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The use of Cone Penetration Tests (CPT) for the study of the dynamic characteristics of the soils

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Abstract – **This paper describes and compares the results of in situ investigations performed on two Sicilian test sites: Augusta Saline (SR) and Catania STM M6 areas. The studies were carried out to determine the variation of shear modulus with depth by Cone Penetration Tests (CPT), Standard Penetration Tests (SPT), Down - Hole Tests (DHT), Seismic Dilatometer Marchetti Tests (SDMT). The available data also enabled one to compare the shear modulus profile obtained by empirical correlations based on CPT and SPT with Down - Hole Test and Seismic Dilatometer Marchetti Test.**

I. INTRODUCTION

The first mechanical penetrometer was first developed in Holland in 1932 using a 35 mm diameter cone attached to inner rods inside a steel pipe and subsequently improved in 1935 at the soil mechanics laboratory of Delft [1]. In 1948 a conical part was added immediately to the tip (Mantle Cone) to prevent soil particle infiltration between internal rod and outer tubes [2]. In 1954, to locally measure soil-steel adhesion, a new tip was designed with a short sleeve behind the cone (Friction Sleeve Cone) [3]. In the second half of the 1960s, the electric cone was developed and Fugro Consulting starts commercial use of electric penetrometer. The cone resistance and local lateral friction are measured by transducers mounted directly above the cone.

The Cone Penetration Test (CPT) is an unbeatable tool for:

- detecting stratigraphic characteristics along a vertical; identify the types of soils crossed;
- interpolate the characteristics of layers between verticals boreholes.

Measured values can also be used to evaluate: angle of shear resistance and drained compressibility of granular soil; undrained shear resistance of cohesive soil.

In the present study, the results of the CPTs were used to evaluate the initial shear modulus G_o in cohesive soil.

For this purpose, two Sicilian test sites were taken into account. The east coast of Sicily is one of the most seismically active areas of Italy. Since 1169, the cities of Augusta (SR) and of Catania has been struck by three disastrous earthquakes with an MKS intensity from IX to XI [4].

The earthquake of January, 11, 1693 is considered one of the biggest earthquakes which occurred in Italy. It is supposed that more than 1500 aftershocks occurred along a period of more than two years after the main shock. This earthquake, with an intensity of XI degree of MKS scale in many centers, struck a vast territory of south-eastern Sicily and caused the partial, and in many cases total, destruction of 57 cities and 60000 casualties.

The 13th December 1990 earthquake, with moderate magnitude (M=5.4) and where the epicenter was located 10 km offshore from the city of Augusta [5], caused 19 victims and severe damages to buildings and infrastructures with an MKS intensity equal to VII [6]. In particular, at Augusta, reinforced concrete buildings with 228 flats located in the Saline site were damaged by this earthquake of moderate magnitude.

In order to study the dynamic characteristics of soils in the Augusta [7] and Catania [8, 9] municipal areas, laboratory and in situ investigations have been carried out to obtain soil profiles with special attention being paid to the variation of the shear modulus (G_o).

Soil stiffness, at small strains, is a relevant parameter in solving boundary value problems such as:

- seismic response of soil deposits to earthquakes [10, 11, 12];
- dynamic interaction between soils and foundations [13, 14, 15];
- design of special foundations for which the serviceability limit allows only very small displacements [16, 17].

In this paper Cone Penetration Tests (CPT) have been performed to know the mechanical characteristics of the investigated soils and to determine by empirical correlations the shear modulus. Moreover the seismic flat dilatometer test (SDMT) was used to provide shear wave velocity (V_s) measurements to supplement conventional inflation readings (p_o and p_1). Soil stratigraphy and soil parameters are evaluated from the pressure readings while the small strain stiffness (G_o) is obtained from in situ V_s profiles and by empirical correlation proposed by Hryciw [18].

