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ANALYSIS OF THE BEHAVIOR OF THE PILED FOUNDATIONS OF A GROUP OF EARTHQUAKE DAMAGED BUILDINGS

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ABSTRACT

The Sicilian earthquake of 13th December, 1990 was not very strong, but it caused considerable damages on structures, included a group of reinforced concrete buildings located in Augusta town on the east coast of Sicily (Italy). To evaluate the possibility to repair these buildings, an investigation on soil, structures and foundations was carried out. As some buildings were founded on piles, load tests on piles of the piled foundations were carried out. The site was well investigated by means of laboratory and in-situ tests including: standard penetration tests, cone penetration tests, dilatometer tests and seismic tests. To evaluate dynamic stress-strain geotechnical characteristics of soils resonant column tests were also performed. In the paper the experimental results of the load tests are analyzed with the aim to study the behavior of the piles subject to additional seismic loads. Load tests showed that the seismic actions have not damaged the effectiveness of the soil-pile system, as the bearing capacity of the piles appeared unchanged in spite of the additional loads applied on the structures during the earthquake. Nevertheless because the existing piled foundations were enable to carry on the additional horizontal seismic forces, a few number of piles were added.

INTRODUCTION

The site under consideration is located on the east coast of Sicily, which is one of the most seismically active areas of Italy (Figure 1). The city of Augusta has been struck by three disastrous earthquakes with an *MKS* intensity from IX to XI (Postpischl, 1985). The Sicilian earthquake of 13th December 1990 was not very strong (*MKS* intensity equal to VII), but it caused 19 victims and damages to buildings and infrastructures.

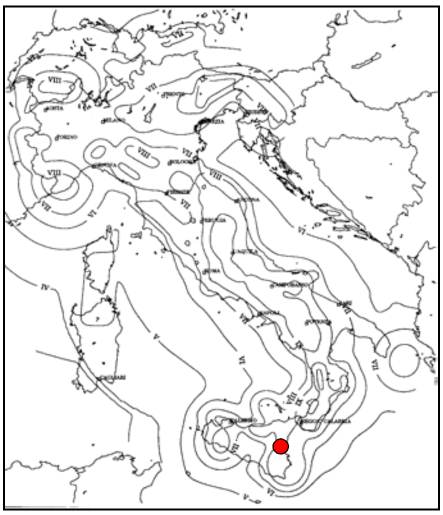

Fig. 1. Site location on the seismic hazard map of Italy.

A group of reinforced concrete buildings with 228 flats, located in the Saline of Augusta site, were heavily damaged (Figure 2) by this earthquake of moderate magnitude ($M = 5.4$). To evaluate the possibility to repair these buildings, an investigation on soil, building foundations and structures was carried out.

As some buildings were founded on piles, to analyze the integrity of the piled foundations after the earthquake and to estimate the effects of the interaction between the piles, three load tests on piles of the existing piled foundations were also carried on. With this aim, three piles have been disconnected from the foundation by the cutting of their head. Then axial and horizontal load tests on piles were executed.

Fig. 2. Damages occurred on buildings.

At the end of the load tests, the connection between piles and foundation was restored.

To determine the geological profile and the geotechnical characteristics of the soil, the site was well investigated by means of in-situ tests such as: dynamic penetration tests (*SPT*), cone penetration tests (*CPT*), dilatometer tests (*DMT*) and seismic tests (*Down-Hole* and *Cross-Hole*), as well as by laboratory tests.

To study the possible amplification phenomena of the site, the soil investigation has been carried out to obtain a soil profile with special attention to the evaluation of the shear modulus (*G*) and damping ratio (*D*) versus depth (Castelli *et al.*, 1995; Cavallaro and Maugeri, 1996; Cavallaro *et al.*, 1999).

To evaluate the dynamic stress-strain geotechnical characteristics of soil, resonant column tests were also performed. A good correspondence between the values of the geotechnical parameters derived from the laboratory tests and those derived by the results of the in situ tests was observed.

For a prevision of the behavior of the piles under additional seismic loads, which must be taken into account for the reinforcement of the damaged buildings, a comparison between the experimental evidences derived from the load tests on piles and the theoretical results obtained by a numerical model was carried on (Castelli *et al.*, 1994; 1995).

