Solid-liquid behaviour of vertically vibrated sand

Comportement solide-liquide d'un sable vibré verticalement

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ABSTRACT
The present paper concentrates on strength degradation of cohesionless granular soils under large cyclic strains. Some experiments on the behaviour of sand when subjected to vertical vibration are characterized. The volume change with time and the influence of acceleration of vibration on the behaviour of sand are displayed. Based on the conceptual work of Barkan (1962), sphere penetration experiments (SPE) are performed.

RÉSUMÉ
Cet article se concentre sur la dégradation de la résistance des sols granulaires pulvérulents sous déformations cycliques de grande amplitude. Nous présentons les résultats d'expériences sur le comportement d'un sable vibré verticalement. La variation de l'indice des vides en fonction du temps et l'influence de l'accélération des vibrations sur le comportement du sable sont décrites. Inspirées des premiers travaux de Barkan (1962), des expériences de pénétration à la sphère sont également réalisées.

Keywords : vibrodriving, vibrocompaction, sphere penetration experiments

1 INTRODUCTION

Vibrodriving is a technique for driving profiles as piles, tubes or sheet-piles swiftly into the soil by transmitting to the driving unit a longitudinal vibrating motion of predetermined frequency and displacement amplitude. The vibrations result in a reduction of the ground resistance, allowing penetration under the action of a relatively small surcharge force (Rodger and Littlejohn, 1980). Historically, it seems that the vibratory driving technique appeared simultaneously in the 30's in Germany and in the former URSS. Pavyluk, who studied the effect of vibrations maintained on soil, introduced in 1931 the concept of driving profiles using vibrations. This work was later reported by Barkan (1962), who studied the effects of vibrations on the mechanical properties of soil, showing that the vertical vibration of a pile remarkably decreases the skin friction of surrounding soil. Figure 1 illustrates the vibrodriving of a pile. Four major actors play a role in the mechanics of the vibratory driving process: the pile to be driven, the selected vibrator, the power generator, and the imposed soil conditions. In practice, the two parameters used to define the range of application of the method are the displacement amplitude and the angular frequency of the vibrator.

Vibrocompaction of granular soils was introduced in Germany in the 30's. Applied to granular media, it is more efficient than static compaction. The purpose of this dynamic compaction is generally improving deformation properties and shear strength of the soil. The result of the compaction is commonly related to soil density. Although research has been conducted on compaction, the physical mechanisms at work during vibrocompaction of sand are poorly understood and the description of the grains behaviour remains incomplete.

The present paper concentrates on strength degradation of cohesionless granular soils under large cyclic strains. It notably describes experiments on vertically shaken dry cohesionless sand. It displays the evolution of porosity during shaking, recirculation of particles and the results of sphere penetration experiments based on the conceptual work of Barkan (1962).

2 CONCEPTUAL MODEL OF BARKAN (1962)

A major part of a pile or profile driving resistance usually comes from soil skin friction, which can be considered as the sum of "dry" friction and "viscous" friction depending on velocity. Barkan (1962) showed that internal friction resistance tends to vanish and that a granular soil starts behaving like a viscous fluid when subjected to intense vibrations. This soil property may be expressed in terms of the coefficient of "vibro-viscosity". This later may be determined with the help of the penetrating sphere method considering the well-known Stokes law. If the steady driving force acting on the sphere only comes from gravity, Stokes law can be applied to the sphere penetrating at a constant rate into vibrated sand, considered as a viscous medium:

$$\mu.V = \frac{2}{9} r^2 \left(\gamma_1 - \gamma_2\right) \tag{1}$$

where μ (Pa.sec) is the "liquid" medium viscosity, V ($m.sec^{-1}$) is the steady sinking velocity, γ_1 ($N.m^{-3}$) is the sphere unit weight and γ_2 ($N.m^{-3}$) is the "liquid" unit weight.

