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Energy-dissipating ability of sandy soils

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ABSTRACT: This paper proposes a dimensionless parameter EDI (energy-dissipating index), readily obtained from conventional triaxial test, that is able to precisely recognize the energy-dissipating ability of soils. This EDI index permits to identify the nonlinear ductile hysteretic response of soils. In addition, for water saturated soils under undrained conditions, it can be used as an indicator of liquefaction susceptibility.

1 INTRODUCTION

In seismic zones, foundations of civil engineering structures must be designed to resist the effects of strong earthquakes and to undergo substantial deformations without suffering excessive damage or loss of strength in face of subsequent load applications. This is also the cases for isolation of vibrations caused by traffic, vibrating machines, blast, shock or impact loadings. How to characterize the damping susceptibility of soil foundation against earthquake or dynamic loadings? The conventional method aims to determine the G shear modulus and the D damping ratio of the soil.

The present paper proposes a dimensionless parameter EDI (energy-dissipating index), readily obtained from conventional triaxial test on soil specimen. This coefficient characterizes the stress-strain curve and expresses the overall or global ductility of soil material. It permits to quantitatively recognize the energy-dissipating ability of soils. Earthquake damage to structures is often caused by large, permanent deformations of the soil. In all types of soils, these deformations are mostly due to shear failure. In noncohesive soils they can be associated with compaction. In saturated noncohesive soils under certain drainage conditions there is also the possibility of loss of strength through cyclic mobility or liquefaction. In the laboratory conventional triaxial test, when subjected to several cycles of high-load reversals, this EDI index identifies the nonlinear ductile hysteretic response of soil. In addition, for water saturated soils under undrained conditions, it can be used as an indicator of liquefaction susceptibility.

2 CHARACTERISTIC THRESHOLD OF SANDY SOILS

Ground motion studies have been considerably developed, in recent years, using constitutive laws for soils under dynamic, vibratory, cyclic and transient loading. Rheological properties of granular soils have been interpreted at the grain level where the solid particles interact with one another leading to a global aggregation (contractancy) or disaggregation (dilatancy) according to the following main deformation mechanisms. Observed macroscopic deformations result mainly from the principal following mechanisms : (1) compaction mechanism that forces the solid particles closer together and leads to a denser packing, (2) distortion mechanism governed by irreversible grain slidings dissipating energy by heat and (3) attrition mechanism caused by breakage of asperities and crushing of grains under high pressures. Using infrared thermography, an experimental approach evidences the distortion mechanism occurring in the granular structure and interprets the main features of the cyclic behaviour of sandy soils [Luong, 1986].

Conventional triaxial tests on several sands show that the lowest point on the volume change axial strain curve, that is, the point of minimum volume of the sample, corresponds to a constant stress ratio [Kirkpatrick, 1961]. The stress peak or maximum of shear resistance occurring at maximum dilatancy rate has been analyzed and interpreted by the stress dilatancy theory [Rowe, 1971]. The asymptotic part of the stress-strain curve determining the ultimate strength has suggested the well-known critical state concept [Schofield & Wroth, 1968]. For our concern, the transient and cyclic loading cases require the analysis of the prepeak part where the stress ratio η_c at zero dilatancy rate defines evidently the characteristic state of the granular material associated with an angle of aggregate friction ϕ_c [Luong, 1980].

The characteristic threshold is readily revealed by the appearance of a dilatancy loop when the load cycle crosses the grain interlocking threshold called characteristic state $\eta_c = (q/p)_c$ (zero dilatancy threshold). Such observations enable the determination of both the entanglement capacity of a granular material and its energy-dissipating ability. Below the characteristic threshold, the intergranular contacts are stable. The limited slidings tend to a maximal aggregation. In this subcharacteristic domain or contractancy zone, a hysteresis loop occurs when reloading. The mechanical behaviour depends on the load history.

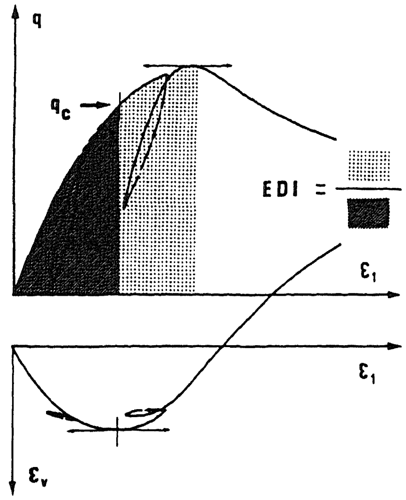

Figure 1. Definition of EDI energy-dissipating index.

