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DYNAMIC GEOTECHNICAL CHARACTERIZATION OF SAN GIULIANO DI PUGLIA SEISMIC AREA

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ABSTRACT

The city of San Giuliano di Puglia (CB), located in the Molise region in Southern Italy, is prone to high seismic risk. For site characterisation of soil deep site investigations have been undertaken. Borings, static and dynamic in situ tests have been performed. Among them Cone Penetration Tests (CPT), Cross-Hole (C-H) Down-Hole (D-H) and Seismic Dilatometer Marchetti Tests (SDMT) have been carried out, with the aim to evaluate the soil profile of shear waves velocity (V_s).
Moreover the following laboratory tests were carried out on undisturbed samples: Oedometer tests, undrained Triaxial tests and Resonant Column tests. The available data enabled one to compare the shear waves velocity profile obtained by empirical correlations, Down Hole tests and Seismic Dilatometer Marchetti Tests. The influence of strain level on G-γ and D-γ curves was evaluated by means of laboratory tests. Two expression to allows the complete shear modulus degradation with strain level and the inverse variation of damping ratio with normalized shear modulus respectively were proposed.
Finally after evaluating the synthetic accelerograms at the bedrock, the ground response analysis at the surface, in terms of time history and response spectra, has been obtained by two non-linear models GEODIN and EERA.

INTRODUCTION

On October 31, 2002, a M_L = 5.4 earthquake struck Molise region in Southern Italy. The strongly non-uniform damage distribution observed in the town of San Giuliano di Puglia suggested that site amplification significantly affected the seismic response of the area. The damages were surprisingly concentrated in the new part of the town, lying on fine-grained soils, where a primary school building collapsed causing the death of 27 children. While the old part, lies on outcropping rock, was less damaged.
In order to develop a seismic microzonation of the area (Baranello et al. 2003), the Department of Civil Protection of the Italian Government committed a comprehensive investigation programme on the subsoil properties. The field and laboratory experimental data allowed the definition of the geotechnical model of subsoil (Silvestri et al., 2006), while a numerical site response analyses were carried out by Puglia et al. (2007).
This paper tries to summarize this information in a comprehensive way in order to provide a case record of site characterization for seismic response analysis.

GEOLOGY OF AREA

Melidoro (2004) and Guerricchio (2005) have proposed an interpretation of the town geological setting of San Giuliano di Puglia area (Figure 1):

- the Faeto flysch (F), that is a sedimentary succession of mainly calcareous soils, either coarse or fine-grained; in particular these can be calcirudites, limestones, calcareous marls, white marls and green clays, differently fractured and fissured;
- a deep layer of Toppo Capuana marly clays (MC), whose maximum thickness has not been assessed yet; at the top, these clays are weathered down to few meters; they are overtopped by a shallow cover of disturbed soil and landslide debris;
- a chaotic complex (C) formed by Varicolored Scaly clays, limestones, calcareous marls, calcarenites and fragments of Faeto flysch.

As shown in Figure 1, the MC formation is in lateral contact with formation F, that emerges in the Southern part of ridge, where the flysch appears to be less fractured and constitutes the foundation soil of the historical part of the town, the Faeto flysch is heavily tectonized and broken up.
The Toppo Capuana marly clay formation at San Giuliano di Puglia consists of three principal units:

- a ‘debris cover’, of less than five meters thickness, including black organic carbonaceous elements, lumps and lenses of white powdery calcite and small calcareous litho-clasts;

- a layer, of two to ten meters thickness, of ‘weathered tawny clays’, characterized by medium to intense fissuring, resulting from the weathering and disturbance of the uppermost part of Toppo Capuana marly clays;
- a deep layer of Toppo Capuana marly clays, called ‘grey clays’ hereafter. The thickness of this layer seems to be around three hundred meters. The grey Toppo Capuana marly clays are less intensely fissured than the weathered tawny clays; in some cases the fissure surfaces are either ochraceous or covered by a black oxidation patina. The polyhedral clay elements, of 2 – 4 cm maximum size, are sharply edged and well embedded within the fissure network. Crystals of selenitic gypsum are detectable in rare lenses or in thin layers of fine sand.

