12 Mar 1991, 10:30 am - 12:00 pm

Energy-Absorbing Ability of Texsol

Phong M. Luong

CNRS-LMS, Ecole Polytechnique, Palaiseau, France

Proceedings: Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, March 11-15, 1991, St. Louis, Missouri, Paper No. 1.60

Energy-Absorbing Ability of Texsol

Phong M. Luong
CNRS-LMS, Ecole Polytechnique, Palaiseau, France

SYNOPSIS: Texsol is a 3D soil-fiber composite, obtained using a technique of soil reinforcement by incorporation of continuous textile fibers. The overall mechanical properties of Texsol result therefore from those of its components: soil and fibers. An experimental approach has been carried out in order to grasp the basic aspects of the stress-strain response of Texsol subjected to monotonic, cyclic and vibratory loadings. The study confirms that the application of Texsol to earthquake resistant earthworks and traffic structures could be of great interest and particularly suitable as shown by its ductility and energy-absorbing capacities that are readily evidenced by the laboratory conventional tests.

INTRODUCTION

Soil reinforcement is an innovating, fruitful and reliable technique for a very large class of engineering works. Especially in the design of earthquake resistant structures, it is interesting to consider flexibility and energy-absorbing capacity which will permit the earthquake displacements to take place without generating unduly large forces.

Texsol (Figure 1) is a 3-dimensional soil-fiber composite resulting from a new technique of soil reinforcement by incorporation of continuous fibers [Leflaive et al 1983, 1985]. Its application to foundation design of civil engineering structures in order to mitigate the destructive effects of earthquakes, vibrating machines, freeway traffic, high speed railways, vibrations and shocks, seems to be of great interest and particularly adequate as shown by the following rheological characteristics readily obtained from conventional laboratory tests.

This paper presents some experimental results on the particular physical and mechanical properties of Texsol at the macroscopic level in connection with the deformation mechanisms occurring at the granular level when Texsol is subjected to cyclic and vibratory loadings. The so-obtained physical data may suggest a realistic numerical modeling of its rheological behaviour.

Traditionally, under monotonic loading, a small number of parameters is sufficient to describe the mechanical behaviour of a soil : for instance, two constant elastic parameters, a criterion of yielding and a plastic flow rule. In the cyclic case, an evolution rule for the state parameters must be added : the Young modulus E and the damping coefficient D may vary as a function of the deformation amplitude or the number of load cycles. Under vibratory and dynamic loading, a realistic numerical model must incorporate nonlinear effects that generally can not be predicted with an equivalent linear elastic model.

This work underlines a series of tests conducted under forced vibrations on Texsol specimens subjected to different excitation amplitudes. The transmissibility analysis of the forced vibratory motion and the characterization of the nature of the observed damping should permit to interpret the obtained results and to deduce the limits of validity of the equivalent linear elastic viscous model.

Fig. 1 Texsol, a promising engineering material.

When soils are subjected to dynamic loadings - caused by earthquakes, explosions, wave or traffic - they are conventionally represented by an equivalent linear model characterized by the density, the applied stresses and the deformation amplitudes. The popularity of the equivalent linear elastic viscous model can be explained by the simplicity of its rheological representation that permits to conduct readily explicit calculations with only two parameters describing the stiffness and the energy dissipation. In addition, its use considerably shortens calculations in case of finite element modelling because the global matrices of damping and rigidity are rewritten after only a small number of calculations.

CHARACTERISTIC STATE OF A GRANULAR SOIL

Deformation mechanisms

In order to analyse and to predict the macroscopic response of soil behaviour under loads, it is necessary to understand how the individual microscopic constituent elements interact both at the grain or aggregate level owing to the particular arrangement of the solid particles within the mass. The principal grain properties are the size, texture and shape. An elongate shape of elastic particles promotes bending mechanisms leading to a decrease of incident angle of contact forces. This induces a high and quasi reversible compressibility at the macroscopic level. The most significant aggregate property of cohesionless materials is its relative compressibility which is especially large in the case of a flocculent or honeycombed structure.

Qualitatively, material aggregates may differ in texture, with respect to the degree of fineness and uniformity, in structure, referred to the pattern in which the particles are arranged in the aggregate, and in consistency. Fine-grained materials may be stable even if the grains touch one another at only a few points, provided the adhesion between the grains is of the same order of magnitude as the weight of the grains.

Quantitatively, they may differ in porosity, relative density, water and gas content. A cohesionless granular material can be considered as a grain assembly where the discrete solid granules are in contact and free to move with respect to their neighbours. It is often assumed that the constituent grains are in direct, elastic contact with one another. The inherent nonlinearity of Hertz relationships between two elastic bodies suggests difficulties in the application of contact theory to the study of granular media [Hardin 1978].

Nevertheless, observed macroscopic deformations of the material are derived essentially from their structural modifications, that is, rearrangements of the constitutive grains inducing irreversible contractive or dilative volume changes :

a. Compaction mechanism that corresponds to a closer packing of solid particles inducing a contractive behaviour.

b. Distortion mechanism caused by irreversible grain slidings leading initially to a contractive behaviour, then interlocking disrupture where the individual particles are plucked from their interlocking sites and forced to slide over the adjacent particles with large distortion of grain arrangement, inducing significant dilative volume changes, phenomenon known as dilatancy.

c. Attrition mechanism subsequent to asperity breakage and grain crushing that modifies the relative density under high stresses. The resulting effect is a contractive behaviour.