Above the characteristic threshold, the grain contacts become unstable, leading to significant slidings due to interlocking breakdown. A reload shows a dilatancy loop with memory loss of load history and a softening phenomenon occurs.

Extensive laboratory tests using conventional triaxial apparatus on various sands substantiate these rheological properties.

Analysis of experimental curves shows that for a given material, these behaviours do not occur randomly, but they 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 , corresponding respectively to the peak stress and the zero dilatancy stress or characteristic threshold, are calculated according to the Coulomb interpretation for a cohesionless material. 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 sliding friction between solid particles.

These experimental observations suggest that, when performing a conventional cylindrical triaxial test, it should be taken into account an **energy-dissipating index EDI** defined by the ratio of the work W_{dm} mobilized up to the peak strength of the stress-strain curve on the distortional work W_{dc} prior to the characteristic threshold (Fig. 1). Expressed in a dimensionless form, this parameter represents a toughness characteristic of the granular material in a well consistent manner when applied to a wide range of soil behaviours.

The larger the EDI index, the better the energy-dissipating ability. The energy-dissipating index may thus be considered as a toughness measure of sandy soil, describing its energy-absorbing ability. In addition, experiments have shown that there occurs no strain-localization in cases of large values of EDI index (> 1). Values of EDI index less than 1 correspond to collapsible soils that are highly unstable and do not dissipate energy prior to their catastrophic failure.

3 ENERGY-DISSIPATING MECHANISM

When a siliceous sand grain slides against another one, there occurs a motion resistance called friction. What is the cause and what really happen on the contact surface ?

Bowden and Tabor [1959] demonstrated that when quartz or glass surfaces slide over another in the dark, small sparkling points of light can be seen at the interface. The friction between grains generates heat in the same fashion as when prehistoric man used silex stones to generate fire.

A consideration of the forces and deformations at each contact surface [Mindlin & Deresiewicz, 1953] may serve as one starting point in interpreting the thermomechanical coupling of sand behaviour under vibratory shearing.

For the simplest case of two like spheres compressed statically by a force which is directed along their line of centres, normal to their initial common tangent plane, the contact theory caused by Hertz predicts a plane, circular contact radius. When an additional tangential force is applied in the plane of contact, the Mindlin's solution shows that the tangential traction is parallel to the displacement and increases without limit on the bounding curve of the contact area.

In accordance with Coulomb's law of sliding friction, slip is assumed to be initiated at the edge of the contact and to progress radially inward, covering an annular area. An annulus of counter-slip is formed and spreads radially inward as the tangential force is gradually decreased. The inelastic character of the unloading process appears evident since the annulus of the counter-slip does not vanish when the tangential force is completely removed.

Under oscillating tangential forces, the load-displacement curve forms a closed loop traversed during subsequent force oscillations between the limits providing that the normal force is maintained constant. The area enclosed in the loop represents the frictional energy dissipated in each cycle of loading. Thus at small amplitudes of the tangential force, energy is dissipated as a result of plastic deformation of a small portion of the contact surface, whereas, at large amplitudes, the Coulomb-sliding effect predominates.

In the conventional triaxial test, if the load is cycled within the subcharacteristic domain below the characteristic threshold η_c , the intergranular contacts remain stable. Small slips lead to a maximum entanglement caused by the relative tightening of constituent granules. The dissipated work given by the hysteresis loop (a) is relatively small. The corresponding heat production is relatively low and negligible.

On the contrary when the shear load is cycled at large amplitude exceeding the characteristic thresholds (compression and extension), the intergranular contacts become unstable, leading to significant slidings caused by interlocking breakdown. A large frictional energy is dissipated (b) as shown in the Fig. 2 and is transformed almost entirely into heat owing to the thermomechanical conversion. If the stress peaks in triaxial compression and extension are not exceeded, the resultant effect is densification because the high amplitude loading benefits in partial loss of strain-hardening during the dilating phase in the supercharacteristic domain leading to a breakdown of the granular interlocking assembly. On

Table I. Thermo-elastic-plastic couplings.