Barkan designed the sphere penetration experiment (SPE) to investigate this phenomenon and establish the coefficient of vibro-viscosity (figure 2). He recorded the sinking velocity of a metallic sphere into a vertically vibrated container filled with sand to the height of 30 to 35 cm. The container, 30 by 30 cm in cross section, 40 cm height, was placed on a vibratory platform enforcing the vertical vibrations. Various "bias" loads could be applied to the sphere by means of a loading system. The penetration of the sphere was recorded with the help of a recorder and counterweights. The sand used was white quartz sand with a grain size ranging between 0.2 and 0.5 mm. The moisture content of this later was close to zero. Before performing a sphere penetration experiment, the sand was vibrated until his minimum void ratio, approximately 0.5 (-), was reached, leading to a volumetric mass of soil about 1770 kg/m³.

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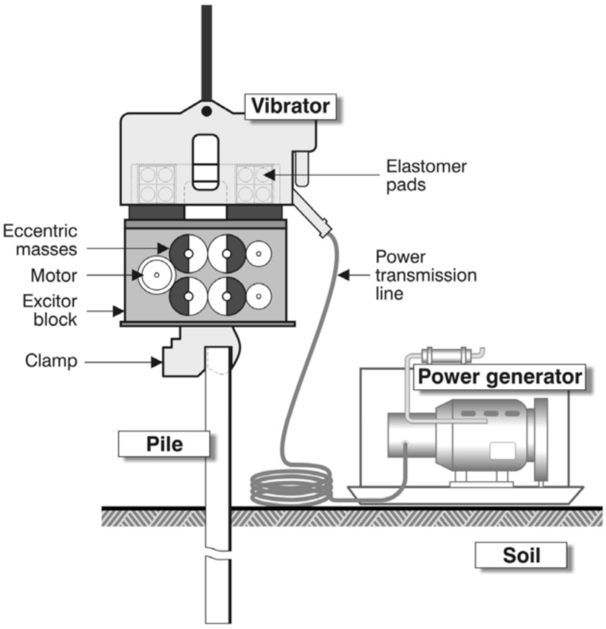

Figure 1. Vibratory Driving of a pile (after Holeyman, 2002).

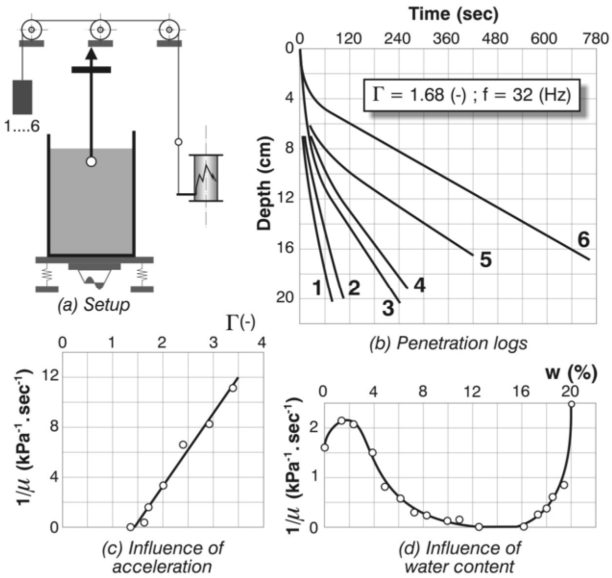

Figure 2. Sphere penetration experiments (after Barkan, 1962).

From the sphere penetration experiments results (figure 2), the sinking velocity of the sphere seemed to obey Stokes law allowing the determination of the coefficient of vibro-viscosity, μ. The inverse of this later was shown to vary linearly with the relative level of acceleration :

$$\frac{1}{\mu} = b(\Gamma - \Gamma_0) \quad (2)$$

where b ($Pa^{-1}.sec^{-1}$) is an empirical parameter and $\Gamma=a/g$ (-) is the non dimensional acceleration where a ($m.sec^{-2}$) is the acceleration amplitude and g ($m.sec^{-2}$) is the gravity acceleration. Γ_0 (-) is approximately 1.5. Upon exceeding this threshold value, there is a significant increase of 1/μ and Barkan considered that soil enters in a vibro-fluidized state and behaves like a viscous liquid.

A number of critical observations can be formulated regarding the early results of Barkan (1962). According to our own experiments discussed in the following sections, the shape of the penetrating logs (Stokes law for all Barkan's results) could depend on the one hand, on the vibration rate applied to the sand (coupled influence of the displacement amplitude and frequency) and on the other hand, on the initial void ratio of the granular medium in the container before beginning the sphere penetration experiment.

