An evaluation of the dynamic shear modulus of a cohesive deposit near Florence, Italy

Une évaluation du module de cisaillement dynamique d'un dépôt cohérent près de Florence (Italie)

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SUMMARY: The cross-hole testing results and the geotechnical data from conventional in situ and laboratory tests referring to a cohesive deposit near Florence, are analyzed from a statistical point of view for microzoning purposes. In order to evaluate the dynamic properties of the deposit, two main statistical analyses were conducted: a spatial variability investigation of the geotechnical properties and a regression analysis between dynamic and static soil parameters. A comparison between the relationships obtained with those found by other investigators shows a few discrepancies which might be explained in terms of the different seismic history of the sites studied.

1 SITE CHARACTERISTICS AND SEISMICITY

The area under study has an extension of about 2.6 km^2 and is located northwest of the historic centre of Florence (Fig. 1).

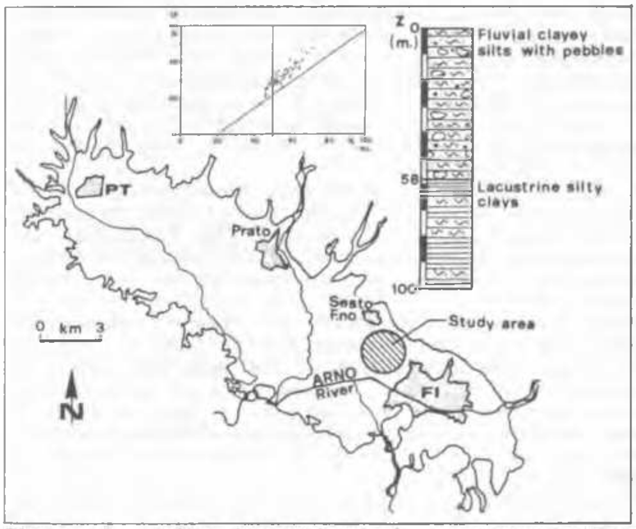

Figure 1. Site investigated, representative soil profile and plasticity chart.

The depth of the bedrock in the area seems to be variable, with discontinuity between 300 m and 450 m from the ground level, due to a system of bedding faults at right angles with each other, which divides it into blocks.
The soil is composed of a sedimentary fluvio-lacustrine deposit, which (see also Fig. 1):

- up to 60 m from the ground surface is prevalently formed by brown clayey silts with diffuse calcareous pebbles, often alternated with layers and lenses of gravel in an abundant clayey-silty matrix;
- beyond 60 m and up to the maximum depth reached with boreholes (100 m from the ground surface) is mainly composed by grey-blue silty clays.

The water static level was measured in correspondence with the lenses of material with relatively higher permeability, at depths between 0.5 and 2.2 m from the ground surface.
As regards seismic hazard, the area under study is classified at present into zones of medium seismicity according to the Italian code. The following conventional characteristics in a period of 500 years are established for this category:

- maximum MM intensity $\geq$ VIII
- maximum acceleration at the bedrock a_{max} = 0.3 g.

The area is not directly crossed by seismogenetic faults and suffers mainly from the activity of four nearby sources located at distances of between 10 and 40 km, whose most relevant characteristics are the following (a) generally very superficial hypocentral distance (H = 3-15 km), (b) maximum magnitude observed: about 5, (c) limited propagation of energy, (d) very brief duration of events (3-15 sec), (e) generally limited number of shocks (1-3), (f) extensive seismic periods.
The area also suffers from the seismic activity of other regions. From the seismic catalogue of historical earthquakes relative to a period of about 1000 years and in a network of 100x100 km around Florence, the following distribution of events results:

MKS intensity	V	VI	VII	VIII	IX
N° of events	48	34	18	7	1

However, the intensity of the strongest event ever occurred in the town was I = VIII MKS, as ground shakings are in general sensibly attenuated by some buried reflecting faults. No instrumental recordings of strong earthquakes are available on the site and in its surroundings.

