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► **To cite this version:**

Minh-Phong Luong. Geotechnical fuse using a soil-fibre composite. Structural Mechanics in Reactor Technology (SMiRT-15), 1999, Séoul, South Korea. pp.121-128. hal-00116555

HAL Id: hal-00116555

<https://hal.science/hal-00116555v1>

Submitted on 16 Sep 2024

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Geotechnical Fuse Using a Soil-Fibre Composite

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ABSTRACT: The paper aims to interpret the physical and mechanical properties of a 3D soil-fibre composite at the macroscopic level in connection with the deformation mechanisms occurring at the granular level when subject to transient, cyclic and vibratory loading. The effectiveness of a new type of stress wave barrier, designed for shielding vibratory ground motion, has been evaluated when using a technique of prestressing on this composite, able to activate micro-friction between soil particles without reaching failure. Findings on energy dissipation by friction, obtained at natural gravity, are validated on centrifuge models that represent larger areas and take into account gravity effects.

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, which result in ground amplitudes, 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. The 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.

Traditionally, ground vibration isolation, based on the principles of reflection, scattering and diffraction of elastic waves, uses rows of cylindrical obstacles installed in the ground, concrete barriers, or open and in-filled trenches. The main features of seismic wave propagation, which have been observed experimentally, would be expected on the basis of a purely elastic earth. However there are differences between observation and theoretical expectation, the principal being a loss of amplitude in excess of that due to geometrical spreading and reflection at boundaries. How to characterise this decrease of amplitude usually called attenuation, or damping susceptibility of soil foundation against earthquake or dynamic loading? The conventional method aims to determine G shear modulus and D damping ratio of soil. Several studies provided data for use in visco-elastic, hysteretic or Ramberg-Osgood models. Recently the results of a micro mechanical study of internal energy dissipation due to slip between contacting granules, introduced by Okada & Nemat-Nasser [1], have been successfully compared with experimental measurements.

The paper reports several series of tests performed in a centrifuge that is capable to generate in flight stress waves propagating through a centrifuged soil mass in order to investigate the effectiveness of the proposed stress wave barrier, using soil energy dissipation [2]. The soil-fibre composite, constituent of the stress wave barrier, is loaded, by means of high capacity anchoring systems, in the super characteristic state domain in order to activate the micro friction mechanism between grains, as discussed hereinafter.

ENERGY-DISSIPATING MECHANISM

When a siliceous sand grain slides against another one, there occurs a motion resistance called friction. Bowden and Tabor [3] 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 in the same fashion as when prehistoric man used silex stones to generate fire. A consideration of forces and deformations at each surface [4] may serve as a starting point in interpreting the thermomechanical coupling of sand behaviour under vibratory shearing. In the conventional triaxial test, if the load is cycled within the subcharacteristic domain below the characteristic threshold, the intergranular contacts remain stable [5]. Small slips lead to a maximum entanglement caused by the relative tightening of constituent grains. The dissipated work given by 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 (compression and extension), intergranular contacts become unstable, leading to significant sliding caused by interlocking breakdown. A large frictional energy is dissipated and transformed almost entirely into heat due to the thermomechanical conversion. If stress peaks in 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 energy-dissipation detection is based on the coupled thermo-visco-elastic-plastic analysis [6]. 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. The quantification of this intrinsic dissipation for soils in an extremely difficult task if infrared thermography is not used. The following tests demonstrate the energy dissipating ability of a soil fibre composite barrier.

A 3D SOIL FIBRE COMPOSITE

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 that will permit earthquake displacements to take place without generating unduly large forces. The composite soil used in this study is a 3-dimensional soil-fibre composite resulting from a new technique of soil reinforcement by incorporation of continuous fibres [7]. Soil grains and fibres are connected each to others by friction. When the soil fibre composite undergoes deformations, friction forces apply tensions on fibres and generate a pseudo cohesion that can be significant if the

used polymer fibres present high mechanical performance [8]. A fibre 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 a very acceptable safety coefficient.

