

CENTRIFUGE MODELLING OF A SEISMIC BARRIER USING SOIL ENERGY DISSIPATION

M.P. LUONG

CNRS-LMS, Ecole Polytechnique, 91128 Palaiseau Cedex, France

ABSTRACT

The paper proposes a new type of stress wave barrier acting as a geotechnical fuse, designed for dissipating the vibratory energy of ground motion. Its effectiveness has been evidenced by experimental results obtained in centrifuge, using an explosive-based earthquake simulator and a drop-ball arrangement. Series of experiments on scale models carried out at 100-gravity level have demonstrated that friction between soil particles is capable to significantly mitigate the intensity of stress waves.

KEYWORDS

Centrifuge dynamic testing, characteristic state soil mechanics, drop-ball arrangement, earthquake simulator, energy dissipation, geotechnical fuse, rheological similarity, soil particle friction, stress wave barrier, wave propagation.

INTRODUCTION

A problem of practical importance for the foundation engineer in urban areas is the protection of existing 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 that often act as an amplifier for the ground vibrations.

Most of the vibrating 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 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 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. 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, Stewart & Campanella, 1991, Yamashita & Toki, 1994 and Campanella, 1994), hysteretic (Iwasaki *et al*, 1978 and Bolton & Wilson, 1989) or Ramberg-Osgood (Ray & Woods, 1988 and Woods, 1994) 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 laboratory experimental measurements, using infrared thermography (Luong, 1994a).

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 does 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.

In the conventional triaxial test, if the load is cycled within the characteristic domain below the characteristic threshold (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 (Kratovich & 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 (Fig. 1).

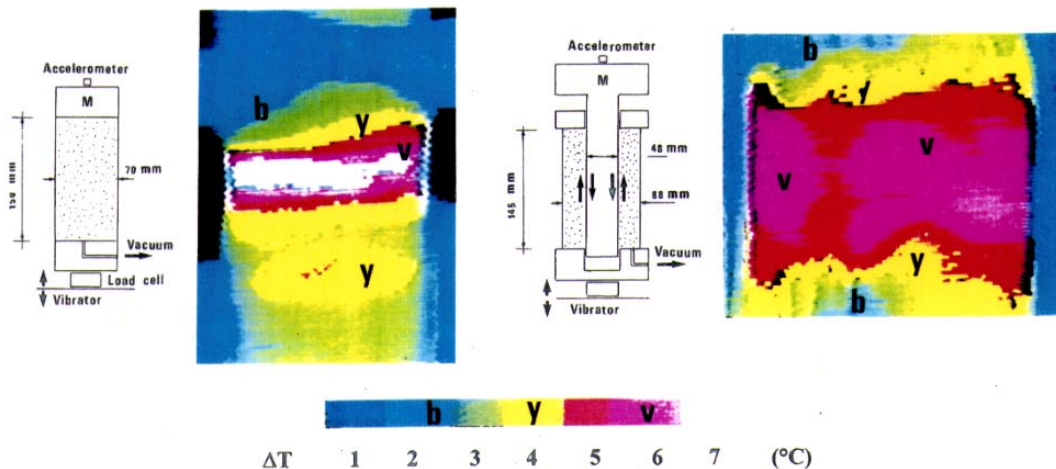


Fig. 1. Intrinsic dissipation of sand under vibratory direct shearing (each colour hue corresponds to 0.2°C).

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.

The proposed protective device, acting as a geotechnical fuse, is a new type of wave barrier, designed to dissipate seismic energy by friction between soil particles. It was 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 \mathbf{A} , along the direction α , if and only if all the eigenvalues λ of the matrix \mathbf{M} are positive.

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

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

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 localization 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).

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.

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, 1994b and Scott 1994).

