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NON LINEAR EFFECTS DURING DYNAMIC LOADING ON PILES

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ABSTRACT

Low and high-strain dynamic loading tests were carried on large diameter piles, bored on very compressible soil. It was possible to analyze the low-strain tests in terms of pile-head impedance, while the results of high-strain tests have pointed out the effects of non-linearity during loading. Such effects can be associated to pile stiffness and damping modification and to soil-pile separation at large strain.

KEYWORDS

dynamic pile testing; impedance; admittance; low-strain; high-strain.

INTRODUCTION

In the last decades, dynamic soil-foundation interaction problems have been closely examined by means of simplified and rigorous models. Two main interaction problems can be pointed out depending whether the dynamic vibrations are directly applied to the foundation or to the surrounding soil. In the first case a complete conventional dynamic analysis can be performed by employing an elastic half-space model (Richart et al, 1970), whereas in the second, two different kinematic and inertial interaction aspects must be considered (Fan et al, 1991; Kavvadas and Gazetas, 1993). With reference to dynamic loading applied to the foundations, impedance functions are largely employed. These account for dynamic equivalent stiffness and damping related to geometry and displacements of foundation and, finally, to soil and foundation mechanical properties. In the paper some steady-state vibration tests results on large diameter bored piles are shown. Both low and high-strain level were investigated. Test results show some non-linear strain-dependent effects during the dynamic loading of the pile.

SOIL-FOUNDATION INTERACTION ANALYSIS: THEORETICAL APPROACHES

With reference to pile-head applied loading, some approaches are available. The early studies are referred to a Winkler soil model, characterized by independent distributed springs and dashpots to account for soil dynamic reaction along the pile shaft. Later Liou and Penzien (1980) have employed the Mindlin solution, in order to describe more carefully the Winkler medium. The most recent approaches are based upon elastic-dynamic theories capable of reproducing the main effects of the dynamic interaction in a more realistic way; in this field three analytical methodologies have been mainly developed. The first approach is based upon simplified theories, which can be derived from continuum (Novak, 1974; Novak and El Sharnouby, 1983) or discrete approach (Gazetas, 1991; Gazetas and Dobry, 1984).

The second approach is based upon the finite element method (FEM) (Blaney et al, 1976; Wolf and Von Arx, 1978; Roesset and Angelides, 1980). The whole soil-pile system is divided into two cylindrical fields, near-field and far-field, capable of reproducing energy absorption at the boundary of the model. The third approach employs a rigorous continuum model in order to reach an appropriate Green function which represents, in the dynamic field, the equivalent of Mindlin static solution. This procedure is based on the boundary element method (BEM) in order to obtain the displacement field induced by uniformly distributed load on cylindrical surface (Kaynia and Kausel, 1982; Sen et al, 1985; Mamoon et al, 1990). Apart from the type of approach used in the dynamic soil-pile interaction analysis, the aim is to provide the impedance-matrix of single pile head in the following form:

$$|\overline{K}| = \begin{vmatrix} \overline{K}_{xx} & \overline{K}_{x\varphi} & 0 \\ \overline{K}_{\varphi x} & \overline{K}_{\varphi\varphi} & 0 \\ 0 & 0 & \overline{K}_{zz} \end{vmatrix}$$

which links complex loading $\overline{T}$, $\overline{M}$, $\overline{N}$ applied to pile head, to complex head displacements $\overline{x}$, $\overline{\varphi}$, $\overline{z}$. Each element of the impedance matrix is a complex function of the frequency, according to the following expression:

$$\overline{K}_{ij} = K_{ij} + i\omega C_{ij}$$

being K_{ij} the dynamic stiffness, C_{ij} the damping and ω the angular frequency. Dynamic stiffness and damping generally depend on loading frequency; however they are also strongly dependent on loading level, due to non-linearity effects occurred near the pile head during strong horizontal loading.