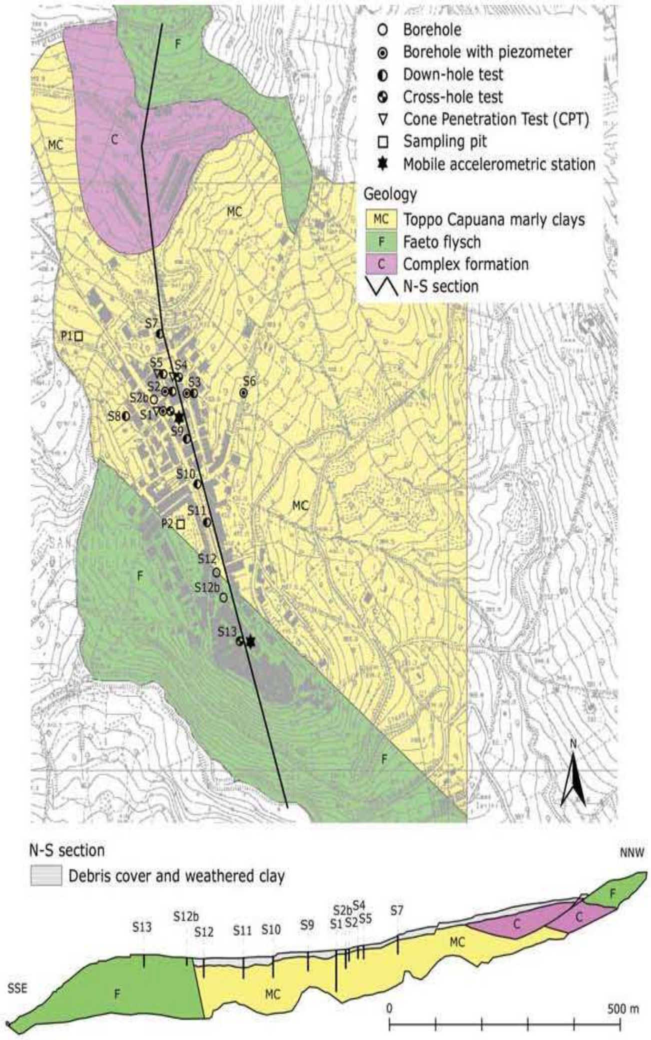

Fig.1. Geological map and N-S section of San Giuliano di Puglia (after Silvestri et al., 2006).

BASIC GEOTECHNICAL SOIL PROPERTIES

Boreholes driven to a depth of 21 m were performed and undisturbed samples were retrieved for laboratory tests. The testing programme consisted of standard classification tests, Oedometer tests, undrained triaxial tests and resonant column tests.

The general characteristics and index properties of the Toppo Capuana marly clay formation at San Giuliano di Puglia are shown, as a function of depth, in figure 2.

The overall values of the main physical properties are summarized in Table 1, which reports the average values. The values of the natural moisture content w_n prevalently range between 17 and 22 %.

Characteristics values for the Atterberg’s limits are: w_l = 53 - 63 % and w_p = 23 - 24 %, with a plasticity index of PI = 30 - 40 % (Silvestri et al., 2006; Vitone, 2005).

Table 1. Physical average properties of the three units.

	Debris Cover	Tawny Clay	Grey Clay
Thickness	≤ 5 m	2 – 10 m	≈ 300 m
Sand Fraction [%]	5.8	3.1	2.4
Silt Fraction [%]	42.0	48.2	51.0
Clay Fraction [%]	51.7	48.6	46.5
γ [KN/m^3]	19.65	21.09	21.23
e [-]	0.72	0.54	0.49
G_s [-]	2.71	2.71	2.73
w_n [%]	22.4	19.5	17.4
w_p [%]	23.8	23.2	23.2
w_l [%]	63.4	53.8	53.2
c' [kPa]	32	32	126
ϕ' [°]	18	18	20

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

The data shown in figure 2 clearly indicate a good 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 3).

The variation of q_c with depth clearly shows the existence of layers with very different mechanical characteristics.

The upper ‘debris cover’ with q_c of about 0.4 to 6.1 MPa. The ‘weathered tawny clays’ has q_c values of about 3.2 to 21.7 MPa. The ‘grey clays’ deep layer has q_c values of about 5.9 to 18.2 MPa. Two transition zones ($q_c \cong$ 14.5 to 21.7 MPa) exists between these three strata at depths of about 5 and 10 m.

