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Cyclic Mobility Effects on Soil-Pile Interaction in Dense Sand

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SYNOPSIS: A methodology to evaluate the effects of earthquake-induced cyclic mobility in dense sand on the soil-pile interaction parameters is presented. The soil behavior under cyclic loading is defined based on the interpretation of consolidated-undrained cyclic triaxial tests on samples reconstituted to the in situ relative density and shear wave velocity. The stress distribution around the pile is determined analytically, and the softened zone is modelled by an annulus of softer soil. The application of this methodology for the design of three submerged-floating tunnels in the Messina Straits, Italy, indicated that even in dense sand the foundation stiffness reduction can be considerable during an earthquake. Comparisons with different approaches available from the literature are discussed.

INTRODUCTION

Pore pressure build up due to seismic shaking may lead loose-contractive saturated sands to complete liquefaction and collapse. On the contrary, in dense sands the soil tendency to dilate when sheared prevents complete liquefaction and sudden strength loss from occurring. However, even dense soils soften due to cyclic mobility effects, and gradually increasing permanent deformations in slopes and foundations are possible (Pelli et al., 1994). Furthermore the soil stiffness reduction associated with pore pressure build-up gradually modifies the seismic behavior of the soil-structure system towards lower frequency values.

In this paper the methodology adopted to evaluate the effects of cyclic mobility on the soil-pile interaction parameters in the Messina Straits, Italy, is presented. The method was applied for the design of three large submerged-floating tunnels linking Sicily to the Italian mainland, held to the seabottom by tethers anchored by large diameter steel piles. The Messina Straits soil is generally composed of dense, gravelly sand.

The method is based on two separate steps. The first step consists of defining the soil susceptibility to softening during a seismic event by using a combination of both field and laboratory tests (as described by Pelli et al., 1995). The testing procedure consists of performing cyclic triaxial tests on specimens reconstituted to match both soil relative density and shear wave velocities as measured in the field (Tokimatsu et al., 1986). The second step, which is the object of this paper, consists of modelling the soil-pile interaction mechanism considering the effects of cyclic mobility. A method for the evaluation of soil-pile interaction changes due to pore pressure build-up was developed by Kagawa and Kraft (1981), whereas rule of thumb reduction factors for lateral coefficients of subgrade reaction are adopted in Japan for bridge design (Iwasaki, 1986). A comparison of these approaches with the proposed method is presented below.

The cyclic mobility effects around piles arise from two separate mechanisms: seismic loading in free field conditions (i.e. without considering the presence of the structure), and pile-soil interaction loading in the near field (i.e. localized, near pile loading depending on the structure seismic response). The free field mechanism involves softening of the whole soil layer susceptible to cyclic mobility. On the other hand, the near field interaction effects, which are often neglected in current design, are only relevant for a small soil volume around the pile, which may however notably affect the foundation behavior.

FREE FIELD EFFECTS

Dense soils tend to soften gradually when cycled in undrained triaxial conditions with a constant applied maximum stress ratio ($\sigma_d/2\sigma_c'$). As shown by Yoshimi et al. (1984) for a dense Niigata sand, the soil stiffness tends to become very small at low stress levels where a 100 per cent pore pressure ratio develops. As soon as the stress is increased, the soil tends to dilate causing a pore pressure reduction, and consequently the soil stiffness increases rapidly.

This complex behavior that controls soil stiffness during cyclic loading can be simplified by considering a linear equivalent modulus, varying depending on the magnitude of the cyclic stress ratio and on the number of cycles applied to the specimen. By adopting this simplifying assumption, the soil stiffness can be related to the ratio between the maximum applied deviatoric stress, σ_d, and the double amplitude axial strain ε_{DA}. At each subsequent cycle a lower soil modulus is recorded.

The modulus reduction due to cyclic mobility was defined as the ratio between the double amplitude axial strain measured at the seventh stress cycle, ε_{DA-7}, and the strain measured at the first cycles, ε_{DA-1}. These particular stress cycles were selected as the extreme seismic event considered for design in the Messina Straits is a near field earthquake, and seven equivalent stress cycles have been assumed for its characterization.

In Figs 1a and 1b examples of the experimental data are plotted as $\sigma_d/2\sigma_c'$ vs ε_{DA} diagrams. Curves are fit to the data obtained at the first and at the seventh stress cycle. Complete testing data is presented by Pelli et al., (1995). At very small strains ($\varepsilon_{DA} = 10^{-5}$), the gradient of all curves is known, as it was measured during the first stage of the tests to match field conditions (Pelli et al., 1995). It can be observed that at low stress levels the data obtained at one and seven stress cycles coincide, meaning that no cyclic mobility is developing; at higher stresses the two curves diverge markedly.