In the paper the results of the experimental investigation on soil and on piled foundations are reported and analyzed. By the analysis of the load tests, the bearing capacity of pile appeared unchanged in spite of the additional axial and horizontal loads acting on the structures during the earthquake. Thus from the point of view of the integrity of the foundations, the recovery of the structures was considered possible. A few number of new piles were added in the existing piled foundations to transfer at the surrounding soil the additional horizontal seismic loads.

SOIL PROPERTIES EVALUATION

The soil deposits under consideration lie over the Iblean Plateau which consists of cretacic-miocenic limestone with intercalations of vulcanite. To the East, the Iblean Plateau borders the Ibleo-Maltese escarpment, to the West the Scicli-Ragusa faults, to the North-West the Scordia-Lentini fault and to the South the graben of the Channel of Sicily (Ghisetti and Vezzani, 1980).

The seismic activity of the region is mainly linked to the tectonic stresses which develop at the border between the Eurasian and African plates. The Iblean Plateau represents a contact area between these two plates. The thickness of the deposits varies from between 50 to 300 m. The upper part of these deposits (less than 15 m) consists of recent and actual alluvial soils which overhang a Pleistocene marine clay which is locally called "*Augusta blue-grey clay*".

The investigated area has plane dimensions of 4100 m^2 and a maximum depth of 80 m. The upper deposits mainly consist of alternating layers of grey-silty-clay and sandy-clay. Layers of sand were found at depths of between 9 and 12 m. The lower deposits mainly consist of a medium stiff, over-consolidated (*OCR* = 2.0 to 6.0), marine clay with low to medium plasticity index. Figure 3 shows the soil profile versus depth of the area where the buildings are located. The water table is located at around - 0.80 meters from the ground surface.

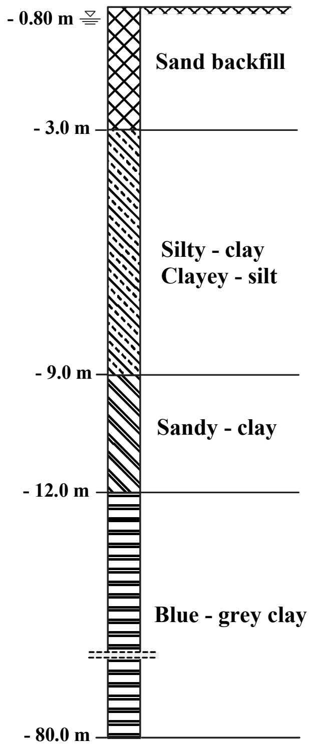

Fig. 3. Soil profile of the examined area.

The index properties and the mechanical characteristics of the Augusta clay derived from the laboratory tests are shown, as function of depth, in Figure 4.

The clay fraction is prevalently in the range of between 60 ÷ 70 %. This percentage decreases to 30 ÷ 40 % at certain depths where a sand fraction of 15 ÷ 30 % and a gravel fraction of 2 ÷ 10 % are present. The silt fraction is in the range of about 25 ÷ 40 %. The values of the natural moisture content w_n prevalently range between 30 and 35 %.

Characteristics values for the Atterberg limits are: w_l = 60 ÷ 65 % and w_p = 22 ÷ 26 %, with a plasticity index *PI* = 30 ÷ 40 %. Data shown in Figure 4 indicate a very high degree of homogeneity of the soil deposit. This indication is also confirmed by comparing the blow counts N_{spt} obtained by the standard penetration tests (*SPT*) and reported in Figure 5, with the penetration resistance q_c derived by the cone penetration tests (*CPT*) reported in Figure 6. In this last case, the variation of q_c versus depth shows the existence of soil layers with different mechanical properties.

In addition to the abovementioned in situ tests, dilatometer tests (*DMT*) and seismic tests (*Down-Hole* and *Cross-Hole*) were also carried out. In Figure 7 the variation versus depth of the material index I_d, coefficient of earth pressure at rest k_o, dilatometer modulus E_d, undrained shear strength c_u obtained by means of the dilatometer tests are reported respectively. Finally Figure 8 shows the variation with depth of the shear waves velocity determined by the cross-hole and down-hole tests. In this case, comparing the values measured, a good agreement between the values of the shear waves velocity V_s determined by means of the two different seismic tests can be observed.

