

Dynamic characterization of soils at Sellano for seismic microzonation

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Summary

This paper describes the results of an in situ study which was carried out in order to determine the geotechnical dynamic soil behaviour of the Sellano area for seismic microzonation, with special attention being paid to the variation of initial shear modulus G_0 with depth. The experimental study was carried out using Down-Hole Test and Standard Penetration Test (SPT) results. General geotechnical characteristics were evaluated on undisturbed samples in static field. The results obtained showed the possibility to use empirical correlations from SPT to evaluate G_0 . The use of a new equation to estimate the initial shear modulus was also proposed. Finally a comparison between normalised laws for different cohesive soils to consider shear modulus decay and damping ratio increase with strain level was proposed.

1. Introduction

Seismic microzonation in urban sites has two principal aspects: the first is related to the site behaviour under shaking such as site amplification, landsliding, settlement and liquefaction, while the second concerns the vulnerability of building to the seismic forces. Particularly the site amplification, which depends on geotechnical soil properties, can affect building safety in different ways.

In order to mitigate the earthquake effects on structures, predictions of dynamical site behaviour have been taken into consideration in many countries. Seismic risk is presented on a zoning map in which zones with different levels of potential hazard are identified. The influence of such factors on local seismic response is, by now, widely recognised, in fact, the technical Committee for Earthquake Geotechnical Engineering of the International Society for Soil Mechanics and Foundation Engineering have recently published the Manual for Zonation on Seismic Geotechnical Hazard (TC4-ISSMGE, 1999) which includes methods for assessing local ground response, soil instability and liquefaction and indicates three levels of zonation.

The first is based on geological survey and interpretation of the existing information from historic documents, including magnitudes and focal mechanisms. Existing correlations of ground motion attenuation with distance allow preliminary maps of expected acceleration to be drawn. A second level of zonation may be achieved at moderate cost by

matching use of additional source of data such as microtremor measurements, field and laboratory collection of geotechnical data. Where a third level of detailed zonation is required, additional field and laboratory investigations will be needed for a specific site. Computer analyses of seismic ground response allow the appreciation of amplification effect, slope instability, settlement and liquefaction potential hazard.

In this paper a geotechnical dynamic characterisation is presented for the soils of the Sellano area (Fig. 1).

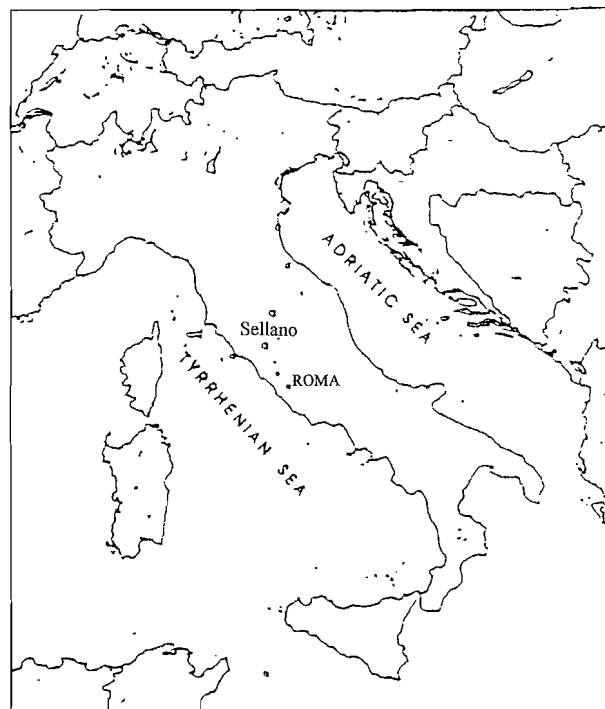


Fig. 1 – Location of Sellano, Italy.

Fig. 1 – Ubicazione di Sellano, Italia.

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The geotechnical soil parameters have been obtained from laboratory and in situ tests. These parameters represent the base elements for a correct seismic microzonation in the Sellano site.

2. The September-October 1997 earthquake

The seismic sequence of 1997 regarding the Umbro-Marchigiano Appennino took place on 3rd September 1997 (at 22:07) with an earthquake shock of magnitude $M_L = 4.5$ located in the Colfiorito and Collecorti zones, followed in the following days by many repetitions of inferior magnitude.

On the 26th September at 24:33 a shock of magnitude $M_L = 5.5$, located in the same epicentral zone, caused high damage especially at Collecorti, Cesi and Colfiorito. At 9:40 of the same day a new shock occurred ($M_L = 5.8$) with the epicentre shifted by about 5 km towards the north-west, that caused damage at Colfiorito, Annifo, Nocera Umbra, Assisi, Foligno, Camerino, Fabriano and in many smaller centres of the Marches and Umbria regions. The epicentre MKS intensity of these two shocks was VIII and IX degrees respectively [MARSAN *et al.*, 2000].

