Dynamic soil properties of silt by the resonant column and the cyclic simple shear methods

P.K.Papakyriakopoulos & S.G.Felekos
Department of Civil Engineering, University of Thrace, Greece
S.A.Savidis
Technische Universität Berlin, FR Germany

1 INTRODUCTION

In the last decade the strong earthquakes and their human and economic effects made more imperative the necessity of studing the seismic behavior of the structures in respect of soil conditions.

The application of mathematical models in order to analyze the rensponse of the soil-structure system under earthquake loads could be useful when the dynamic behavior of the soil is known. The estimation of the unlinear behavior of soil under dynamic loading requires the determination of the shear modulus and the material damping of the soil. These dynamic soil properties are determined by laboratory and field methods.

This research presents a laboratory investigation of the main factors affecting the dynamic soil properties in silty soils by the resonant column and the cyclic simple shear methods. The above investigated factors were the density of the soil in terms of void ratio, the confining pressure and the strain amplitude.

An empirical relationship for estimating the low amplitude shear modulus (G_0) for silt was proposed. The high amplitude shear modulus (G) and material damping (D) were properly normalized. The results of resonant column tests were compared with the results of cyclic simple shear tests. The results of the present research were correlated with laboratory results of similar investigations and with related empirical relationships. Diagrams showing the typical variation of dynamic soil properties in silty soils were given.

2 EQUIPMENT AND TESTING METHODS

The resonant column device of the StoKoe's type, Hardin and Music (1965), Anderson and StoKoe (1978), was used. The end condition of the specimen is "fixed-free" and the specimen is isotropically consolidated under confining pressure. The shear modulus is determined from the first mode torsional natural frequency of the soil specimen. The material damping is determined from the free vibration decay curve wich is generated by stopping the excitance at resonance. The one day low amplitude shear modulus (G_0) and material damping (D_0) at different stages of loading were determined by the resonant column method. The high amplitude shear modulus and material damping (G, D) at the final stage of loading, at different stages of strain amplitude were also determined by the resonant column method.

The cyclic simple shear device of the Norwegian Geo Institute (NGI) type, Bjerrum and Landva (1966), was used. The is consolidated prior to application of shear stresses under a vertical load. The horizontal cyclic shear stress, strain and displacement are monitored with time during the test. The c shear modulus is determined from the shear stress, shear strai at the 10th cycle of excitation. The one day high amplit modulus (G) at different stages of strain amplitude was deter the cyclic simple shear method.

3 SAMPLING AND MATERIAL PROPERTIES

Nine undisturbed specimens of boreholes of three different a prepared for resonant column tests, taken from the city of Kala southern Greece. One remoulded specimen for resonant column one remoulded specimen for cyclic simple shear tests w prepared. The depth of sampling was between 9 and 22 m. The sand-silt soil is deposited by Nedon river and is cons saturated, gray coloured sandy silt and silty sand, with no p and medium density up to dense. The standard penetration N_{SPT} the places of sampling were varying between 19 and 44.

The depth of sampling and the physical properties of the sa shown in table 1.

Table 1. Soil specimens data.

Spe- cimen	Depth (m)	Gravel (%)	Sand (%)	Silt- Clay (%)	w (%)	γ_d (KN/m^3)	e	Soil Typ (US
S1	12.8–13.2	2	36	62	19.0	17.06	0.52	ML
S2	19.5–20.1	0	70	30	17.0	17.16	0.51	SM
S3	9.0– 9.6	0	26	74	32.0	14.51	0.82	ML
S4	11.3–11.9	0	37	63	34.0	14.12	0.90	ML
S5	18.8–19.4	0	66	34	26.5	15.59	0.72	SM
S6A	21.3–21.9	0	58	42	26.0	16.18	0.66	SM
S6B–R	21.3–21.9	0	58	42	25.7	15.98	0.68	SM
S6C–R	21.3–21.9	0	58	42	28.0	15.29	0.73	SM
S7	11.9–12.5	0	40	57	20.5	17.45	0.53	ML
S8	14.0–14.3	0	58	42	30.0	15.20	0.77	SM
S9	14.3–14.5	0	58	42	19.0	17.35	0.55	SM

RC: Resonant column test CS: Cyclic simple shear test L

U : Undisturbed specimen R : Remoulded specimen

4 LABORATORY DYNAMIC SOIL PROPERTIES

In low amplitude strain condition (0.0001%) the dynamic soil p are not affected by the strain amplitude and they are defin low amplitude dynamic properties (G_0 and D_0).