2 GEOTECHNICAL DESCRIPTION AND SPATIAL VARIABILITY OF SOIL PROPERTIES

In order to evaluate the seismic response of the site, the geotechnical properties and their

variability were investigated, to a depth of about 60m from the ground surface, by means of N. 25 boreholes, N. 201 standard penetration tests (SPT), N. 57 cone penetration tests (CPT), N.1 cross-hole test and laboratory tests on 60 undisturbed samples.
Because of the diffuse, but not uniform, presence of pebbles and lenses of gravel in a clayey matrix, the penetrometric profiles are very irregular and only rarely can be reciprocally correlated. A statistical analysis of the CPT tests (Ghinelli and Vannucchi, 1988) has led to the conclusion that:

- more than 90% in volume of the soil is classifiable on the basis of the Schmertmann diagram (1978) as inorganic clay, often silty and at times sandy silt of high consistency;
- in the matrix of cohesive soils, there are diffused pebbles in the measure of 7% :
- organic clays and mixed soils are present in modest amounts and only in the top metres of the deposit.

Table 1: Statistical distribution of CPT data

	CLAY AND SILT (3188 observations)			PEBBLES, GRAVEL AND SAND IN CLAYEY SILT (250 observations)		
	q_c (KPa)	f_s (KPa)	I_f (-)	q_c (KPa)	f_s (KPa)	I_f (-)
MEAN	5796	308	19.1	10983	144	97.3
ST. DEV.	3785	164	7.2	7463	116	70.5
SKEWNESS	3.7	1.9	1.5	1.4	1.9	3.4
KURTOSIS	20.9	6.1	2.2	1.7	4.9	15.6
CV (%)	65	53	37	68	81	72

Table 2: Statistical distribution of SPT

N° OBSERVATIONS	201
MEAN VALUE	38.9
STANDARD DEV.	17.3
SKEWNESS	0.33
KURTOSIS	2.03
COEFF. OF VAR. (%)	47

In Table 1 and Table 2 the statistical distribution parameters of the penetrometric measurements are summarized.
It can be noted that, even if dispersed, the coefficient of variation of the CPT and SPT data falls into the values generally observed, that is 30-85% (Lee et Al., 1983).
In Fig. 2a the N_{spt} values versus depth are shown: they indicate the presence of very high random components, with a correlation coefficient r = 0.338. However, both mean value and standard deviation increase, even if irregularly, with the depth (Fig. 2b). In addition to local inclusions, this irregularity is also due, to the different number of observations in the layers (Fig. 2c).
Geotechnical laboratory tests were run on 60 undisturbed samples taken at depths of between 1.5 and 44.5 m from the ground surface.The representative points in the plasticity chart (Fig. 1) are distributed on a band parallel to Line A. A summary of the statistical parameters of the geotechnical properties of the soil is given in Table.3.
This is a clayey silt of good consistency, moderately overconsolidated, not very compressible nor swelling, of very low permeability, fairly

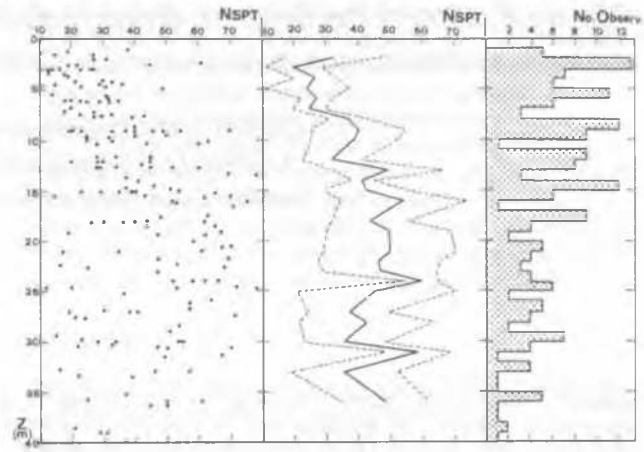

Figure 2. N_{spt} versus depth: a) single values; b) mean and standard deviation within layers thick 1 m; c) number of observations for each layer.