Particularly up to -10 meters from the ground surface, an average value of the shear waves velocity V_s = 320 m/s can be assumed.

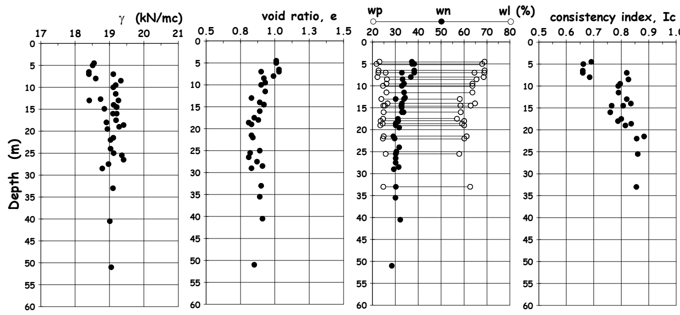

Fig. 4. Soil properties derived by laboratory tests.

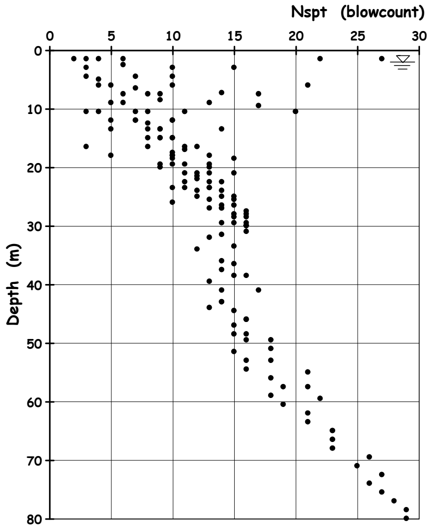

Fig. 5. Standard penetration test results.

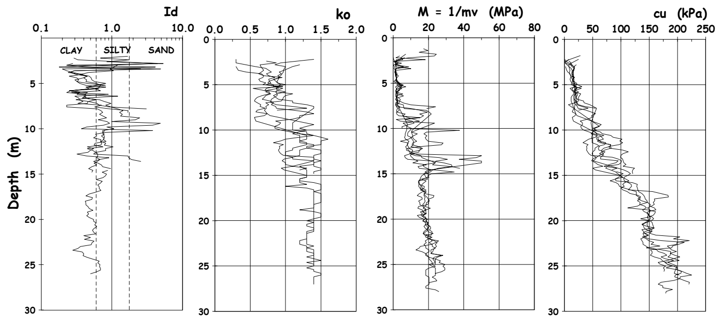

Fig. 7. Marchetti's flat dilatometer test results.

An average value of the shear waves velocity approximately equal to $V_s = 530$ m/s can be estimated up to -30 meters from the ground surface.

The Marchetti's flat dilatometer tests (*DMT*) were used to assess *OCR* and the coefficient of earth pressure at rest k_o (Figure 7) following the procedure suggested by Marchetti (1980). For a depth up to - 10 m from the ground surface, *DMT* results show an *OCR* ranging between 1 to 3 (k_o = 0.5 ÷ 1), showing that the upper clay deposit can be considered normally consolidated or lightly over-consolidated. For the lower clay deposit, the *OCR* values obtained by *DMT* range from 5 to 7 (k_o = 1.0 ÷ 1.5) with an average value equal to 6 up to a depth of about - 30 m.

The small strain shear modulus of soil G_o can be considered an essential parameter for estimation of the soil response, especially in the case of dynamic loading. In this case the modulus G_o was determined both by in-situ than by laboratory tests.

The equivalent shear modulus (G_o) and the damping ratio (D) was determined in the laboratory both by means of Resonant Column tests (*RCT*) and cyclic loading torsional shear tests (*CLTST*). Moreover it was attempted to assess G_o also by means of empirical correlations based on in-situ test results.

By laboratory tests, the G_o values were determined at shear strain levels of less than 0.001 %. It is possible to observe that quite a good agreement exists between the laboratory and in-situ test results. The G_o values for the upper silty-clay steadily increase from 20 to 80 MPa with depth.

In the transition zone, where stiff sand layers are present, G_o increases up to 110 MPa. In the lower blue-grey clay G_o values range in the range 80 up to 120 MPa.