Test procedure

The loading parameters of axisymmetric triaxial tests are :

Mean stress	$p = (\sigma_1 + 2\sigma_3)/3$
Deviatoric stress	$q = \sigma_1 - \sigma_3$
Deviatoric level	$\eta = q/p$

The corresponding deformation parameters are defined by :

Volumetric strain	$\epsilon_v = \epsilon_1 + 2\epsilon_3$
Deviatoric strain	$\epsilon_q = 2(\epsilon_1 - \epsilon_3)/3$
Dilatancy rate	$\delta = \dot{\epsilon}_v{}^i / \dot{\epsilon}_q{}^i$

The work increment due to stress tensor σ and strain increment tensor $\dot{\epsilon}$ is given by :

$$\dot{W} = \sigma : \dot{\epsilon} = (p\, I + s) : (\dot{\epsilon}_v + \dot{e})$$

The total work increment W can be separated into a volumetric component $\dot{W}_v$ and a deviatoric component W_s , s and e denote respectively stress and strain deviator tensors. The volumetric work increment is written as the product of stress and strain increment tensor invariants. Owing to some assumptions on strain increment along the cylindrical triaxial stress path where elastic strain is relatively small, the dissipated irreversible work increment is given by :

$$\dot{W}^i = p\, \dot{\epsilon}_v{}^i + q\, \dot{\epsilon}_q{}^i$$

With the notation $\sigma_1 \geq \sigma_2 \geq \sigma_3 \geq 0$ in compression used in soil mechanics, we note a jump of principal stress axis between compression and extension states in conventional triaxial test. The Mohr-Coulomb criterion for a cohesionless material is given by :

$$f(\sigma) = \mathrm{Max}\, [\ \sigma_i\, (1 - \sin\phi) - \sigma_j\, (1 + \sin\phi)\ ]$$

where ϕ denotes the internal friction angle and i, j = 1 to 3. At failure the deviatoric levels in triaxial compression $\eta^+{}_f$ and extension $\eta^-{}_f$ are respectively given by :

$$\eta^+{}_f = 6 \sin\phi^+{}_f\ /\ (3 - \sin\phi^+{}_f)$$

and

$$\eta^-{}_f = 6 \sin\phi^-{}_f\ /\ (3 + \sin\phi^-{}_f)$$

The characteristic state values in triaxial compression and extension are written by substituting f by c index. Tests are conducted either with a constant stress rate $\dot{\sigma}$ or a constant strain rate $\dot{\epsilon}$. Letters ϵ, ϵ^e and ϵ^i denote respectively total, elastic and irreversible strain. For example, contraction or dilation ϵ_v may be the resulting value of elastic volume increase or decrease $\epsilon_v{}^e$ and irreversible volume change $\epsilon_v{}^i$ due to dilatancy or contractancy or both.

Characteristic Threshold

Extensive laboratory tests on diverse granular materials show that the lowest point on the volume change axial strain curve, that is, the point of minimum of the sample volume, corresponds to a constant stress ratio just as suggested by [Kirkpatrick 1961]. The stress peak or maximum of shear resistance occurring at maximum dilatancy rate has been analysed and interpreted by the stress-dilatancy theory [Rowe 1971]. The asymptotic part of the stress-strain curves determines the ultimate strength of the well-known critical state concept [Schofield & Wroth 1968].

For our concern, the transient and cyclic loading cases require the analysis of the prepeak region where the stress ratio η_c at zero dilatancy rate defines evidently the characteristic state of the granular material [Luong 1980] associated with an angle of aggregate friction.

Thus the deviatoric stress level corresponding to the zero of the volume change rate determines unambiguously the characteristic threshold CT ; the granular material is in a "characteristic state" having the following properties :

1. the volume change rate is zero and
2. the stress level attained by the material is an intrinsic parameter that defines a characteristic friction angle $\phi_c = \sin^{-1} [3\eta_c\ /\ (\eta_c + 6)]$ determining the interlocking capacity of the grain assembly.

The value of ϕ_c is independent of initial material density. At any point on the characteristic line CL, the rate of the irreversible volume change is strictly zero ; this is verified by a loading test along this line.

The position of the effective loading point relative to the CL line determines its mechanical behaviour. In particular, the material undergoes large deformations after crossing the characteristic threshold CT into the supercharacteristic domain in which the characteristic value η_c is exceeded.

The characteristic line CL divides the allowable stress space into two regions : (i) subcharacteristic region corresponding to an interlocking of grain structure or contractancy and (ii) supercharacteristic region where disaggregation of granular material or dilatancy occurs. Thus every closed stress path in the subcharacteristic domain exhibits a contractive soil behaviour illustrated by an irreversible compaction whereas a closed load cycle in the supercharacteristic domain leads to an irreversible volume expansion.
A very accurate and readily available experimental procedure for the determination of the characteristic threshold η_c is as follows : η_c is revealed by the appearance of a dilatancy loop with volume change during a load cycle crossing the characteristic line CL.