The low amplitude dynamic properties of the tested soil, d by the resonant column method at one day of confinement, are table 2 and in fig. 1a.

Table 2. Low amplitude dynamic properties ($t=$ 1day, $\gamma=0.0001\%$).

Specimen	Shear Modulus G_0 (MPa) at σ_0 (MPa)				Material Damping D_0 (%) at σ_0 (MPa)			
	0.05	0.10	0.20	0.40	0.05	0.10	0.20	0.40
S1	42.0	95.1	122.6	155.4	3.0	2.0	2.0	2.5
S2	46.6	60.3	85.9	135.1	3.0	2.6	3.3	
S3	52.5	78.8	105.1	150.0	2.0	2.0	2.3	2.1
S4	32.0							
S5	48.0							
S6A	61.6	84.7	121.6	182.0	2.2	2.4	1.7	1.0
S6B-R	42.0	64.0	95.0	152.0	1.6	1.4	1.4	1.1
S7	66.1	101.9	135.1	177.8				
S8	40.5				2.0			
S9	82.8							

R : Remoulded specimen

The low amplitude shear modulus (G_0) is increased with the confining pressure; the low amplitude material damping (D_0) is slightly decreasing when the confining pressure is increasing (fig. 1a). There is a fluctuation in variation of G_0 values with void ratio (e) at different values of the confining pressure (σ_0). This fluctuation is affected by any possible disturbance of the samples during sampling or transportation and during testing period by any variation in voltage which influences the drive and control systems of the apparatus.

In high amplitude strain condition, the dynamic soil properties are mainly affected by the strain amplitude and they are defined as the high amplitude dynamic properties (G and D). The high amplitude dynamic properties of the tested soil are shown in fig. 1b in terms of normalized shear modulus (G/G_0) and normalized material damping (D/D_0) vs normalized strain amplitude ($\gamma/\sqrt{\sigma_0}$).

The normalized shear modulus (G/G_0) at the same confining pressure (σ_0) is decreased with increasing strain amplitude (γ); the normalized material damping (D/D_0) is increased with strain amplitude. The normalized shear modulus (G/G_0) at the same strain amplitude is increased with confining pressure (fig. 2a).

The strain amplitude (γ) is normalized according to Shibata and Iwasaki (1981), by deviding the strain amplitude (γ) with the square root of the confining pressure ($\sqrt{\sigma_0}$). On this normalization, the normalized shear modulus (G/G_0) depends only on the strain amplitude (fig. 2b).

The results of the shear modulus (G) and the strain amplitude (γ) of the cyclic simple shear tests are normalized in order to compare them with the results of the resonant column tests.

The confining pressure (σ_0) during the cyclic simple shear tests is:

$$\sigma_0 = \frac{2 K_0 \sigma_v + \sigma_v}{3} , \qquad (1)$$

where σ_v is the vertical pressure applied to the specimen and K_0 is the coefficient of earth pressure at rest. Assuming that K_0 is equal to 0.5, the strain amplitude of cyclic simple shear tests are normalized.

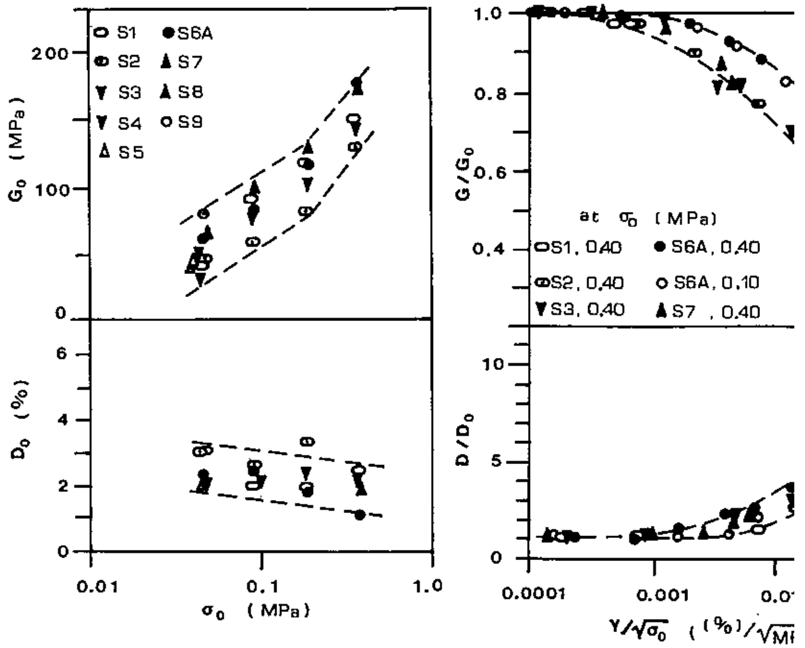

Figure 1. Dynamic soil properties of the tested soil; (a) var G_0 and D_0 with σ_0 at one day of confinement; (b) variation in D/D_0 with $\gamma/\sqrt{\sigma_0}$.

