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SYNOPSIS The method adopted for the evaluation of the soil liquefaction potential in the Messina Straits, Italy, is presented and the results are discussed. The study was carried out for the design of three submerged floating tunnels linking Sicily to the Italian mainland. The method is based on a combined approach where field measurements are used to partly re-create the original soil fabric in the specimens for cyclic laboratory tests. The method is suitable for offshore investigations where recovery of truly undisturbed samples is hardly possible. The results show that in this way a much higher resistance to liquefaction is predicted than from conventional laboratory tests. The results of indirect methods based only on CPT records or shear wave velocity measurements in the field are presented first, and their limitations that led to the selection of an improved laboratory testing program are outlined.

INTRODUCTION

The recovery of truly undisturbed samples for soil liquefaction studies is very difficult, particularly in deep offshore waters where techniques such as in situ soil freezing (e.g., Sego et al., 1993; Yoshimi, et al., 1994) are hardly possible at present. Often even the use of thin walled piston samplers is not possible due to the presence of gravel and cobbles, and heavy dynamic samplers have to be adopted. On the other hand, it is well known that reconstituting the samples at the estimated in situ relative density is not sufficient to obtain representative results in most soils because the original soil fabric, which is completely lost, has a sensible, sometimes dramatic effect on the soil cyclic behavior.

In this paper, the method adopted for the evaluation of the soil liquefaction potential in the Messina Straits, Italy, is presented, and the results are discussed. The study was carried out for the design of three submerged-floating tunnels linking Sicily to the Italian mainland, held to the sea bottom by tethers anchored through large diameter steel piles. The Messina Straits soil is generally composed of dense, gravelly sand, and the results presented refer to data collected near the Calabria shore. The method discussed herein, which was developed by Tokimatsu et al. (1986), involves a combined use of the available in situ measurements (tip cone resistance q_c and shear wave velocity V_s) and of improved consolidated-undrained cyclic triaxial tests. The cyclic tests were carried out on samples reconstituted to match both the in situ relative densities and shear wave velocities with the purpose of partly re-creating the original soil fabric.

The results obtained by the proposed method are compared with conventional cyclic triaxial tests, where only the in situ relative densities were matched during sample preparation. The results of liquefaction potential evaluations based on field measurements alone are presented first, and their limitations that led to the selection of an improved laboratory testing program are outlined.

LIQUEFACTION POTENTIAL EVALUATIONS BY FIELD TESTS ALONE

The correlations developed by Robertson and Campanella (1985) and Tokimatsu and Uchida (1990), based respectively on q_c and V_s, were applied in the Messina Straits. The required input data were obtained from seismic cone records and from laboratory classification tests, and the results are presented in Fig. 1. In several cases potentially liquefiable zones were detected at considerable depth, where occurrence of liquefaction seems unrealistic. This may be due to the presence of fine rich zones which remained undetected during sampling. Both cone resistances and shear wave velocities predicted liquefaction zones of different extent, but no reliable indication on the strain level which may develop in the dense Messina soil is possible from this data alone.

Therefore, in order to obtain quantitative information on the potential cyclic mobility effects and on the resulting deformations, the improved laboratory testing program described below was undertaken.

IMPROVED CYCLIC TESTS: METHODOLOGY

The tests were carried out at the Tokyo Institute of Technology adopting the procedure developed by Tokimatsu et al. (1986). The procedure (see Fig. 2) consists of reconstituting the specimens in the laboratory in such a way that their elastic shear modulus and dry unit weight are equal to the in situ values estimated from field tests. It is based on the principle that reconstituted specimens having the same elastic shear modulus and dry unit weight as the soil in situ would also