Based on the characteristic state concept, this phenomenological approach evidences :
(a) the stress path importance which influences more or less a deformation mechanism associated with large volume changes, or predominant distortional strains,
(b) the mechanical hardening inducing a behaviour contrast between the initial loading on a virgin material and the subsequent cycles of unload and reload,
(c) the appearance of a more or less marked hysteresis loop indicating the presence or not of a contact network modification, or eventually of a significant compressibility of constituent grains, and
(d) the load induced anisotropy, as a function of the morphological nature of grain.

RHEOLOGICAL PROPERTIES OF TEXSOL

Tests have been conducted on cylindrical specimens : 70 mm in diameter. For each test, stress-strain curves recorded during loading gives the volume change referred to the initial volume and the axial displacement Δh referred to the initial height h_0 as a function of the axial force ΔF referred to the initial section S_0 of the specimen (Figure 2).

Fig. 2 Conventional triaxial tests on Texsol

Depending on the material and confining pressure, two types of behaviour can be distinguished during the course of loading :
i - a volumetric compaction followed by a *continuous dilation* until the failure of the material,
ii - a continuous compaction until failure.

Analysis of experimental curves shows that for a given material, these two types of behaviour do not occur randomly, but present a continuous evolution with the confining pressure : the dilatancy phenomenon vanishes when the confining pressure increases and prevents the breakdown of granular structure interlocking.
The friction angle values ϕ_f and ϕ_c are calculated according to the Coulomb interpretation for a cohesionless material. When the material does not present a characteristic threshold up to the imposed load level, the granular interlocking breakdown does not occur for this case of loading.

The characteristic threshold corresponds in these conditions to the stress threshold where phenomena of disaggregation occur and allow the dissipation of energy generated by relative friction between solid particles. These experimental observations suggest that the following indicators should be taken into account when performing a conventional cylindrical triaxial test :

(1) a **compaction index I_c** defined (Figure 3) by the ratio of the work W_{cc} corresponding to particle interlocking on the global dilatancy work at failure W_{cm} : the lower this compaction or disaggregation index, the easier the particle interlocking breakdown. Thus the index I_c evaluates the susceptibility of Texsol to be contractant or dilatant.

(2) a **flow index I_f** defined (Figure 3) by the ratio of the distortional work W_{fc} prior to the characteristic threshold on the work W_{fm} mobilized up to maximal resistance at failure : the lower this index, the better the energy absorption offered by Texsol. The flow index may thus be considered as a toughness measure of Texsol, describing its energy-absorbing ability.

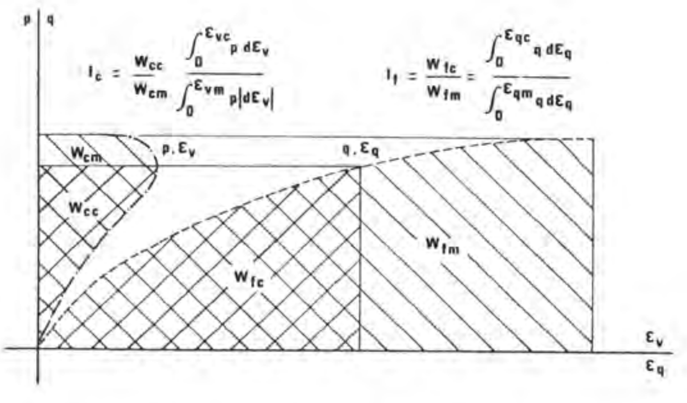

Fig. 3 Definition of indices I_c and I_f

Practically it is easy to recognize that these indices depend upon the nature of the constituent soil, content and strength of the fibers. For very soft and collapsible materials, these two indices will be greater than one.

Deformability

In addition to the mechanical behaviour of the constituent soil, Texsol permits large deformations at failure, 6 to 7 % instead of 2 to 6 % for soil without reinforcement [Luong & Khay 1987]. As shown by the low values with respect to 1 of the flow index, Texsol offers an excellent toughness when loaded until failure (Figure 4).

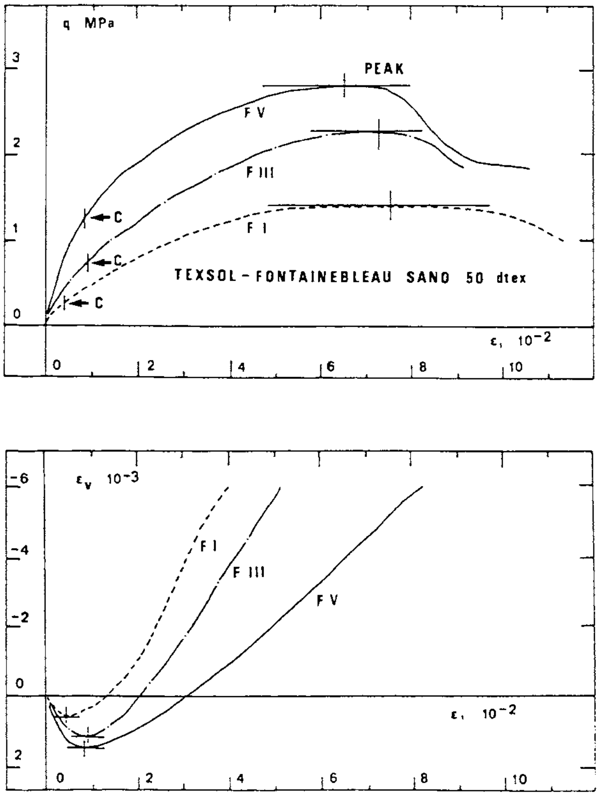

Fig. 4 Stress-strain curves of Texsol

Pseudo cohesion

In Texsol, soil grain and fibers are connected each to others by friction. When Texsol undergoes deformation, the friction forces apply tensions on fibers and generate for Texsol a pseudo cohesion (Figure 5) that can be significant if the used polymer fibers present high mechanical performance.