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 $1,520 \text{ kg.m}^{-3}$. The tests were run at 100 *g*, respecting the usual scaling relationships (Centrifuge 88, 91 and 94 conferences). A row of high capacity anchoring systems (simulated in centrifuge by compressed air microjacks pulling on anchored steel cables) provides a large enough load (about 0.2 MPa on ground surface) to bring the soil there in the supercharacteristic state, close to yielding, but much lower than the peak stress in order to avoid soil failure (Fig. 2). An automatic control system provided adjustment of anchoring forces in order to ensure the effectiveness of the proposed device in a second earthquake or aftershock.

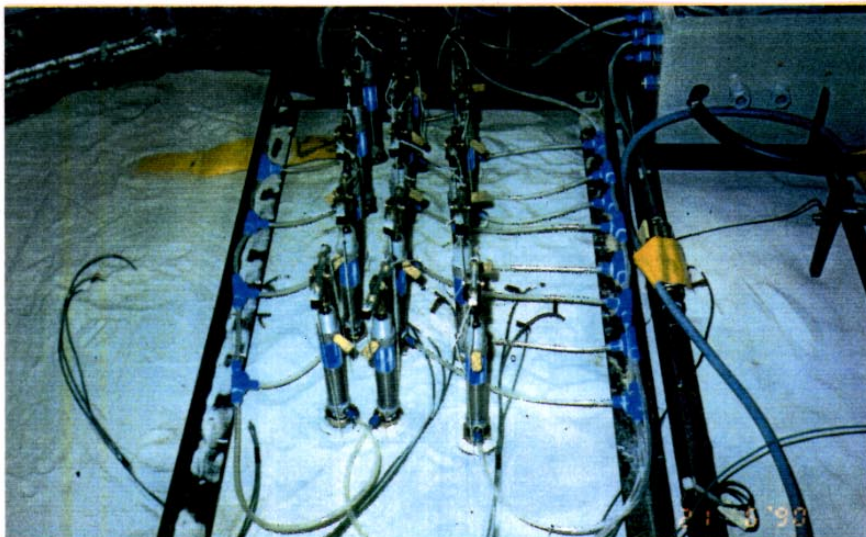


Fig. 2. Stress wave barrier using soil energy dissipation.

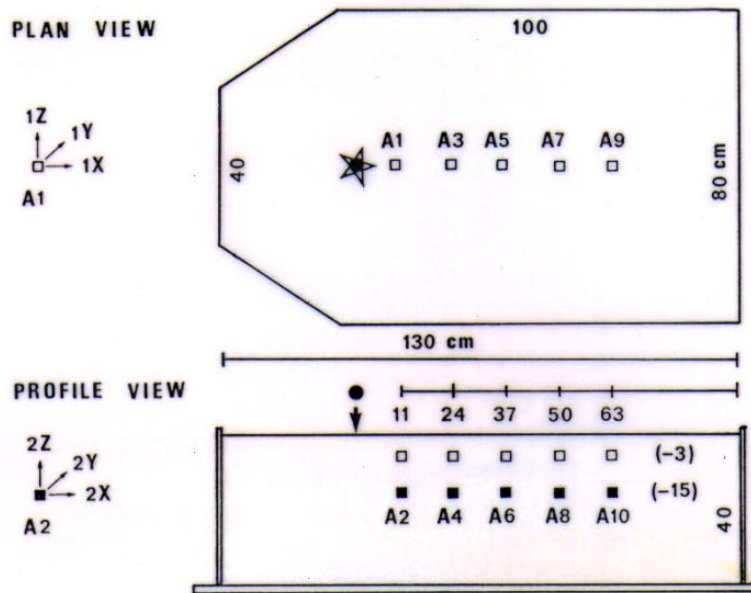


Fig. 3. Location of 3D-accelerometers in soil mass.