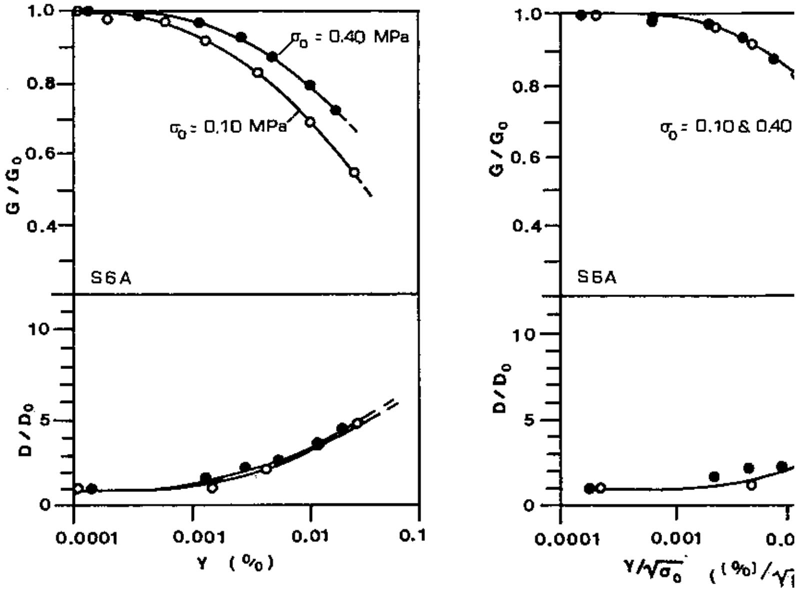

Figure 2. Normalization of the high amplitude dynamic soil pr (a) variation in G/G_0 and D/D_0 with γ; (b) variation in G/G_0 with $\gamma/\sqrt{\sigma_0}$.

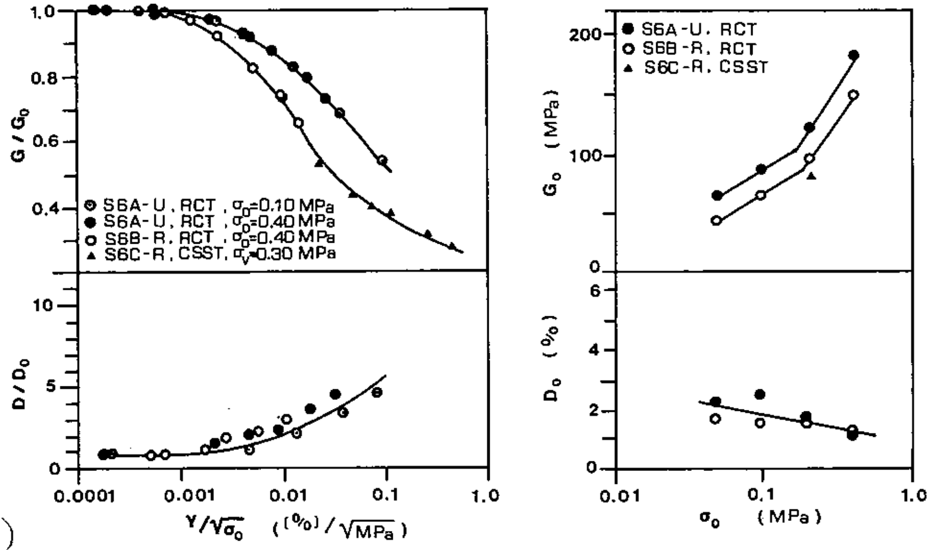

Figure 3. Dynamic soil properties of the undisturbed (U) and remoulded (R) specimens; comparison between the results of resonant column (RCT) and cyclic simple shear (CSST) tests.