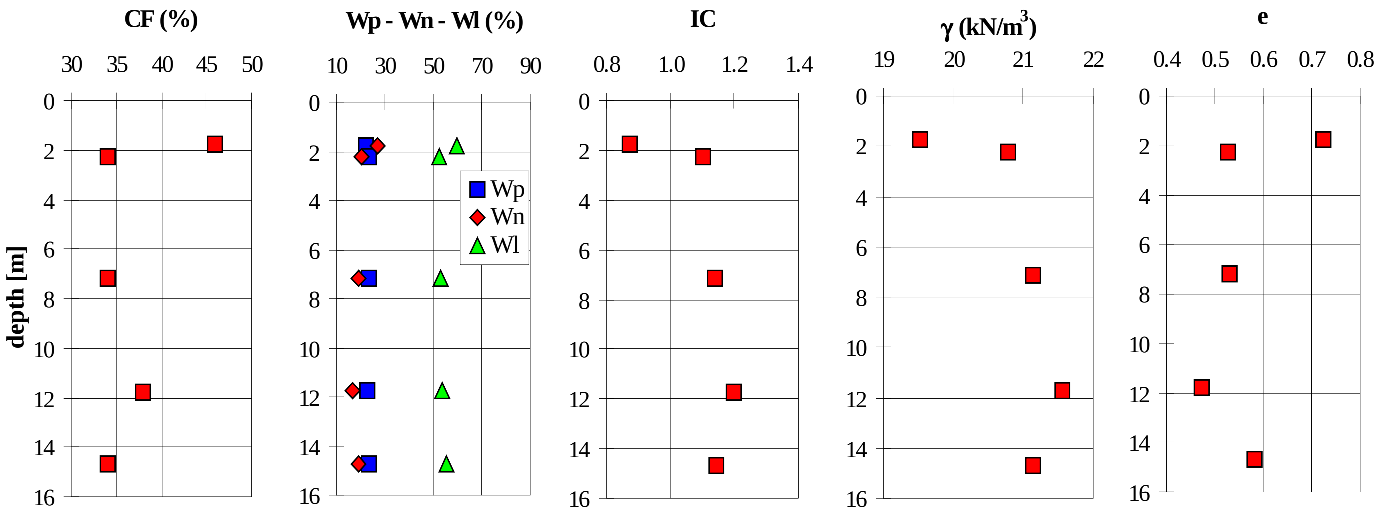

Fig.2. Index properties of Toppo Capuana marly clays.

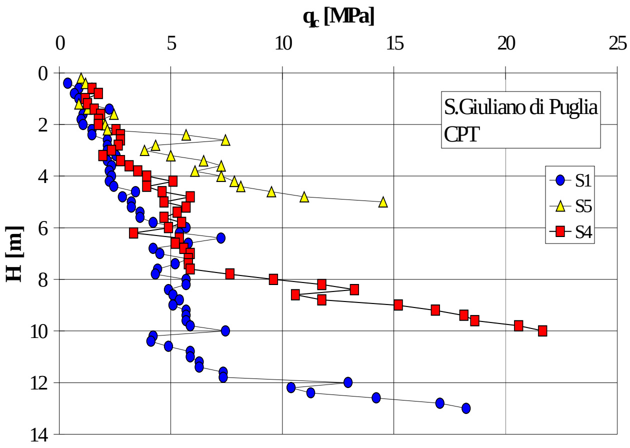

Fig. 3. Static cone penetration test results.

SHEAR MODULUS AND DAMPING RATIO FROM LABORATORY TESTS

Shear modulus G and damping ratio D of Toppo Capuana marly clay formation were obtained in the laboratory from Resonant Column tests (RCT). The laboratory test conditions and the obtained small strain shear modulus G_o are listed in Table 2.

The undisturbed specimens were isotropically reconsolidated to the best estimate of the in situ mean effective stress. The size of solid cylindrical specimens are Radius = 25 mm and Height = 100 mm.

Table 2. Test Condition for Toppo Capuana marly clay formation specimens.

Borehole No.	H [m]	σ'_{vc} [kPa]	e	PI	RCT	G_o [MPa]	ΔU_{max} [kPa]
S3C1	1.75	98	0.720	37	U	36	11
S5C2	7.15	155	0.523	30	U	144	30
S11C1	2.25	350	0.579	29	U	133	9
S11C3	11.75	397	0.464	31	U	173	2
S11C4	14.70	397	0.506	32	U	145	5

where: U = Undrained.