GEOTECHNICAL INVESTIGATION AND DYNAMIC TESTS ON PILES

Dynamic loading tests were performed on some piles of the Livorno-Civitavecchia highway (Tuscany, Italy) along the Coltano viaduct (Carrubba et al, 1994). The site is constituted by marshy clays affected by very poor mechanical properties. Geotechnical investigations have shown a static penetrometric resistance smaller than q_c = 0,5 MPa, till to 16 meters below the ground. Resistance values of the order of q_c = 1,0 MPa are reached at a depth of 24,0 m from the ground (fig.1). Due to a very poor strength and compressibility of the sediments, large diameter bored piles were employed. The piles ϕ 1,200 mm in diameter and 58 m in length, are provided with a sheet-steel along the first 20 m in order to mitigate any negative skin friction induced by the consolidation of the less consistent upper soils. During the preliminary investigation at the Coltano site, a ϕ 1,200 mm in diameter and 60 m in length pile-test was built (fig.1), in order to perform a loading test non carried to failure. Later a high strain horizontal dynamic loading test was performed on the same pile. Some vertical low-strain dynamic loading tests were performed on the neighbour similar piles. The horizontal high-strain dynamic tests were carried out by means of a 20 KN vibrodina with variable angle masses and operating frequency between 0 and 25 Hz. The induced dynamic loading in the horizontal direction is of sinusoidal type, with amplitude F related to the out-of-phase β angle between the eccentric masses and to the frequency of rotation, f, according to the expression:

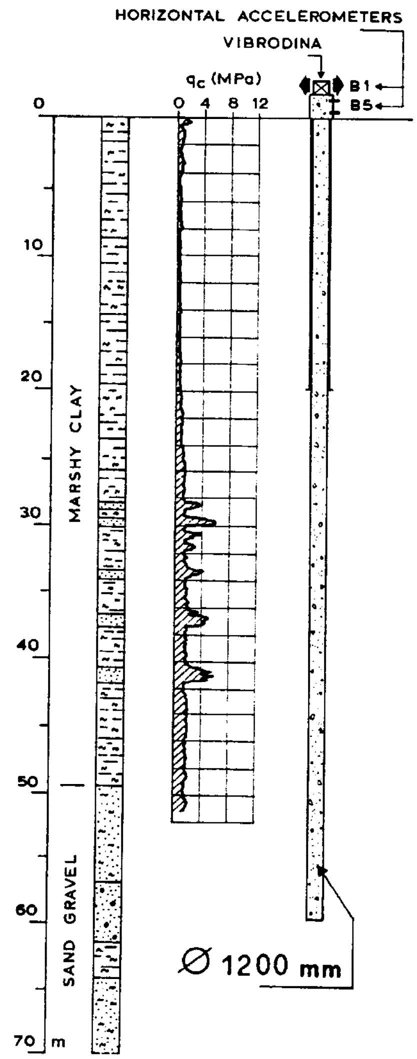

Fig.1 - Geotechnical properties of soils at the Coltano site

$$F = 1{,}026\ f^2 \cos(\beta / 2)$$

From an operative point of view a β angle equal to 176° was imposed, so an horizontal maximum loading of the order of 20 KN was reached. The horizontal dynamic response of the pile head was monitored by means of two horizontal one-dimensional accelerometers, B1 and B5, with 0,1 cm/s^2 sensitivity. Low-strain vertical dynamic loading tests were performed in terms of vertical admittance. An impulsive loading was applied to the pile head and the response was analyzed in the frequency domain.

INTERPRETATION OF THE VIBRATION TESTS

In fig.2 some results of low-strain vertical vibration tests, in terms of axial admittance versus frequency, are shown.