Thus the application of soil-fibre composite to foundation design of civil engineering structures in order to mitigate the destructive effects of earthquakes, vibrating machines, highway 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, the soil-fibre composite permits large deformations at failure, 6 to 7 % instead of 2 to 6 % for soil without reinforcement [8]. When compared to the corresponding values for plain soil, soil-fibre composite offers excellent toughness behaviour. In addition this material is capable to dissipate a great amount of energy in cases of large amplitude of cyclic loading as shown by the hysteresis loops (B1), (B2) and (B3) when compared to loop (b) for plain sand (Figure 1).

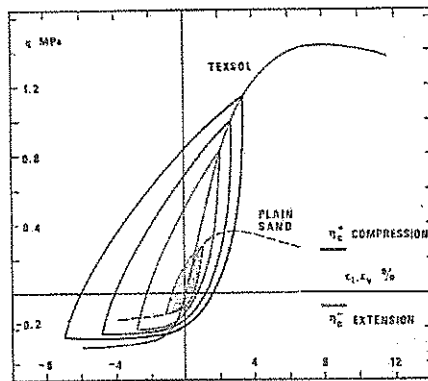


Figure 1: A soil fibre composite under large amplitude loading.

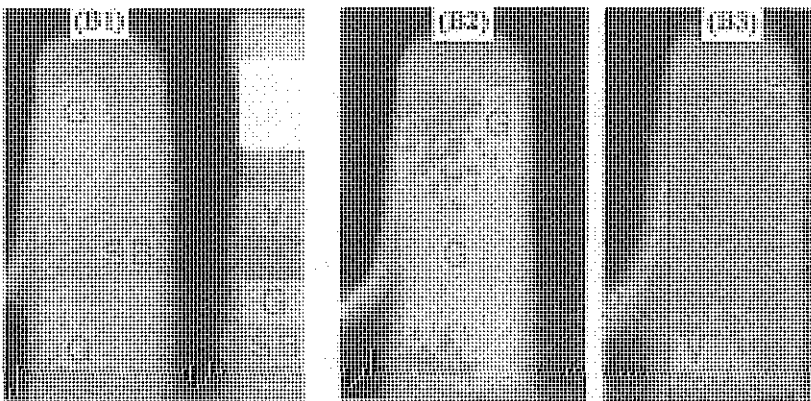


Figure 2: Thermal images of a sand-fibre composite specimen after 200 load cycles corresponding to stress-strain loops (B1), (B2) and (B3) (each colour hue represents $\Delta T = 0.2^{\circ}\text{C}$).

WAVE ISOLATION USING A GEOTECHNICAL FUSE

The barrier disturbs the natural spreading of waves and also screens buildings at a certain region behind the barrier. Isolation of structures and machine foundations from ground transmitted vibrations by installation of wave barriers has been attempted many times. However this technique has met with varying degrees of success. Several numerical, experimental and analytical techniques have been applied to study the surface wave propagation across different types of barriers or in-filled trenches.

The proposed geotechnical fuse, used as dissipative barrier, has been suggested by a theoretical idea concerning the stability of the soil element in presence of wave propagation. For geomaterials, experimental evidence of mechanical behaviour that contradicts Drucker's stability postulate, has been shown by a great number of geotechnical researchers [9]. Within the theory of plasticity, using wave propagation considerations, Mandel (1964) showed that Drucker's postulate was a sufficient but not a necessary condition for a material to be stable, due to the frictional nature of sliding between soil particles [10]. 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 showed that a wave could propagate in a material with an elastic-plastic matrix A , along the direction α , if and only if all the eigenvalues λ of the matrix M are positive.