II. INVESTIGATION PROGRAM AND BASIC SOIL PROPERTIES

A. Augusta Saline

The Augusta clay investigated area has plane dimensions of 4100 m^2 and a maximum depth of 80 m. The clay fraction (CF) 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 observed. The silt fraction is in the range of about 25 - 40 %. The values of the natural moisture content w_n prevalently range from between 30 and 35 %. Characteristics values for the Atterberg limits are: w_L = 60 - 65 % and w_p = 22 - 26 %, with a plasticity index of PI = 30 - 40 %. The laboratory data clearly indicate a very high degree of homogeneity of the deposit. This indication is also confirmed by comparing the penetration resistance q_c from mechanical cone penetration tests (CPT) performed at different locations over the investigated area (Figure 1). The variation of q_c with depth clearly shows the existence of layers with very different mechanical characteristics. The upper Holocene silty clay has poor mechanical characteristics with q_c of about 0.3 to 0.6 MPa. The lower Pleistocene clay has q_c values of about 2 to 4 MPa. A transition zone with interbedded stiff sand layers ($q_c \cong 15$ to 35 MPa) exists between these two strata at depths of about 10 and 15 m. The soil deposits can be classified as inorganic clay of high plasticity. The preconsolidation pressure σ'_p and the over-consolidation ratio OCR = σ'_p / σ'_{vo} were evaluated from the 24h compression curves of 7 incremental loading (IL) oedometer tests. Moreover, 10 Marchetti's Flat Dilatometer Tests (DMT) was used to assess OCR and the coefficient of earth pressure at rest K_o following the procedure suggested by Marchetti [19].

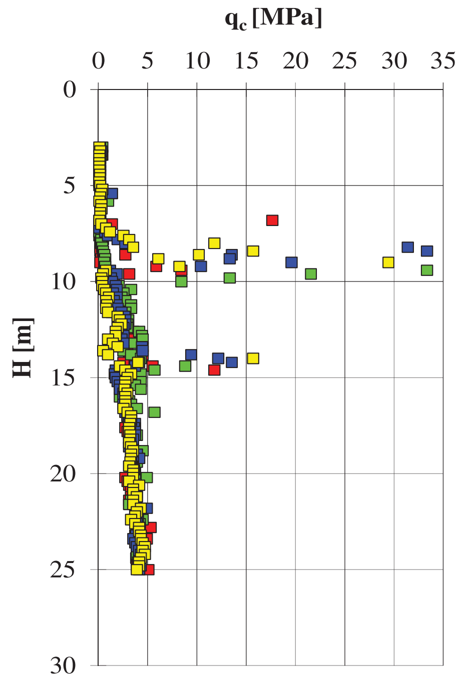

Fig. 1. Static cone penetration test results for Augusta Saline area.

The information obtained from laboratory and in situ tests is summarised in Figure 2. For depths of up to 10 m, DMT [19] results show an OCR from 1 to 3 (K_o = 0.5 ÷ 1.0), which means that the upper Holocene deposit is normally consolidated or lightly over consolidated. For the lower Pleistocene clay, the OCR values obtained from DMT range from 5 to 7 (K_o = 1.0 ÷ 1.5) with an average value equal to 6 up to about 30 m depth.