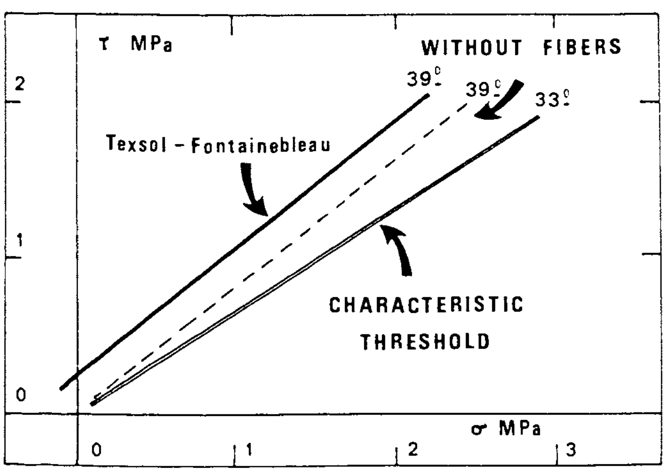

Fig. 5 Intrinsic curve of Texsol

A fiber content of 0.1 % gives a cohesion greater than 100 kPa, sufficient to ensure the stability of a vertical wall of 10 m high with an very acceptable safety coefficient.

Liquefaction potential

Laboratory liquefaction tests have shown that Texsol presents a stabilization of the response loop when subjected to a cyclic loading (Figures 6). This accommodation behaviour allows a very important absorption of energy when compared to the case of soil without reinforcement which completely liquefies [Luong et al 1986].

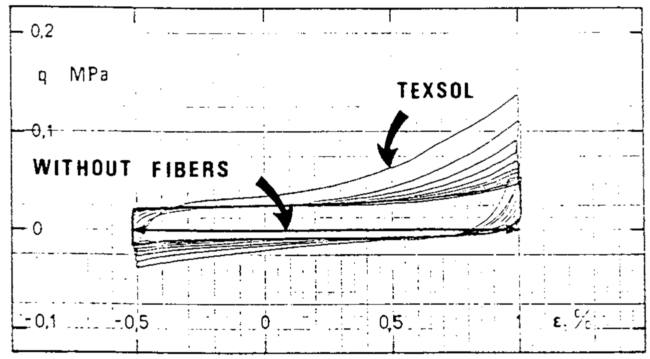

Fig. 6a Cyclic liquefaction of Texsol under controlled strains

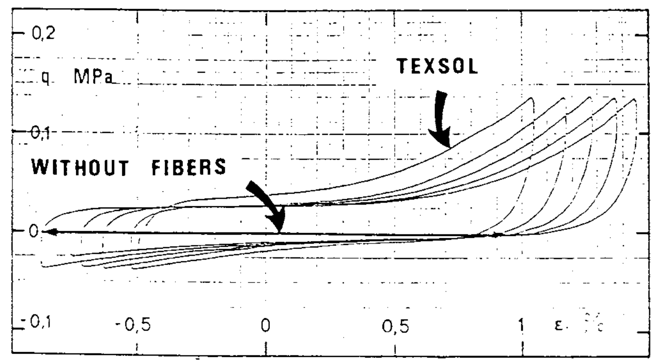

Fig. 6b Cyclic liquefaction of Texsol under controlled stresses

Radial stress path

On radial stress path, the ratio η = q/p or deviatoric level is maintained constant. It is noted that, from an initial state, any isotropic and/or deviatoric loading generates immediately irreversible strains. Although the macroscopic stress state of loading is isotropic, it can be imagined that a great number of grain contacts are in a limiting state. A modification of the initial stress state, even very small, induces sliding between these grains.

During the first loading, the irreversible strains induce a change in the granular structure of the specimen by grain rearrangement. The material accommodes to the applied load. This hardening generates around the followed stress path, during the first loading, a domain where the material presents an almost reversible behaviour. Experimentally, the radial cyclic tests permit to evidence readily the reversibility of the tested material :

a - During these tests, the irreversible plastic strains decrease rapidly with the number of load cycles.

b - The load-unload curve becomes a closed curve if the ratio η is less than the characteristic threshold.

c - The stress-strain relationship during unloading is practically identical for subsequent load cycles.

This property during radial unloading has been recognized by several authors.

Constant mean stress path

Triaxial compression tests on granular materials of a similar void ratio were conducted in order to evaluate their deformation characteristics. The applied stress was controlled so as to maintain constant the mean principal stress p, while the deviatoric stress q was increased at a constant rate.
Test results have illustrated the significant influence of mean stress on the rheological behaviour of the material, at the granular level related to friction, compressibility, kinematics of grain, or equally at the global level concerning the breakdown interlocking threshold or the maximal strength. It is thus necessary to examine also the rheological response of the material subject to constant mean stress path which promotes the occurrence of rheological phenomena such as contractancy and dilatancy of the granular skeleton.