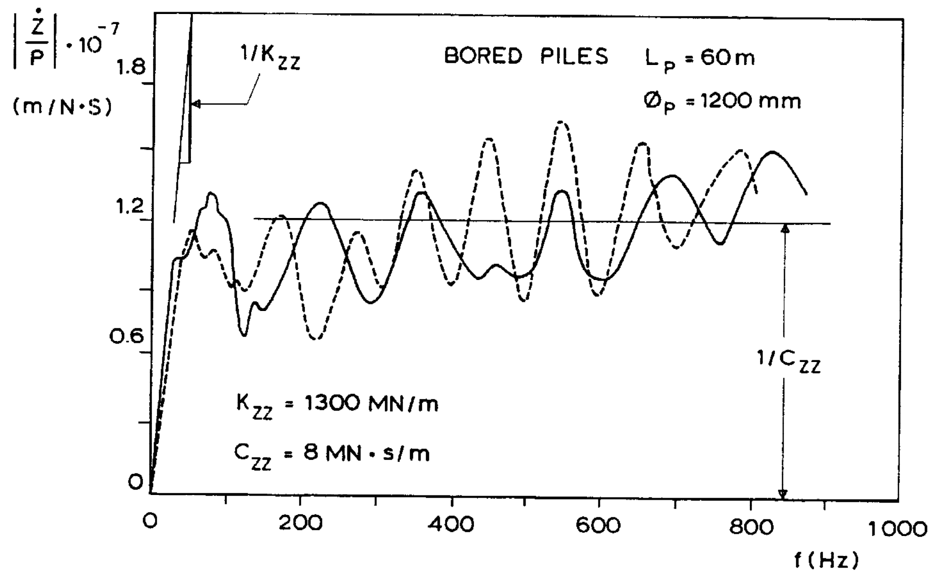

Fig.2 - Vertical admittance test results on ϕ 1200 mm piles

The ratio between vertical head velocity $\dot{Z}$ and head load P with frequency, provides the vertical admittance profile of the pile; as shown by Carrubba and Maugeri (1995) the latter can be interpreted in a simplified form, in terms of pile-head impedance. In this case the foundation can be compared to an equivalent massless simple damped oscillator; according to this model the following expression was obtained:

$$\left|\frac{\dot{Z}(t)}{P(t)}\right| = \frac{\omega}{\sqrt{K_{zz}^2 + C_{zz}^2\,\omega^2}} \tag{1}$$

From the experimental data reported in fig.2, the following parameters have been evaluated:

$K_{zz} \cong 1300$ MN/m $\qquad$ $C_{zz} \cong 8$ MN · S/m

The initial stiffness obtained from the static vertical loading test (fig.3) is in a well agreement with the dynamic stiffness: in this case a value of $K_{zz} \cong 1150$ MN/m was obtained. Due to linear-elastic behaviour of the piles at low strain, the equivalent massless simple oscillator model shows roughly constant impedance components K_{zz} and C_{zz} with frequency. In this case, the Novak pile-head impedance approach can be employed:

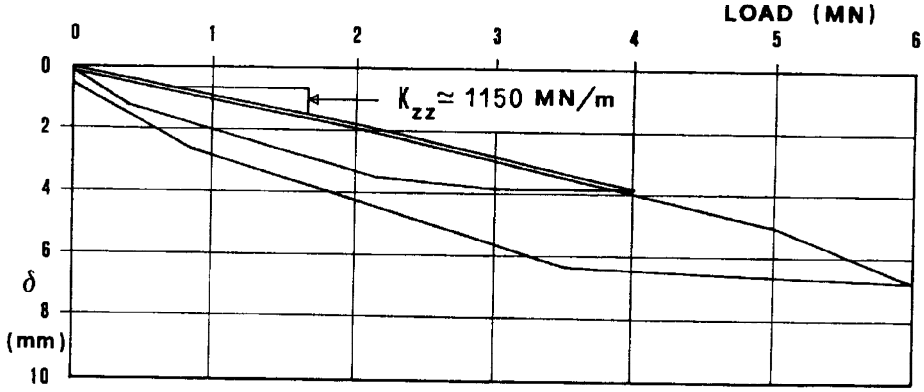

Fig.3 - Vertical static load test on ϕ 1200 mm pile

$$K_{zz} = \frac{E_p A_p}{R_p} f_{v1} \qquad\qquad C_{zz} = \frac{E_p A_p}{V_s} f_{v2}$$

