gauge point 2 at time t-T. Thus both terms are known at time t. The remaining term on the right-hand side of Eq. (7) becomes known in a successive way, with the aid of the fact that only the downward travelling wave is present in the pile at the very early stage of pile driving.

At the same time, we can readily evaluate $\sigma_u(x_1,\ t)$ from Eq. (8).

Stress, velocity and displacement at pile head

Let us put that $T_1=x_1/c$. Then, the stress at the pile head can be related to the stress amplitudes at gauge point 1, as follows:

$$\sigma(0,\ t)=\sigma_d(x_1,\ t+T_1)+\sigma_u(x_1,\ t-T_1) \quad (9)$$

Similarly, the particle velocity at the pile head can be expressed as

$$v(0,\ t)=(c/E)\cdot[\sigma_d(x_1,\ t+T_1)-\sigma_u(x_1,\ t-T_1)] \quad (10)$$

It is then straightforward to evaluate the pile-head displacement, $u_0(t)$, as follows:

$$u_0(t)=\int_0^t v(0,\ t')dt' \quad (11)$$

Energy transmitted to the pile

An important feature of the method of two-point strain measurements lies in that it permits us to evaluate the energy transmitted to the pile through the relation:

$$W(t)=\int_0^t \sigma(0,\ t')\cdot v(0,\ t')\cdot A\cdot dt' \quad (12)$$

along with Eqs. (9) and (10). In Eq. (12), A denotes the cross-sectional area of the pile.

OFFSHORE TEST PILING: A CASE STUDY

Outline of the offshore test piling

The offshore test piling discussed below was performed in 1986 with open-ended steel pipe piles, in association with the design of foundation piles for the access bridge that spans the Kansai International Airport island and the mainland (Fig. 2). It is noteworthy that both the airport island and the access bridge are being actively constructed, with the scheduled start of operation in 1993.

The stratification of the submarine deposit along the axis of the access bridge is indicated in Fig. 3. Note that the soil conditions are getting worse as the airport island is approached, owing principally to the increased thickness of the alluvial clay (A_c) and Pleistocene clays such as C_1, C_2 and so forth.

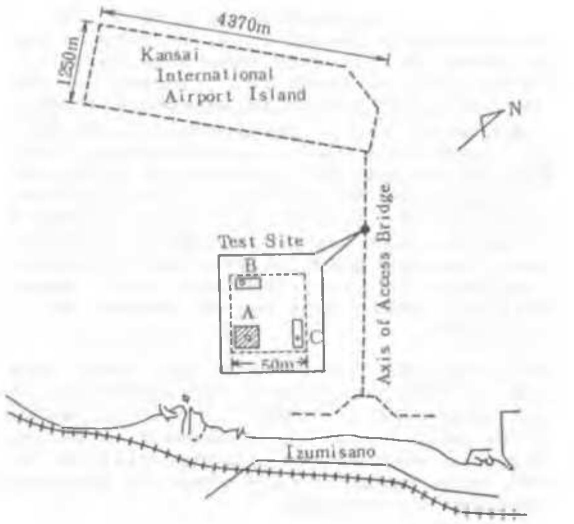


Fig. 2 Airport Island and Access Bridge in Osaka Bay, Japan

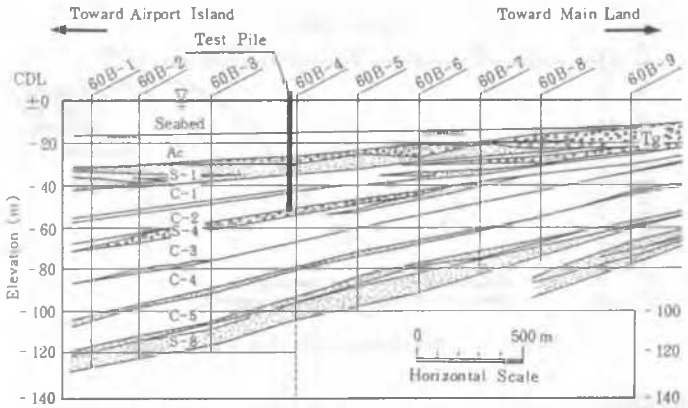


Fig. 3 Stratification along the Access Bridge

Of the three test pilings carried out, we take up the test piling designated as T_1 only. The dimension of the test pile may be summarized as follows: outer diameter=1.5 m; wall thickness=22 mm; and length=58 m. The test pile was instrumented with strain gauges (WFLA-6-IL) at a total of 12 sections, as shown in Fig. 4. Note that at each section of strain measurement, four strain gauges were mounted 90 degrees apart on the inner surface of the pile. Note also that the protection of the strain gauges using steel channels increased the cross-sectional area, A, of the test pile to 1171 cm^2.