VIBRATORY BEHAVIOUR OF TEXSOL

This work examines the behaviour of cylindrical specimens loaded by inertia forces generated by a steel mass fixed on the top and excited at the bottom by a forced motion. Subjected to forced vibrations, a Texsol specimen will offer the possibility of analyzing the conditions where its rheological response can be assimilated as an equivalent linear elastic model with damping.
The chosen experimental procedure is based on the consideration of a single degree-of-freedom system. A cylindrical specimen of Texsol of mass m is confined by a constant pressure σ_3. The harmonic excitation is imposed at the bottom and controlled by a given acceleration. A rigid steel mass M = 3m, placed on the top, generates a vibratory loading on the specimen. Texsol is then loaded uniaxially because the specimen can move only in the vertical direction (Figure 7).

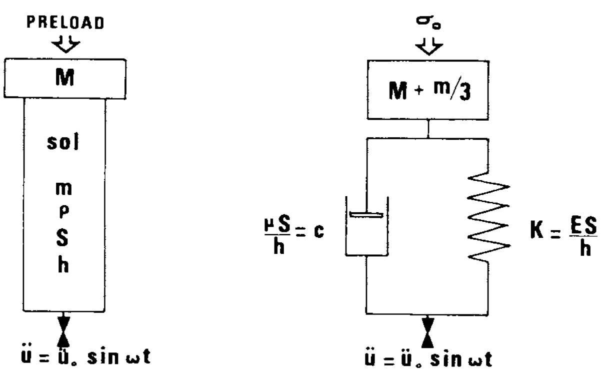

Fig. 7 Vibratory testing on Texsol

This vibratory testing aims to make evidence of three salient features of Texsol : (a) the resilience of vibratory loads developed by the mass M and self-weigth m, (b) the energy dissipation caused by the material anelasticity during loading and (c) the influence of the deviatoric stress level η.
The vibratory behaviour of Texsol has been evaluated by the following characteristics of its response to forced sinusoidal vibrations :
i. absolute transmissibility : it is a measure of motion reduction or of transmitted force through the specimen. If the source of vibration is an oscillating motion (resp. force) at the base (displacement or acceleration excitation), transmissibility is the ratio of the vibration (resp. force) amplitude measured at the base to the vibration (resp. force) amplitude measured on the top.
ii. relative transmissibility : it is the ratio of the amplitude of the relative motion of the specimen to the amplitude of the excitation motion imposed at the base. The deformation of Texsol mitigates the motion transmitted from the bottom to the top. This characteristic is particularly interesting in the case of vibratory isolation.
iii. motion response : it is the ratio of the displacement amplitude of the mass on the top to the quotient of the intensity of the excitation force to the static stiffness of the Texsol.
The nature and the degree of transmissibility are determined by the characteristics of the damper.
When the damping increases, the transmissibility at the resonance decreases. In the case where damping is important, the absolute transmissibility tends to high values of the forced frequency asymptotically towards a line the slope of which is inversely proportional to the forced frequency. The maximum value of the absolute transmissibility associated to the condition of resonance is a function of the material damping.

Viscous damper

The linear elastic spring and the viscous damper are assumed to be linear and massless separated elements, rigidly connected between the mass on the top and the base in motion. The damper has the characteristic property of transmitting a force F_C that is directly proportional to the relative velocity $\dot{\delta}$ ($F_C = c.\dot{\delta}$) where $\delta = x - u$ is the relative displacement. This damper is referred to as a linear damper.
In the case of a motion excitation at the specimen base, the differential equation is writen as follows :

$$\left(M + \frac{m}{3}\right)\ddot{x} + \frac{(\dot{x} - \dot{u})\mu S}{h} + \frac{(x - u)ES}{h} = F_0 \sin\omega t$$

When the displacement at the base varies sinusoidally with time $u = u_0 \sin \omega t$, a steady-state condition exists after the oscillations at the natural frequency ω_n are damped out, defined by the displacement x of the mass on the top :

$$x = T_A\, u_0 \sin(\omega t - \psi)$$

where T_A and ψ are respectively the motion transmissibility and phase angle.

$$T_A = x_0/u_0 = F_T/F_0 =$$

$$[\{1+(2D\omega/\omega_0)^2\}/\{(1-\omega^2/\omega_0^2)^2+(2D\omega/\omega_0)^2\}]^{1/2}$$

$$\psi = \tan^{-1}[2D(\omega/\omega_0)^3/(1-\omega^2/\omega_0^2+4D^2\omega^2/\omega_0^2)]$$

$$T_R = \delta_0/u_0 = [(\omega/\omega_0)^4/\{(1-\omega^2/\omega_0^2)^2+(2D\omega/\omega_0)^2\}]^{1/2}$$

As the damping increases, the transmissibility at resonance decreases and the absolute transmissibility at the higher values of the forcing frequency ω increases. For an undamped material, the absolute transmissibility at higher values of the forcing frequency varies inversely as the square of the forcing frequency. When the material embodies significant viscous damping, at high values of the forcing frequency, the absolute transmissibility curve becomes asymptotic to a line whose slope is inversely proportional to the first power of the forcing frequency.
The maximum value of absolute transmissibility associated with the resonant condition is a function solely of the damping in the material. For a lightly damped material, i.e., for $\zeta < 0.1$, the maximum absolute transmissibility is :

$$T_{max} = 1/2D$$

where $D = c / c_c$ is the fraction of critical damping.