being E_p, A_p, R_p the longitudinal modulus, the cross section and the radius of the pile respectively. For the shear stress wave in the soil V_s a parabolic distribution with depth was assumed, while f_{v1} and f_{v2} are two dimensionless stiffness and damping function. For $E_p \cong 2{,}5 \cdot 10^4$ MN/m^2, $A_p \cong 1{,}13$ m^2, $R_p \cong 0{,}60$ m , $V_s \cong$ 200 m/s, $f_{v1} \cong 0{,}03$, $f_{v2} \cong 0{,}05$ the following values have been obtained:

$$K_{zz} \cong 1400 \text{ MN/m} \qquad\qquad C_{zz} \cong 7 \text{ MN} \cdot \text{S/m}$$

which are in a good agreement with the experimental ones. Results of horizontal high-strain dynamic tests are shown in fig.4 in terms of horizontal response spectrum; the latter have been obtained as the ratio between horizontal acceleration $\ddot{x}$ and load H versus frequency. The extension of the impedance approach to the horizontal loading case can be made in terms of massless simple damped oscillator again; so we have:

$$\left|\frac{\ddot{x}(t)}{H(t)}\right| = \frac{\omega^2}{\sqrt{K_{HH}^2 + C_{HH}^2\,\omega^2}} \qquad (2)$$

The stiffness K_{HH} and damping C_{HH} parameters are related to the free-rotate and translate pile-head condition. At this regard the Novak approach provides:

$$K_{HH} = \frac{E_p J_p}{R_p^3} f_{H1} \qquad\qquad C_{HH} = \frac{E_p J_p}{R_p^2 V_s} f_{H2}$$

with J_p moment of inertia of the pile and f_{H1}, f_{H2} two dimensionless stiffness and damping functions. For this problem f_{H1} = 0,0035 and f_{H2} = 0,009 have been estimated, and $K_{HH} \cong 40$ MN/m and $C_{HH} \cong 0{,}30$ MN·S/m evaluated. Equation (2) is drawn in fig.5 together with the horizontal response spectrum of accelerometer B5.