high shear strength in undrained conditions, and with a brittle type failure.
The considerable variability of several geotechnical properties (for example the unconfined compressive strength q_u) must be attributed to the diffuse , but not uniform, presence of pebbles and gravels sometimes of small dimensions.
The values of the permeability coefficient indicated in Table 3 refer to only the clayey silt matrix of the deposit; the presence of lenses of coarser material - even if in a cohesive matrix - leads locally to much higher values in the permeability coefficient, even on the order of 10^{-5} - 10^{-4} cm/sec.
It is to be noted, moreover, that the values of the coefficient of variation of the different properties always fall within the limits of the values generally recorded in the deposits considered as "uniform" and correspond to the lowest limit (Table 4).
From a statistical point of view it should be observed that, as regards the reliability of the results, the large number of samples makes it possible to effect - in the case of normal-type distribution - an evaluation of the average of the population with a precision variable between 1% and 20%, at a "level of confidence" equal to 95% (Lumb, 1974).
As results from Table 3, the hypothesis that the distribution fits to the normal can be accepted only for a few properties, namely W, I_p and e_o.
As regards the variation in the geotechnical properties with the depth, the statistical analysis demonstrated that in general they are scarcely correlated (Table 5 and Figure 3), even if a clear trend of the maximum values of OCR can be observed. A possible explanation is that in the zone explored, the effects of lithostatic pressure are compensated by the effects of overconsolidation.
The properties therein considered are the most significant ones for the purposes of seismic analysis.
For a better understanding of the uniformity characteristics of the soil, a collection of SPT data and of other geotechnical properties was made in a large area (about 100 Km^2) surrounding the zone in question. A total of N. 422 N_{spt}-values were collected, as well as the laborato-

Tab 3 : Statistical distribution of geotechnical properties

	W	W_L	W_P	I_P	γ	G_s
	(%)	(%)	(%)	(%)	KN/m^3	KN/m^3
MEAN	23.2	55.2	23.1	32.1	20.5	27.4
SDEV.	4.25	6.46	2.71	6.42	0.60	0.40
SKEW.	0.82	0.29	-0.03	0.22	-0.09	0.12
KURT.	4.12	2.27	2.51	2.90	2.35	2.1
CV %	18	12	12	20	3	1
	e_o	p_c	OCR	C_c	C_s	$Kx10^9$
	(-)	(KPa)	(-)	(-)	(-)	(cm/s)
MEAN	0.62	269	1.67	0.214	0.058	2.05
SDEV	0.10	80	0.65	0.052	0.025	1.06
SKEW.	0.51	0.25	1.41	1.28	2.50	1.29
KURT.	3.24	2.26	5.39	4.41	10.61	4.44
CV %	16	30	39	24	43	52
			q_u	r	c'	Φ'
			(KPa)	(-)	(KPa)	(°)
MEAN VALUE			249	9.4	47.5	22.6
STANDARD DEVIATION			119	3.8	33.2	4.52
SKEWNESS			0.28	0.32	0.34	-0.17
KURTOSIS			1.82	3.01	2.14	2.46
COEFF. OF VAR. (%)			48	40	70	20

Table 4 : Comparison of the coefficients of variation of geotechnical properties on the site and those obtained by other investigators.

PROPERTY	CV % SITE	CV% LITERATURE (Lee et Al.,1983)
Liquid limit	12	2-48
Plastic limit	12	9-29
Plasticity index	20	7-79
Density	3	5-10
Void ratio	16	13-42
Compressibility	24	18-73
Permeability	52	200-300
Undrained cohesion	48	20-50
Friction angle	20	12-56

ry-test results on 215 samples.
In the following, the site directly investigated will be named "site A" and the wider area "site B". The term deposit is comprehensive of the two sites.
The statistical analysis for testing the homogeneity of the deposit included:
- an analysis of the interdependence of the variables considered;
- a comparison between the statistical distributions of the data relative to the site A and of those of the site B.

Since the variables result as practically uncorrelated, it was possible to make a comparison of the distributions of data relative to the site A and to the site B, and to test the hypothesis H_o of the equality of means of the two populations. The results obtained are summarized in Table 6, in which are reported the levels of significance at which the hypothesis can be accepted. The maximum value obtained is 0.10; for the soils, this value is generally considered as acceptable for making a data pool.