The low amplitude shear modulus (G_0) of the cyclic simple shear tests is computed with the division of the shear modulus G by the normalized shear modulus (G/G_0) of the resonant column test. There is a good agreement between the measured resonant column and computed cyclic simple shear test results (fig. 3).

The low amplitude shear modulus (G_0) of the undisturbed specimen is greater than the low amplitude shear modulus (G_0) of the remoulded specimen at the same confining pressure (σ_0). The normalized shear modulus (G/G_0) of the undisturbed specimen is greater than the G/G_0 of the remoulded specimen at the same normalized strain amplitude ($\gamma/\sqrt{\sigma_0}$). The material damping of the remoulded specimen has similar values with the undisturbed specimen (fig. 3).

5 ESTIMATION OF THE LOW AMPLITUDE DYNAMIC SOIL PROPERTIES

The low amplitude shear modulus (G_0) of a soil is mainly affected by the confining pressure and the density of the soil. Seed and Idriss (1970) have been proposed that the influence of the density in terms of relative density or void ratio could be simply described by the coefficient $K_{2,max}$ and the G_0 could be estimated by the relationship:

$$(2) \qquad G_0 = 1000\ K_{2,max}\ (\sigma_0)^{0.5},$$

where G_0 and σ_0 are in psf. The above relationship in SI is:

$$(3) \qquad G_0 = 6.9\ K_{2,max}\ (\sigma_0)^{0.5},$$

where G_0 and σ_0 are in MPa.

The laboratory G_0 results of the tested soil were used for th
of the variation of the coefficient $K_{2,max}$ with void rati
regration analysis of the coefficient $K_{2,max}$, an empirical rela
for estimating the coefficient $K_{2,max}$ is proposed:

$$(4) \qquad K_{2,max} = 51\ (1 - 0.43\ e).$$

Consequently, the low amplitude shear modulus (G_0) in MPa
estimated from the confining pressure (σ_0) in MPa and the voi
(e) by the following empirical relationship:

$$(5) \qquad G_0 = 345\ (1 - 0.43\ e)\ (\sigma_0)^{0.5}.$$

Seed and Idriss (1970) and Seed et al (1986) have been conclu
the in-situ coefficient $K_{2,max}$ for sand is varied from 30 fo
sand to 75 for dense sand. The above researhers have been c
that there is a good agreement between the in-situ and the la
coefficient $K_{2,max}$ results for sand. The variation of the coe
$K_{2,max}$, determined in the laboratory, with the void ratio is fl
from 34 to 70 when void ratio varies from 0.90 to 0.40.

The results of the present research concludes that the coe
$K_{2,max}$ for silty sand and sandy silt is varied from 31 to 42 wh
ratio varies from 0.90 to 0.40. The low amplitude shear modulus
the silty soils is lower than the G_0 of the sandy soils
variation from 10 % in loose condition to 40 % in dense conditi

The low amplitude shear modulus (G_0) that have been determine
resonant column method in silty soils by Shen et al (1985), Wu
(1984) and StoKoe et al (1980), were correlated with the esti
by the empirical relationship that is proposed by this research
results were also correlated with the estimated G_0 by e
relationships. The above empirical relationships have been prop
all the types of soil by Hardin (1978) and for sandy soils by
and Tatsuoka (1977), Shibata et al (1970) and Seed and Idriss (

The present research proposes a relationship which e
satisfactorilly the laboratory G_0 of silty soils (fig. 4). Th
good agreement between the results of the other studied e
relationships, but all of them overestimate the laboratory G_0 f
soils.

The low amplitude material damping (D_0) of the tested s
correlated with the D_0 results that have been determine
resonant column method in silty soils by Shen et al (1985), St
al (1980) and Haupt (1987). There is a good agreement between
amplitude material damping (D_0) of the tested soil and the res
the above investigations (fig. 5). The low amplitude material
is slightly decreased with increasing the confining pressur
variation of D_0 is not signifficant. The D_0 could be consi
constant with an approximated value equal to 2.0 %.