$$d\varepsilon_{jj} = A_{ijkl} \cdot d\sigma_{kl}$$

$$\text{where } k = 1, 2, 3 \text{ and } \lambda_k > 0$$

$$M_{ik} = A_{ijkl} \cdot \alpha_j \cdot \alpha_l$$

If one of the eigenvalues λ is ≤ 0 , one of the corresponding components of the perturbation cannot propagate. This implies instability and possible appearance of strain localisation along a shear band or sliding zone along this direction. This phenomenon occurs when the stress state reaches the supercharacteristic domain where frictional mechanism is very active between soil particles, or when loading is cycled near the characteristic threshold. A very important amount of mechanical energy (several tens of $\text{kJ}\cdot\text{m}^{-3}$) can then be dissipated in soil mass by heat as evidenced by infrared vibrothermography (Figure 2). Several centrifuge tests on scale models have successfully demonstrated the promising efficiency of this innovative type of geotechnical fuses [11]. Soil-fibre composite, presenting a very high stress peak, is preferred to plain soil in order to ensure the effectiveness of the proposed device in cases of a second earthquake or subsequent aftershocks.

CENTRIFUGE TESTING

In order to predict the prototype behaviour correctly from observation, scaling laws must be established for model and prototype, taking into account three groups of equations governing the physical phenomena: (i) balance equations or general laws, (ii) constitutive relations or rheological laws, and (iii) boundary conditions or initial references and boundary values. In centrifuge testing, the scaling relationship emphasises the relevant effect of self-weight induced stresses appropriate to the prototype earth structures [12].

Experiments were carried out in the 200 g-ton centrifuge built by Latécoère in 1964 at the CEA-CESTA centre near Bordeaux France (g denotes natural gravity). The arm has a radius of 10.5 m to the centre of the swinging platform. The centrifuge is equipped with 108 low noise electrical slip rings. The motor drive unit comprises 4 suspended motors (350 HP

each) and 4 Ward Leonard groups (250 kVA each). The run-up time to 100 g is 60 sec. The rotating container of internal dimension length (= 1.30 m) by width (= 0.80 m) by height (= 0.40 m), mounted on the swinging platform, was filled with soil fibre prepared to the density of $1,520 \text{ kg.m}^{-3}$ (Figure 3).

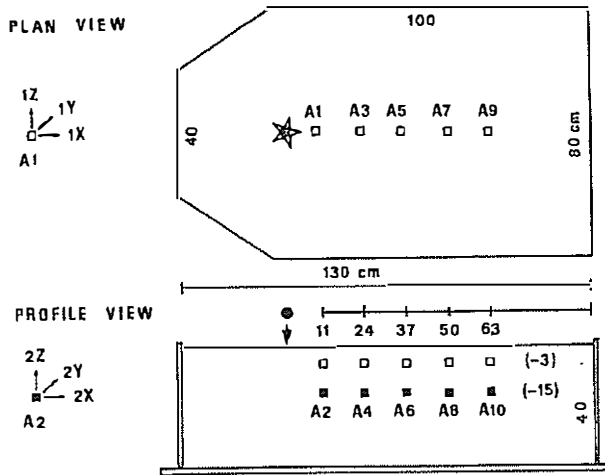


Figure 3: CESTA's centrifuge facilities.

Tests were run at 100 g, respecting usual scaling relationships as proposed at Centrifuge 88, 91 and 94 conferences. A row of high capacity anchoring systems (simulated in centrifuge by compressed air micro jacks pulling on anchored steel cables) provides a large enough load (about 0.2 MPa on ground surface) to bring the soil-fibre composite there in the supercharacteristic state. This device activates dilatancy mechanisms, but much lower than the peak stress in order to avoid soil failure (Figure 4). An automatic control system provides adjustment of anchoring forces in order to ensure the effectiveness of the proposed device in a second earthquake or aftershock. The motion was detected by 3D piezo-electric accelerometers which provided data on the horizontal (x), transverse (y) and vertical (z) movements at different locations in the soil mass: A1, A3, A5, A7, A9 and A2, A4, A6, A8, A10 respectively installed at 3 cm (three metres) deep and 15 cm (fifteen metres) deep. Charge amplifiers delivered a voltage proportional to electric charge and independent of the capacity of the lines. Signals were recorded on magnetic tapes. With the same magnetic tape recorders, all the signals have been read again and sent to analog channels with programmable low pass anti-aliasing filter, a hold circuit and a multiplexer. An Hanning window weights each sample. The frequency response function resolution is about 1.25 Hz. Measurement error has been evaluated at 2.5 per cent. Two types of input motions have been used in centrifuge.

