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Infrared Thermography of Dissipation in Soil

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INFRARED THERMOGRAPHY OF DISSIPATION IN SOIL

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ABSTRACT

The paper introduces infrared thermography as a noncontact and non-destructive technique that conveniently offers the possibility of evaluating the energy-dissipating ability of soil, traditionally difficult to be determined using traditional techniques. It allows records and observations in real time of heat patterns produced by the dissipation of energy caused by friction between grains. Such dissipative heat occurs when soil is subjected to vibratory loading exceeding the characteristic threshold, and it evidences the distortion mechanism. This energy dissipation mechanism influences the wave speed, intergranular attenuation, and dispersion through particles contacts. 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 macroscopic mechanical response of soils subjected to cyclic or vibratory loading.

INTRODUCTION

A problem of practical importance for the foundation engineer in urban areas is the protection of structures against ground-transmitted waves generated by earthquake hazards or other vibrations such as external traffic, machinery, blasting, causing disturbances to adjacent structures. Most of the vibratory energy affecting structures nearby is carried by surface waves that travel in a zone close to the ground surface. Soil may act as a vibration transmitter, thereby modifying the intensity, frequency content and spatial distribution of ground shaking and it therefore induces the structural damage. It is then possible to reduce the ground-borne vibrations significantly by placing a suitable wave barrier in the ground around the structure. The conventional method aims to determine the G shear modulus and the D damping ratio of soil. Several studies provided data for use in visco-elastic, hysteretic or Ramberg-Osgood models. Recently the results of a micromechanical study of internal energy dissipation due to slip between contacting granules, introduced by Okada & Nemat-Nasser [1994], have been successfully compared with experimental measurements.

This paper proposes an infrared thermographic technique, capable to recognize quantitatively the energy-dissipating ability of soils.

CHARACTERISTIC THRESHOLD

Rheological properties of granular soils can be interpreted at the grain level where the solid particles interact with one another leading to a global aggregation (contractancy) or disaggregation (dilatancy) [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 or 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 toward a maximal aggregation. In this subcharacteristic domain or contractancy zone, a hysteresis loop occurs when reloading. Above the characteristic threshold, the grain contacts become unstable, leading to significant sliding due to interlocking breakdown. A reload shows a dilatancy loop with memory loss of load history and a softening phenomenon occurs. 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 (Figure 1).

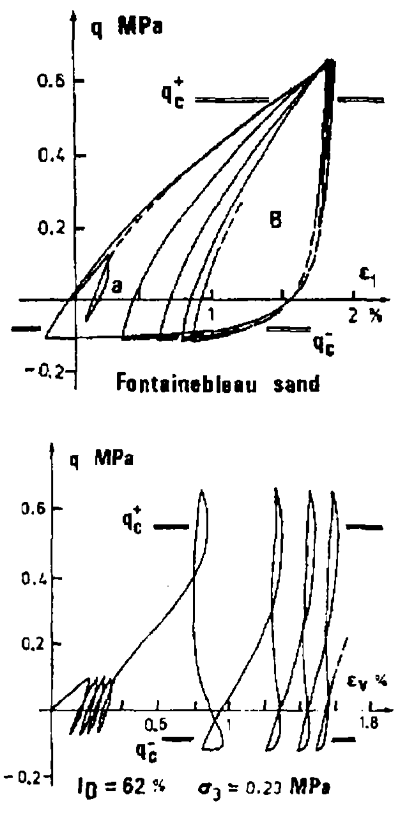

Fig. 1. Conventional triaxial test on sand.

ENERGY DISSIPATION MECHANISM

When a siliceous sand grain slides against another one, there occurs a motion resistance called friction. Bowden and Tabor [1959] demonstrated that when quartz or glass surface slides over another one in the dark, small sparkling points of light can be seen at the interface. The friction between grains generates heat. A consideration of forces and deformations at each surface [Mindlin & Deresiewicz 1953] may serve as a starting point in interpreting the thermomechanical coupling of sand behavior under vibratory shearing. For the simplest case of two like spheres compressed statically by a force which is directed along their line of centers, normal to their initial common tangent plane, the contact theory, after 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 tension 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. For small tangential forces, it has been suggested that the tangential displacement, necessary to relieve the singularity in tension, takes the form of an elastic deformation of the asperities. An increase in applied tangential force causes the asperities at the edge of the contact surface to deform plastically through relatively large strains, a process that leads to a marked increase in energy dissipation and to severe damage to the surfaces. Thus at small amplitude of the tangential force, energy is dissipated as a result of plastic deformation of a small portion of the contact surface, whereas at large amplitude the Coulomb sliding effect predominates.

In the conventional triaxial test, if the load is cycled within the subcharacteristic domain below the characteristic threshold, the intergranular contacts remain stable. Small slips lead to a maximum entanglement caused by the relative tightening of constituent grains. 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 (in compression q^-_c and extension q^+_c), the intergranular contacts become unstable, leading to significant slidings caused by interlocking breakdown. A large frictional energy (B) 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.