The hammer used is a diesel hammer (MH-72B) that has a ram weighing 7.2 tf (70.6 kN). A cushion comprising synthetic rubbers with thin steel plates being spaced, was set in between the anvil and the pile cap.

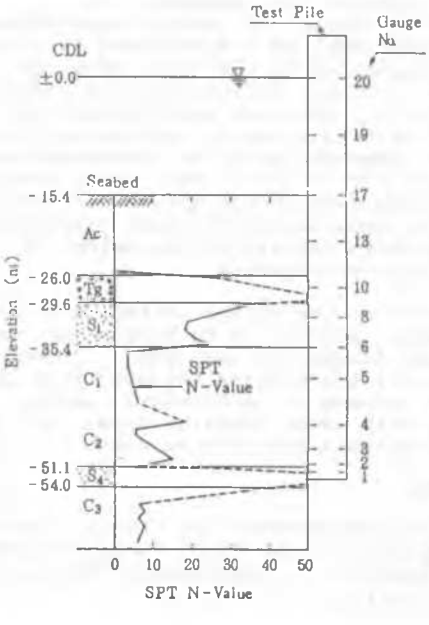


Fig. 4 Test Pile in Final Seating, together with Ground Conditions

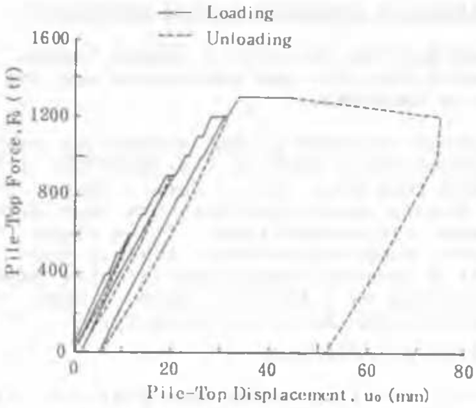


Fig. 5 Results of Static Test Loading

The final seating of the test pile was selected so that the point resistance of the relatively thin stratum of dense sand designated as S-4 may be evaluated, together with the assessment of the side resistance of the overlying soils (see Fig. 4). The bounce and set records at the last ten blows showed that the permanent set per blow, S, was equal to 2 mm whereas the rebound per blow, K, amounted to 7 mm. The corresponding stroke, h, of the hammer was equal to 2.39 m on average.

The static loading test performed 35 days after the final driving, showed that the test pile had an ultimate, axial bearing capacity of 1300 tf (12.7 MN), as illustrated in Fig. 5. Note that a larger portion of the bearing capacity was due to the shaft resistance, and the point resistance was only equal to 300 tf (2.9 MN).

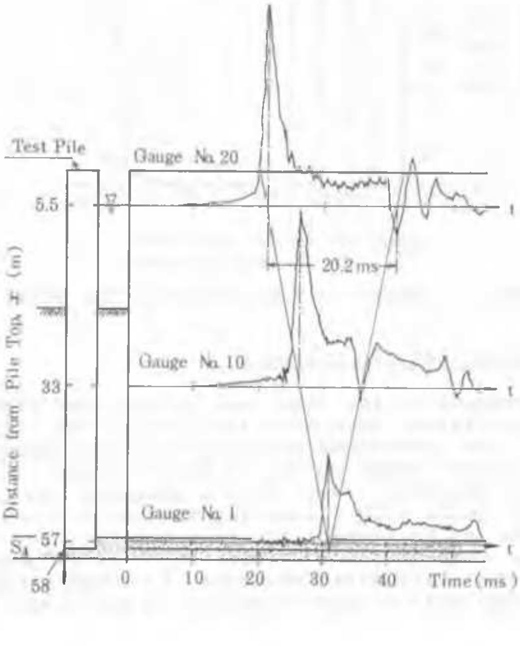


Fig. 6 Recorded Stress Waveforms

Examination of recorded stress waveforms

The peak driving force of a diesel hammer may be created when the gas combustion and the ram impact is combined.