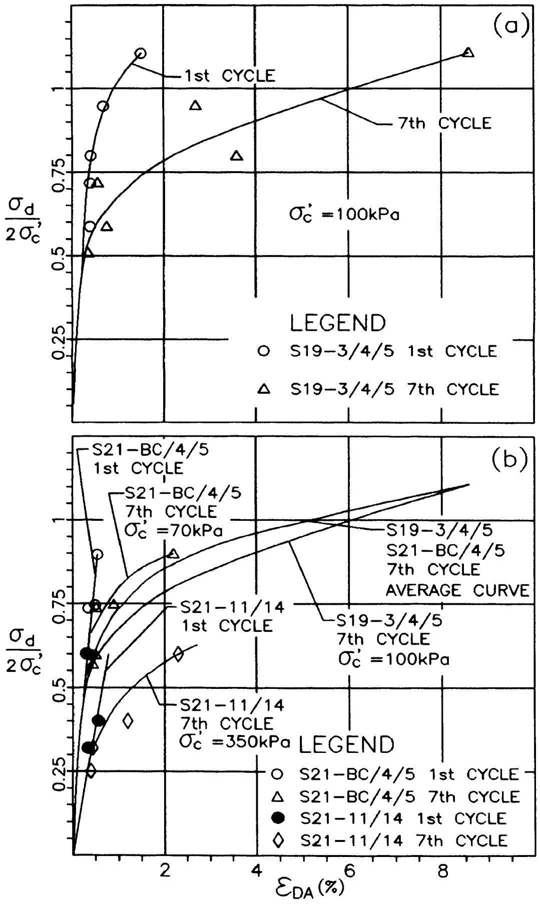

Fig. 1 Results of CU cyclic triaxial tests at 1 and 7 stress cycles: a) Sample S19-3/4/5, b) Samples S21-BC/4/5 and S21-11/14

Based on these curves the initial stiffness reduction factors shown in Fig. 2 (free field line) were developed. The top 15-20 meters were found to be the most relevant for pile soil interaction, while limited stiffness reduction at larger depths have no practical implications.

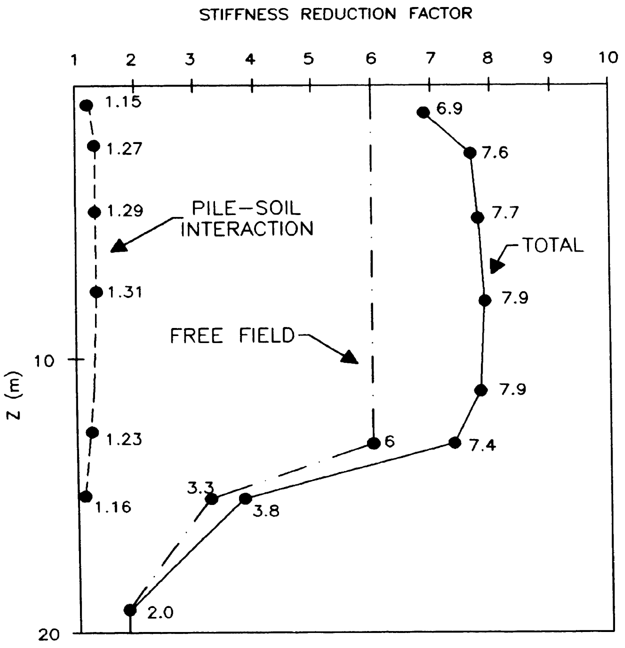

Fig. 2 Initial Stiffness Reduction Factors

LATERAL SOIL-PILE INTERACTION

Softening of the lateral soil-pile interaction parameters (P-Y) induced by local cyclic mobility was estimated based on the theoretical study of lateral reaction mechanisms of piles by Baguelin et al. (1977). The effects of radial pore pressure dissipation (Martin et al., 1980) were found to be minor, due to the large pile diameter (2.5 meters). Therefore they were conservatively neglected.

The soil surrounding the pile is assumed subdivided into two separate zones (Fig. 3): a radial disturbance zone within which the local interaction effects are relevant in terms of induced cyclic mobility, and an external zone where the local effects are not relevant and a free field condition can be assumed. The original elastic modulus (with no cyclic mobility effects) in the free field was back calculated at several depths from the solution given by Baguelin et al. (1977) by comparison with the API P-Y curves at low displacement levels, assuming no disturbed zone and taking Poisson's ratio equal to 0.5. A fraction of the original modulus (see Fig. 2), was then applied to the free field zone as E_{ff} (i.e. representative of cyclic mobility effects).