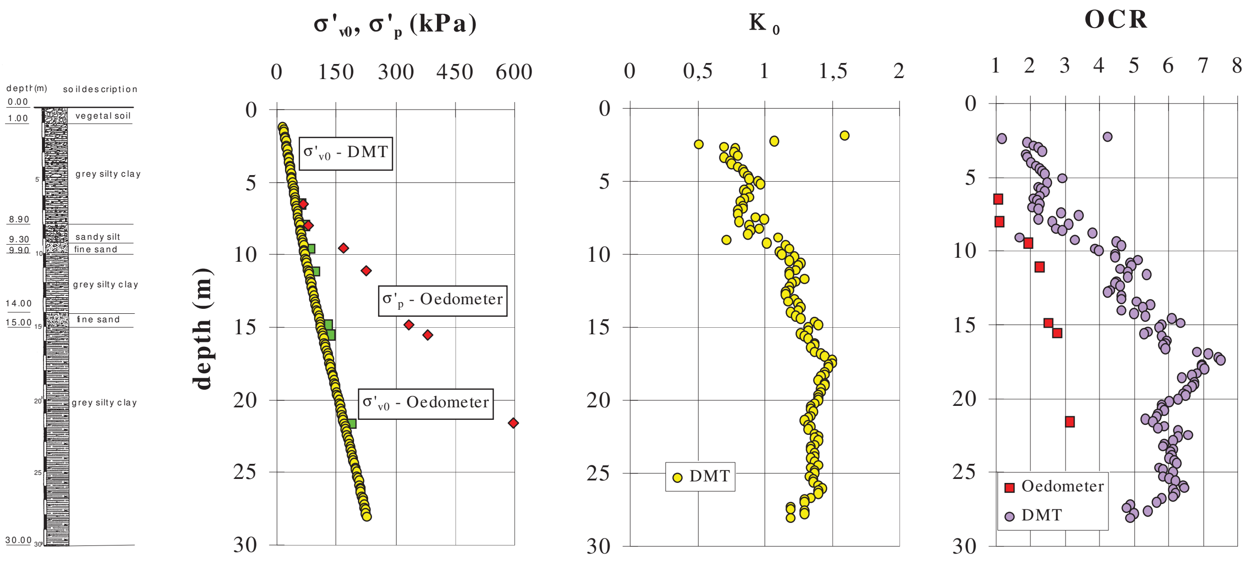

Fig. 2. Stress history from laboratory and in situ tests for Augusta Saline area.

The OCR values inferred from oedometer tests are lower than those obtained from in situ tests.
One possible explanation of these differences could be that lower values of the preconsolidation pressure σ'$_p$ are obtained in the laboratory because of sample disturbance.

B. Catania STM M

The investigated STM M6 area, located in the South zone of the city, has plane dimensions of 212400 m^2 and a maximum depth of 100 m..
The STM M6 site consists of fine alluvial depos-its, the clay fraction (CF) is predominantly in the range of 2 - 54 %. This percentage decreases to 0 - 2 % at the depth of 95 m where a sand fraction of 4 - 9 % is observed.
The gravel fraction is always zero. The silt fraction is in the range of about 50 - 100 %. The values of the natural moisture content, w_n, range from between 22 and 56 %.
Characteristic values for the Atterberg limits are: w_L = 54 - 84 % and w_p = 27 - 46 %, with a plasticity index of PI = 22 - 41 %.
The good degree of homogeneity of the deposit is confirmed by comparing the penetration resistance q_c from mechanical cone penetration tests (CPT) performed at different locations over the investigated area (Figure 3). The variation of q_c with depth clearly shows the very poor mechanical characteristics of soil.
Typical values of q_c are in the range of 0.01 to 0.49 MPa. The soil deposits can be classified as inorganic silt of high compressibility and organic clay. Typical range of physical characteristics, index properties and strength parameters of the deposit are reported in Table 1.

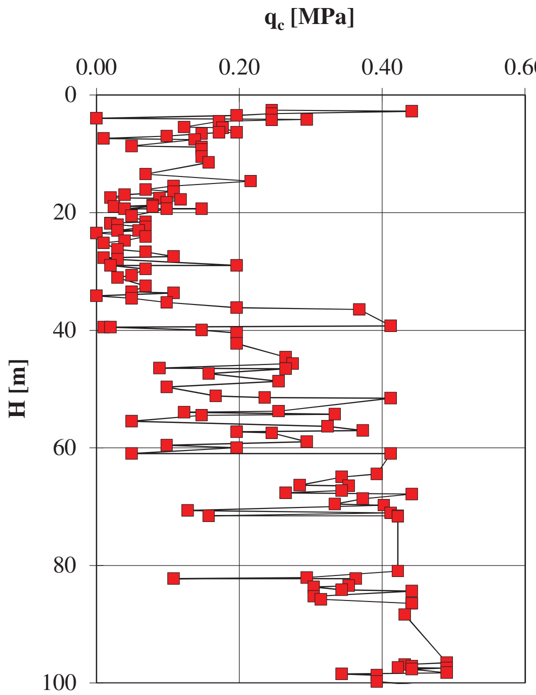

Fig. 3. Static cone penetration test results for Catania STM M6.