The values of shear modulus G_o determined by the elastic theory, assuming that: $G_o = \rho V_s^2$, where ρ = mass density = 0.71 kNsec^2/m^4, are 63 MPa for the first 10 meters of soil and 229 MPa for the remaining soil, with a small difference between the values of shear modulus G_o determined by this procedure and the corresponding values obtained by resonant column tests especially in the first 10 meters of soil.

A very good agreement was observed (Figure 9) between the value of G_o determined by the laboratory tests and those derived by the following empirical correlation proposed by Hryciw (1990):

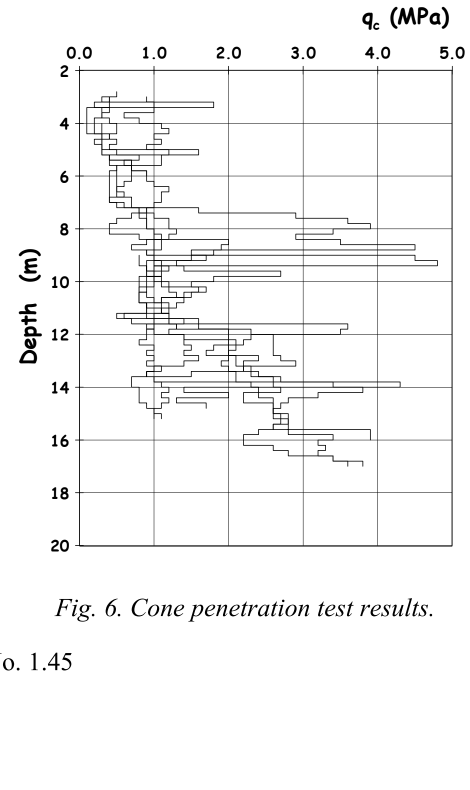

Fig. 6. Cone penetration test results.

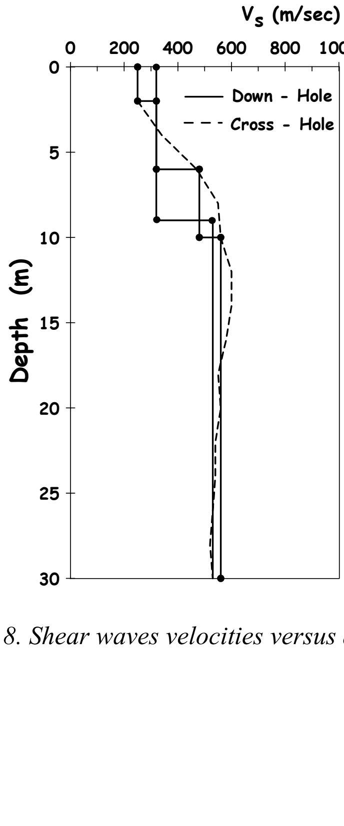

Fig. 8. Shear waves velocities versus depth.

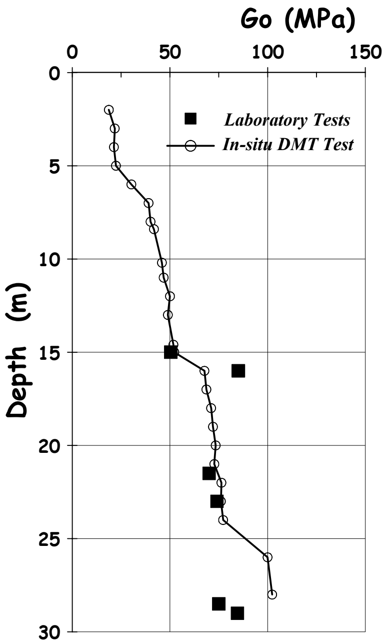

Fig. 9. G_o values versus depth.

$$G_o = \frac{530}{(\sigma'_v/P_a)^{0.25}} \cdot \frac{(\gamma_D/\gamma_w) - 1}{2.7 - (\gamma_D/\gamma_w)} k_o^{0.25} (\sigma'_v P_a)^{0.5} \qquad (1)$$

where P_a is the atmospheric pressure, σ'_v is the effective vertical stress, γ_D and k_o are respectively the unit weight and the coefficient of earth pressure at rest determined according to Marchetti (1980) by means of DMT results.