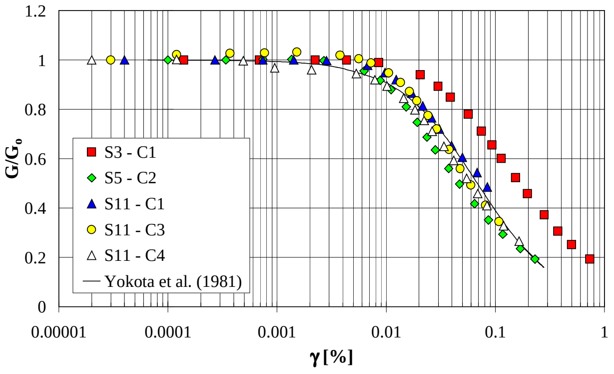

Fig. 4. G/G_o-γ curves from RCT tests.

Figure 4 shows the results of RCTs normalized by dividing the shear modulus G(γ) for the initial value G_o at very low strain.

The experimental results of specimens from Toppo Capuana marly clay formation were used to determine the empirical parameters of the eq. proposed by Yokota et al. (1981) to describe the shear modulus decay with shear strain level:

$$\frac{G(\gamma)}{G_o} = \frac{1}{1+\alpha\gamma(\%)^{\beta}} \qquad (1)$$

in which:
$G(\gamma)$ = strain dependent shear modulus;
γ = shear strain;
α, β = soil constants.
The expression (1) allows the complete shear modulus degradation to be considered with strain level.
The values of $\alpha = 24$ and $\beta = 1.184$ were obtained for Toppo Capuana marly clay formation.

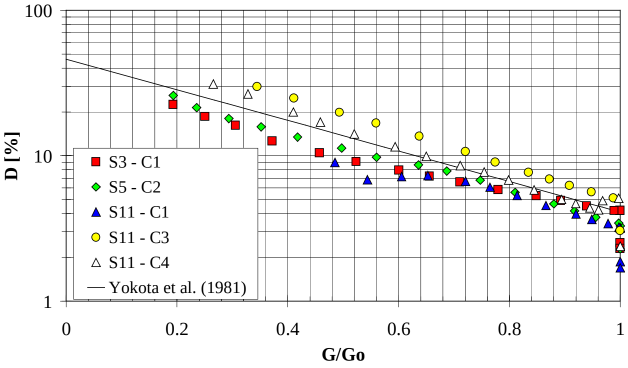

Fig. 5. D-G/G$_o$ curves from RCT tests.

As suggested by Yokota et al. (1981), the inverse variation of damping ratio with respect to the normalized shear modulus has an exponential form as that reported in Figure 5 for the central area of Catania:

$$D(\gamma)(\%) = \eta \cdot \exp\left[-\lambda \cdot \frac{G(\gamma)}{G_o}\right] \qquad (2)$$

in which:
$D(\gamma)$ = strain dependent damping ratio;
γ = shear strain;
η, λ = soil constants.
The values of $\eta = 46$ and $\lambda = 2.420$ were obtained for Toppo Capuana marly clay formation.
The equation (2) assume maximum value $D_{max} = 46$ % for $G(\gamma)/G_o = 0$ and minimum value $D_{min} = 4.09$ % for $G(\gamma)/G_o = 1$.
Therefore, eq. (2) can be re-written in the following normalized form:

$$\frac{D(\gamma)}{D(\gamma)_{max}} = \exp\left[-\lambda \cdot \frac{G(\gamma)}{G_o}\right] \qquad (3)$$

EVALUATION OF G$_O$ FROM PENETRATION TESTS

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) Hryciw (1990):

$$G_o = \frac{530}{(\sigma'_v/p_a)^{0.25}} \frac{\gamma_D/\gamma_w - 1}{2.7 - \gamma_D/\gamma_w} K_o^{0.25} \cdot (\sigma'_v \cdot p_a)^{0.5} \qquad (4)$$

where: G_o, σ'_v and p_a 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 Marchetti (1980).

b) Mayne and Rix (1993):

$$G_o = \frac{406 \cdot q_c^{0.696}}{e^{1.13}} \qquad (5)$$

where: G_o and q_c are both expressed in [kPa] and e is the void ratio. Eq. (5) is applicable to clay deposits only.

c) Jamiolkowski et. al. (1995):

$$G_o = \frac{600 \cdot \sigma'^{0.5}_m p_a^{0.5}}{e^{1.3}} \qquad (6)$$

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. (6) 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 (1996) for Holocene clay deposits.
Eqs. (5) and (6) incorporate a term which expresses the void ratio; the coefficient of earth pressure at rest only appear in eq. (4). However only eq. (4) tries to obtain all the input data from the DMT results.
The G_o values obtained with the methods above indicated are plotted against depth in Figure 6. The method by Jamiolkowski et al. (1995) was applied considering a given profile of void ratio and K_o. The coefficient of earth pressure at rest was inferred from DMT.
The methods by Hryciw (1990) and Jamiolkowski et. al. (1995) show very different G_o values of the soil respect to the method by Mayne and Rix (1993). On the whole, equation (5) seems to provide the most accurate trend of G_o with depth, as can be seen in Figure 6. The DMT material index was not

capable of detecting the presence of different strata at depths of about 5 and 10 m.