The earthquake of the 26th September 1997 was the strongest seismic event during the last century, for this area and can be considered the reference earthquake for the Umbria and Marches regions. The recorded magnitude, equal to the characteristic value of higher events of this Appennino section, shocked a geological structure many tens of square kilometres large. The study of this area is important for the knowledge of the seismic process of the Appennino.

This earthquake allowed the establishment of not only a comparison with the seismotectonic knowledge of Umbria, but also it emphasized especially a seismic deformation of stretching type with extension in SW-NE direction. Either the temporal sequence trend or the magnitude distribution along the time showed the complexity of the process of energy released, with the superimposition of many events with magnitude greater than 5.0, and the moving of different fragments of fault.

On 3rd October 1997 a shock of magnitude $M_L = 4.8$ struck the area, again causing panic among the population. This event was localised lightly more to the north of the previous, near Nocera Umbra. After numerous shocks on the meridional margin of this the seismogenetic zone were recorded: on 4th October ($M_L = 4.3$), near Sellano and Preci, to about 10 km south of Colfiorito; on 6th October at 23:24 ($M_L = 5.3$) and on 7th October

at 5:09 ($M_L = 4.1$), localised in the zone of Casenove, at few kilometre west of Colfiorito. On 12th October 1997 a shock of magnitude $M_L = 5.1$ occurred at 11:08 with epicentre in the Sellano and Preci zones, at the meridional extremity of the active zone during the entire sequence, causing new damage. In the two following days, almost all seismic repetition was concentrated in this sector. At 15:23 on the 14th October, another shock of magnitude $M_L = 5.4$ struck the same area, with an epicenter near the Communes of Sellano and Preci. The epicentres of greater shocks which struck Sellano are shown in Fig. 2.

The seismic events of September-October 1997 generated a seismogenetic zone with an extension of about 30 km, concerning many segments of faults. The seismic activity was concentrated principally along two of these segments: one along Colfiorito, the other one along Sellano. To the meridional extremity of the activated zone the seismogenetic structure of Valnerina is located, influenced by the seismic sequence of 1979, which should have released the greater share of energy.

The 14th October earthquake was felt as far as Rome, where at 13:23 a shock was felt with particular evidence in the historic centre and in the areas near to the alluvial valley of the Tevere.

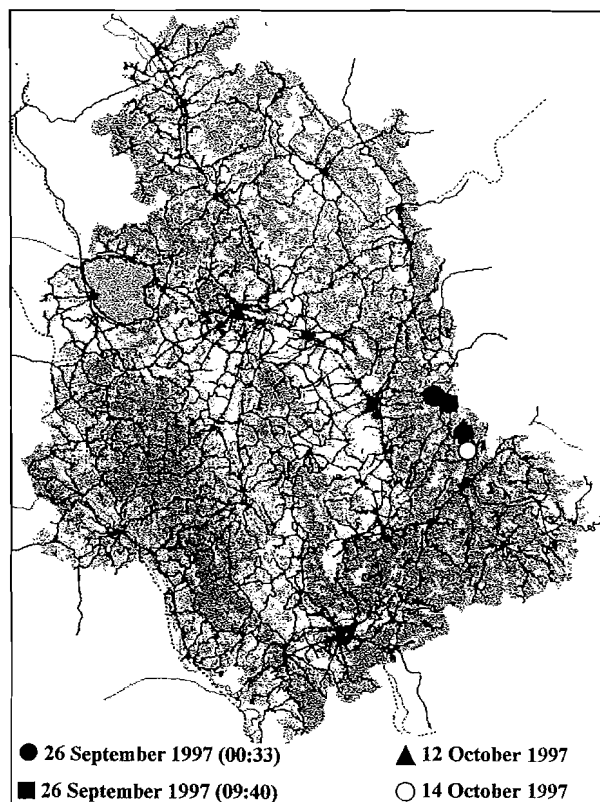


Fig. 2 – Epicentre of main shocks in Sellano area.

Fig. 2 – Epicentri delle scosse nell'area di Sellano.

The maximum intensity reached in the epicentral area from 4th September to 14th October was equal to IX MKS during the seismic sequence of 9:40 of 26th September, which was the highest magnitude of the sequence.

The higher damage and total falls were widely diffuse in buildings of poor quality.

Moreover it is possible to note the presence of environmental effects such as [DOLCE and LAROTONDA, this issue]: site amplification and landslides [MASSIMINO *et al.*, this issue].