Finally, an assessment of the values of the undrained shear strength c_u determined by dilatometer tests, cone penetration tests and laboratory tests has been carried out (Figure 10).

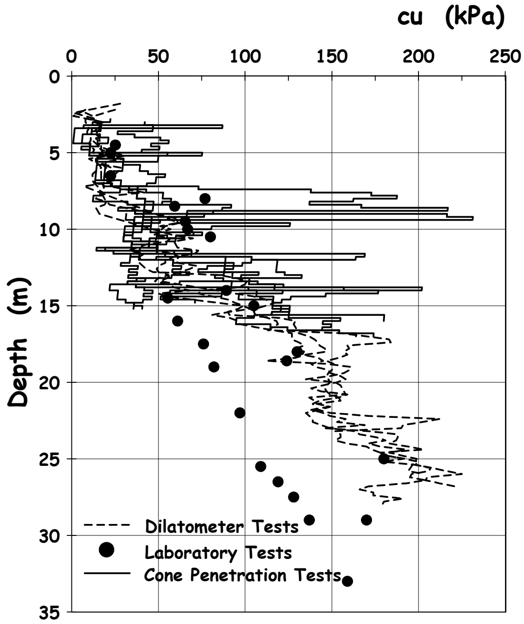

Fig. 10. Assessment of the undrained shear strength values.

To express the variation of the undrained shear strength versus depth, the following relationship was derived: $c_u\ (kPa) = 7.5\ z$, where z is the depth from the ground surface.

PILE LOAD TESTS PROGRAM

The group of reinforced concrete buildings damaged by the Sicilian earthquake of 13th December, 1990 are founded on bored piles having a length of 20 meters and a diameter of 500 mm.

To evaluate the integrity of the piled foundations after the earthquake, the piles were inspected and also an experimental load tests program was carried out. Three piles placed beneath the existing foundations were chosen and their head was disconnected from the foundation (Figure 11) to execute vertical and horizontal load tests. At the end of the load tests, the connection between piles and foundation was restored.

Two different loading and un-loading cycles have been carried out. The piles were subjected to a maintained load and during each step of loading, the pile head settlements were measured. To not damage the piles, the load was applied in different stages up to around 150 % of the working load equal to 650 kN.

The experimental results show that the measured settlements were less 7.2 mm for the maximum load applied and less than 2.0 mm for the design load.

The residual settlement was ranging between 1.0 and 0.34 mm and the trend of the load-settlement curves derived by the load tests, named *Test no.1* (Figure 12), *Test no.2* (Figure 13) and *Test no.3* (Figure 14), shows a marked non-linear behavior of the soil-pile interaction. In particular, load-settlement curves seem to follow a hyperbolic law, then the loading curve may be analyzed by transforming the data and plotting to yield a straight-line relationship in a plane (*settlement*, *settlement/load*), the slope of which allows to estimate the ultimate failure load, as suggested by Chin (1970). The ultimate pile capacity is assumed generally equal to 90 % of the value so determined.

According to this procedure the ultimate failure load derived by the load tests is ranging between around 1.5 MN and 1.7 MN (Figure 15), in a very good agreement with the value of 1.53 MN computed in undrained conditions by the well-known Vesic's pile capacity relationships.

Fig. 11. View of the load test on a pile of the piled foundation.

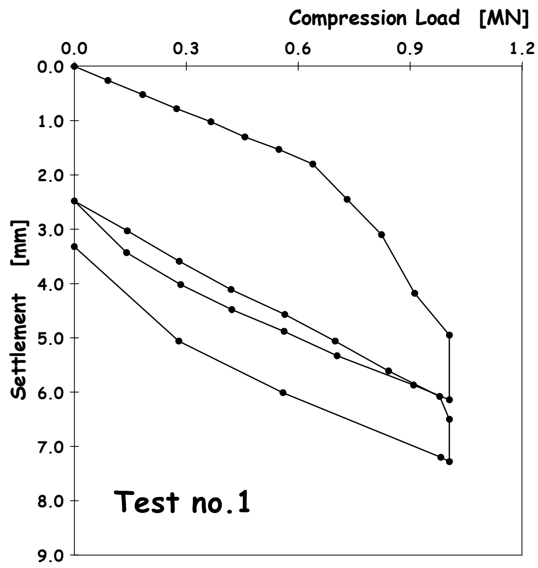

Fig. 12. Test no.1: Measured load-settlement curve.

