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Efficiency of a Seismic Barrier Using Soil Energy-Dissipation

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ABSTRACT

The paper aims to analyse the dissipative behaviour of soils in connection with ground vibration isolation. The effectiveness of a new type of stress wave barrier for reduction of vibrating ground motion has been evidenced by experimental results obtained on centrifuge scale models. A drop-ball arrangement has been devised to generate Rayleigh waves in centrifuge. Series of experiments on scale models carried out at 100 gravities level has demonstrated that friction between soil particles is able to significantly mitigate the intensity of stress waves.

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 and other vibrations such as external traffic, machinery, blasting, which result in ground amplitudes, causing disturbances to adjacent structures.

Most of the vibrating energy, affecting structures nearby, is carried by surface (Rayleigh) 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 therefore 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 usefulness of such wave barriers is directly associated with the proper isolation of the Rayleigh wave energy. Traditionally, ground vibration isolation, based on the principles of scattering and diffraction of elastic Rayleigh waves, uses rows of cylindrical obstacles installed in the ground, concrete barriers or open and in-filled trenches.

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 loading. Soil damping behaviour has been considered as the main phenomenon, able to mitigate the intensity of stress wave propagating through soil mass. Several studies provided data for use in visco-elastic [Hardin & Drnevich 1972 and Stewart & Campanella 1991], hysteretic [Iwasaki et al 1978 and Bolton & Wilson 1989] or Ramberg-Osgood [Ray & Woods 1988] models. Recently, the results of a micromechanical study of internal energy dissipation due to slip between contacting granules, introduced by Okada & Nemat-Nasser [1994], has been successfully compared with experimental measurements.

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CENTRIFUGE TESTING

In dynamic geotechnical engineering, the best approach is to observe the behaviour of the actual structure and check the accuracy of the existing procedure or to establish a new design technique, abstracting new assumptions from observations of the full-scale structure. Unfortunately, full-scale tests to observe the behaviour of an actual structure are always very costly, time-consuming and they sometimes may be very dangerous. Furthermore, it is impossible to carry out a parametric study and to check the reproducibility of the test results. Therefore the need for scaled modelling arises to replace full-scale observations.

The scaled reproduction of wave propagation is advantageous for several reasons:

- The problem at hand is too complex or too little explored to be amenable to an analytical solution; empirical information on relevant physical phenomena is needed.
- Scale models permit transformation of systems to manageable proportions and investigation of model size effects.
- Scaled modelling shortens experimentation.
- It promotes a deeper understanding of the phenomenon under investigation: failure mechanisms and analyses.
- It verifies numerical models.
- Direct modelling can be used to check the design of full scale structures.

In order to predict the prototype behaviour correctly from observation, scaling laws must be established for the model and the prototype, taking into account three groups governing the physical phenomena: balance equations or general laws, constitutive relations or rheological laws, and 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 [Luong 1992].

EXPERIMENTAL ARRANGEMENT

The experiment were carried out in the 200 *g*-ton centrifuge built by Latécoère in 1964 at the CEA-CESTA centre near Bordeaux France (g denotes the 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 Fontainebleau sand rained to the density of 1,520 $kg.m^{-3}$. The tests were run at 100 *g*, respecting the usual scaling relationships (Centrifuge 88 [Corté 1988] and 91 [Ko and McLean 1991] conferences).

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 (Figure-1): 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.

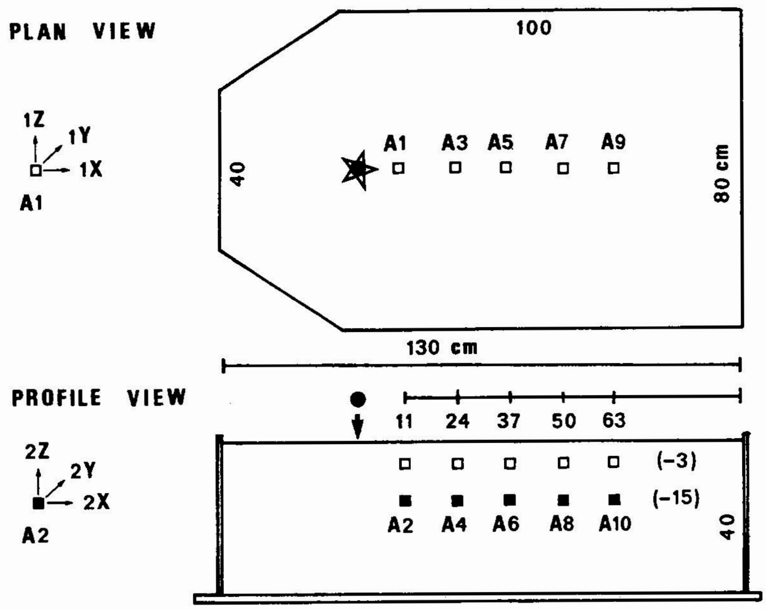

Figure-1: Location of 3D-accelerometers in soil mass.

All the 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. Each sample is weighted by an Hanning window. The frequency response function resolution is about 1.25 Hz. The measurement error has been evaluated at 2.5 per cent.

A drop-ball arrangement (Figure-2) has been installed in a large swinging container to produce Rayleigh shear 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).

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 the dynamic studies presented at Centrifuge 88 and 91 conferences. An impact technique may readily generate high stress wave energies. The frequency content due to a ball drop can be theoretically controlled by varying ball size 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.