3. Investigation program and soil properties

The investigated area covered the entire Comune of Sellano and a maximum depth of 30 m. The area pertaining to the investigation program and the locations of the boreholes and field tests are shown in Fig. 3. The investigation consisted in 13 boreholes driven at various depths. Seismic in situ tests were also performed, including down-hole. To characterise the in situ shear strength, Standard Penetration Tests were employed. The tests were carried out inside the boreholes, at intervals between 1.5 and 3 m depending on soil stratum investigation variability. The aim of in situ tests was to correlate N_{SPT} with the initial shear modulus G_0 of soil by means of empiri-

cal correlations. Inclinator and piezometer measurements were also performed.

Undisturbed samples were retrieved by means of an 86 mm Shelby tube sampler.

The Sellano deposits showed a complex subsoil. The upper stratum, at a depth of about 15 m and more, consists of debris accumulation with shear wave velocity V_s values less than 200 m/s.

The lower soils generally consist of an alternance of green marl ("Scaglia Variegata"), grey clayey-marl ("Scaglia Cinerea") and red calcareous marl ("Scaglia Rossa") with interbedded a sandy-silt or clayey-silt matrix. In these stratum higher values of shear wave velocity were recorded.

The general characteristics and index properties of the Sellano soil are shown, as a function of depth, in Fig. 4; while typical range of strength parameters of the deposits encountered in the Sellano area are reported in Tab. I. The values of the natural moisture

Tab. I – Mechanical characteristics for the Sellano area.

Tab. I – Caratteristiche meccaniche dell'area di Sellano.

g [kN/m ³]	W_n [%]	W_l [%]	W_p [%]	c' [kPa]	φ' [°]
18.7-19.4	20-25	27-37	15-23	0.10-0.28	23-26

where: c' (cohesion) and φ' (angle of shear resistance) were calculated from direct shear tests.