$\mathcal{SV}$ = Internal variables and postulations	Stored energy at microlevel	Internal energy dissipation rate	Heat to plasticity
■ [Dillon, 1963] No $\mathcal{SV}$ $\epsilon_{ij}{}^p$ responsible for D	0	$\sigma_{ij}\,\dot{\epsilon}_{ij}{}^p = \sigma'_{ij}\,\dot{\epsilon}'_{ij}{}^p$	0
■ [Lee, 1969] $\mathcal{SV}$ = plastic power $\sigma_{ij}\,\dot{\epsilon}_{ij}{}^p$	$(1-\gamma)\,\sigma_{ij}\,\dot{\epsilon}_{ij}{}^p$ $(0.9 \le \gamma \le 1.0)$	$\gamma\,\sigma_{ij}\,\dot{\epsilon}_{ij}{}^p$	0
■ [Nied-Batterman, 1972] $\mathcal{SV} = \omega$	$\Lambda\,\sigma_{ij}\,\dot{\epsilon}_{ij}{}^p$	$(1-\Lambda)\,\sigma_{ij}\,\dot{\epsilon}_{ij}{}^p$	$T\chi\,\partial\Lambda/\partial\chi$
$\chi\dot{\omega} = \sigma_{ij}\,\dot{\epsilon}_{ij}{}^p$ with χ = dislocation energy	Λ = energy stored/inelastic energy expanded		
■ [Raniecki-Sawczuk, 1975]	$\chi(K,T)\dot{K}$	$\sigma_{ij}\,\dot{\epsilon}_{ij}{}^p - \pi\dot{K}$	$T\,\partial\pi/\partial T$
$\mathcal{SV}$ = work-hardening K		$\pi = \mathcal{SV}$ conjugate	
$\dot{K} = \omega(\sigma_{ij}\,,T)\,\sigma_{ij}\,\dot{\epsilon}_{ij}{}^p$ with ω = integrating factor			
■ [Mroz-Raniecki, 1976] $\mathcal{SV}$ = K	$\sigma_{ij}\,\dot{\epsilon}_{ij}{}^p - \pi\dot{K}$		
$\dot{K} = \sigma'_{ij}\,\dot{\epsilon}'_{ij}{}^p$	$\pi = -\partial D/\partial\dot{K}$		$T\,\partial\pi/\partial T = 0$
■ [Lehman, 1979] $\mathcal{SV}$ = K	$\dot{K} = (1-\xi)\,\sigma_{ij}\,\dot{\epsilon}_{ij}{}^p$	$\xi\,\sigma_{ij}\,\dot{\epsilon}_{ij}{}^p$	0
$\dot{K} = (1-\xi)\,\sigma_{ij}\,\dot{\epsilon}_{ij}{}^p$ with ξ = experimentally determined constant			

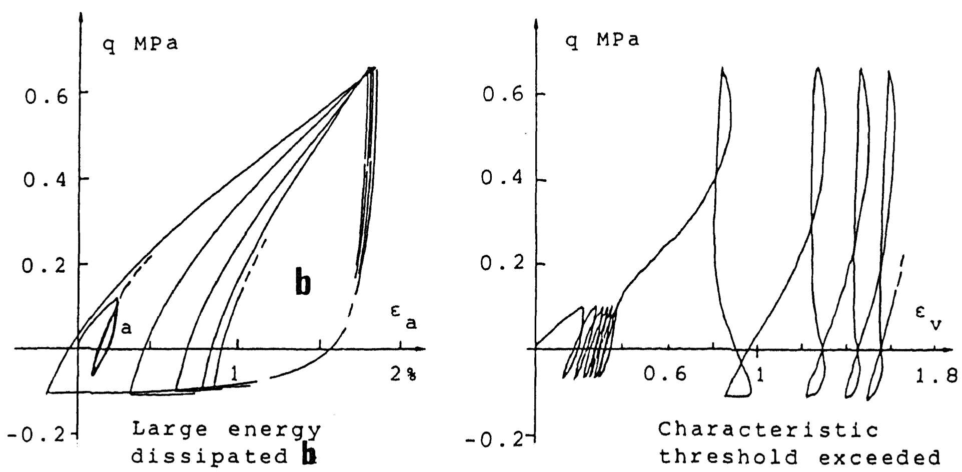

Figure 2. Large amplitude loading in conventional triaxial test.

each reload, the tightening mechanism induces new irreversible volumetric strains and recurs each time with a renewed denser material. This case is particularly interesting when energy needs to be dissipated without risk of soil failure.

The theoretical background of the energy-dissipating mechanism is based on the coupled thermo-visco-elastic-plastic analysis [Kratochvil & Dillon, 1969]. This leads to a coupled thermomechanical equation where the intrinsic dissipation term is predominant in this case. The work done to the system by plastic deformation is identified as the major contribution to the heat effect.

In the framework of thermo-elastic-plasticity, there exists a general acceptance that not all the mechanical work produced by the plastic deformation can be converted to the thermal energy in the solid. A larger portion of the work is believed to have been spent in the change of material microscopic structure as shown in Table I.