6 ESTIMATION OF THE HIGH AMPLITUDE DYNAMIC SOIL PROPERTIES

The normalized shear modulus (G/G_0) vs $\gamma\sqrt{\sigma_0}$ of the tested so
correlated with the G/G_0 results that have been determine
resonant column method in silty soils by Shen et al (1985) and
et al (1980). The above G/G_0 results were also correlated
estimated by the empirical relationships that have been propo

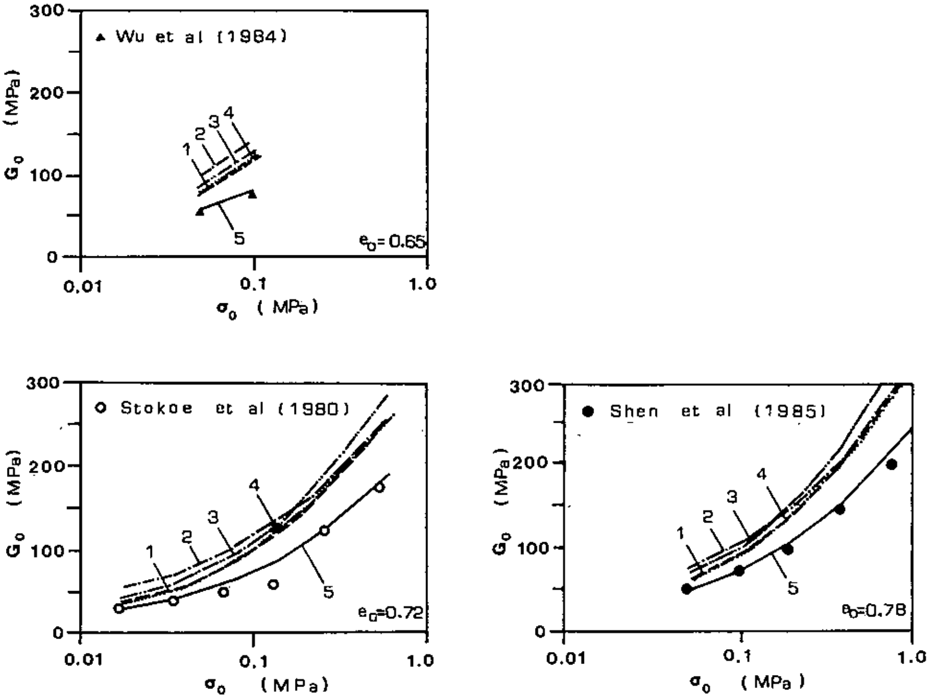

Figure 4. Use of the proposed empirical relationship (5) to predict the G_0 of similar investigations; correlation with similar relationships proposed by (1) Hardin (1978), (2) Iwasaki and Tatsuoka (1977), (3) Shibata et al (1970) and (4) Seed and Idriss (1970).

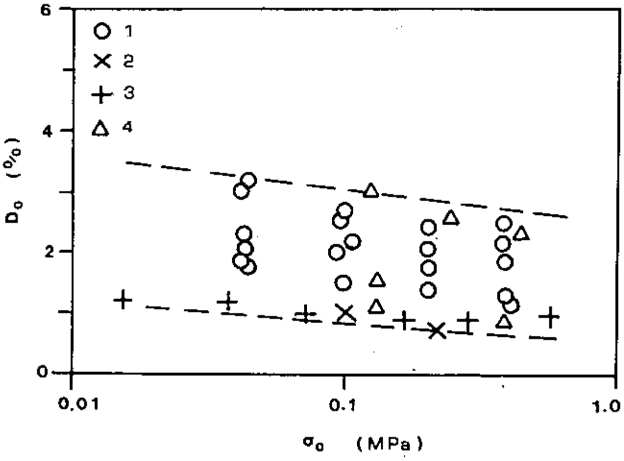

Figure 5. Variation in D_0 with σ_0; correlation between the results of (1) this research and results of similar investigations. Data from (2) Shen et al (1985), (3) Stokoe et al (1980) and (4) Haupt (1987).

sandy soils by Iwasaki and Tatsuoka (1977) and Shibata and (1975) and with the normalized medium curve of sand that Idriss (1970) have been recommended. There is a good agreement the normalized shear modulus (G/G_0) of the present researc results of the above investigations (fig. 6).

The normalized material damping (D/D_0) vs $\gamma/\sqrt{\sigma_0}$ of the tes were correlated with the D/D_0 results that have been determin resonant column method in silty soils by Shen et al (1985), S al (1980) and Haupt (1987). The above D/D_0 results were also c with the normalized medium curve for sand that Seed and Idris have been recommended. There is a good agreement between the n material damping (D/D_0) of the present research and the result above investigations (fig. 6).

The normalized dynamic properties G/G_0 and D/D_0 for silty so be estimated from curves and proposed empirical relationships soils.