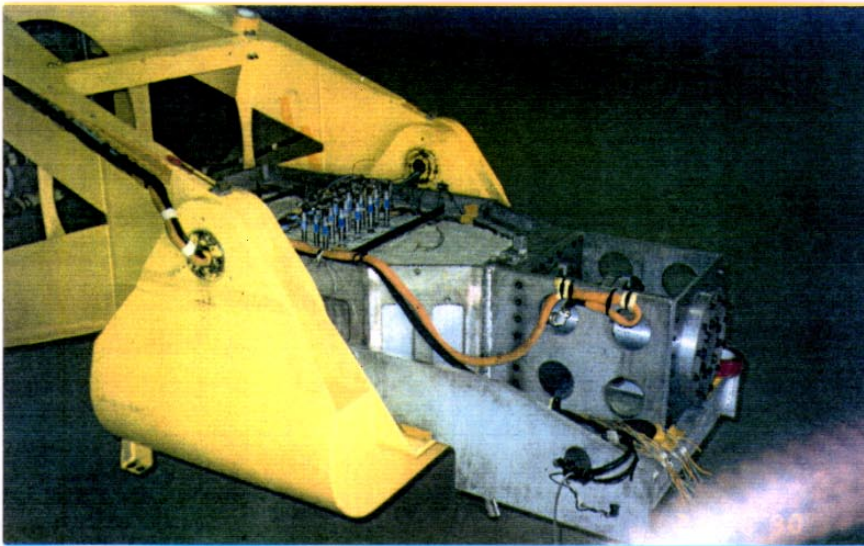


Fig. 4. CESTA's earthquake simulator using series of explosives.

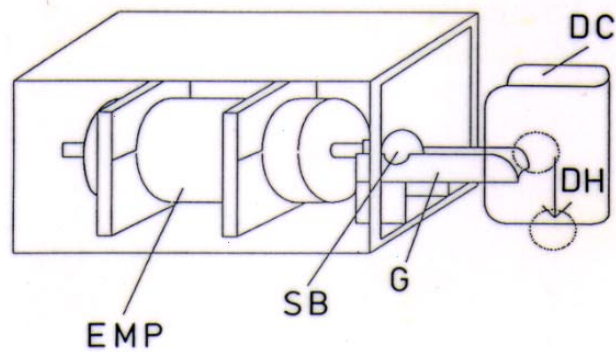


Fig. 5. Drop-ball arrangement in centrifuge.

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 (Fig. 3): 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. 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.

Two types of input motions have been used in centrifuge:

1. The ground motion simulator (Fig. 4) of the centrifuge Latécoère at CEA-CESTA (Devaure 1980) uses explosives, yielding an energy of about 2 kJ/gramme. 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 sec 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.

2. A drop-ball arrangement (Fig. 5) 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 in the dynamic studies presented at Centrifuge 88, 91 and 94 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.

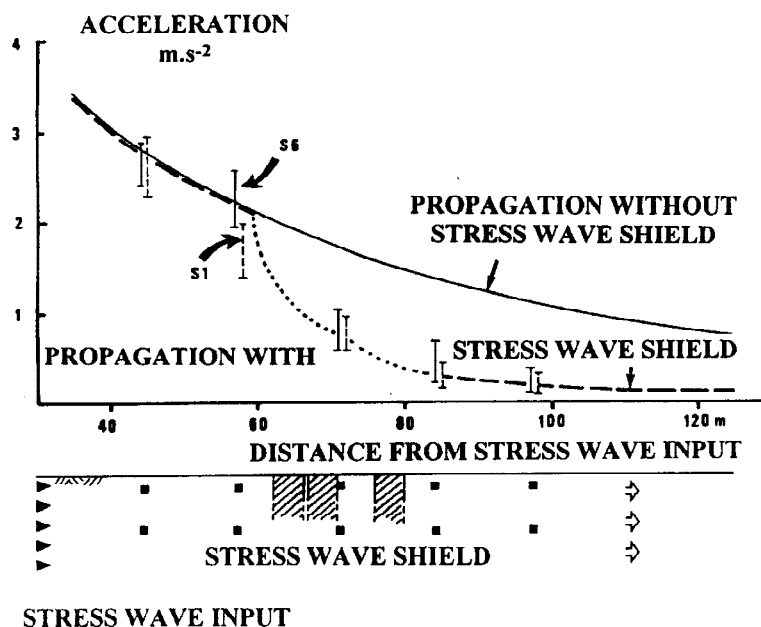


Fig. 6. Efficiency of the proposed dissipating wave barrier when using sequenced explosions in the CESTA' earthquake simulator.