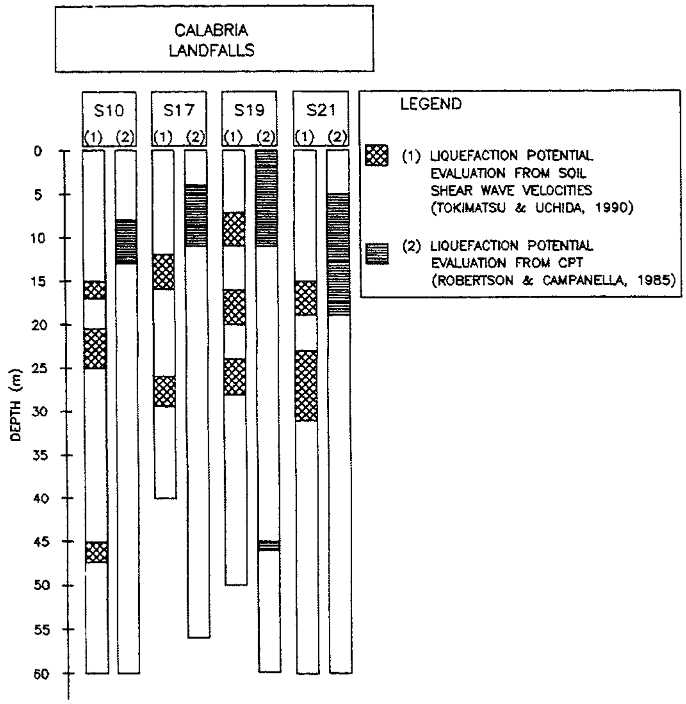
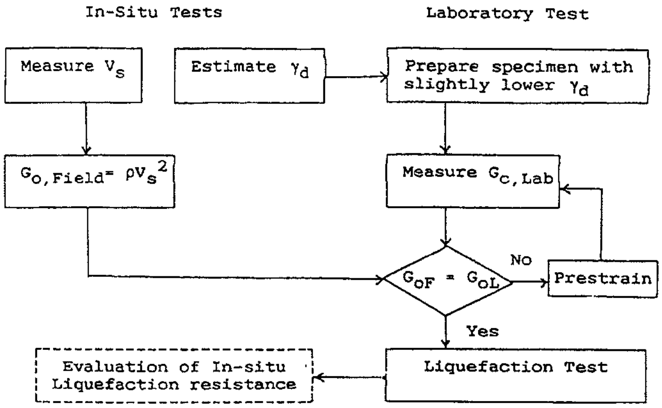


Fig. 1 Results of Liquefaction Potential Evaluations by Indirect Methods

retain their original liquefaction resistance (Tokimatsu et al., 1986; 1988).

Two test apparatuses were used. Each triaxial cell was equipped with a load transducer and two pairs of gap sensors, so that the elastic shear modulus of the specimens could be measured at any stage of the test.

The specimens were formed in a mold by the pluviation-through-air-method at a dry unit weight sligthly lower than the specified value. Saturation was obtained with the aid of CO_2 gas, applying a back pressure up to 400 kPa, and a confining pressure of 30 kPa. The specimens were then consolidated and subjected to one or more series of 10,000 cycles of deviator stress, at a frequency of either 1 or 2 Hz under drained conditions. The cycles generated a double amplitude axial strain on the order of 0.1 %, and the cycle series were repeated until the required elastic modulus was obtained. At the end of each series of cycles the specimens were consolidated for about two hours to allow stabilization of the elastic modulus; then the specimen modulus was measured by cyclically changing the axial stress under undrained conditions, and inducing in the samples shear deformations on the order 10^{-5}. This shear modulus was compared with the shear wave velocity measured in the field, which is representative of strain levels on the order of 10^{-6}, also considering the G/G_{max} curves obtained by resonant column tests.



NOTE: G_{OF} AND G_{OL} OBTAINED AT STRESS LEVELS OF 10^{-6} AND 10^{-5} RESPECTIVELY.