The work done in plastic deformation per unit volume can be evaluated by integrating the material stress-strain curve. This internal dissipation term constitutes an important part of the nonlinear coupled thermomechanical effect.

The quantification of this intrinsic dissipation for soils is an extremely difficult task if infrared thermography is not used. This paper emphasizes the advantages of the infrared thermographic technique for the detection of this effect.

4 INFRARED VIBROTHERMOGRAPHY

Infrared thermography utilizes a photon-effect detector in a sophisticated electronics system in order to detect radiated energy and to convert it into a detailed real-time thermal picture on a video system. Temperature differences in heat pattterns as fine as 0.1 °C are discernible instantly and represented by several distinct hues.

This technique is sensitive, nondestructive and noncontact, thus ideally suited for records and observations in real time of heat produced by the heat transformation of energy caused by friction between grains of sheared sandy soil. No interaction at all with the specimen is required to monitor the thermal gradient.

The quantity of energy emitted by infrared radiation is a function of the temperature and the emissivity of the specimen. The higher the temperature, the more important is the emitted energy. Differences of the radiated energy correspond to differences of temperature.

Soils present a very low thermomechanical conversion under monotonic loading. However plastic deformation, whereby sliding between grains occurs creating permanent changes globally or locally, is one of the most efficient heat production mechanisms. Most of the energy that is required to cause such plastic deformation is dissipated as heat. Such heat generation is more easily observed when it is produced in a fixed location by reversed or alternating slidings because of vibratory reversed applied loads. These considerations define the use of vibrothermography as a nondestructive method for observing the energy-dissipating ability of granular material.

5 ENERGY-ABSORBING CAPACITY OF TEXSOL

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 (Fig. 3) is a 3-dimensional soil-fibre composite resulting from a new technique of soil reinforcement by incorporation of continuous fibres [Leflaive et al, 1983]. 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 findings using infrared vibrothermography.

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 very large values of its EDI index when compared to the corresponding values for plain soil, Texsol offers an excellent toughness when loaded until failure and is able to dissipate a great amount of energy when subjected to large amplitude of cyclic loadings as shown by the loops (B1), (B2) and (B3) when compared to loop (b) for plain sand (Fig. 4, 5, 6 et 7).

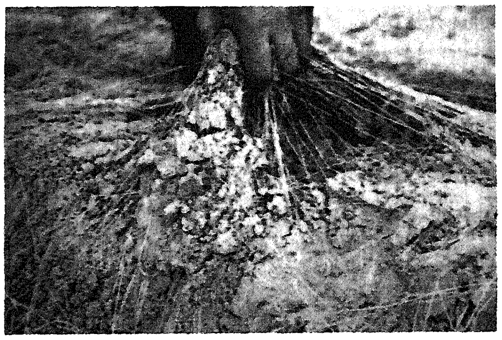

Figure 3. Texsol, a promising engineering material.

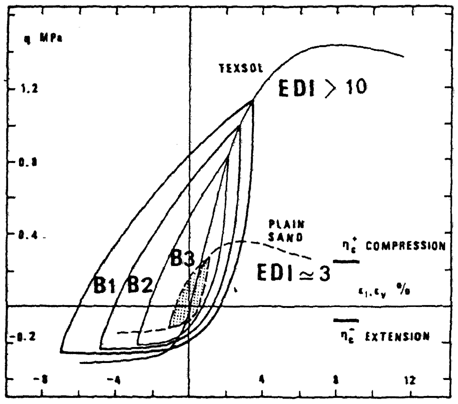

Figure 4. Comparison of stress-strain curves of plain sand and Texsol.

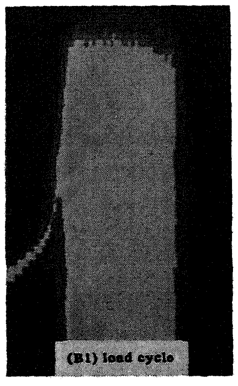

Figure 5. Thermogram of the Texsol specimen corresponding to 200 load cycles for (B1) loop (Each colour hue represents ΔT = 0.2 °C).

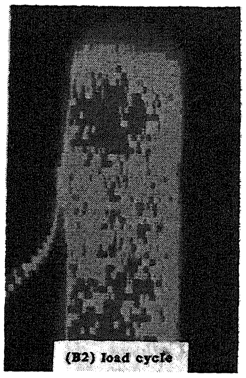

Figure 6. Thermogram of the Texsol specimen corresponding to 200 load cycles for (B2) loop (Each colour hue represents $\Delta T = 0.2\ ^oC$).