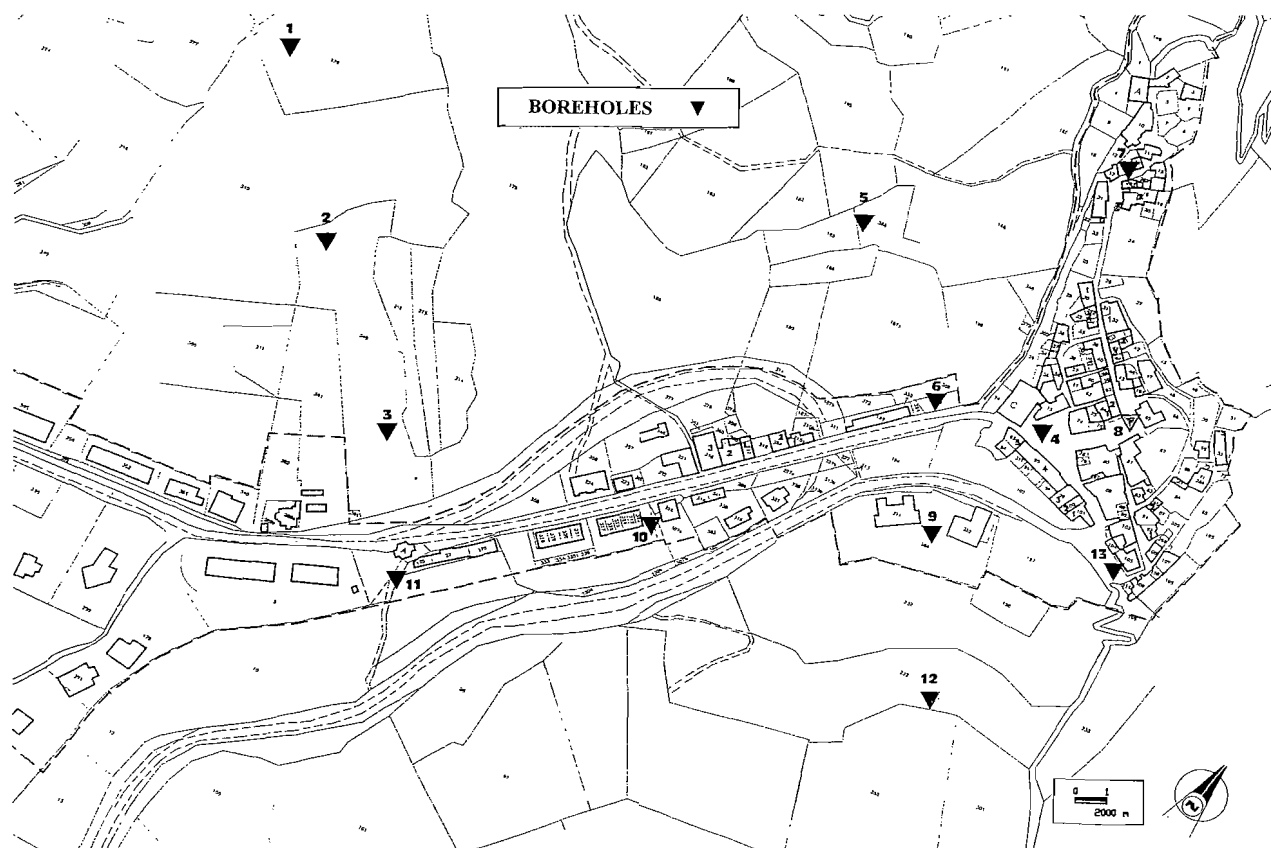


Fig. 3 – Lay-out of investigation program.

Fig. 3 – Mappa del programma di indagine.

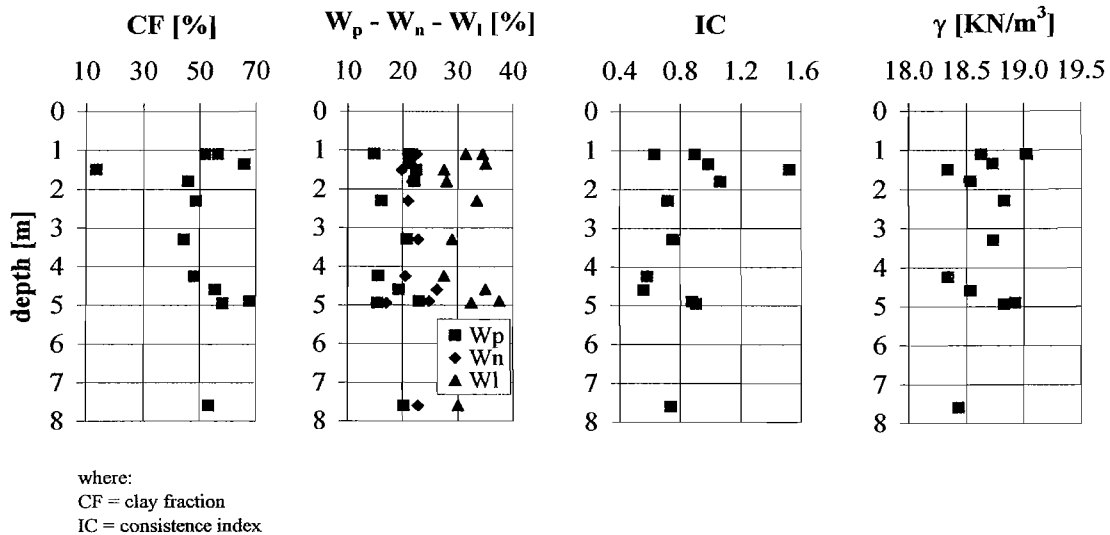


Fig. 4 – Index properties of Sellano soil.
 Fig. 4 – Indice delle proprietà del suolo di Sellano.

content w_n prevalently range from between 17 and 26%. Characteristics values for the Atterberg limits are: $w_L = 27 - 37\%$ and $w_p = 15 - 23\%$, with a plasticity index of $PI = 6 - 17\%$. The data shown in Fig. 4 clearly indicate a very low degree of homogeneity of the deposit. This indication with depth is also confirmed by analysing the shear wave velocity V_s from down-hole tests (DH – Borehole 4) performed over the investigated area (Fig. 5). The variation of V_s with depth clearly shows the existence of layers with very different mechanical characteristics. The soil deposits can be classified as CL inorganic soil of low plasticity (Fig. 6).

4. Shear modulus from in situ tests and evaluation from SPT tests

The values of G_0 were evaluated by means of the following empirical correlations based on standard penetration test results.

a) OHTA and GOTO [1978]:

$$V_s = 54.33 \cdot (N_{SPT})^{0.173} \cdot \alpha \cdot \beta \cdot \left(\frac{Z}{0.303}\right)^{0.193} \quad (1)$$

where: V_s = shear wave velocity (m/s), N_{SPT} = number of blows from SPT, Z = depth (m), α = age factor (Holocene = 1.000, Pleistocene = 1.303), β = geological factor (clays = 1.000, sands = 1.086),

b) YOSHIDA and MOTONORI [1988]:

$$V_s = \beta (N_{SPT})^{0.25} \cdot \sigma'_{v0}{}^{0.14} \quad (2)$$

where: V_s = shear wave velocity (m/s), N_{SPT} = number of blows from SPT, σ'_{v0} = vertical pressure, β = geological factor (any soil = 55, fine sand = 49),

c) IMAI and YOSHIMURA [1970]:

$$V_s = 76 (N_{SPT})^{0.33} \quad (3)$$

where: V_s = shear wave velocity (m/s), N_{SPT} = number of blows from SPT,

d) OHBA and TORIUMI [1970]:

$$V_s = 84 (N_{SPT})^{0.31} \quad (4)$$

where: V_s = shear wave velocity (m/s), N_{SPT} = number of blows from SPT.