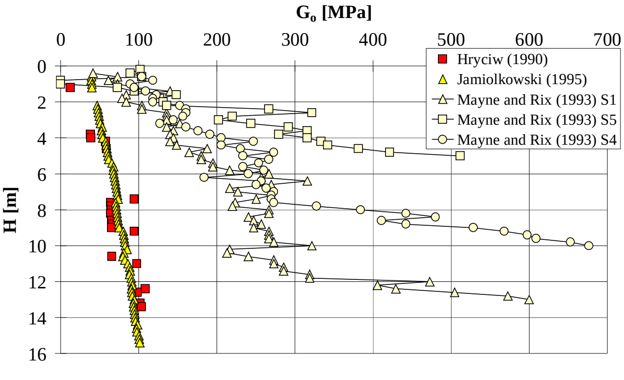

Fig. 6. G_o *from different empirical correlations.*

SHEAR MODULUS FROM IN SITU TESTS

Values of G_o have been obtained from Down-Hole (D-H) and Seismic Dilatometer Marchetti Test (SDMT). The SDMT provides a simple means for determining the initial elastic stiffness at very small strains and in situ shear strength parameters at high strains in natural soil deposits. Location of SDMT tests at San Giuliano di Puglia site is shown in Figure 7.

Figure 8 shows the values of G_o obtained in situ from D-H tests and Seismic Dilatometer Marchetti Test (SDMT).

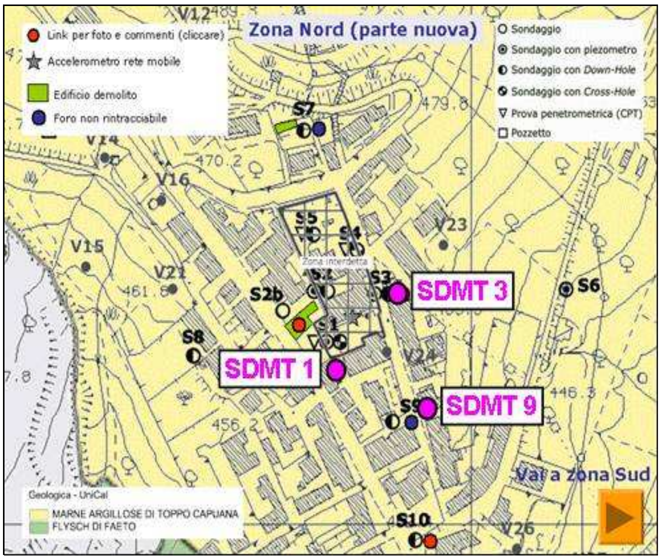

Fig. 7. Location of SDMT tests at San Giuliano di Puglia.

The G_o values are plotted in Figure 8 against depth. It is possible to see that quite a good agreement exists between the D-H tests results.

Higher values of G_o was obtained by SDMT. Considering the Figures 6 and 7 it is possible to see a good agreement between the G_o results obtained by Mayne and Rix (1993) and by in situ SDMT.

While always in the Figures 6 and 8 the results by D-H tests are comparable with those obtained by Hryciw (1990) and Jamiolkowski et. al. (1995) correlations.