2a.

2b.

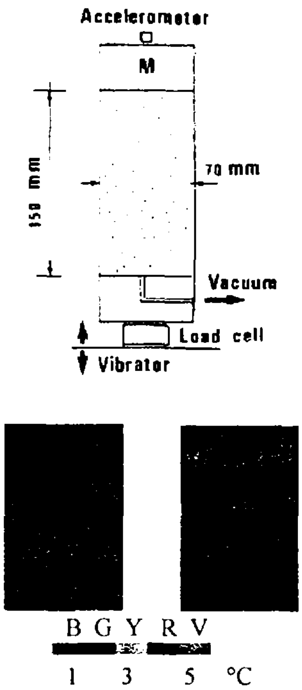

Fig. 2. Heat due to intrinsic dissipation of a fine sand under vibratory shearing.

INFRARED VIBROTHERMOGRAPHY

Infrared thermography has been successfully employed as an experimental method for detection of plastic deformation during crack propagation under monotonic loading of a steel plate or as a laboratory non-intrusive technique for investigating damage, fatigue, creep, and failure mechanisms.

The heat dissipation evidenced here is associated with a plastic work of distortion. The infrared thermographic technique commonly uses 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. Detected temperature differences in heat patterns as fine as 0.1 °C are discernible instantly and represented by several distinct hues.

This method is sensitive, non-intrusive, nondestructive, and noncontact, thus ideally suited for records and observations in real time of heat patterns produced by the heat transformation of energy caused by friction between grains of sheared sand. No interaction at all with the specimen is required to monitor the thermal gradient. The quantity of energy W 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 radiated energy correspond to differences of temperature.

The AGA 782 SW infrared scanner unit [1984] comprises:

- a set of infrared lens that focuses the electromagnetic energy radiating from the object's being scanned into the vertical prism,
- an electro-optical scanning mechanism that discriminates the field of view in 10,000 pixels by means of two rotating vertical (180 rpm) and horizontal (18,000 rpm) prisms with a scanning rate of 25 fields per second,
- a set of relay optics containing a selectable aperture unit and a filter cassette unit that focuses the output from the horizontal prism onto a single element point detector, located in the wall of a Dewar chamber,
- a photo voltaic SW short waves infrared detector composed of Indium Antimonide InSb that produces an electronic signal output varying in proportion to the radiation from the object within the spectral response 3.5 µm to 5.6 µm,
- a liquid nitrogen Dewar that maintains the InSb detector at the working temperature of −196 °C allowing a very short response (1 µsec),

and a control electronics with preamplifier that produces video signal on the display screen.

A cylindrical dry sand specimen, - characterized by its dry unit weight γ_d = 15.7 kN.m^{-3}, its void ratio e = 0.72 and its relative density I_D = 0.62, confined under a constant isotropic pressure of 100 kPa -, is subjected to a vibratory axial force, generated by a steel mass, located on the top of the specimen and excited by an electromagnetic vibrator (Figure 1a).

When the frequency reaches 87 Hz with a controlled displacement of 1 mm at the base, the specimen (70 mm in diameter and 150 mm high) is subjected to stationary stress waves and presents a striction zone where the deviator stress level η exceeds the characteristic threshold η_c of interlocking breakdown of the granular structure.

The heat dissipation, evidenced here, is associated with a plastic work of distortion. 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. Soil presents 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 sliding because of vibratory reversed applied loads (Figure 1b). These considerations define the use of vibrothermography as a nondestructive method for observing the energy-dissipation ability of granular material. A scanning camera was used, which is analogous to a television camera. It utilizes an infrared detector in a sophisticated electronics system in order to detect radiated energy, and to convert it into a detailed real-time thermal picture in a video system both color and monochromatic. Response times are shorter than a microsecond.

INFLUENCE OF GRANULAR SLIDING DISSIPATION ON WAVE PROPAGATION

An interesting experimental result has been obtained in laboratory on a sand column (Figure 3) confined by vacuum pressure and locally subjected to tightening rings (Figure 4) so that the stress state reaches the supercharacteristic stress domain.

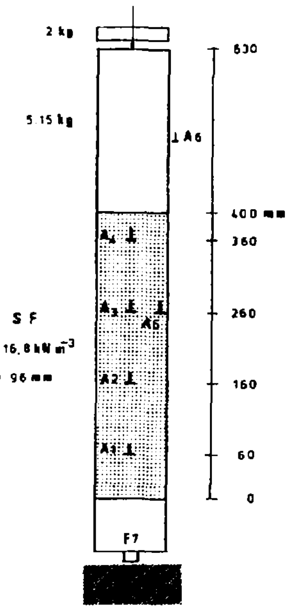

Fig. 3. Sand column subject to falling mass loading.