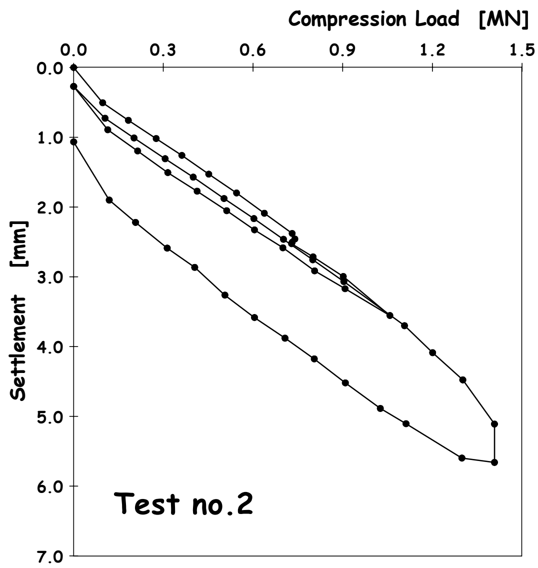

Fig. 13. Test no.2: Measured load-settlement curve.

The safety factor of the soil-pile system derived by the back-analysis of the load tests is greater than 3, thus the effectiveness of the piled foundation was considered able to support axial loads, instead of the damages occurred on the structures due to the earthquake.

To evaluate the piles performance due to lateral forces, after conducting the axial tests, lateral loading tests were also performed on two piles. Figures 16 and 17 report the experimental load-deflection curve derived by the load *Test no.1* and *2* respectively.

The experimental results have been utilized to define non-linear "*p-y"* curves and to analyze, by a computer code proposed by the writers (Castelli *et al.*,1995), the behavior of the examined bored piles subjected to horizontal loads, due to a scenario earthquake

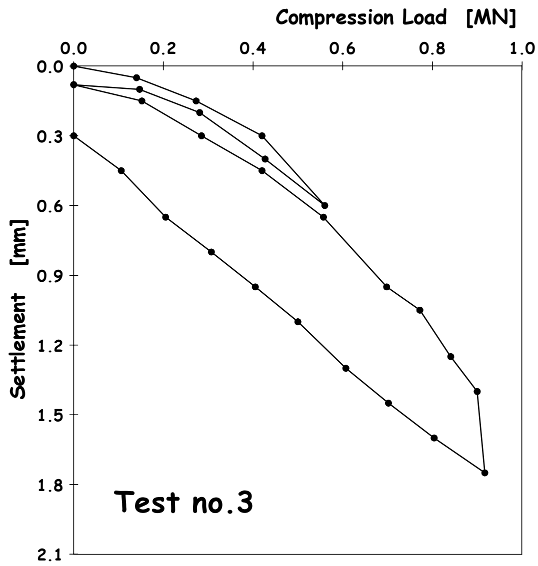

Fig. 14. Test no.3: Measured load-settlement curve.

having an intensity greater of that registered on 13th December, 1990.

Predicted lateral responses based on dilatometer-evaluated model parameters agreed well with measured field behavior from the two lateral pile load tests. It is found that, also in the case of lateral loading, the hyperbolic representation of load-deflection curves provides an objective means to determine the ultimate lateral load capacity (Castelli *et al.*, 1995), which is comparable with the computed values based on Brom's theory. The experimental results show that the measured lateral deflection for the maximum load applied was ranging between 1.5 and 4.0 mm, while the residual lateral deflection was ranging between 0.45 and 1.3 mm. The ultimate failure lateral load derived by the hyperbolic representation of the load-deflection curve is equal to around 1.9 kN.

The ultimate failure lateral load was not able to support horizontal seismic forces for the scenario earthquake, thus a few number of piles were added to the existing piled foundations.