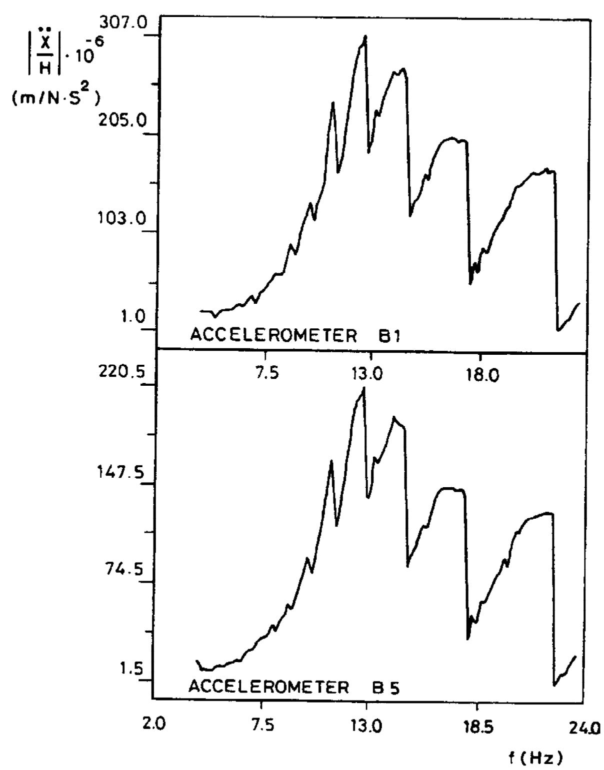

Fig.4 - High-strain horizontal response spectra of ϕ 1200 mm pile

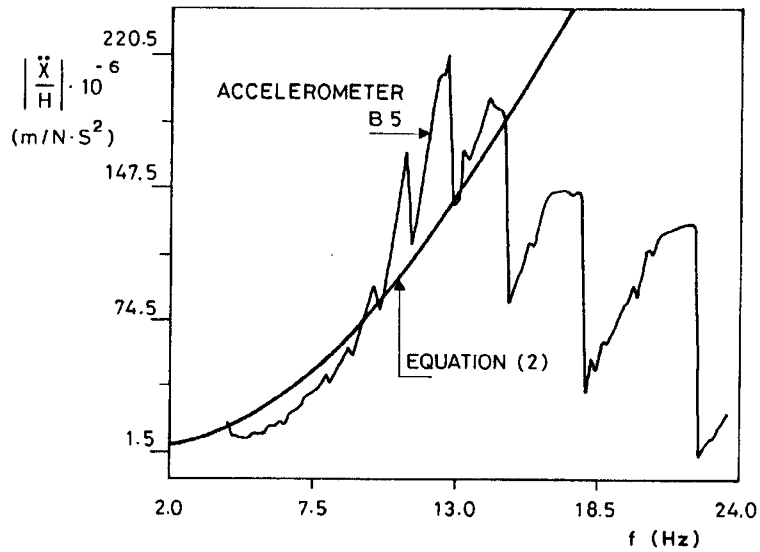

Fig.5 - Comparison between low and high strain horizontal response spectra of ϕ 1200 mm pile

It can be noticed a good agreement at low frequencies, where the induced dynamic loads are related to low pile displacements. For more relevant dynamic loads and displacements, the extension of the impedance approach to the pile-head loading requires the introduction of a simple damped oscillator with mass, in order to model the response amplification and the decay with frequency. In this case we have (fig.6).

$$\left|\frac{\ddot{x}(t)}{H(t)}\right| = \frac{\omega^2}{\sqrt{\left[K_{HH} - M\omega^2\right]^2 + C_{HH}^2\,\omega^2}} \tag{3}$$

being the mass M related to the relative soil-pile separation during vibrations. The linear-elastic approach is no more correct and both K_{HH} and C_{HH} may modify with stress-level. According to equation (3), as load increases with frequency, the modification of K_{HH}, C_{HH} and M leads to new equivalent simple damped oscillators, with a response envelope similar to the response spectrum of fig.5.

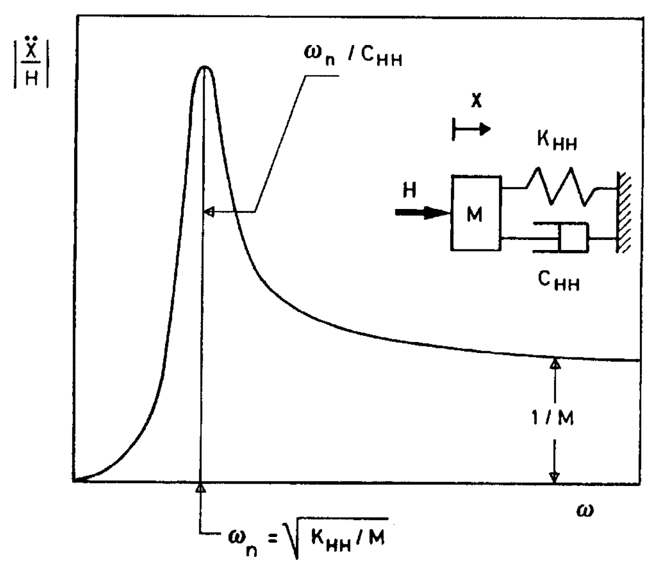

Fig.6 - Qualitative response spectrum of damped simple oscillator with mass

CONCLUSION

The dynamic behaviour of a large diameter bored pile has been analyzed by means of low and high strain loading tests. The behaviour at small strain can be well predict in terms of head impedance, with constant stiffness and damping with frequency. In this case a linear-elastic theory, as that one proposed by Novak and El Sharnouby (1983), gives a good estimation of the pile stiffness and damping. When more relevant pile displacements are mobilized, non linear effects are shown. In this case the impedance must be defined in terms of equivalent damped oscillator with mass, in order to account for dynamic response increment and reduction with frequency. As loads increase, the non linear effects are mainly induced by relative soil-pile separation, mass and stiffness variation and damping growth.

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