Fig. 2. Outline of Testing Procedure

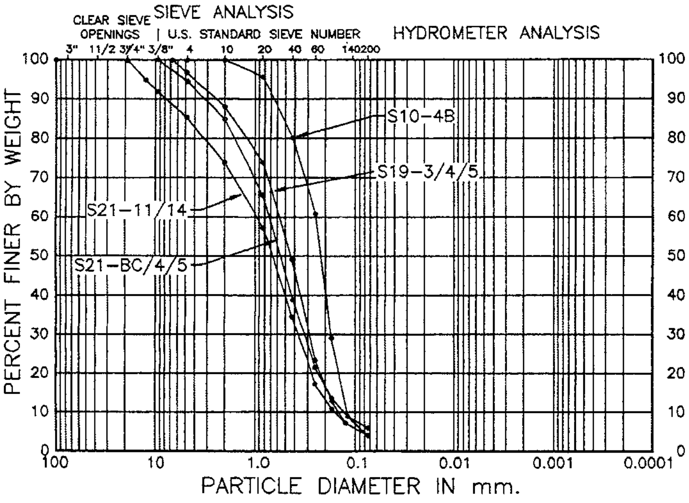


Fig. 3. Grain Size Curves of Samples Used for the Improved Tests

SAMPLE	DEPTH (m)	γ_d (1,2) (kN/m^3)	$G_{0,F}$ (1) (MPa)	$G_{0,L}$ (2) (MPa)	σ_c' (2) (kPa)
S10-4B	11-12	15.6	120	92	110
S19-3/4/5	7-12	16.3	82.5	70	100
S21-BC/4/5	3-11	16.2	106	85	70
S21-11/14	35-50	16.8	225	180	350

(1) Estimated from field measurements.
(2) Adopted in the laboratory.

Table I. Main Characteristics of the Tested Samples

IMPROVED CYCLIC TESTS: RESULTS

In total 20 specimens were tested, obtained from 4 samples recovered at 4 different locations. The grain size curves are shown in Fig. 3, and the main sample characteristics are listed in Table I. The soil relative density, estimated conservatively from CPT records, varied between 65 and 78 per cent, where the applied confining pressure σ_c' was varied, depending on sample depth, between 70 and 350 kPa.

The results are shown in Fig. 4, where for each sample the cyclic stress ratio $\sigma_d/2\sigma_c$' is plotted against the number of cycles for double