The information obtained from laboratory and in situ tests is summarized in Figure 4. The OCR values obtained from SDMT range from 1 to 10 (K_o = 0.5 to 1) with an average value equal to 1.2 up to about 10 for the 40 m deep sounding. The OCR values inferred from oedometer tests are lower than those obtained from in situ tests.

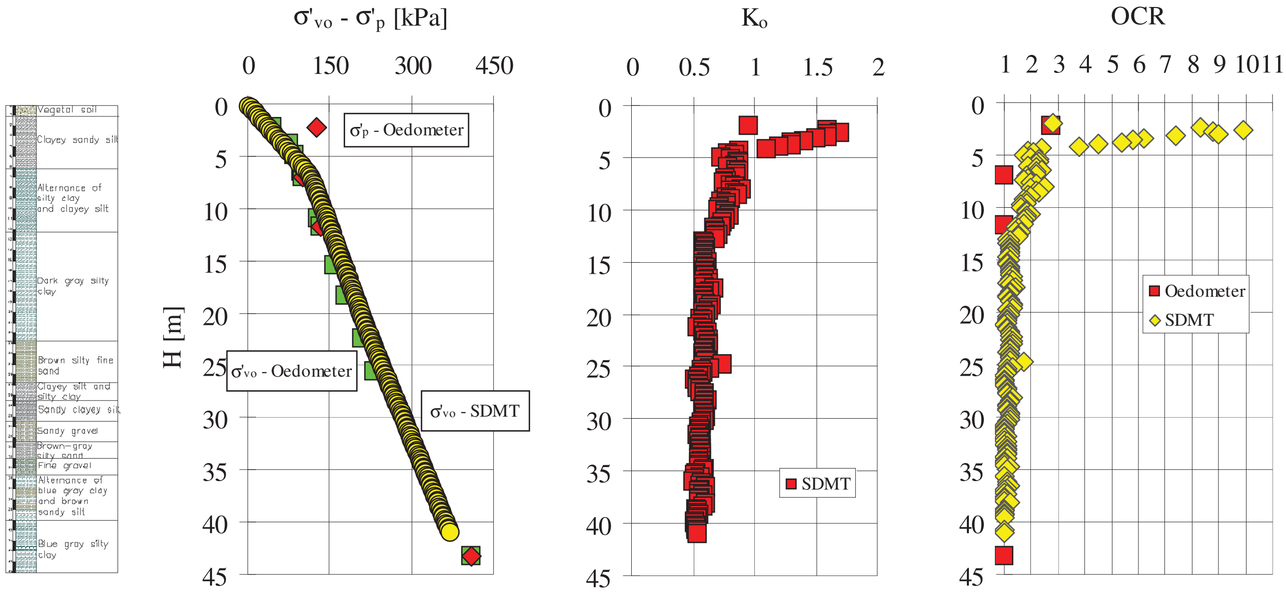

Fig. 4. Stress history from in situ and laboratory tests.

Table 1. Mechanical characteristics for Catania STM M6 area.

γ [kN/m³]	e	c_u [kPa]	c' [kPa]	ϕ' [°]
16.6-20.2	0.56-1.51	28.75-203.61	2.41-21.7	16-18

where: c_u (Undrained shear strength), c' (Cohesion) and ϕ' (Angle of shear resistance) were calculated from and C-U and C-D Triaxial Tests.

One possible explanation of these differences could be the same proposed in the previous paragraph.