Coulomb damper

The differential equation of motion in case of Coulomb damping is given by :

$$(M+m/3)\ddot{x} \pm Ff + (x-u)ES/h = F_0 \sin\omega t$$

The equivalence of energy dissipation involves equating the energy dissipation per cycle for viscous- and Coulomb-damping :

$$\pi c\omega\delta_0^2 = 4\ Ff\delta_0$$

The equivalent viscous damping coefficient for a Coulomb-damped material is given by :

$$c_{eq} = 4Ff/\pi\omega\delta_0 = j(4Ff/\pi\dot{\delta}_0)$$

Since $\dot{\delta}_0 = j\omega\delta_0$ is the relative velocity, the equivalent linearized dry friction damping force can be considered with an amplitude $j(4Ff/\pi)$. With $c_c = 2k/\omega_0$, the equivalent fraction of critical damping is :

$$D_{eq} = c_{eq}/c_c = 2\omega_0 Ff/\pi\omega k\delta_0$$

Substituting δ_0 and solving for D^2_{eq} :

$$D^2_{eq} = (2\eta\omega_0/\pi\omega)^2(1-\omega^2/\omega_0^2)^2/[\omega^4/\omega_0^4-(4\eta/\pi)^2]$$

where $\eta = Ffh/ESu_0$ is the Coulomb damping parameter for displacement excitation.

The equivalent fraction of critical damping is a function of the displacement amplitude u_0 of the excitation since the Coulomb damping parameter η depends on u_0 .
When the excitation is defined by the acceleration amplitude, we have :

$$\eta\ddot{u}_0 = Ff\omega^2h/ES\ddot{u}_0$$

For relatively high forcing frequencies, the relative transmissibility of acceleration (Figure 8) approaches a constant value $4\xi/\pi$ où $\xi = Ff/(M+m/3)\ddot{u}_0$ is the Coulomb damping parameter for acceleration excitation.

RHEOLOGICAL NONLINEARITIES OF TEXSOL

The correlation of experimentally determined and theoretically predicted results by comparison of records of time-histories is difficult. Thus data reduction is useful in minimizing or eliminating the irrelevancies of the measured data to permit ready interpretation of differents aspects of nonlinearities [Bourdin et al 1989].

The forced vibration response curves obtained from swept sine wave on Texsol specimens confined under an isotropic pressure σ_3 = 100 kPa clearly demonstrate the softening behaviour of Texsol subjected to increasingly severe loadings : the accelerations imposed at the base have been : 5, 10 and 20 m/s^{-2}.

The resonnant peaks are respectively swept over to the low values of frequency : 127 Hz, 118 Hz and 116 Hz associated with the damping coefficients D = 7.5, 14.5 and 18.9 % with q = 300 kPa (Figures 9).