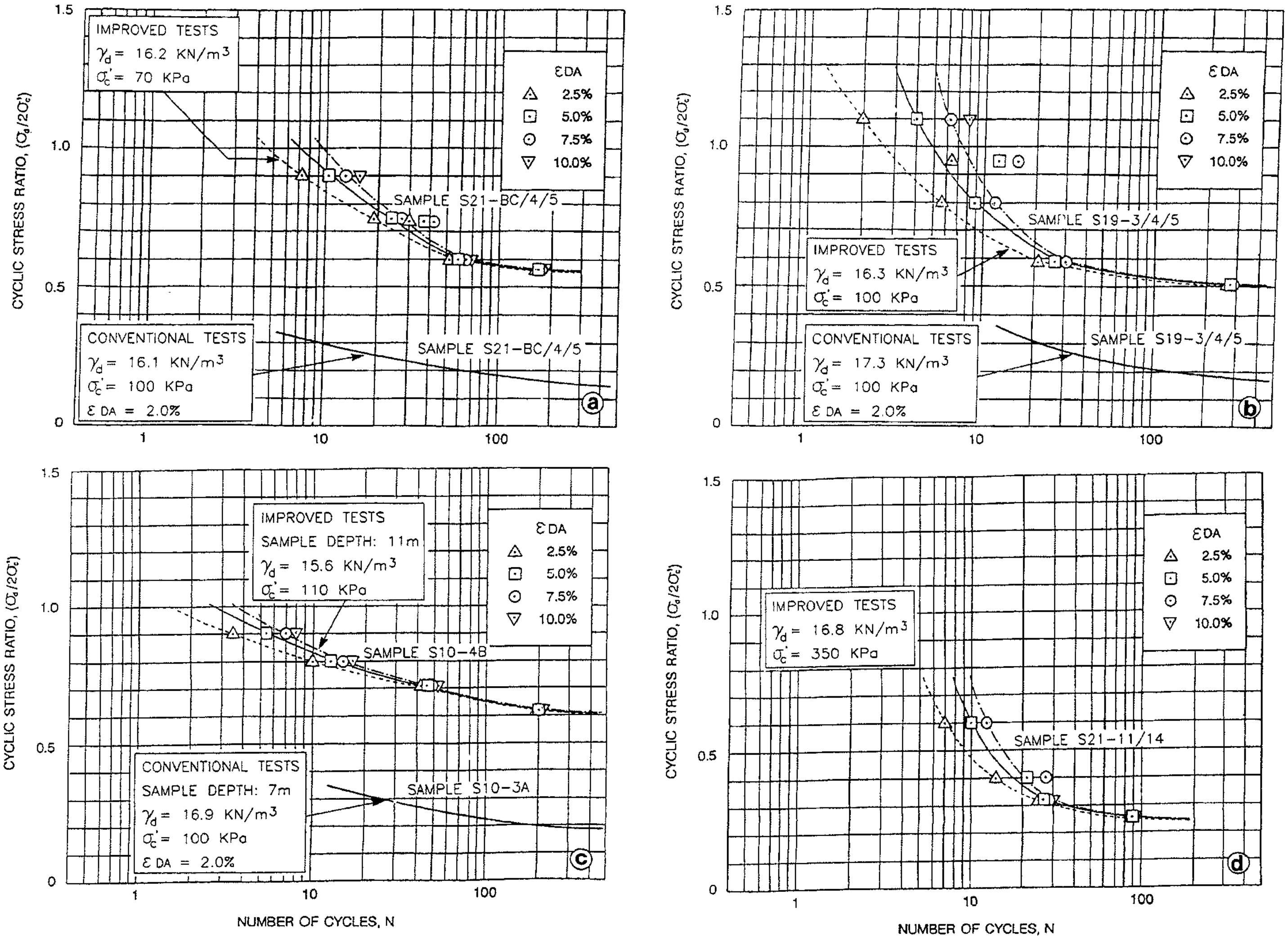


Fig. 4 Results of Improved and Conventional Triaxial Cyclic Tests, a) Sample S21-BC/4/5, b) Sample S19-3/4/5, c) Samples S10-3A and S10-4B, d) Sample S21-11/14.

amplitude axial strains (ε_{DA}) comprised between 2.5 and 10.0 %. These results indicate that the resistance to liquefaction of this sand is high, and as expected decreases when the confining pressure is increased.

In the same figure the results of improved and conventional tests are compared. Specimens obtained from the same sample (Fig. 4a, 4b), or from samples recovered at the same location but at slightly different depth (Fig. 4c) are considered. The difference between the two approaches is apparent, although the dry unit weights are close, and sometimes the conventional tests have been performed in denser soils. Yoshimi et al. (1989) observed that the reduction of liquefaction resistance caused by sample disturbance is well correlated with the change in shear modulus. Applying their experimental correlation to tentatively update the results of the conventional tests, a sharp increase in the resistance to liquefaction (up to triaxial stress ratios exceeding 0.75) was anticipated, which compares well with the results obtained by the improved tests.

The shear stress ratios τ/σ_v' in the field can be obtained by the following relationship:

$$\left(\frac{\tau}{\sigma_v'}\right)_{\text{field}} = 0.9\,\frac{1+2K_o}{3}\left(\frac{\sigma_d}{2\sigma_c'}\right)_{\text{triaxial}} \qquad (1)$$

where 0.9 is a factor to correct for multidirectional shear, K_o is the coefficient of earth pressure at rest, taken as 0.5, and σ_v' is the vertical effective stress.