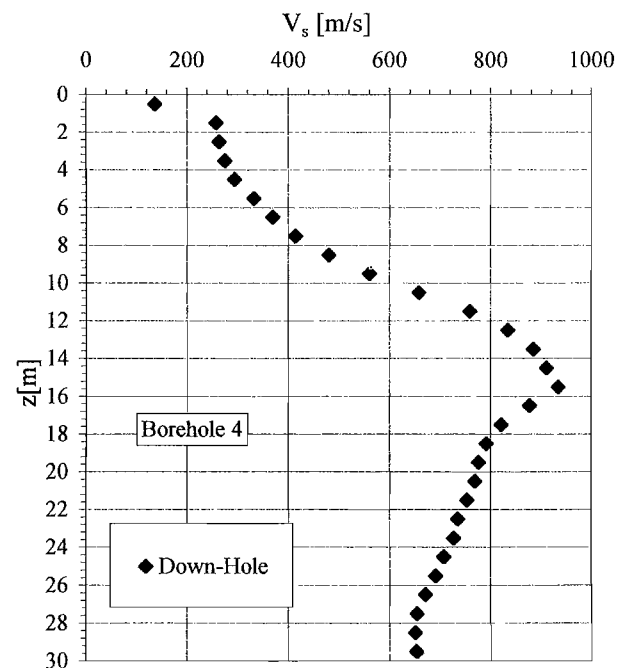


Fig. 5 – V_s from in situ tests.
 Fig. 5 – V_s ricavati dalle prove in situ.

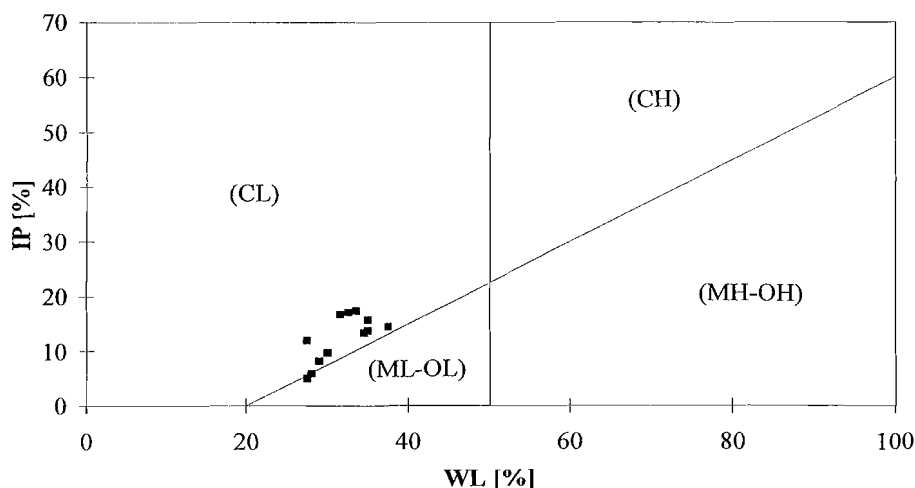


Fig. 6 – Plasticity chart.

Fig. 6 – Carta della Plasticità.

While the small strain shear modulus is evaluated by the well known equation:

$$G_o = \rho V_s^2 \quad (5)$$

where ρ = mass density

The G_o values obtained with the methods indicated above are plotted against depth in Fig. 7. The YOSHIDA and MOTONORI [1988] correlation was used with $\beta = 55$.

In Fig. 7 the values of G_o measured in situ from down-hole tests are also shown. In the case of in situ tests, the G_o values are determined by the recorded values of shear wave velocity V_s . A reasonable agreement between the in situ results and the initial shear modulus values evaluated by means of the proposed empirical correlations is observed. On the whole, Eq. (4) seems to provide the most accurate trend of G_o with depth, as can be seen in Fig. 7. Unfortunately the standard penetration tests were performed in correspondence to upper strata.

On the basis of experimental results Zuccarello (2000) has proposed the following expression of the shear wave velocity:

$$V_s = 80 (N_{SPT})^{0.31} \beta_{SPT} \eta' \quad (6)$$

where: $\beta_{SPT} = N_{SPT}$ factor, $\eta' =$ geological factor

In Tabs. II and III the range of change for the β_{SPT} and η factors are reported.