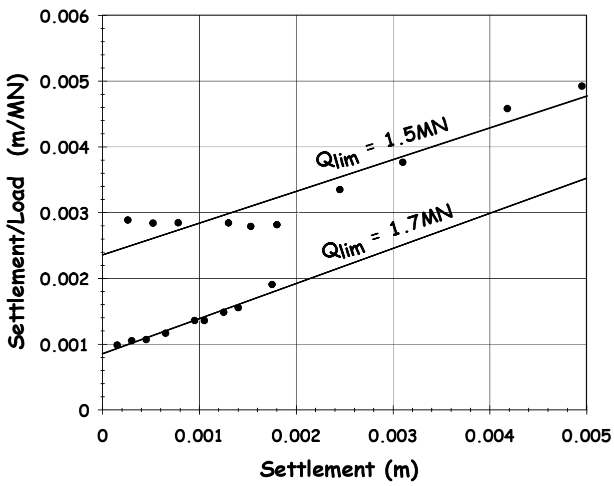

Fig. 15. Evaluation of the ultimate vertical failure load.

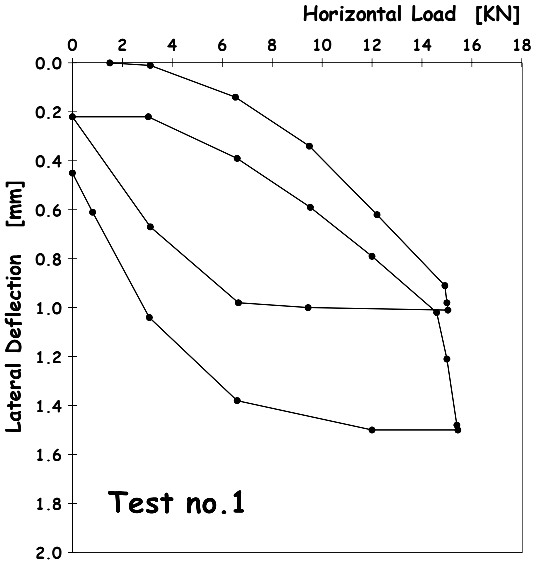

Fig. 16. Test no.1: Measured load-lateral deflection curve.

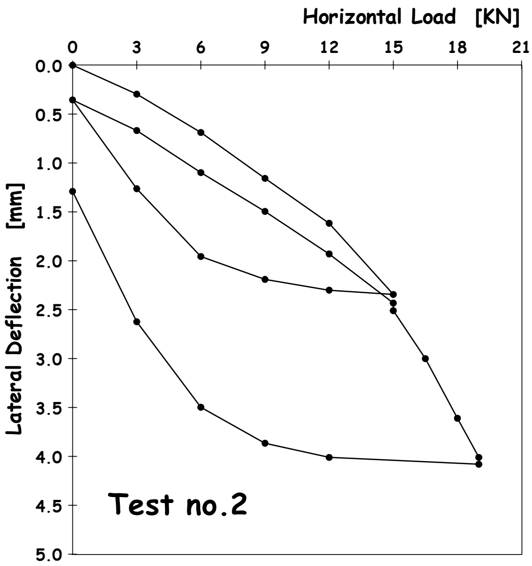

Fig. 17. Test no.2: Measured load-lateral deflection curve.

CONCLUDING REMARKS

The design of bored single pile and pile groups for axial and lateral capacity has tended to rely on semi-empirical design methods that make it difficult for practical designers to select the appropriate procedure. It would, therefore, be preferred to define more reliable and relevant soil parameters that can be adopted as input in the design methods. With this aim, the paper describe the results of an experimental investigation carried out on a group of reinforced concrete buildings located on the east coast of Sicily (Italy) damaged by the Sicilian earthquake of 13th December, 1990. To evaluate the possibility to repair these buildings, an investigation on soil, structures and foundations was carried out. As some buildings were founded on piles, to analyze the integrity of the piled foundations after the earthquake, loading tests on piles were also carried on. Three piles placed beneath the existing foundations were chosen and their head was disconnected from the foundation to execute vertical and horizontal load tests. To evaluate the pile performance due to lateral forces, after conducting the axial tests, lateral loading tests were also performed on two piles.

At the end of the load tests, the connection between piles and foundation was restored.

The analysis of the experimental measurements derived by the loading tests, evidences that the effectiveness of the piled foundation can be considered able to sustain axial loads but not horizontal loads. Because of this a few number of piles were added to the existing piled foundations.

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