In Fig. 5 the strain values measured in the laboratory at 7 load cycles (typical of the extreme near field event in the Messina Straits) are compared with the stress ratios computed for the site by means of numerical response analyses. The results are plotted at an equivalent depth, where the mean effective stress in the field is equal to the confining pressure applied in the triaxial tests. This figure shows that the top 10-15 meters of soil are subjected to cyclic mobility effects. Pelli et al. (1994; 1995) discuss approaches to account for the deformability increase due to cyclic mobility on slope deformations and soil-pile interaction, based on the results of the improved tests.

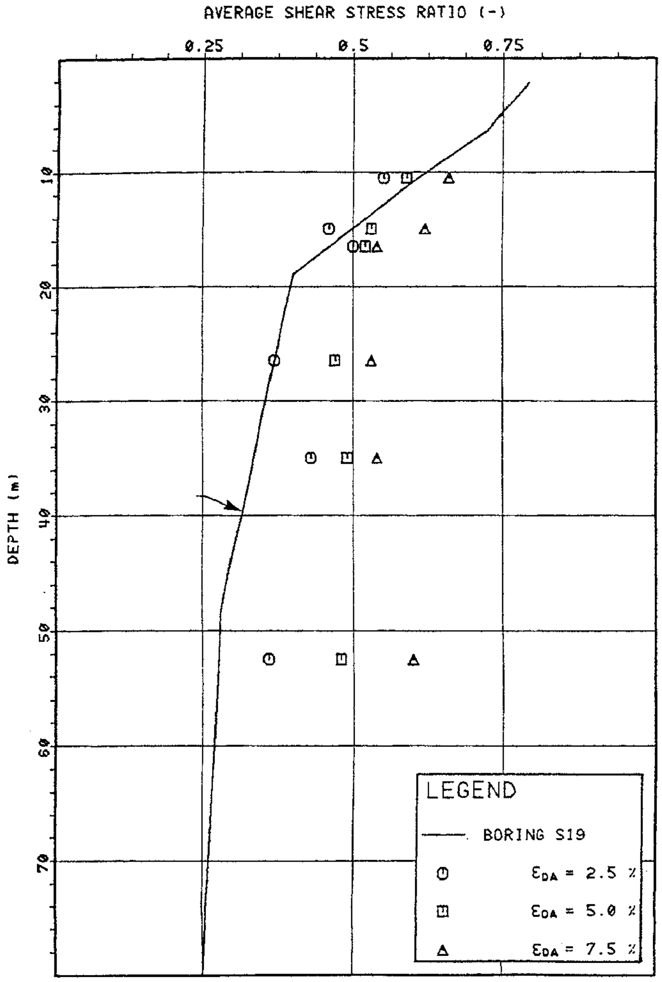


Fig. 5. Test Results Compared with Computed Stress Ratios

CONCLUSIONS

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

1) Although very effective and practical in a number of design cases, the use of indirect methods alone for liquefaction potential evaluation is often insufficient. In particular, for large offshore structures in seismic areas the gradual softening of dense sands associated with pore pressure build up cannot be predicted reliably by these methods.

2) Conventional laboratory tests, carried out on samples reconstituted to match only the in situ relative density, are not representative of field conditions and tend to underestimate the soil resistance to liquefaction. On the other hand, recovery of truly undisturbed samples is hardly possible today in the offshore environment, and even recovery of semi-disturbed samples by thin walled piston samplers is often not possible in gravelly and cobbly soils.

3) The combined use of field and laboratory tests presented herein is a powerful approach for offshore investigations, and in general for those cases where recovery of undisturbed samples is not possible. The samples are reconstituted in the laboratory matching the in situ relative density and the shear wave velocity measured in the field, so that the original soil fabric is partially restored. Note that seismic CPT records are relatively inexpensive, and are usually obtained on a routine basis during offshore investigations in seismic areas.

4) To date, the sand void ratio used to reconstitute the samples in the laboratory is estimated on the basis of the cone tip resistance, as more accurate means are not easily applicable offshore. Need for improvement is recognized in this area.

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