5. Normalised laws for seismic microzonation

The variation of initial shear modulus G_o with depth has been related to N_{SPT} data by means of equations proposed in the above paragraph, while the dependence on shear strain level was not known at this time because dynamic laboratory tests on undisturbed samples were still not available.

An advanced seismic microzonation requires a dynamic geotechnical characterisation of the soil in the laboratory by means of resonant column tests in order to determine the variation of shear modulus and damping ratio with strain level. At this stage because laboratory results in the dynamic field are not available, the results so far available for similar soil and particularly for the Fabriano soil are considered, where severe damage occurred during the 1997-1998 Umbria-Marches earthquakes.

The resonant column tests (RCTs) were performed on undisturbed specimens isotropically re-consolidated to the best estimate of the in situ mean

Tab. II – β_{SPT} factor.Tab. II – Fattore β_{SPT} .

N_{SPT}	β_{SPT}
≤ 20	1.0
20 – 40	0.8
40 – 60	0.75
≥ 60	0.7

Tab. III – η factor.Tab. III – Fattore η .

Soil	h
Filling / Covering soil	0.9
Prevalently sandy	1.0
Low / Medium compact clay	1.1
Plastic clay	1.15
Compact clay	1.2
Calcareous debris	1.4
Rocky subsoil	3.5

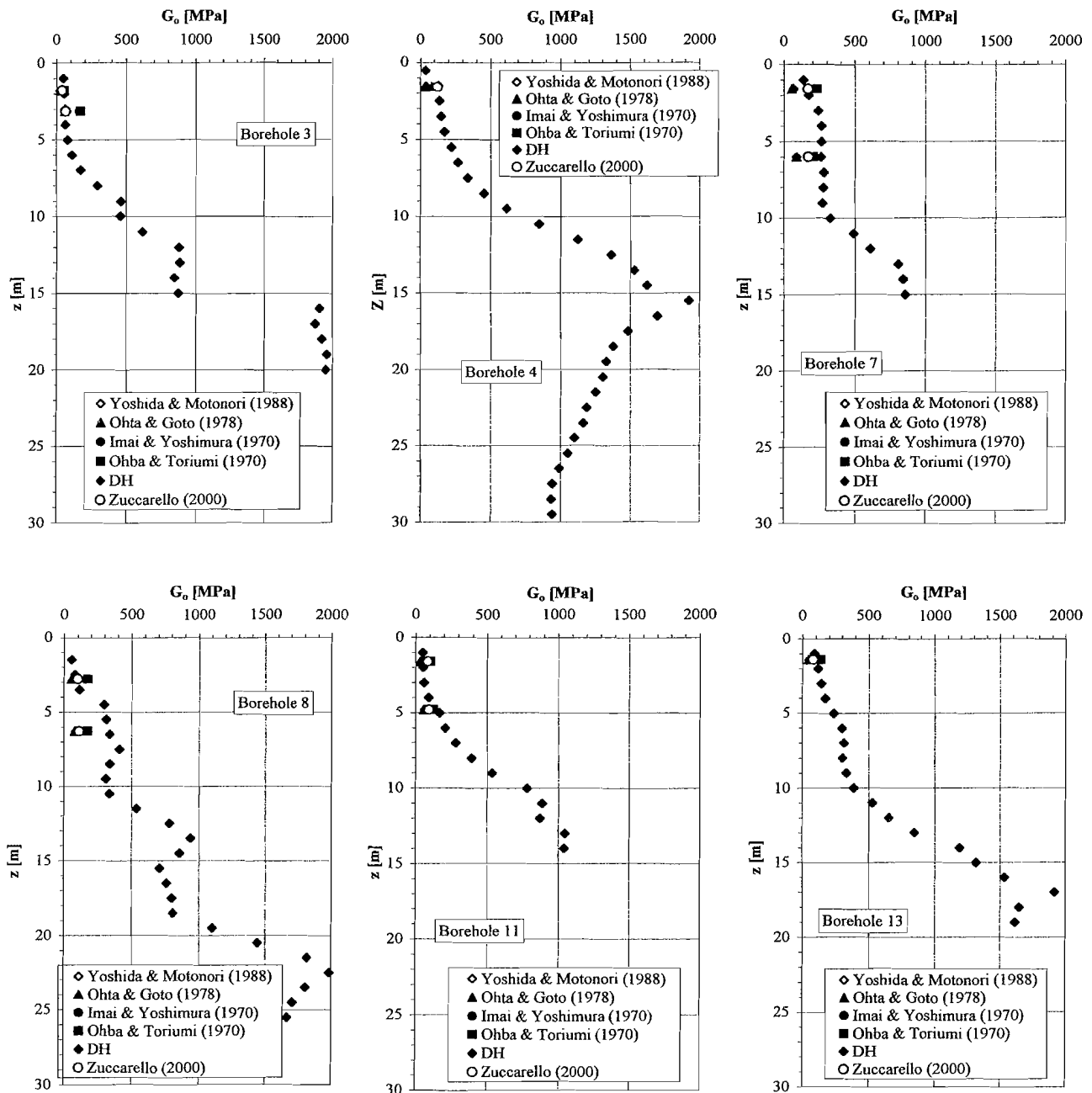


Fig. 7 – G_0 from different empirical correlations.