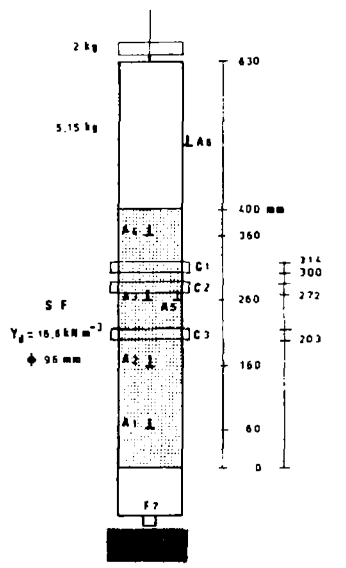

Fig. 4. Sand column equipped with dissipative barriers.

This dissipative barrier has been suggested by a theoretical idea concerning the stability of the soil element in the presence of wave propagation. For geomaterials, experiment evidence of mechanical behavior that contradicts Drucker's stability postulate, has been shown by a great number of geotechnical researchers [Lade *et al* 1988].

Within the theory of plasticity, using wave propagation considerations, Mandel [1964] showed that Drucker's postulate was a sufficient but not necessary condition for a material to be stable, due to the frictional nature of sliding between soil particles [Hardin 1978]. Based on the assumption that a stable material is able to propagate a small perturbation in the form of waves, Mandel proposed a necessary condition for stability. He stated that a wave could propagate in a soil cylinder (Figure 5) characterized by an elastic-plastic matrix A, along a direction α, if and only if all the eigenvalues λ of the matrix M are positive.

$$d\varepsilon_{ij} = A_{ijkl} \bullet d\sigma_{kl}$$
$$M_{ik} = A_{ijkl} \bullet \alpha_j \bullet \alpha_i$$

where k = 1, 2, 3 and $\lambda_k > 0$.

If one of the eigenvalues λ is ≤ 0, one of the corresponding components of the perturbation cannot propagate. This implies material instability, and the possible appearance of strain localization along a shear band or sliding zone along a certain direction. This phenomenon occurs when the stress state reaches the supercharacteristic domain [Luong 1982] where the friction mechanism is very active between soil particles, or when the loading is cycled near the characteristic threshold. A large amount of mechanical energy (several tens of $kJ.m^{-3}$) could then be dissipated in soil mass by heat as evidenced by infrared vibrothermography [Luong 1986]. Acceleration records, before and after installation of such energy-distribution barriers have shown their effectiveness (Figure 5).

The microstructural wave propagation behavior, based on contact effects, provides a consistent explanation of wave attenuation and dispersion characteristics caused by the energy-dissipation mechanism that is located on a very large number of microscopic contact areas. At the macroscopic level, the propagation of mechanical waves through granular media [Aboudi 1973] occurs along a complex network of paths determined by the material's particulate microstructure [Shukla *et al* 1991, Zhu *et al* 1991], with profound directional dependency. The process of energy transfer is determined by the granular contact interactions between the various grains in the media, and these interactions are primarily controlled by the particle" material properties, the local packing and the deviator stress level [Luong 1986].

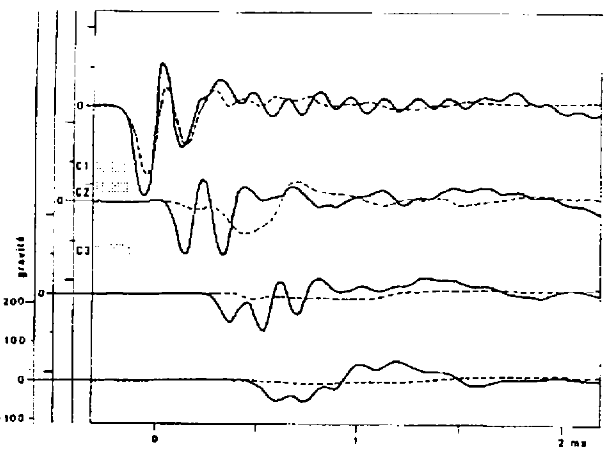

Fig. 5. Efficiency of dissipative wave barrier.

The dynamic response of buildings due to soil vibration could be mitigated using this type of protective device, acting as a geotechnical fuse, designed to dissipate wave energy by friction between soil particles. Several series of tests on reduced scale models performed in geotechnical centrifuge have demonstrated the efficiency of shielding against ground borne stress waves [Luong 1994, 1995 and 1998].

CONCLUDING REMARKS

The present work aims to interpret the physical and mechanical properties of particulate soils at the microscopic level in relation with the deformation mechanisms occurring at the granular level in order to demonstrate the energy-dissipating ability of soils using the conventional 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 analyzing its applicability to earthquake-resistant or vibration-isolating foundations.

In soil dynamics, the contact effects provide the basic microstructural mechanisms that govern the way mechanical waves will propagate from particle to particle. They determine the proper stiffness and damping characteristics that influence the wave speed and intergranular wave attenuation and dispersion.

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 macroscopic mechanical response of sandy soils subject to cyclic and vibratory loading.

Infrared thermography readily evidenced the intrinsic dissipation of a fine sand, caused by friction between grains. This energy dissipation mechanism influences the wave speed, intergranular attenuation, and dispersion through particle contacts.

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