For the Messina Straits project the dynamic interaction analyses indicated much higher loads at the soil-pile interface than obtainable by cyclic triaxial testing. Thefore a limiting value of γ_{cyc} equal to 10 per cent was assumed to characterize the near pile disturbance zone between zero and 15m of depth based on Seed et al. (1985). On the other hand, in the laboratory a reduction by 5-6 times of the elastic modulus was obtained for equivalent γ_{cyc} values of approximately 6.5 per cent, which is applicable at the boundary of the disturbance zone. Therefore the ratio $\alpha = E_{dz}/E_{ff}$ was set conservatively equal to 0.6.

In order to estimate the radius of the disturbed zone, the following parameters must be defined: 1) horizontal force per unit length, T, transmitted by the pile to the soil at each depth; 2) the average stress ratio $\sigma_d/2\sigma_o'$ at the pile-soil interface and at various distances from the pile; 3) stress ratio below which free field conditions can be assumed.

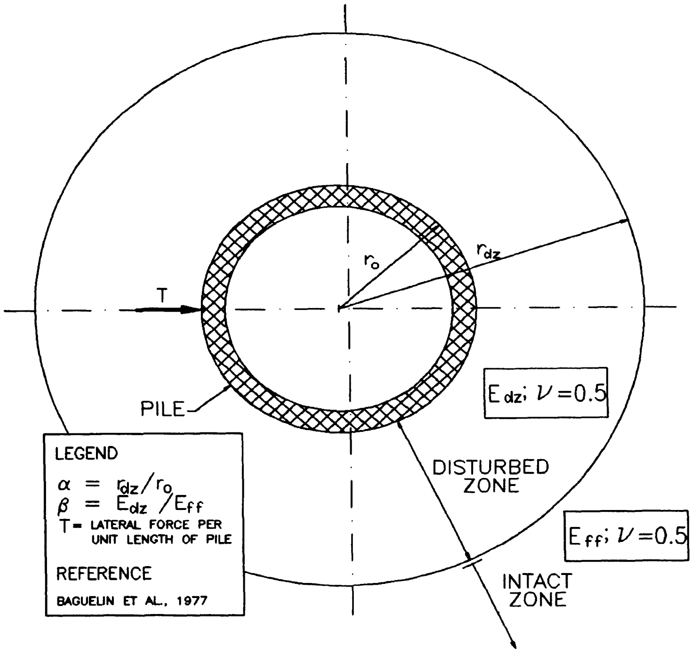

Fig. 3 Model of Near Pile Disturbance

The pile-soil horizontal forces resulting from dynamic numerical analyses were adopted, and $\sigma_d = T / 2r_o$ was assumed conservatively at the soil-pile interface.

The average stress ratios

$$(\sigma_d/2\sigma_o')_{ave}=0.65(\sigma_d/2\sigma_o')_{max} \qquad (1)$$

at various distances from the pile were estimated based on the near pile stress distributions given by Baguelin et al. (1977), and assuming K_o = 0.8 (API, 1991). A limit stress ratio value of approximately one was adopted based on the laboratory results to define the boundary between the disturbed zone and the free field domain.

The results of the analyses are summarized in Fig. 2, where the initial stiffness reduction factors obtained for free field conditions and local soil-pile interaction (dotted lines) and the resulting global reduction factor (solid line) are plotted versus depth. Most reduction takes place between zero and 15 meters whereas small effects are found at larger depth. Note that the group effect is not explicitly accounted for, but it can be considered by retaining an appropriate stiffness reduction factor.

In order to introduce soil softening in the soil-pile interaction analyses, the backbone P-Y curves adopted for the response analyses had to be properly modified. For the Messina Straits project the equivalent modulus found on the basis of the laboratory tests was consistent with the stress levels anticipated in free field conditions. On the contrary the stress levels anticipated in proximity to the pile were by far higher than reached during the tests. Extending this modulus up to failure (i.e. shifting towards larger displacement values the P-Y curve) is excessively conservative as stiffening associated with dilation is a well known phenomenon and has been observed both in the laboratory (e.g. Yoshimi et al., 1984) and during cyclic horizontal loading tests on real size piles (e.g., Ting, 1987). Therefore the increase in displacement at the pile top was computed by adopting the P-Y curves obtained at Mustang Island by Reese et al. (1974), which allow a decrease in the initial modulus of subgrade reaction while maintaining the shape of the curve for lateral displacements larger than 1/60 pile diameters constant. Then the stiffness reduction factor to be applied to the bilinear curves adopted to model pile-soil interaction in the numerical models were back calculated (Fig. 4).