Fig. 7 – G_0 per le differenti correlazioni empiriche.

effective stress. The size of solid cylindrical specimens are Radius = 25 mm and Height = 100 mm. The G_0 values are determined at shear strain levels of less than 0.001 %.

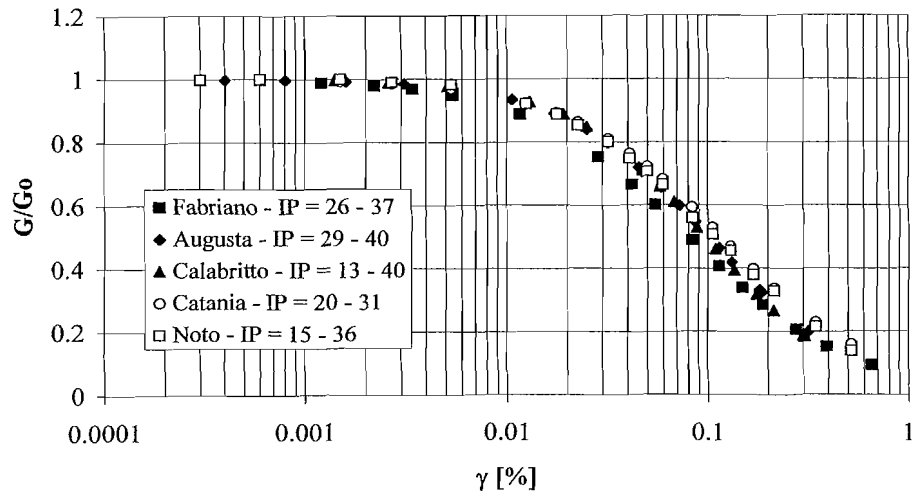
For RCTs the damping ratio was determined using the steady-state method during the resonance condition of the sample.

Fig. 8 shows the results of RCTs in terms of degradation of shear modulus with strain evaluated for different cohesive soils retrieved in other Italian seismic sites: Augusta [MAUGERI and FRENNA, 1995; CAVALLARO and MAUGERI, 1996; CAVALLARO, 1997; LO PRESTI *et al.*, 1998; CAVALLARO *et al.*, 1998; FRENNA

and MAUGERI, 1995], Calabritto [MAUGERI and CAR-RUBBA, 1997], Catania [CAVALLARO *et al.*, 1999b], Fabriano [CAVALLARO *et al.*, 2000a] and Noto [CAVALLARO *et al.*, 1999a, 2000b]. The results have been normalised by dividing the shear modulus $G(\gamma)$ for the initial value G_0 at very low strain.

The normalised shear modulus shown in Fig. 8 has little dependence on stress history, plasticity index and stress level, while it is mainly dependent only on the shear strain level.

The experimental results of specimens were used to determine the empirical parameters of the equation proposed by YOKOTA *et al.* [1981] to de-

Fig. 8 - G/G_0 - γ curves from RCTs.Fig. 8 - Curva G/G_0 - γ dalla RCTs.

scribe the shear modulus decay with shear strain level:

$$\frac{G(\gamma)}{G_0} = \frac{1}{1 + \alpha \gamma(\%)^\beta} \quad (7)$$

Expression (7) allows the complete shear modulus degradation to be considered with strain level.

As suggested by YOKOTA *et al.* [1981], the inverse variation of damping ratio in respect to the normalised shear modulus has an exponential form, like that reported in Fig. 9:

$$D(\gamma)(\%) = \eta \cdot \exp \left[-\lambda \cdot \frac{G(\gamma)}{G_0} \right] \quad (8)$$

in which: $D(\gamma)$ = strain dependent damping ratio; γ = shear strain and η, λ = soil constants. Equation (8) assumes the maximum value D_{\max} for $G(\gamma)/G_0 = 0$ and a minimum value D_{\min} for $G(\gamma)/G_0 = 1$.