Beyond the threshold value, Γ_0, there is no information about potential sphere refusal conditions, as Stokes' law does not entail such limitation.

There is a lack of indication about the vibrated sand behaviour. Barkan (1962) did not describe the movement of the soil particles. Is the sand submitted to general convective motion or is there just a downward segregation movement of the sphere in the vibrated sand which is in settlement?

For the purposes of investigating these questions, a new SPE apparatus was designed at UCL.

3 NEW SPE APPARATUS

Figure 3 presents the SPE apparatus designed and constructed at UCL. In the lower part, a cylindrical transparent polycarbonate container (52 cm height and 40 cm diameter) is vertically actuated by a servo-controlled MTS hydraulic jack. The movement imposed to the container is sinusoidal. Samples of 65 kg of Fontainebleau sand are prepared dry by pouring, resulting in a volumetric mass close to 1470 kg/m³ or initial void ratio, e_{init}=0.8 (-). In the upper part, the sphere penetrometer is only free to move vertically. The penetration of the sphere was recorded with the help of a 500 mm course inductive HBM standard displacement transducer. The sphere diameter is 28.58 mm. The total mass of the sphere penetrometer is 1.77 kg.

The Fontainebleau sand is a fine quartz sand with uniform grain size (uniformity coefficient of Hazen, c_u=1.6 and d_{50}=0.19 mm). The grain-size distribution ranges from 0.1 to 0.4 mm. The grain shape can be characterized as subangular. The volumetric mass of the sand is 2642 kg/m³. The minimum volumetric mass of dry sand, reached with loose bulk density test, is γ_{min}= 1406 kg/m³, e_{max}=0.88 (-) and the maximum volumetric mass of dry sand, reached with Kolbuszewski method (Kolbuszewski, 1948), is γ_{max}=1702 kg/m³, e_{min}=0.55 (-). The critical state angle of shearing, Φ_{crit}, is expected close to 30°.

4 VERTICALLY VIBRATED SAND BEHAVIOUR

Because of its granular nature, soil behaviour is difficult to categorize. It is a geometrically complex assemblage of grains of various sizes and shapes resulting in a particular granulometry and a presence of voids defining its porous character. When dense dry cohesionless soil is subjected to shearing in deviatoric conditions, its volume tends to expand (Reynolds, 1885). Conversely, if loose dry cohesionless soil is subjected to cyclic loading, its granular skeleton tends to shrink.

When cohesionless soil is vertically vibrated under gravitational field, several phenomena occur. The following paragraphs describe the void ratio variation with the time during vertical vibrations and the influence of the vibration rate on the resulting dry density and on the sand behaviour.

4.1 *Volume change with time*

Ermolaev and Senin (1968) have suggested a relationship between void ratio and time for vertical vibrations :

$$e(t) = e_\Gamma + (e_{init} - e_\Gamma)\exp(-\beta_t t) \quad (3)$$

where e (-) is the void ratio, e_{init} (-) is the initial void ratio resulting from dry pouring, t is the time (min), e_Γ (-) is the minimum void ratio which can be reached with the imposed

Figure 3. UCL Sphere Penetration Experiment (SPE) apparatus.

acceleration amplitude, Γ (-), β_t (min^{-1}) is a coefficient depending on the nature of the soil and acceleration amplitude. Barkan (1962) has suggested the following equation for e_Γ :

$$e_\Gamma = e_{min} + (e_{init} - e_{min})\exp(-\alpha\Gamma) \tag{4}$$

where α (-) is the index of vibratory compaction only depending on the nature of the soil.

Figure 4 presents the void ratio-time curve during vertical shaking for one experiment with the UCL-SPE apparatus. The inset of the figure is the semi-logarithmic representation of that curve. The acceleration amplitude and frequency were respectively set to Γ=1 (-) and f = 13 (Hz). Initially, the void ratio quickly decreases. Then the volume change is slowing and the void ratio leads towards an asymptotic value, e_Γ=0.62 (-), depending on the acceleration amplitude of the vibrations, Γ=1 (-). The estimated void ratios are computed using equations (3) and (4) with β_t=2.5 (min^{-1}), α=1.3 (-). These values are within the range reported by Kolmayer (1970).

