# Energy-Dissipating Ability of a Three Dimensional Soil-Fibre Composite

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ABSTRACT: The 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. Taking into account stress and strain states, it provides an appropriate indicator for predicting the geotechnical damping performance of textile reinforced soil under dynamic loadings. An experimental approach, using infrared vibrothermography, has evidenced the energetic dissipation of Texsol caused by local friction between solid grains. The infrared thermographic technique, which couples mechanical and thermal energy, offers the potential of directly monitoring the stress state of particle rearrangement and predicting the geotechnical response of fibre reinforced soils.

## 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 large masses of saturated noncohesive soils under certain drainage conditions there is also the possibility of loss of strength through liquefaction or cyclic mobility.

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.

## 2 CHARACTERISTIC THRESHOLD OF SOIL

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.

An experimental approach using infrared thermography 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 types of 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 and Wroth, 1968). For our concern, the transient and cyclic loading cases require the analysis of the prepeak part where the stress ratio $\eta_c = (q/p)_c$ (q and p respectively denote the deviator and mean stresses) at zero dilatancy rate defines evidently the characteristic state of the granular material associated with an angle of aggregate friction $\phi_c$ (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. 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.

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 $\phi_f$ and $\phi_c$ , 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.
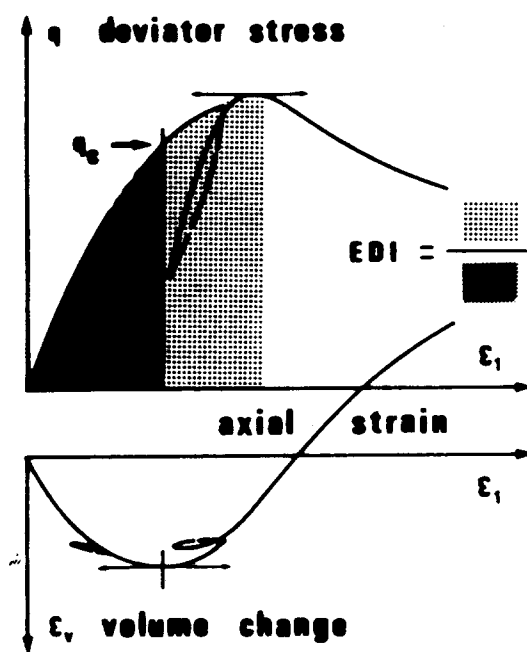


Fig. 1 Definition of EDI energy-dissipating index

## 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 and 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, the number of the intergranular contacts remains stable. Small slips between the solid particles lead to a maximum entanglement caused by the relative tightening of constituent granules. The dissipated work given by the hysteresis loop 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 (in compression and extension), the intergranular contacts become unstable, leading to significant slidings caused by interlocking breakdown. A large frictional energy is dissipated 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 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 and Dillon, 1969). This leads to a very important 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.

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 the 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 $^{0}$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 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 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 vibrothermo- graphy.

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 and 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 (Fig. 2).
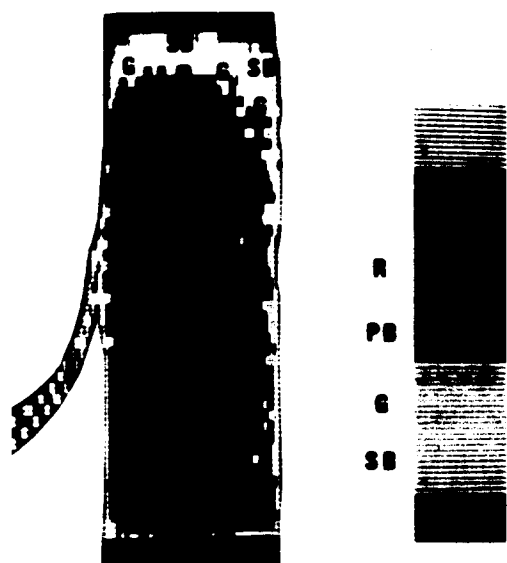


Figure 2. Thermogramme of the Texsol specimen corresponding to 200 load cycles (Each colour hue represents $\Delta T = 0.2\ ^0C$).

## 6 CONCLUDING REMARKS

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

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. This 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 soils.

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