Therefore, equation (8) can be re-written in the following normalised form:

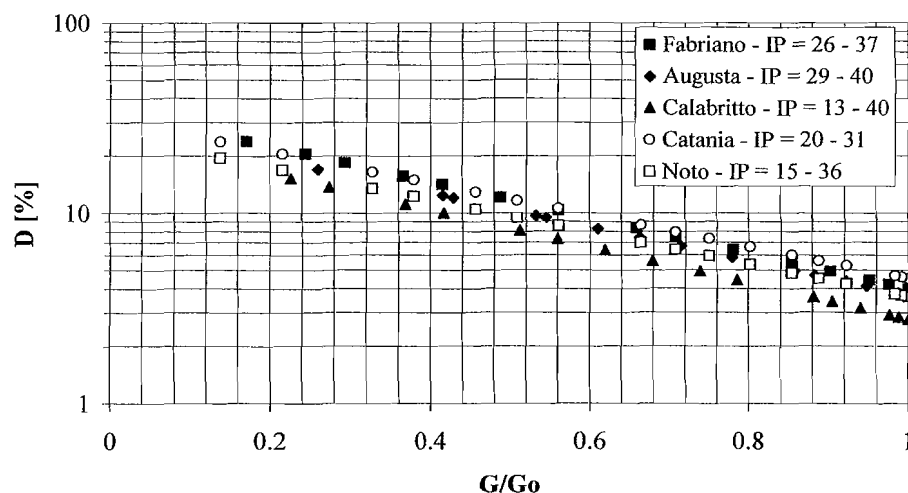
$$\frac{D(\gamma)}{D(\gamma)_{\max}} = \eta \cdot \exp \left[-\lambda \cdot \frac{G(\gamma)}{G_0} \right] \quad (9)$$

The values of empirical parameters of eqs. (7) and (8) are reported in Tab. IV. The η, λ parameters were obtained from the damping values assessed by means of the steady-state method.

Tab. IV - Soil constants for investigated areas.

Tab IV - Costanti del terreno per le aree investigate.

Site - (Soil)	α	β	η	λ
Augusta - (Clay)	14	1.24	18	1.52
Calabritto - (Clay)	20	1.28	25	2.2
Catania - (Clay)	11	1.119	31	1.921
Fabriano - (Silty Clay)	15.29	1.08	34.66	2.16
Noto - (Clayey Sand)	15	1.28	25.6	1.952

Fig. 9 - D - G/G_0 curves from RCTs.Fig. 9 - Curva D - G/G_0 dalla RCTs.

Considering that the influence of the number of cycles N on D has been found to be negligible, in the case of clayey soils for strain levels of less than 0.1 % [CAVALLARO 1997, LO PRESTI *et al.* 1996, LO PRESTI *et al.* 1997a, LO PRESTI *et al.* 1997b], it is supposed that RCT provides the large values of D at very small strain (Fig. 9) because of the rate (frequency) effect, in agreement with data shown by SHIBUYA *et al.* [1995] and TATSUOKA *et al.* [1995].

Concluding remarks

A geotechnical dynamic characterisation of the Sellano soil for seismic microzonation is presented in this paper.

Available data enabled one to define the small strain shear modulus profile with depth by in situ down-hole tests and standard penetration tests. Empirical equations between the small strain shear modulus and penetration test results were used to infer G_0 from SPT. The values of G_0 were compared to those measured in a DH test. This comparison clearly indicates that a certain relationship exists between G_0 and the penetration test results, which would encourage one to establish empirical correlations for a specific site. A new empirical correlation for the Sellano site was thus proposed.

Finally a comparison between normalised laws for different cohesive Italian soils to consider shear modulus degradation and damping ratio increase with strain level was proposed.

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Caratterizzazione dinamica dei terreni di Sellano ai fini di una microzonazione sismica

Sommario

Il presente lavoro riporta i risultati di uno studio in situ svolto con l'obiettivo di determinare il comportamento geotecnico dinamico del terreno dell'area di Sellano ai fini di una microzonazione sismica, con particolare attenzione alla variazione del modulo di taglio iniziale G_0 con la profondità. Lo studio sperimentale è stato svolto utilizzando i risultati delle prove down-hole e delle prove Penetrometriche Dinamiche (SPT). Caratteristiche geotecniche generali, in campo statico, sono state ottenute su campioni indisturbati. I risultati ottenuti hanno mostrato la possibilità di utilizzare correlazioni empiriche, basate su prove SPT, per stimare G_0 . È stato inoltre proposto l'utilizzo di una nuova equazione per valutare il modulo di taglio iniziale. Infine è stato presentato un confronto fra differenti leggi normalizzate in grado di stimare, nei terreni coesivi, la degradazione del modulo di taglio e l'incremento dello smorzamento in funzione del livello di deformazione.