Table 5 : r values of some geotechnical properties with depth

Property :	γ	I_p	e_o	OCR	q_u
r :	0.021	0.336	-.057	-0.266	-0.056

Table 6: Significance levels at which the hypothesis of equality between means can be accepted for different geotechnical properties.

W	WL	WP	eo	OCR	Cc	Cs	qu
0.10	0.10	0.10	0.001	0.002	0.002	0.10	0.05

4 EVALUATION OF SHEAR MODULUS AT SMALL STRAIN

The dynamic properties at small strains were investigated by means of cross-hole tests performed between two boreholes located about 5 meters apart at a depth of 40 m from the ground surface, with constant test interval equal to 1 m. The technology and executive procedures used are those described by Carabelli and Superbo (1983). The stratigraphic column of the site explored and the plots of the shear (V_s) and longitudinal (V_p) waves velocities, of the shear

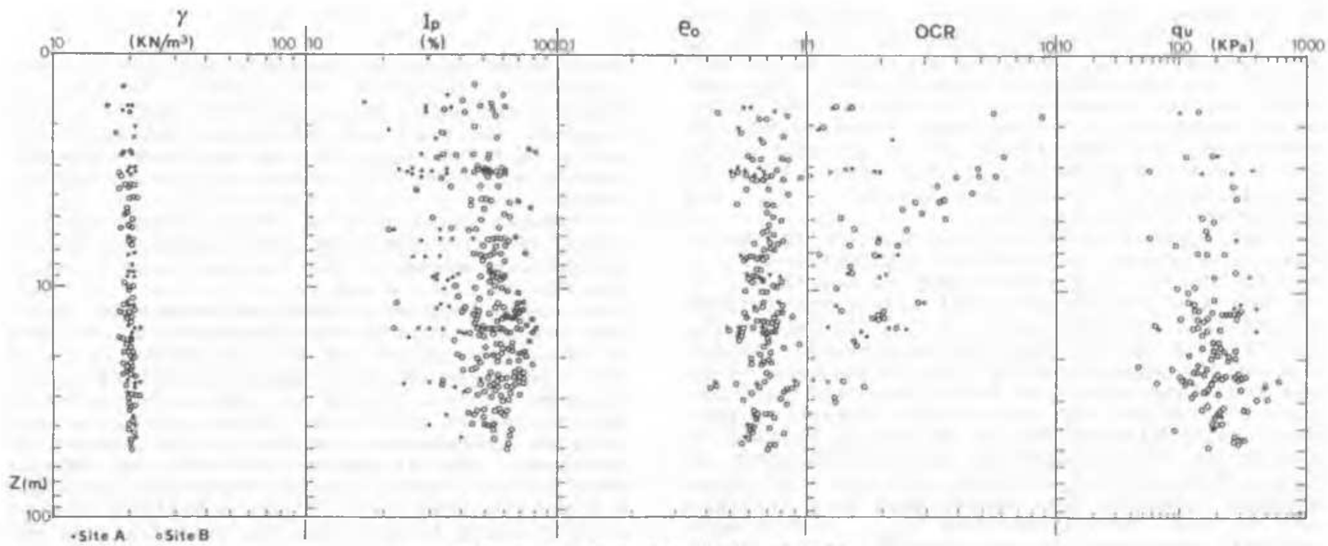

Figure 3. Geotechnical profiles

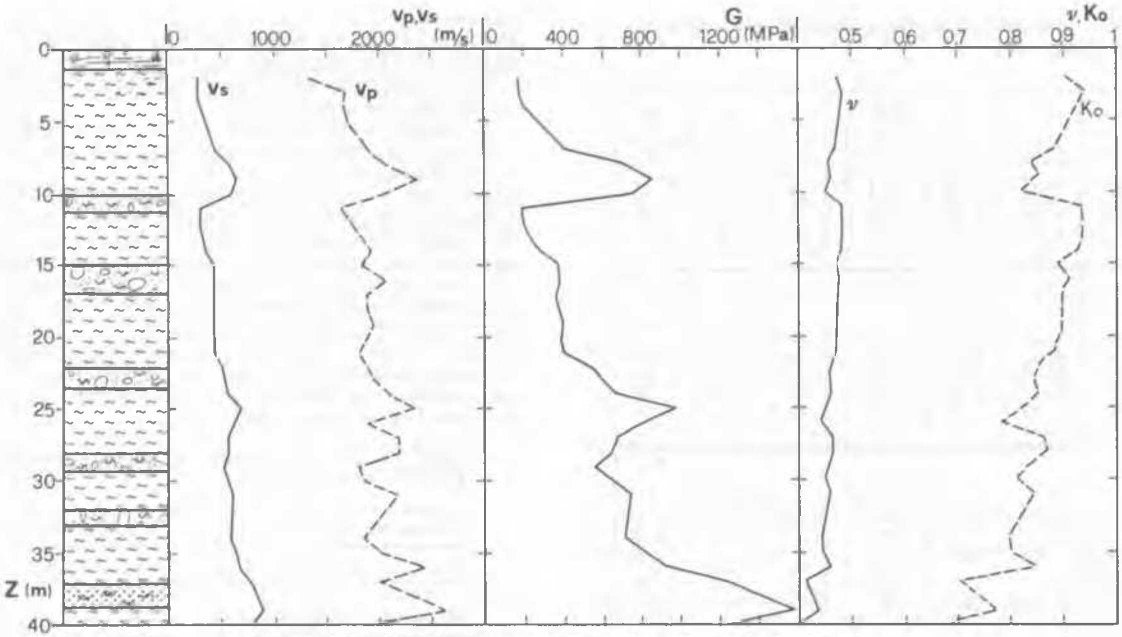

Figure 4. Plots of geophysical testing results

modulus at low strain levels (G), of the Poisson's coefficient (ν), and of the coefficient of earth pressure at rest (K_o), are shown in Fig.4. The diagrams of the shear and longitudinal waves velocities show values increasing with the depth and evidencing a somewhat uneven pattern due to the presence of pebbles and gravels, which leads to rapid increases in the velocity values. In general, V_s varies on an average between 300 m/s on the surface and 750 m/s in depth; while V_p varies between 1700 and 2300 m/s Instead, ν and $K_o = \nu/(1-\nu)$ decrease with depth. In consideration of the "uniformity" of the deposit ascertained with the preceding geotechnical and statistical analysis, and in order to extend the results of the geophysical tests to the study of other verticals inside the deposit, some empirical equations in terms of different parameters have been studied.