1. A drop-ball arrangement has been installed in a large swinging container to produce Rayleigh waves. An electromagnetic motor (EMP) pushes horizontally the steel ball (SB - mass = 0.5 kg) along a guide (G) toward a thin steel wall (DC) that controls its vertical drop (DH - height = 0.1 m).

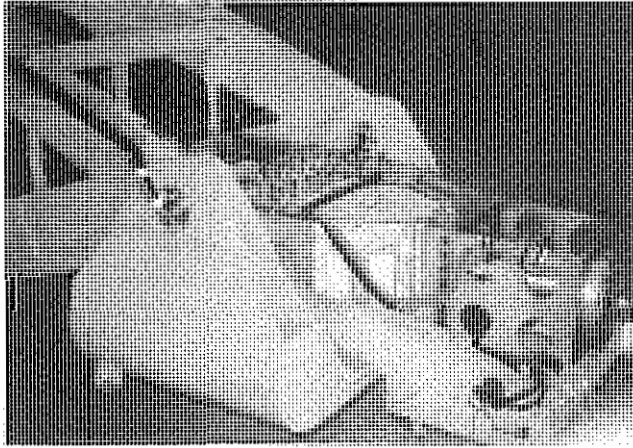


Figure 4: Centrifuge modelling of a geotechnical fuse.

2. The ground motion simulator of the centrifuge Latécoère at CEA-CESTA uses explosives, yielding energy of about 2 kJ/gram. One detonator releases a simulated short duration of 1.8 sec (to be compared with a near-field, impulsive type ground motion such as Parkfield earthquake of 1-sec duration). Two series of explosions can simulate far-field long duration, relatively severe and symmetric type cyclic excitations (such as the El Centro earthquake of 12 secondes duration). The maximum duration of simulated earthquake in CESTA's centrifuge is about 15 sec when using ten detonators. Charges of 1 to 5 grammes are exploded at the plate at the end of an air blast modification chamber; up to 10 charges may be held by this plate and may be detonated in any sequence. The resulting air blast is modified by resonating cavities and springs supported metal plates, and finally the air pressure is applied to the vertical face of a soil mass through a rubber membrane.

The use of impact excitation, together with a Fast Fourier Transform (FFT) based spectrum analyser to determine the dynamic characteristics of soil, is potentially a very attractive technique as attested in the dynamic studies presented at Centrifuge 88, 91 and 94 conferences. An impact technique may readily generate high stress wave energies. Varying ball size can theoretically control the frequency content due to a ball drop and drop height as defined by the Hertz elastic solution for impact; the size of the impacting ball is the most significant factor for controlling input frequency content. The resulting frequency distribution will be essentially broad band, and control of input frequency bandwidth is limited. An impact usually gives excitation across a relatively broad frequency range and the upper limit of this range can be tailored to suit the particular test by varying the ball material. Therefore it is frequently possible to investigate the whole low frequency range of interest in a single test. The test is also very quick to set up since the need for connecting and aligning a shaker is eliminated.

Applying on the soil mass an additional loading such that the stress state locally reaches the super characteristic threshold has simulated such a conceptual dissipating wave barrier. This loaded region will mitigate the wave energy as shown by the decreased amplitude of acceleration records (Figure 5). Several successive tests have been performed with the same device, demonstrating that it remains effective after several simulated earthquakes. However it is possible to adjust the preloading of the seismic shield by means of pulling on the tie rods.