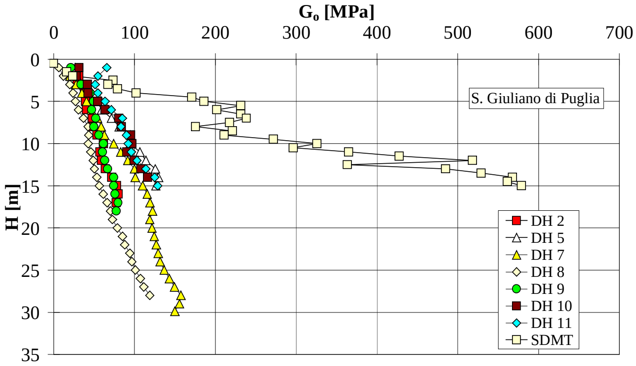

Fig. 8. G_o *from in situ tests.*

GROUND RESPONSE ANALYSIS AT THE SOIL SURFACE USING DIFFERENT V_S PROFILES

The site response was made by 1-D non-linear computer code GEODIN. The code implements a one-dimensional simplified, hysteretic model for the non-linear soil response (Frenna and Maugeri, 1995). The S-wave propagation obtained by D-H and SDMT occurs on a 1-D column having shear behavior. The column is subdivided in several, horizontal, homogeneous and isotropic layers characterized by a non-liner spring stiffness G(γ), a dashpot damping D(γ) and a soil mass density ρ. Moreover, to take into account the soil non-linearity, laws of shear modulus and damping ratio against strain have been inserted in the code. The 1-D columns have a height of 30 m and are excited at the base by accelerograms obtained from the recording of the aftershocks of the earthquake of October 31, 2002 (M_L = 5.4; Mw = 5.7) (Lat. 41.76; Long. 14.94) (see Figure 9). The analysis provides the time-history response in terms of displacements, velocity and acceleration at the surface. Using this time history, response spectra concerning the investigated site have been deduced.

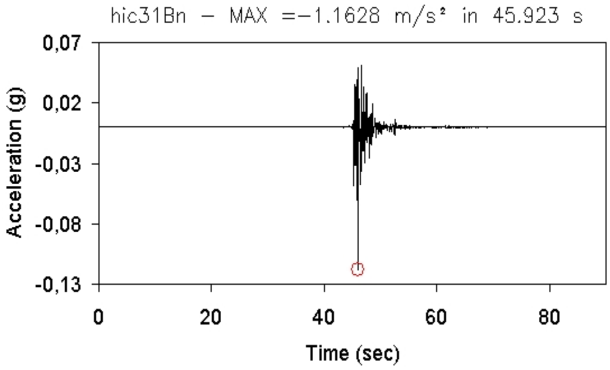

Fig. 9. Acceleration (g) of the recorded aftershock used for analyses of local seismic response.

The soil response at the surface was also modeled using the Equivalent linear Earthquake site Response Analyses of Layered Soil Deposits computer code EERA (Bardet et al., 2000) for calculus of amplitude ratios and spectral acceleration.

Figure 10 shows as example the stratigraphy of borehole S3 (near SDMT 3) with indication of V_s profile. It is possible to find a layer, of about three meters thickness, of ‘weathered tawny clays’, characterized by medium to intense fissuring, resulting from the weathering and disturbance of the uppermost part of Toppo Capuana marly clays; then a deep layer of Toppo Capuana marly clays, called ‘grey clays’ hereafter.

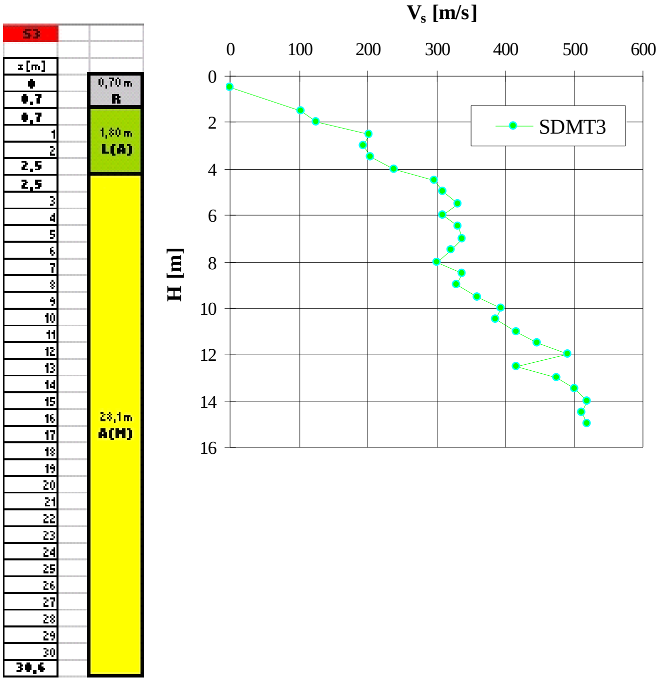

Fig. 10. Stratigraphy of borehole S3 (near SDMT 3) with indication of Vs profile.

In Figure 11 is reported the time history of accelerations at the soil surface, to allow calculus respectively of amplitude ratios and response spectra using GEODIN and EERA.