As is known, in the specific literature the relations most frequently used for clays link V_s and G with the N_{spt}-values, σ'_m, c_u, and other laboratory test parameters such as e_o, I_p, and OCR. The soil parameters to which the shear wave velocities and the shear modulus at low amplitude were correlated in the present study are: number of blows (N_{spt}), the depth (z), the average effective confining pressure (σ'_m) and the variable $N_1 = N_{spt}/\sigma'_m$.

Through inspection of the loglog scattergrams in Fig. 5, a linear relation was hypothesized.

As regards the N_{spt} values used in the study, it is important to observe that, in a preliminary analysis it was seen that, by utilizing in the regressions the few N_{spt}-values directly measured in the same holes of the cross-hole test, the resulting relations had a very low correlation coefficient and were rather unstable. This fact was considered due to the local presence of inclusions which randomize sensibly the plot of N_{spt}. Since the V_s-measure is a global-type measure - and for this reason much less influenced by local inclusions than N_{spt} - for a more reliable analysis, it was adopted the criterion of considering, for each metre of depth, the mean of the N_{spt} data performed in the site A. The profile thus obtained, which is reported in Fig. 2b, exhibits a significant trend with the depth. An analogous profile was obtained utilizing all the N_{spt} data available in the deposit (site A + site B).

A summary of the empirical equations obtained is shown in Tables 7, 8, 9 and 10. In these Tables the first row shows the results obtained assembling the data which refer to the site A and the second row to those of the whole deposit.

A multivariate analysis, performed taking simultaneously into account the influence of the depth and of N_{spt}, led to the following equations:

$$V_s = 261\ z^{0.24}\ N_{spt}^{-0.01} \quad (m/s)$$

$$G = 139\ z^{0.48}\ N_{spt}^{-0.01} \quad (MPa)$$

$$r = 0.691$$

These relationships, formally similar to those proposed by Ohta and Goto (1978), indicate that the two variables are correlated, that the depth explains the most part of the variability of V_s and G, and that N_{spt} does not influence significantly the results, unless it is considered alone.