III. EVALUATION OF G_O FROM PENETRATION TESTS

The small strain shear modulus G_o can be evaluated by laboratory Resonant Column Tests (RCT) [20, 21] or in situ by Down - Hole tests and SDMT [22, 23, 24, 25] using the relationships: $G_o = \rho V_s^2$ (where: ρ = mass density) based on theory of elasticity.

It was also attempted to evaluate the small strain shear modulus by means of the following empirical correlations based on penetration tests results or laboratory results available in literature.

a) Ohta & Goto [26]

$$V_s = 69 \cdot N_{60}^{0.17} \cdot Z^{0.2} \cdot F_A \cdot F_G \quad (1)$$

where: V_S = shear wave velocity (m/s), N_{60} = number of blow/feet from SPT with an Energy Ratio of 60 %, Z = depth (m), F_G = geological factor (clays = 1.000, sands = 1.086), F_A = age factor (Holocene = 1.000, Pleistocene = 1.303)

$$G_o = \rho \cdot V_s^2 \quad (2)$$

where ρ = mass density

b) Hryciw [18]

$$G_o = \frac{530}{(\sigma'_v/p_a)^{0.25}} \frac{\gamma_D/\gamma_w - 1}{2.7 - \gamma_D/\gamma_w} K_o^{0.25} \cdot (\sigma'_v \cdot p_a)^{0.5} \quad (3)$$

where: G_o, σ'_v and pa are expressed in the same unit; p_a = 1 bar is a reference pressure; γ_D and K_o are respectively the unit weight and the coefficient of earth pressure at rest, as inferred from DMT results according to [10].

c) Mayne & Rix [27]

$$G_o = \frac{406 \cdot q_c^{0.696}}{e^{1.13}} \quad (4)$$

where: G_o and q_c are both expressed in [kPa] and e is the void ratio. Eq. (4) is applicable to clay deposits only.

d) Jamiolkowski et. al. [28]

$$G_o = \frac{600 \cdot \sigma_m'^{0.5} p_a^{0.5}}{e^{1.3}} \quad (5)$$

where: $\sigma'_m = (\sigma'_v + 2 \cdot \sigma'_h)/3$; p_a = 1 bar is a reference pressure; G_o, σ'_m and p_a are expressed in the same unit.

The values for parameters which appear in eq. (5) are equal to the average values that result from laboratory tests performed on quaternary Italian clays and reconstituted sands. A similar equation was proposed by Shibuya and Tanaka [29] for Holocene clay deposits.

Eqs. (5) incorporate a term which expresses the void ratio; the coefficient of earth pressure at rest only appear in eqs. (3). However only eq. (3) tries to obtain all the input data from the DMT results.

As regard Augusta Saline the G_o values obtained with the methods above indicated are plotted against depth in Figure 5. The method by Jamiolkowski et al. [28] was applied considering a given profile of void ratio and K_o. The coefficient of earth pressure at rest was inferred from DMT. The method by Mayne and Rix [27] was applied only to the cohesive strata, disregarding the high values of q_c encountered in the sandy layers that exist between 10 and 15 m. The N_{60} values, experimentally deter-mined during SPT, did not show any important variation in the transition zone at depths between 10 and 15 m, where thin layers of stiff sand exist. Standard Penetration Tests were performed at intervals from 1.5 to 3.0 m. The quite large interval used could explain why the thin sand layers were not detected. Consequently, the obtained G_o values, in the transition zone, resulted to be quite low. The DMT material index indicated the presence of sandy layers at depth of about 10 and 15 m and at the same depths the dilatometer modulus greatly increased. However, the method by Hryciw [18] was not capable of detecting these stiff strata as can be seen in Figure 5.