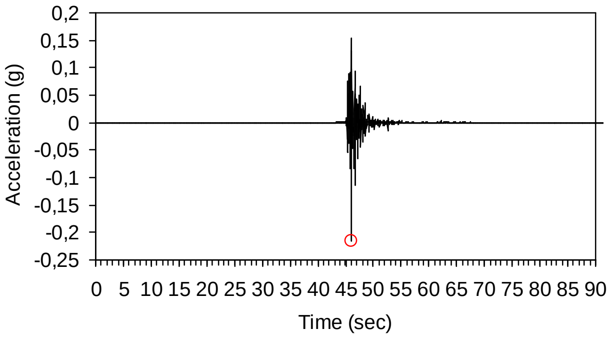

Fig. 11. Time history of acceleration at the soil surface (g) of the recorded aftershock of earthquake of October 31, 2002.

Figure 12 shows the variation with depth of maximum shear strain, ratio G/G_{max} and damping ratio at each of the calculation iteration step performed using EERA. At the first calculation step, the ratio G/G_{max} is equal to 1, and the damping ratio is constant. After a few calculation steps, the distributions of ratio G/G_{max} and damping ratio converge toward their final values.

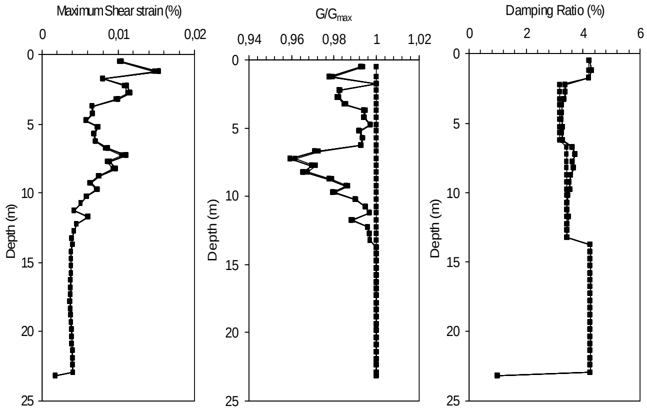

Fig. 12. Variation with depth of maximum shear strain, ratio G/G_{max} and damping ratio.

Figure 13 shows the corresponding variation with depth of maximum shear stress during calculations, and the converged maximum acceleration.

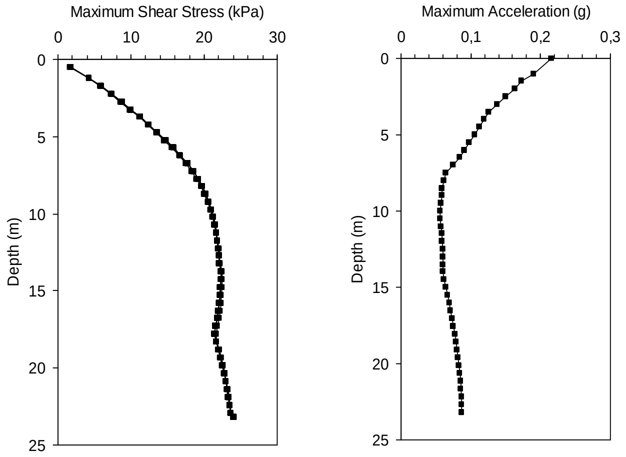

Fig. 13. Variation with depth of maximum shear stress during calculations, and the converged maximum acceleration.

Figure 14 shows the time histories of shear strain, shear stress and energy dissipated per unit volume, and the stress-strain loop computer at sub-layer No. 4.

Figure 15 shows the computed amplitude of amplification ratio between bottom and free surface and the computed amplitude of Fourier amplitude at free surface.