A comparative study with other similar correlations of literature was also conducted and the results are shown in the Figures 7 and 8, and in the Tables 7, 8, 9 and 10.

This comparison shows that the equations, obtained for the sites investigated and in the range of practical values of the variables, give higher estimates of the dynamic properties.

In general, the reasons for such a deviances are attributed to different causes dealing with testing techniques, nature of the materials involved, spatial variability of the deposits etc. In this case, appears reasonable hypothize a sensible influence of the previous seismic stress-strain history, as the seismicity is much lower than in the other sites investigated.

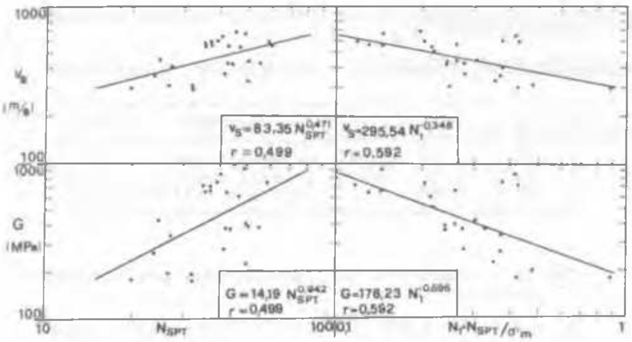

Fig 5. Scattergrams of V_s and G vs. N_{spt} and $N_1 = N_{spt}/\sigma'_m$.

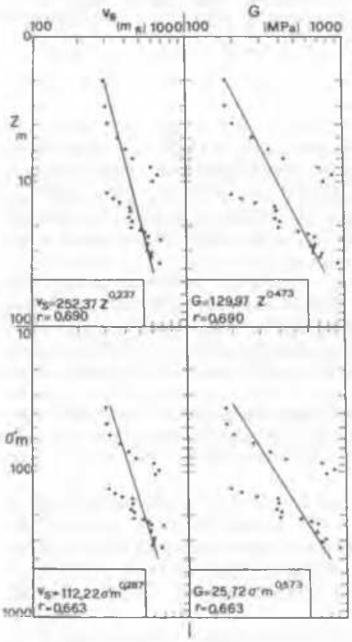

Figure 6. Scattergrams of V_s and G versus z and σ'_m.

Tab. 7 - Comparison of some correlations between V_s values and N_{SPT}

$V_s = a\cdot(N_{SPT})^b$ (m/sec); r = correlation coeff.

N	a	b	r	Authors	Soil
1	83.3	0.471	0.499	present paper	Clay
2	71.5	0.535	0.500	present paper	Clay
3	55.0	0.500	-	Seed (1983)	-
4	48.0	0.550	-	Maugeri (1983)	Clay
5	102.0	0.292	-	Muzzi (1984)	Clay
6	91.2	0.400	-	Imai (1977)	All
7	97.0	0.314	0.868	Imai et al.(1982)	All
8	107.0	0.274	0.721	Imai et al. "	Clay
9	87.8	0.292	0.690	Imai et al. "	Sand
10	75.4	0.351	0.791	Imai et al. "	Gravel
11	128.0	0.257	0.712	Imai et al. "	Clay*
12	110.0	0.285	0.714	Imai et al. "	Sand*
13	136.0	0.246	0.550	Imai et al. "	Gravel*
14	85.6	0.340	0.726	Ohta & Goto(1978)	Clay
15	93.1	0.249	0.787	Ohta & Goto "	Clay
16	134.8	0.249	0.787	Ohta & Goto "	Clay
17	8.5	1.000	-	Marcuson +al(1978)	Sand
18	100.0	0.300	-	Sykora +al.(1983)	Sand
19	80.6	0.331	-	Muzzi (1984)	Sand