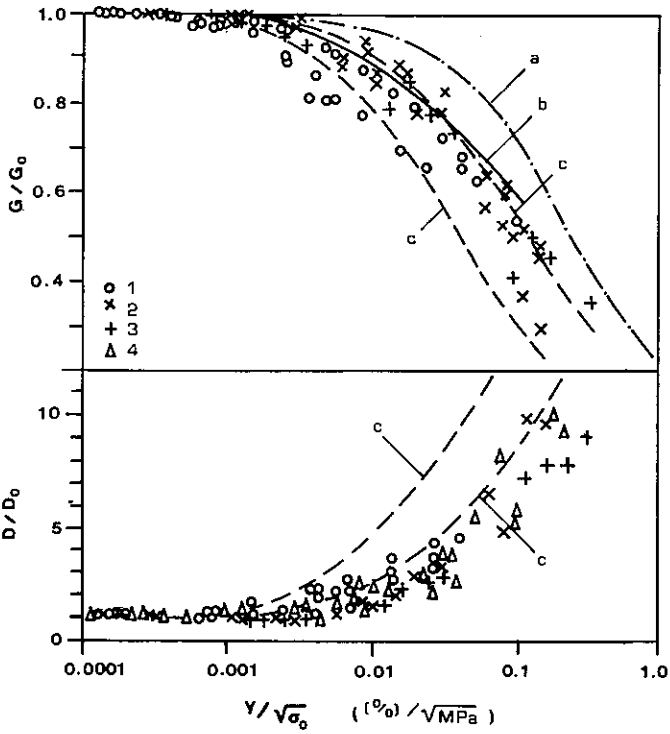

Figure 6. Variation in G/G_0 and D/D_0 with $\gamma/\sqrt{\sigma_0}$; correlatio (1) the results of this research and results of similar invest Data from (2) Shen et al (1985), (3) StoKoe et al (1980) and ((1987); empirical relationships proposed by (a) Shibata and (1975) and (b) Iwasaki and Tatsuoka (1977); (c) medium n curves for sand reccomanded by Seed and Idriss (1970).

7 SUMMARY AND CONCLUSIONS

The main factors that influence the dynamic soil properties of the silty soils were investigated in the laboratory by the resonant column and the cyclic simple shear methods. Variation in shear modulus and material damping with magnitude of confining pressure and with strain amplitude were studied. The results of the resonant column tests were compared with the results of the cyclic simple shear tests. Variation in the coefficient $K_{2,max}$ with void ratio was studied. Using regration analysis, an empirical relationship for estimation of the coefficient $K_{2,max}$ is proposed. An empirical relationship for estimation of the low amplitude shear modulus from the confining pressure and the void ratio of silty soils is also proposed. The results of this research were correlated with results of similar studies in silty soils and with results estimated by related empirical relationships. The conclusions of this investigation are as follows.

The variation of dynamic soil properties with confining pressure and strain amplitude is as expected. The low amplitude shear modulus (G_0) is increased with confining pressure (σ_0), the material damping (D_0) is slightly decreased. The high amplitude shear modulus (G) and the material damping (D) are satisfactorilly normalized in terms of G/G_0 and D/D_0 vs $\gamma/\sqrt{\sigma_0}$. The normalized shear modulus G/G_0 of the undisturbed specimen is greater than the normalized shear modulus (G/G_0) of the remoulded specimen in the same normalized strain amplitude.

The normalization of the results of the cyclic simple shear test proved very effective. By this procedure, the comparison between the results of the resonant column and the cyclic simple shear tests is possible. There is a good agreement between the measured G_0 by the resonant column test and the computed G_0 of the cyclic simple shear tests.

The estimation of the low amplitude shear modulus (G_0) by the coefficient $K_{2,max}$ is proved an effective method for evaluation of G_0. The laboratory coefficient $K_{2,max}$ for silty soils is lower than the coefficient $K_{2,max}$ for sand. The empirical relationship proposed by this research estimates satisfactorilly the laboratory G_0 of silt, in relation with other proposed empirical relationships which overestimate the G_0 of silt. The low amplitude material damping (D_0) of silty soils could be considered constant, with an approximated value equal to 2%.

The related empirical relationships and the curves of a similar research for sand estimate satisfactorilly the normalized high amplitude dynamic properties of silty soils.

The empirical relationships contribute to the prediction of the dynamic soil properties, but their application, without performing laboratory or/and in situ tests, is not sufficient for the accurate estimation of the dynamic soil responce. Laboratory tests must be performed in sufficient undisturbed specimens in order to predict a credible estimation of the dynamic soil properties.

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