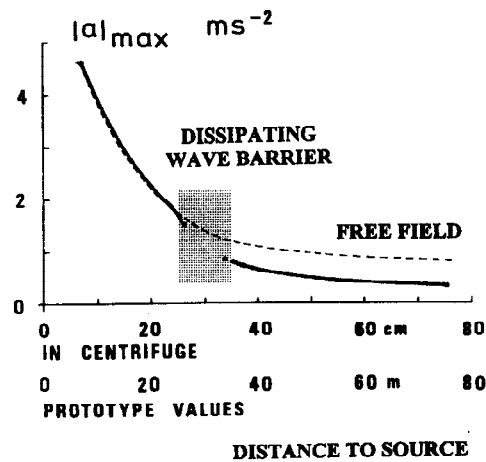


Fig. 7. Effectiveness of the proposed dissipating wave barrier when using the drop-ball arrangement.

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. In order to remove reflected waves, acceleration peaks in the complex cepstrum are suppressed by a weighting window. The inverse cepstral transform gave original signals without any reflected waves (Semblat, 1995).

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. Several successive tests on the same device have been performed with the earthquake simulator using sequenced explosions in centrifuge (Fig. 6) and with the drop-ball arrangement (Fig. 7). These centrifuge tests demonstrated that it remains effective after several loading events. However it is possible, if necessary, to adjust the preloading of the seismic shield by means of pulling on the tie rods.

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. This protective device acts as a geotechnical fuse for shielding against ground borne stress waves.

The proposed device is particularly interesting since the large forces, necessary to bring the soil mass in the supercharacteristic state, close to peak deviator stress, are readily supplied by the ground itself thanks to high capacity anchoring systems.

REFERENCES

- Aboudi, J. (1973). Elastic waves in half-space with thin barrier. *J. Engng Mech., ASCE*, 99-1, 69-83.
 Ahmad, S. & T.M. Al-Hussaini (1991). Simplified design for vibration screening by open and filled trenches. *J. Geot. Engng, ASCE*, 117-1, 67-88.