The instant of such a peak stress can readily be identified on each of the recorded stress waveforms (see Fig. 6). Here, three time-stress traces associated with the last blow of the hammer are exemplified. It is clear that the peak compression wave travels down the pile at a constant speed and reflects back at the pile tip as a tension wave. Note that this permits the bar wave velocity, c, to be identified as 5200 m/s.

From Fig. 6 it is also seen that the first peak amplitude of stress tends to decay along the pile due to the soil resistance. This aspect is more clearly seen from Fig. 7. It is important here to discriminate that the sharp decay in the peak amplitude observed in the lower four meters of the test pile is due to the reflection of the precursing waves at the pile tip as the tension waves. This is readily understandable in view of the fact that the gas combustion is preceded by the gas compression phase; Indeed, the effects of such gas forces are well recognized on the stress waveforms shown in Fig. 6.

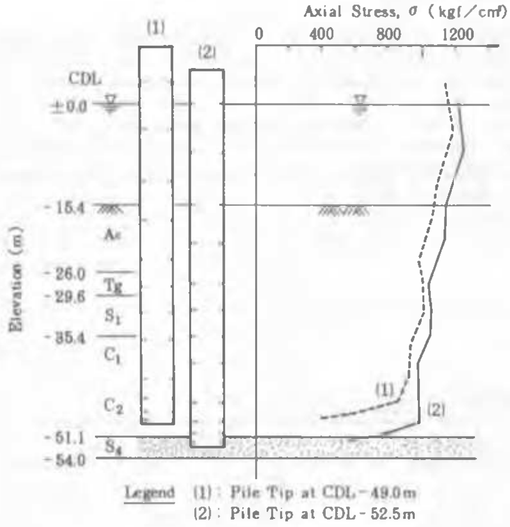


Fig. 7 Decay in Peak Stress along Pile

Assessment of pile movement

The movement of the pile head by the last blow is calculated here by using Eqs. (10) and (11). The waveforms selected are those measured at the gauge points 20 and 17 above the ground surface. The data processing on a digital basis with a sampling time of 0.1 ms, permits us to predict the pile movement in a manner such as shown in Fig. 8. It is seen that the calculated movement is compatible with what was directly measured in the field.

Assessment of energy transmission

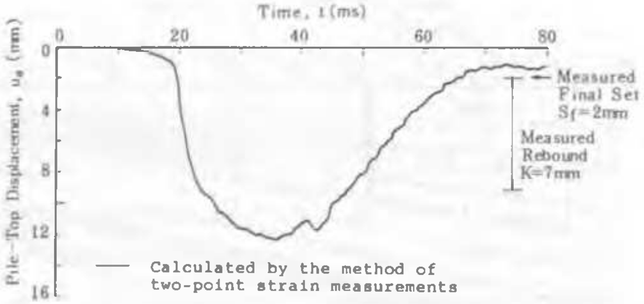


Fig. 8 Movement of the Pile Head

The energy transmitted to the pile is now calculated for the last blow, on the basis of Eqs. (9), (10) and (12). The calculated energy, W, divided by the potential energy of the hammer, Mgh, is shown in Fig. 9 against the elapsed time, t. It is seen that the energy actually transmitted to the pile is only 45% of the potential energy of the hammer.

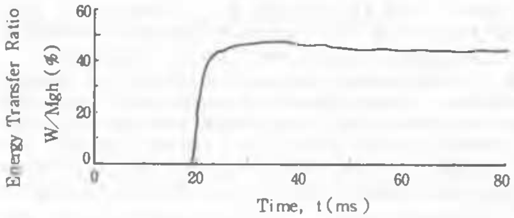


Fig. 9 Predicted Transmission of Energy

CONCLUDING REMARKS

The above finding regarding energy transmission has a practical implication. Consider Hiley's formula, for example. It is common practice in Japan to adopt manufacturer's rated energy (Mgh) as a substitute for the net energy transmitted to the pile from the diesel hammer. If one follows this procedure for the test pile, then one would obtain an estimate of bearing capacity as high as 3128 tf (30.7 MN), compared with the measured bearing capacity of 1300 tf (12.7 MN). Note here that such a large discrepancy can substantially be resolved by considering the real transmission of energy with the aid of the method of two-point strain measurements.

Also, note that the method of two-point strain measurements permits us to bypass the modelling of gas forces and cushions. Indeed, its capability of identifying the evolution of the pile-head stress is particularly useful when combined with more familiar types of wave-equation analysis for pile driving.

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