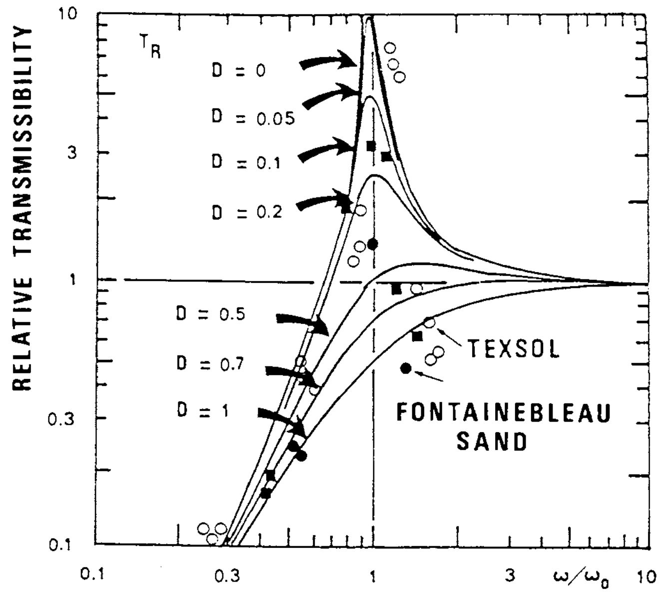

Fig. 8 Relative transmissibility of Texsol

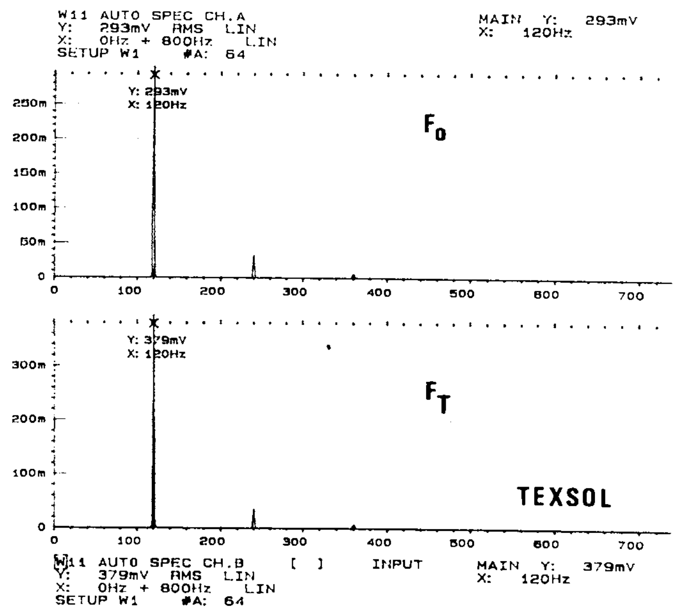

Fig. 9a Spectra of excitation F_0 on top and transmitted force F_T at the base where is imposed an acceleration of 50 $m.s^{-2}$

In the case of a linear behaviour, if the frequency of the free vibration is ω_0, then a periodic external force of frequency ω can excite free oscillations in addition to steady-state forced vibration of frequency ω. But since every material possesses some damping, the free vibration eventually disappears, leaving only the steady-state forced vibrations. In a nonlinear system, the free vibration contains many higher harmonics. Hence, it is possible that an exciting force with a frequency corresponding to one of these higher harmonics might be able to excite and sustain that particular harmonic component of the free vibration, in addition to the normal forced vibration.

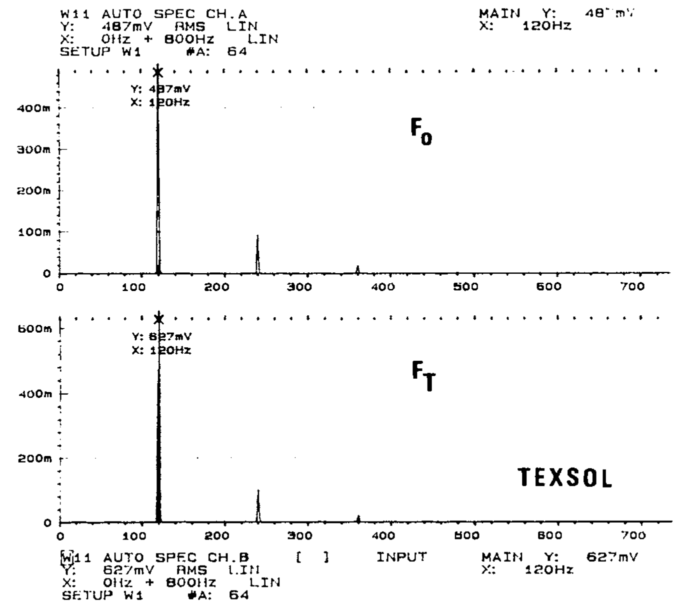

Fig. 9b Force spectra F_0 et F_T when an acceleration of 75 m.s^{-2} is imposed at the base

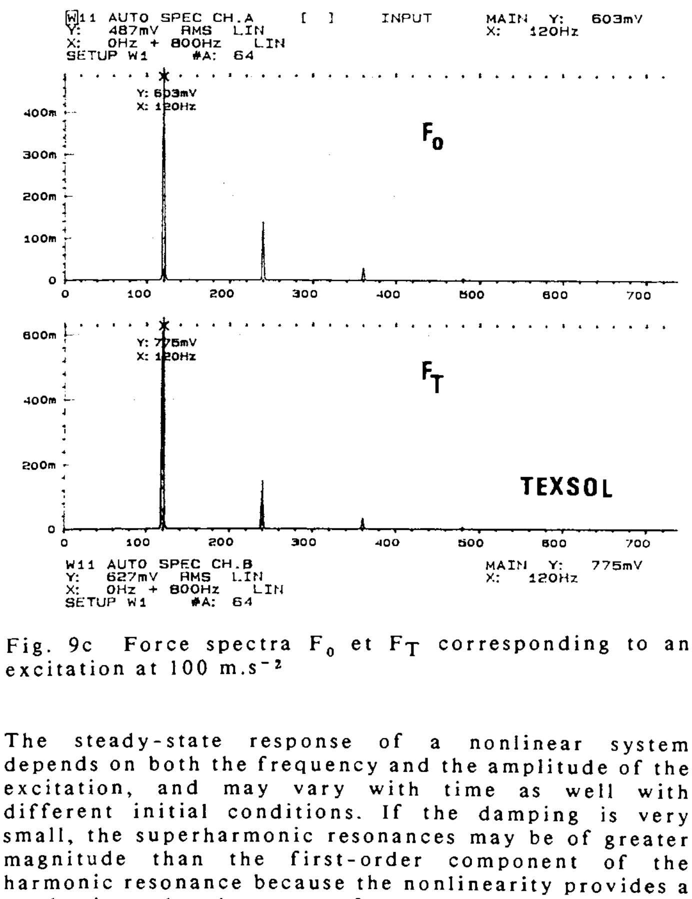

Fig. 9c Force spectra F_0 et F_T corresponding to an excitation at 100 m.s^{-2}

The steady-state response of a nonlinear system depends on both the frequency and the amplitude of the excitation, and may vary with time as well with different initial conditions. If the damping is very small, the superharmonic resonances may be of greater magnitude than the first-order component of the harmonic resonance because the nonlinearity provides a mechanism whereby energy from the excitation may be transferred to the higher harmonics.