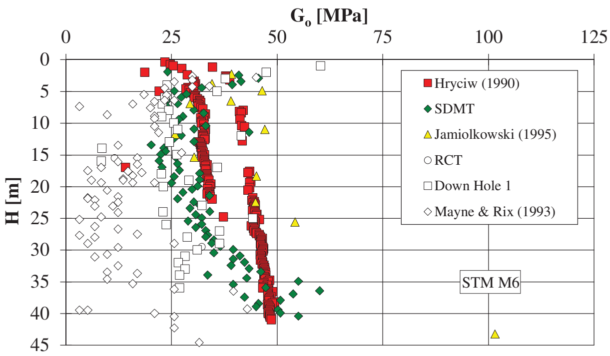

Fig. 5. G_o from different empirical correlations for Augusta saline area.

All the considered methods show very different G_o values of the Holocene and Pleistocene clay strata. On the whole, eq. (4) and (5) seems to provide the most accurate trend of G_o with depth. It is worthwhile to point out that the considered equations overestimate G_o for depths greater than 20 m.

As regard Catania STM M6 the G_o values obtained with the methods above indicated are plotted against depth in Figure 6. The method by Jamiolkowski et al. [28] was applied considering a given profile of void ratio. The coefficient of earth pressure at rest was inferred from SDMT.

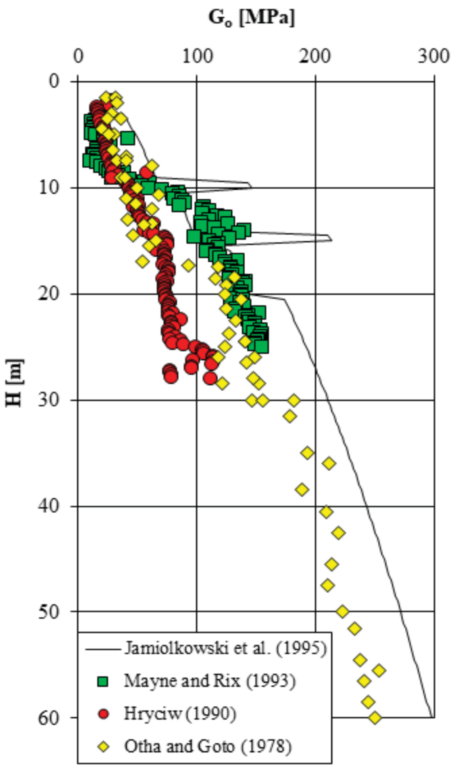

Fig. 6. G_o from different empirical correlations for Catania STM M6 area.

All the considered methods show very different G_o values of the Holocene soil. On the whole, equation (3) and (5) seems to provide the most accurate trend of G_o with depth, as can be seen in Figure 6. It is worthwhile to point out that equation (5) overestimated G_o for depths greater than 25 m.

IV. CONCLUDING REMARKS

A site characterisation for seismic response analysis has been presented in this paper. On the basis of the data shown it is possible to draw the following conclusions:

A. Augusta Saline

- empirical correlations between the small strain shear modulus and penetration test results were used to infer G_o from SPT, CPT and DMT. This comparison clearly indicates that a certain relationship exists between G_o and the penetration test results, which would encourage one to establish empirical correlations for a specific site. This approach makes it possible to consider the spatial variability of soil proper-ties in a very cost effective way.
- relationships like those proposed by Jamiolkowski et al. [28] or Shibuya and Tanaka [29] seems to be capable of predicting G_o profile with depth in both Holocene and Pleistocene deposits. The accuracy of these relationships could obviously be improved if the parameters which appear in the equations were experimentally determined in the laboratory for a specific site.

B. Catania STM M6

- SDMT were performed up to a depth of 42 meters. The results show a very detailed and stable shear wave profile.
- empirical correlations between the small strain shear modulus and penetration test results were used to infer G_o from CPT and SDMT. The values of G_o were compared to those measured with SDMT and DH tests. This comparison indicates that some agreement exists between empirical correlations and SDMT and DH test.
- moreover SDMT measurements are much more stable and repeatable than DH test, so the SDMT is a powerful investigation tool.
- SDMT, because of three independent measurements of p_o, p_1 and V_s, gives shear modulus at small strain and large strain for detecting soil non linearity.

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