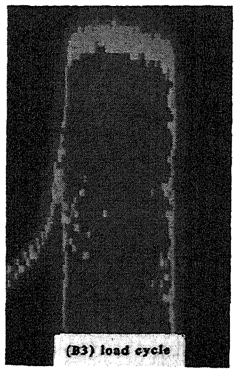

Figure 7. Thermogram of the Texsol specimen corresponding to 200 load cycles for (B3) loop (Each colour hue represents $\Delta T = 0.2\ ^oC$).

6 EDI INDEX OF LIQUEFIED SOILS

Many failures of earth structures, slopes and foundations on saturated sands have been caused by the liquefaction of the sands. A common feature of all the preceding cases is that the sands responsible for the failures would be considered loose in any classification system, whether based on SPT blowcounts, cone penetration or relative density. Some of the failures were triggered by earthquake shaking and others by monotonic increases in shear stress in the sand. However, once the failures were induced, the sand deformed until the shear stresses acting on the sand were reduced to very low values, as indicated by extreme flattening of slopes, sinking of buildings and by flotation of lighter structures. Thus, in all cases there was a loss of shear strength that was not regained with continued deformation.

Liquefaction is a mechanical behaviour wherein a saturated sand loses a large percentage of its shear resistance and flows in a manner resembling a liquid until the shear stresses acting on the mass are low as its reduced shear resistance. This phenomenon has been observed in place [Seed, 1968] on many occasions and it has been readily reproduced in the laboratory [Canou, 1989]. Liquefaction is the result of undrained failure of a fully saturated highly loose sand (Fig. 8 and 9).

It is recognized that the basic cause of liquefaction in saturated cohesionless soils during earthquakes is the build up of excess hydrostatic pore pressure due to the application of shear stresses induced by seismic ground motion. Thus the **EDI** index can be determined in this laboratory test by the ratio of the work W_{dm} mobilized up to the peak strength q_{max} of the stress-strain curve on the distortional work W_{dc} corresponding to the maximum value u_{max} of pore pressure build up.

7 CONCLUDING REMARKS

The present work aims to interpret the physical and mechanical properties of sandy soils at the macroscopic level in relation with the deformation mechanisms occurring at the granular level when subject to cyclic and vibratory loadings.

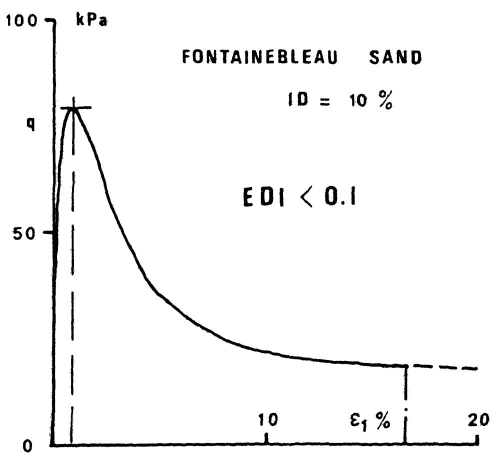

Figure 8. Stress-strain curve of a saturated Fontainebleau sand under undrained condition.

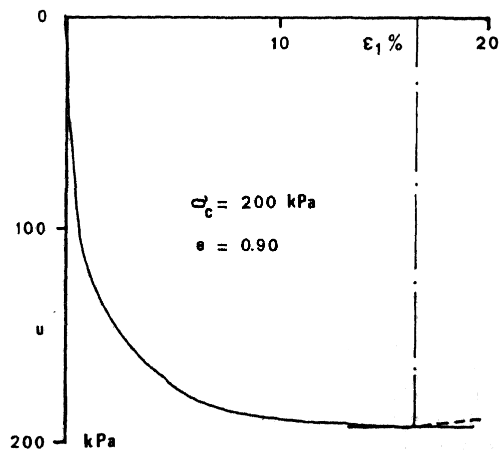

Figure 9. Pore pressure build up during the test.

This experimental approach has demonstrated the energy-dissipating ability of sandy soils using the conventional cylindrical triaxial tests and infrared vibrothermography.

The characteristic state concept reveals to be quite suitable for determining the threshold of interlocking breakdown of sandy soils and also for analysing its applicability to earthquake-resistant or vibration-isolating foundations.

The **EDI** energy-dissipating index is a measure of the energy absorbed during soil structure disaggregation in the nonlinear portion of the stress-strain curve above the characteristic threshold. It gives the numerical value to the toughness and is independent of the units used. The index is particularly useful in analysing the rheological behaviour of the soil. It readily discriminates between high and low energy absorbing materials.

Taking into account stress and strain states, **EDI** index is an appropriate indicator for predicting the geotechnical damping performance of sandy soils.

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