* Diluvial

Tab. 8 - Comparison of some correlations between G values and N_{SPT}

$G = a\cdot(N_{SPT})^b$ (MPa); r = correlation coefficient

N	a	b	r	Authors	Soil
1	14.2	0.942	0.499	present paper	Clay
2	10.4	1.070	0.500	present paper	Clay
3	14.1	0.680	0.867	Imai et al.(1982)	All
4	17.3	0.607	0.715	Imai et al. "	Clay
5	12.3	0.611	0.671	Imai et al. "	Sand
6	8.1	0.777	0.798	Imai et al. "	Gravel
7	24.6	0.555	0.712	Imai et al. "	Clay *
8	17.4	0.631	0.728	Imai et al. "	Sand *
9	31.3	0.526	0.552	Imai et al. "	Gravel*
10	16.0	0.710	0.921	Ohsaki +al.(1973)	Clay

* Diluvial

5 CONCLUSIONS

From the results obtained we can observe the following:

a) As a result of the <u>spatial variability analysis</u>, it may be concluded that, even if apparently dispersed, the soil properties at the site exhibit similar trends: both geotechnical and statistical analyses indicated that the homogeneity of the deposit can be postulated for microzoning purposes. The uniformity of the geotechnical properties of the site under study is also confirmed by the stability of the results of the regression equations obtained by considering both the geotecnical data from site A and those collected in the wider surrounding area.

b) Among the <u>empirical correlations</u> studied which link the S-wave velocity and dynamic modulus to the NSPT-values, to the depth, to the average effective confining pressure and to N_1 values, those with the depth and the confining pressure present the highest correlation coefficients. This fact is not surprising being the soil made up of weakly over-consolidated clay with abundant calcareous inclusions.

The presence of the pebbles considerably influences the N_{spt} values, increasing the dispersion of this parameter. For this reason the mean values evaluated on the various strata and referring to several verticals were assumed. The comparison of the correlations found with other equations obtained by different researchers indicates that these latter ones underestimate the dynamic properties of the deposit. This occurs also for relations dealing with sands and gravels, in different geological conditions. Due to the presence of alternations of different materials, it has in fact seemed appropriate not to limit the comparison to the equations valid only for clayey soils. Considering the geotechnical properties of the deposit, these discrepancies do not appear to be justified, unless we refer to the seismic history of the deposit. In fact, the site lies in an area of modest seismicity, while the empirical equations of the literature generally refer to highly seismic sites. From this point of view, correlations which would include even a representative index of the seismicity would permit, for engineering applications, more significant and reliable comparisons.

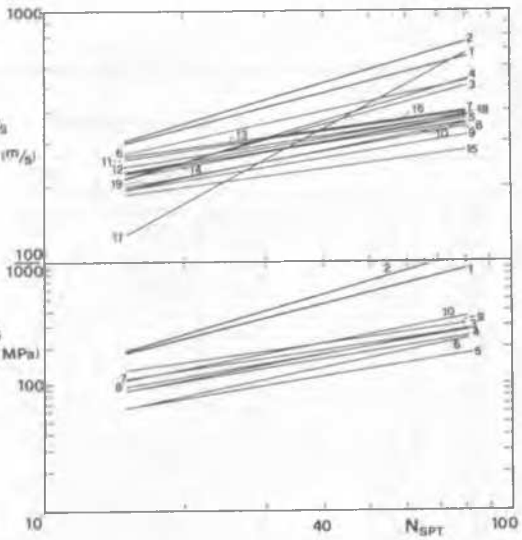

Figure 7. Comparison of V_s and G versus N_{spt} relationships by several Authors (see Tabb. 7,8)

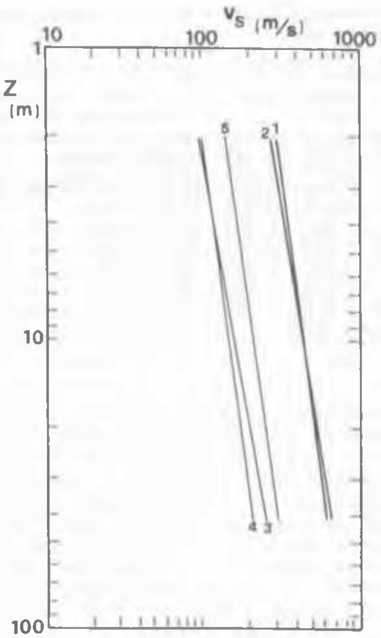

Figure 8. Comparison of V_s and G versus z relationships by several Authors (see Tab. 10)