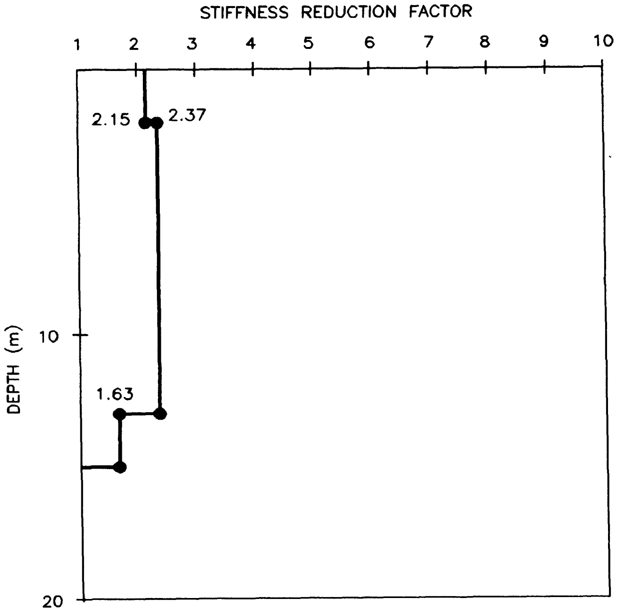

Fig. 4 Equivalent Stiffness Reduction Factors for Bilinear P-Y Curves

These reduction factors correspond to a shift of the curve towards larger displacement values, and can be compared with the numbers based on existing methodologies (Kagawa and Kraft, 1981; Iwasaki, 1986). Assuming an average pore pressure ratio of 0.8, which is representative of the cyclic tests on the Messina Straits sand, and adopting Kagawa and Kraft's criterion, a reduction factor of 2.2 results which is close to the value computed here. Note, however, that for a different number of cycles the equivalent modulus would change without affecting the average pore pressure (Fig. 1) and this variation would not be considered by the Kagawa and Kraft criterion. For the same pore pressure ratio the recommendations provided by Iwasaki

(1986) provide a modulus reduction factor of 1.5 for linear elastic interaction parameters, which is a little stiffer but not very different from what found in this study.

The results of the analyses carried out based on the API (1991) P-Y curves and on the reduction factors depicted in Fig. 4, are shown in Fig. 5.

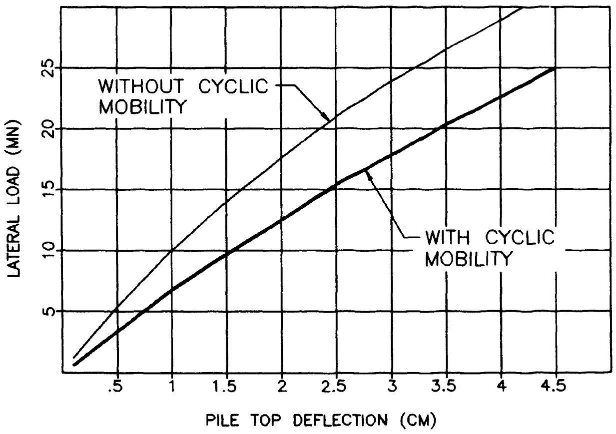

Fig. 5 Effect of Stiffness Reduction on Lateral Load-Displacement Curve

CONCLUSIONS

Based on the discussion presented above the following conclusions can be drawn:

1) The application of the methodology described in this paper for the Messina Straits project indicated that even in dense sand the foundation stiffness reduction can be relevant during strong motion earthquakes.
2) The near field effects cannot be neglected in many cases as the forces trasmitted by the pile to the surrounding soil may exceed considerably the seismic loads in the free field.
3) The analytical approaches available from the literature tend to relate the soil stiffness directly to the excess pore pressure developing during the earthquake. In dense sand an approach based on deformations, cyclic stress ratios and number of cycles is more appropriate and easily applicable for design.
4) Soil stiffness, pore pressure build-up, soil pile interaction response and structure seismic responsed are mutually related. Therefore the methodology should be applied iteratively to find the equivalent foundation stiffness giving consistent interaction forces and soil properties.

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