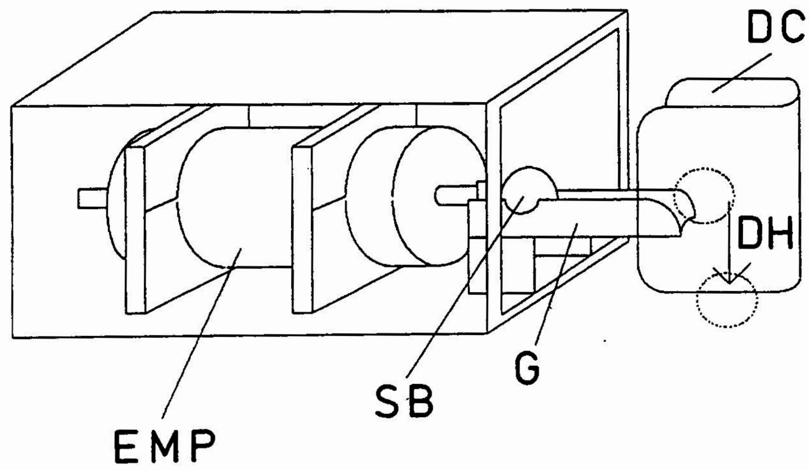

Figure-2: Drop-ball arrangement in centrifuge.

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 vibrating 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 Hertz's contact theory predicts a plane and circular contact. 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. 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 characteristic domain below the characteristic threshold η_C [Luong 1980], 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 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 and transformed almost entirely into heat owing to the thermomechanical conversion. If the stress peaks in triaxial compression and extension are not exceeded, the resulting effect is densification because the high amplitude loading benefits in partial loss of strain-hardening during the dilating phase in the super characteristic 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 & 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. The quantification of this intrinsic dissipation for soils is an extremely difficult task if infrared thermography is not used [Luong 1994].

STRESS WAVE MITIGATION BARRIER

The dynamic response of buildings due to soil vibration can be mitigated by various different techniques:

- Use of friction elements at appropriate locations within a structure to increase the structural damping through energy dissipation at these locations.
- Change of the vibration behaviour of a building by changing the soil around the foundation.
- Mounting of special devices such as rubber bearings, springs or a combination of springs and dampers at the foundation of the building.
- Reduction of the spreading waves by installing a wave barrier like a trench, a concrete wall or a wall consisting of air cushions.

The barrier disturbs the natural spreading of the waves and so screens the 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 [Barkan 1962, Dolling 1966, Woods 1968, Aboudi 1973, Haupt 1977, Liao & Sangrey 1978 and Ahmad & Al-Hussaini 1991]. Several numerical, experimental and analytical techniques have been applied to study the surface wave propagation across different types of barriers or in-filled trenches.

This paper presents some experimental results obtained with a new type of wave barrier, designed to dissipate seismic energy by friction between soil particles. It suggested by a theoretical idea concerning the stability of the soil element in the 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 [Lade et al 1987, 1988].

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 [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 showed that a wave can 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.

$$d\varepsilon_{ij} = A_{ijkl}.d\sigma_{kl}$$

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

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 instability, and the possible appearance of strain localisation along a shear band or sliding zone along a certain direction.

This phenomenon occurs when the stress state reaches the super characteristic domain where the frictional mechanism is very active between soil particles, or when the loading is cycled near the characteristic threshold. A very important amount of mechanical energy (several tens of $kJ.m^{-3}$) can then be dissipated in soil mass by heat as evidenced by infrared thermography [Luong 1986].

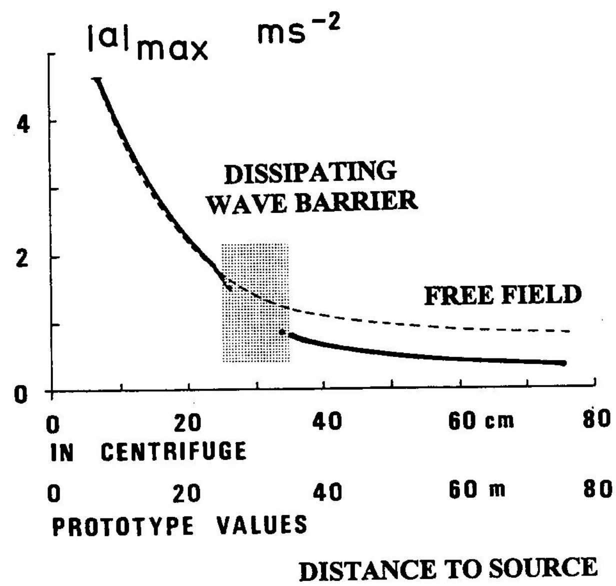

Figure-3: Efficiency of the proposed disipating wave barrier.

In the centrifuge, such a conceptual dissipating wave barrier has been simulated by applying on the soil mass an additional loading such that the stress state locally reaches the super characteristic threshold. This loaded region will mitigate the wave energy as shown by the decreased amplitude of acceleration records (Figure-3).

CONCLUDING REMARKS

Centrifuge modelling of wave propagation in soils is very useful for a realistic evaluation of the dynamic soil properties involved in the interpretation of the geotechnical performance of earthquake-resistant and vibration isolating structure models. A dissipative barrier using intrinsic dissipation of soil has been successfully modelled in centrifuge. Experimental results showed that friction between soil particles is able to efficiently mitigate the intensity of stress-waves.

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