Tab. 9 - Comparison of some correlations between G values and σ'_m

$G = a\cdot(\sigma'_m)^b$ (MPa); r = correlation coefficient

N	a	b	r	Authors	Soil
1	25.7	0.573	0.663	present paper	Clay
2	14.0	0.697	0.713	present paper	Clay
3	22.0	0.500	-	Anderson +al(1978)	Clay

Tab.10 - Comparison of some correlations between V_s values and z

$V_s = a\cdot(z)^b$ (m/sec); r = correlation coefficient

N	a	b	r	Authors	Soil
1	252.4	0.237	0.690	present paper	Clay
2	223.4	0.284	0.735	present paper	Clay
3	79.0	0.312	0.765	Ohta & Goto(1978)	Clay
4	84.4	0.245	0.822	Ohta & Goto "	Clay[a]
5	121.1	0.245	0.822	Ohta & Goto "	Clay[b]

a = Olocen
b = Pleistocen

REFERENCES

Anderson,D.G., Espana, C.& McLamore,V.R.(1978). Estimating in situ-shear moduli at competent sites. Proc. ASCE Special Conf. on Earth.Eng. and Soil Dyn., Pasadena, California, vol. 1, pp.181 -197.

Carabelli, E. & Superbo S. (1983). Caratterizzazione dinamica dei terreni di fondazione mediante misure in sito della velocita' di propagazione di onde di volume. A.G.I. XV Conv.Naz.Geot., Spoleto, vol. I, pp.77-82.

Ghinelli, A. & Vannucchi, G. (1988). Statistical analysis of cone penetration testing: an application. Proc. ISOPT-1, Vol.2, pp. 757-769

Imai, T. (1977). P-and S-wave velocities of the ground in Japan. Proc. IX ICSMFE, vol.2, pp. 257-260.

Imai, T.& Tonouchi,K. (1982). Correlation of N value with S-wave velocity and shear modulus. Proc. ESOPT II, Amsterdam, vol.1, pp.67 -72.

Lee , I.K., White W.& Ingles, O.G. (1983). Geotechnical Engineering. Pitman Publ.Inc.Boston pp. 497

Lumb, P. (1974). Application of Statistics in Soil Mechanics, cap.3 in Soil Mechanics- New horizons, Lee (ed.), Newnes-Butterworths, London, pp. 44-111.

Marcuson, W.F., Ballard, R.F. & Cooper, S.S. (1978). Comparison of penetration resistance values to in situ shear wave velocities. Proc. 2nd Int. Conf. on Micr. for Safer Constr. - Res. and Appl., San Francisco, vol. 2, pp. 1013-1023.

Maugeri, M. (1983). Correlazione in situ della velocita' delle onde di taglio con i valori Nspt. A.G.I. XV Conv.Naz.Geot., Spoleto, vol. III, pp. 203-208.

Muzzi, F. (1984). Personal comunication.

Ohta, Y.& Goto, N. (1978). Empirical shear wave velocity equations in terms of characteristic soil indexes. Earth.Eng. and Struct.Dyn., vol. 6, pp. 167-187.

Ohsaki, Y. & Iwasaki, R. (1973). On dynamic shear moduli and Poisson's ratios of soil deposits. Soils and Foundations,vol.13, No.4, pp. 61-73.

Schmertmann, J.H. (1978). Guidelines for cone penetration test performance and design. U.S. Dep. Transp., Fed. Highw. Adm., Rep. n. FHWA-TS-78-209, Washington D.C.

Seed H. B. (1983). Dynamic aspects of geotechnical engineering. ISMES Continuing education seminars Bergamo, Italy.

Sykora, D.W.& Stokoe, K.H.(1983). Correlations of in-situ measurements in sands of shear wave velocity, soil characteristics and site conditions. Geot. Eng. Report. GR 83-33, Civ. Eng. Dept. Univ. Texas, Austin.