- Barkan, D.D. (1962). *Dynamics of basis and foundations*. Mc Graw Hill, New York.
- Bolton, M.D. & J.M.R.Wilson (1989). An experimental and theoretical comparison between static and dynamic torsional soil tests. *Géotechnique*, 39-4, 585-599.
- Bowden, F.P. & D.Tabor (1959). *Friction and lubrication*. Dunod, Paris.
- Campanella, R.G. (1994). Field methods for dynamic geotechnical testing: an overview of capabilities and needs. *Dynamic Geotechnical Testing II*, Ebelhar, Drnevich & Kutter ed., ASTM STP 1213, 3-23.
- Devaure, B. (1980). *Contribution à l'étude et à la mise au point d'un système de simulation d'ondes sismiques*. Mémoire de Diplôme d'Ingénieur CNAM, CRA de Bordeaux, France.
- Dolling, H.J. (1966). Efficiency of trenches in isolating structures against vibrations. *Symp. Vibration in Civil Engineering*. Butterworths, 273-276.
- Hardin, B.O. (1978). The nature of stress-strain behavior of soils. *Conf. Earthquake Engng and Soil Dynamics, ASCE, Pasadena, I*, 3-90.
- Hardin, B.O. and V.P.Drnevich (1972). Shear modulus and damping in soils: measurement and parameter effects. *J. Soil Mechanics and Foundations, ASCE*, 98-SM6, 603-624.
- Haupt, W.A. (1977). Isolation of vibration by concrete core walls. *9th ICSMFE, Tokyo*, 2, 251-256.
- Iwasaki, T., F.Tatsuoka & T.Yoshikazu (1978). Shear moduli of sands under cyclic torsional shear loading. *Soils and Foundations*, 18-1, 39-56.
- Kratochvil, J. & O.W.Dillon (1969). Thermodynamics of elastic-plastic materials as a theory with internal state variables. *J. Appl. Phys.*, 40, 3207-3218.
- Lade, P.V., R.B.Nelson & Y.M.Ito (1987). Nonassociated flow and stability of granular materials. *J. Engng Mech., ASCE*, 113-9, 1302-1318.
- Lade, P.V., R.B.Nelson & Y.M.Ito (1988). Instability of granular materials with nonassociated flow. *J. Engng Mech., ASCE*, 114-12, 2173-2191.
- Liao, S. & D.A.Sangrey (1978). Use of piles as isolation barriers. *J. Geot. Engng, ASCE*, 104-9, 1139-1152.
- Luong, M.P. (1980). Stress-strain aspects of cohesionless soils under cyclic and transient loading. *Int. Symp. on Soil under Cyclic and Transient Loading, Balkema, Rotterdam*, 315-324.
- Luong, M.P. (1986). Characteristic threshold and infrared vibrothermography of sand. *Geot. Testing J., GTJODJ*, 9-2, 80-86.
- Luong, M.P. (1992). Centrifuge testing. *Earthquake Engineering, AFPS, OEPA, VI(6)*: 781-794.
- Luong, M.P. (1994a). Evaluation of soil dissipative behaviour. *Performance of ground and soil structures during earthquakes, 13th ICSMFE TC4, New Delhi*, 109-118.
- Luong, M.P. (1994b). Centrifuge simulation of Rayleigh waves in soils using a drop-ball arrangement. *Dynamic Geotechnical Testing II*, Ebelhar, Drnevich & Kutter ed., ASTM STP 1213, 385-399.
- Mindlin, R.D. & H.Deresiewicz (1953). Elastic spheres in contact under oblique forces, *J. Appl. Mech.*, 327-344.
- Mandel, J. 1964. Conditions de stabilité et postulat de Drucker. *IUTAM Symp. Rheology and Soil Mechanics, Grenoble*, 58-68.
- Okada, N. & S.Nemat-Nasser (1994). Energy dissipation in inelastic flow of saturated cohesionless granular media. *Géotechnique*, 44-1, 1-19.
- Ray, R.P. & R.D.Woods (1988). Modulus and damping due to uniform and variable cyclic loading. *J. Geot. Engng, ASCE*, 114-8, 861-876.
- Scott, R.F. (1994). Review of progress in dynamic geotechnical centrifuge research. *Dynamic Geotechnical Testing II*, Ebelhar, Drnevich & Kutter ed., ASTM STP 1213, 305-329.
- Semblat, J.F. (1995). Soils under dynamic and transient loadings: dynamic response on SHPB, wave propagation in centrifuge medium (in french). *Rapport Etudes et Recherches des LCPC, Paris, France*.
- Stewart, W.P. & R.G.Campanella (1991). In situ measurement of damping of soils. *2nd Int. Conf. Recent Advances Geotech. Earthquake Engng and Soil dynamics, St Louis, MO, USA, Paper N°1.33*, 83-92.
- Woods, R.D. (1968). Screening of surface waves in soils. *J. Soil Mechanics and Foundations, ASCE*, 94-SM4, 951-979.
- Woods, R.D. (1994). Laboratory measurement of dynamic soil properties. *Dynamic Geotechnical Testing II*, Ebelhar, Drnevich & Kutter ed., ASTM STP 1213, 165-190.
- Yamashita, S. & S.Toki (1994). Effects of anisotropy on modulus and damping ratio of sand. *Performance of Ground and Soil Structures during Earthquakes, 13th ISSMFE TC4, New Delhi*, 125-130.