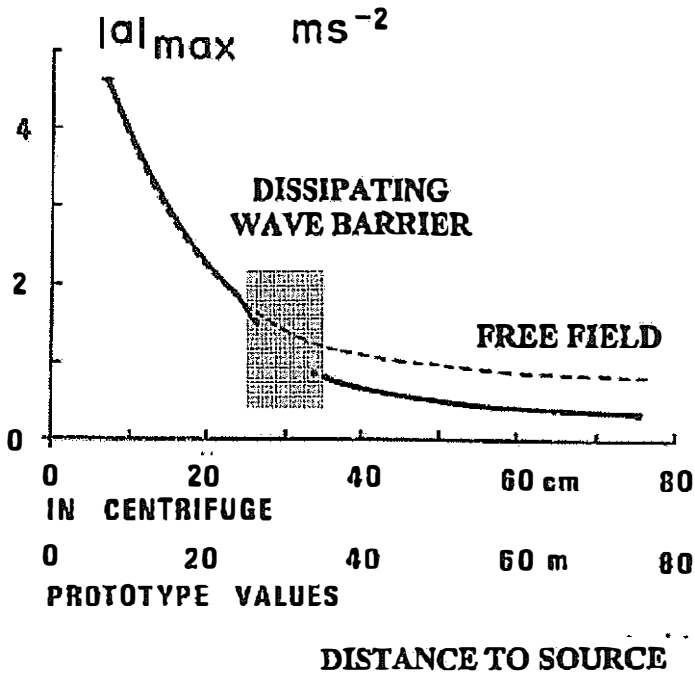


Figure 5: Effectiveness of the proposed dissipating wave barrier when using the CESTA's drop ball arrangement.

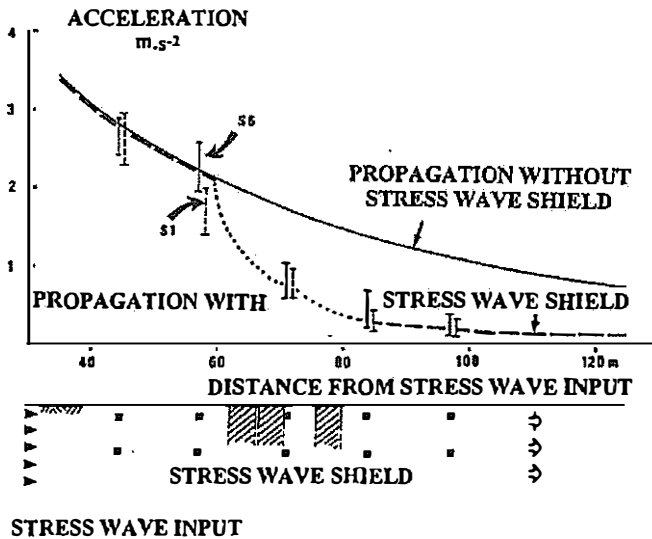


Figure 6: Effectiveness of the proposed dissipating wave barrier when using the CESTA's earthquake simulator.

CONCLUDING REMARKS

1. The present work aims to interpret the physical and mechanical properties of soil-fibre composite at the macroscopic level in relation with the deformation mechanisms occurring at the granular level when subjected to transient, cyclic, vibratory and dynamic loading.
2. 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.
3. A non-destructive testing technique, using infrared vibrothermography, has evidenced the intrinsic dissipation of a sandy soil-fibre composite, caused by friction between grains. This energy dissipation mechanism influences the wave speed and intergranular attenuation and dispersion through particle contacts.
4. A geotechnical fuse has been proposed to energetically mitigate ground borne wave propagation, using friction between soil particles. The findings obtained at natural gravity have been validated on centrifuge scale models that represent larger areas and take into account the effects of gravity forces.

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