Two essential differences between subharmonic and superharmonic oscillations may be noted :
(1) subharmonics may occur under very special conditions while superharmonics always occur;
(2) damping only diminishes the amplitudes of superharmonic vibrations, but may completely prohibit the existence of subharmonic vibrations if it is greater than a certain value.

CONCLUDING REMARKS

This experimental approach has shown some salient aspects of the rheological behaviour of Texsol on some stress paths using the conventional cylindrical triaxial cell.
This experimental work aims to interpret the physical and mechanical properties of Texsol at the macroscopic level in relation with the deformation mechanisms occurring at the granular level when subject to cyclic and vibratory loadings.
In practice, the vibratory behaviour of Texsol may be approximated by an equivalent linear elastic viscous model - with a viscous or a Coulomb damper - in the restrictive case of a low deviatoric stress level, i.e. stress state sufficiently near the isotropic axis of the stress space, in the subcharacteristic domain where soil presents an adapted or accommoded behaviour. This hypothesis remains valid when strains are sufficiently small so that the distribution of contact forces between particles are not modified and also in case where the granular structure is not disorganized by resonance phenomena.
The characteristic state concept reveals quite suitable for determining the threshold of interlocking breakdown of Texsol and also for analyzing its applicability to earthquake resistant foundations.
The compaction index I_d and flow index I_c, taking into account stress and strain states, are appropriate indicators for predicting the geotechnical performance of Texsol.

REFERENCES

Barkan D.D. (1962), Dynamics of Basis and Foundations, Mc Graw Hill, ew York.
Crede C.E. (1951), Vibration and Shock Isolation, John Wiley & Sons, New York.
Bourdin B., M.P. Luong and P. Morlier (1989), "Caractérisation des Non-Linéarités Apparues lors des Essais de Vibrations Forcées en Centrifugeuse", Revue Française de Géotechnique, Paris.
Das B.M. (1983), Fundamentals of Soil Dynamics, Elsevier, New York.
Freitag, D.R. (1986), "Soil Randomly Reinforced with Fibers", Journal of Geotechnical Engineering, Vol. 112, 8:823-826.
Gray, D.H. and T. Al-Refeai (1986), "Behavior of Fabric- versus Fiber-Reinforced Sand", Journal of Geotechnical Engineering, Vol. 112, 8:804-820.
Hardin, B.O. (1978), "The Nature of Stress-Strain Behavior of Soils", Proc. of the Conference on Earthquake Engineering and Soil Dynamics, Pub. 1, ASCE, Pasadena, CA, 3-90.
Khay, M. et J.P. Gigan (1990), "TEXSOL - Ouvrages de soutènement", Guide Technique, LCPC-SETRA, Paris.
Kirkpatrick, W.M. (1961), "Discussion on Soil Properties and their Measurement, Proc. 5th Conference on Soil Mechanics and Foundation Engineering, III, Dunod, Paris, 131-133.
Leflaive E. & J.M. Cognon (1985), "Un Nouveau Matériau, le Texsol", Revue Travaux, N° 602, Sept., 1-13.
Leflaive E., M. Khay and J.C. Blivet (1983), "Le Texsol", Bull. Liaison Labo P. et Ch., No. 125, Mai-Juin, 105-114.
Luong M.P. (1980), "Stress-strain Aspects of Cohesionless Soils under Cyclic and Transient Loading", Proc. ISSCTL, Balkema, 315-324.

Luong M.P. and M. Khay (1987), "Comportement Géotechnique du Texsol", 4e Colloque Franco-Polonais de Mécanique des Sols Appliquée, Grenoble.
Luong M.P., E. Leflaive and M. Khay, 1986, "Propriétés Parasismiques du Texsol", 1er Colloque de Génie Parasismique, St Rémy-lès-Chevreuse, 3:49-58.
Maher, M.H. and R.D. Woods (1990), "Dynamic Response of Sand Reinforced with Randomly Distributed Fibers", Journal of Geotechnical Engineering, Vol. 116, No. 7, July, 1116-1131.
Richart, F.E. Jr, J.R.Jr Hall and R.D. Woods (1970), Vibrations of Soils and Foundations, Prentice Hall, Englewood Cliffs, New Jersey.
Rocard, Y. (1971), Dynamique Générale des Vibrations, Masson et Cie, Paris.
Rowe, P.W. (1971), "Theoretical Meaning and Observed Values of Deformation for Soils. Stress-Strain Behaviour of Soils",R.G.H. Parry Ed., Cambridge, 143-194.
Ruzicka, J.E. and R.D. Cavanaugh (1958), "Mechanical Impedance Methods for Mechanical Vibrations", ASME, 109.
Schofield, A.N. and C.P. Wroth (1968), Critical State Soil Mechanics, Mc-Graw Hill, London.
Timoshenko, S. (1939), Théorie des Vibrations à l'Usage des Ingénieurs, Librairie Polytechnique Ch. Béranger, Paris et Liège.
Warburton, G.B. (1966), "Transmission of Vibrations", Vibration in Civil Engineering, Session II, 43-59, Butterworths, London.