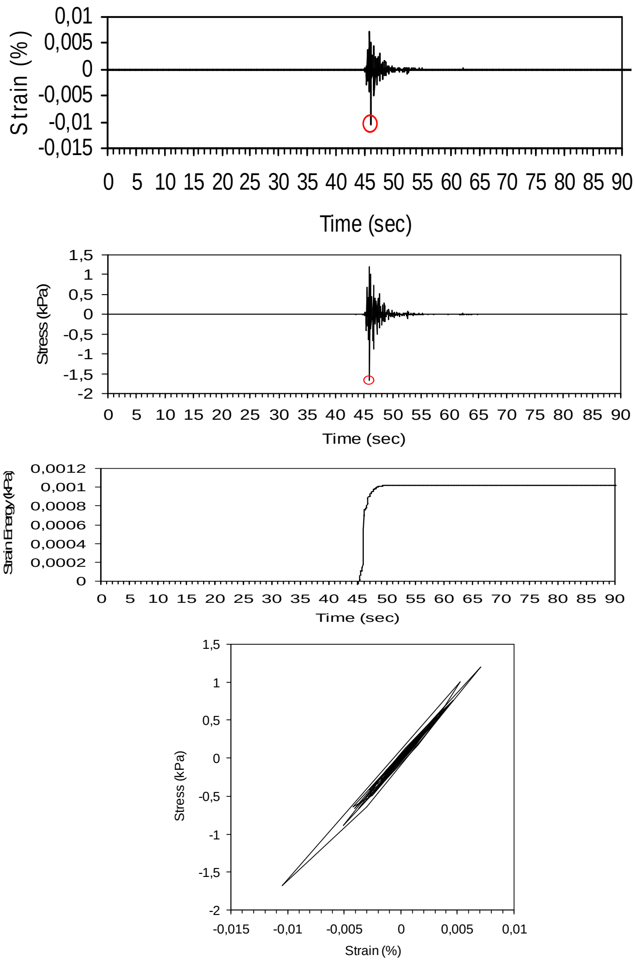

Fig. 14. Time histories of shear strain, shear stress and energy dissipated per unit volume, and the stress-strain loop computer at sublayer No. 4.

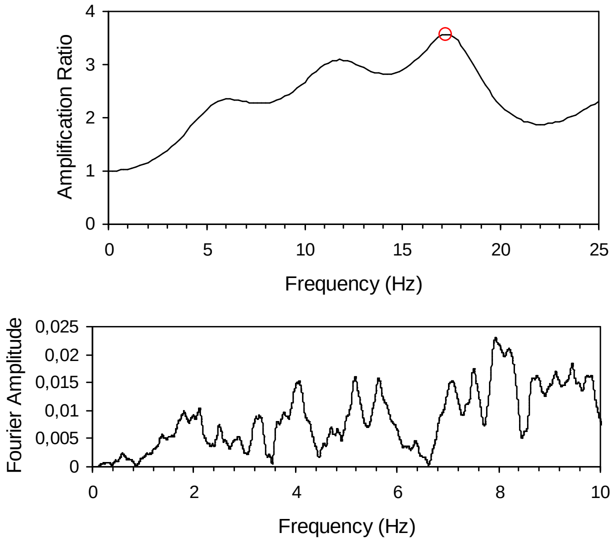

Fig. 15. Computed amplitude of amplification ratio between bottom and free surface and computed amplitude of Fourier amplitude at free surface.

Response spectra at the soil surface have been then obtained from GEODIN and EERA using components of the recorded earthquake. Figure 16 displays the acceleration response spectra computed at free surface for a 5 % critical damping ratio.

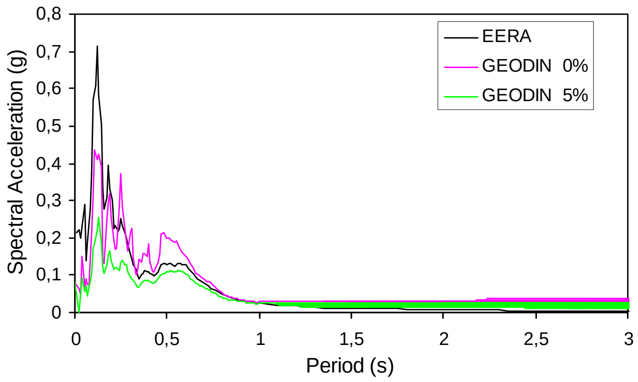

Fig. 16. Acceleration response spectra computed at free surface for a 5 % critical damping ratio.

CONCLUDING REMARKS

In this paper some information concerning G and D of San Giuliano di Puglia area in the Molise region for seismic response analysis have been presented. Available data enabled one to define the small strain shear modulus profile to describe the G and D variation with strain level. Experimentally determined G_o profiles from in situ tests were compared to that inferred from laboratory test results. It was then possible to evaluate the seismic response of the soil excited at the base by accelerograms obtained from the recording of the aftershocks of the earthquake of October 31, 2002. The site response was made by 1-D non-linear computer code GEODIN and also by the Equivalent linear Earthquake site Response Analyses of Layered Soil Deposits computer code EERA. The analysis provided the time-history response at the surface, the computed amplitude of amplification ratio between bottom and free surface and the acceleration response spectra at the free surface.

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