4.2 *Dry density after vibration*

When non cohesive soil is vertically vibrated under gravitational field, Mogami and Kubo (1953) and Barkan (1962) assert that the volume change depends mainly on the acceleration of the vibrations.

D'Appolonia D. J. and D'Appolonia E. (1967) have conducted laboratory tests where an open container of air-dry dune sand is placed upon a shaking table and subjected to vertical vibration. Figure 5 illustrates the relationship between sand density after vibrations and acceleration for these experiments. If the peak acceleration is less than 1g, one can surmise a moderate densification of the sample. When the acceleration is greater than 1g, the sand cannot fully follow the downward motion of the container and goes into free-fall. When the sand reaches the bottom of the container, there is an impact and a propagation of stresses within the granular medium in the form of force chains. For peak accelerations between 1g and about 2.5g, this free-fall-impact condition is repeated each cycle. This pattern results in efficient densification. Beyond that range of peak accelerations, there is a dedensification of the sample. Unfortunately, D'Appolonia D. J. and D'Appolonia E. (1967) do not describe the motion of the sand particles within this acceleration range. The frequency of the vertical vibrations seems to have no influence on the dry density results, as illustrated on figure 5.

4.3 *Sand behaviour during vibration*

The influence of acceleration amplitude was explored with the UCL-SPE apparatus and vertically vibrated sand behaviour was observed during shaking. These experiments lead to the following preliminary observations.

If the peak acceleration is less than 1g, there is a densification of the sample. The efficiency of this densification depends on the initial void ratio of the sample. The equations (3) and (4) appear to be solely valid within this densification range.

When acceleration amplitude reaches 1g, several phenomena come into competition. The first phenomenon, described by D'Appolonia D. J. and D'Appolonia E. (1967), is the free-fall-impact condition which could result in efficient densification. But simultaneously, there is an instability in the sand heap characterized firstly by the emergence of an inclined free surface, secondly by a continuous flow of particles rolling down the inclined surface and thirdly by convective transport inside the vibrated sample which recirculates sand grains at the top of the heap as observed by Evesque and Rajchenbach (1989).

If the acceleration amplitude is still increased, the inclined surface is dislocated. The whole granular medium convects in response to vertical vibrations. There is an upward granular flow in the center of the container and a downward granular flow in a thin layer along the sides. This phenomenon is called convection and is due to the inelastic frictional interactions between the grains and the walls of the container. Additionally, there is a new state of the free surface with the development of particular geometrical shapes intermittently accompanied by grain projections.

5 SPHERE PENETRATION EXPERIMENTS

5.1 *Field of application of the SPE's*

It is necessary to define the field of application of sphere penetration experiments. As a first approach, sphere penetration experiments will be performed in vibrated sand sample presenting a horizontal surface, hence, within the densification and convection ranges described in Section 4.3.

5.2 *SPE's procedure*

In Barkan's experiments, the sand seems to be prepared for all experiments following the same procedure. It is always vibrated with optimum acceleration allowing minimum void ratio, e_{min}=0.5 (-). The UCL procedure is different in that regard, depending on the vibration range.

For the UCL-SPE's conducted within the densification range, the sand is initially vibrated until the equilibrium (steady-state) void ratio, e_Γ, corresponding to the chosen acceleration amplitude, Γ, is reached. Then, vibrations are stopped and the sphere is lowered onto the sample resulting in a quasi-static penetration. Once the static equilibrium is reached, vibration of the container is resumed and dynamic penetration is recorded.

For the UCL-SPE's performed within the convection range, the sample is vibrated until the continuous convection state is reached. Then the sphere is lowered onto the vibrated surface of the sample and its dynamic penetration recorded.

5.3 *Results of the SPE's*

Figure 6 presents sinking logs for two vibrations, with respectively, 1.5 mm displacement amplitude, f = 5 (Hz) and e_Γ=0.69 (-) within the densification range and 1.5 mm

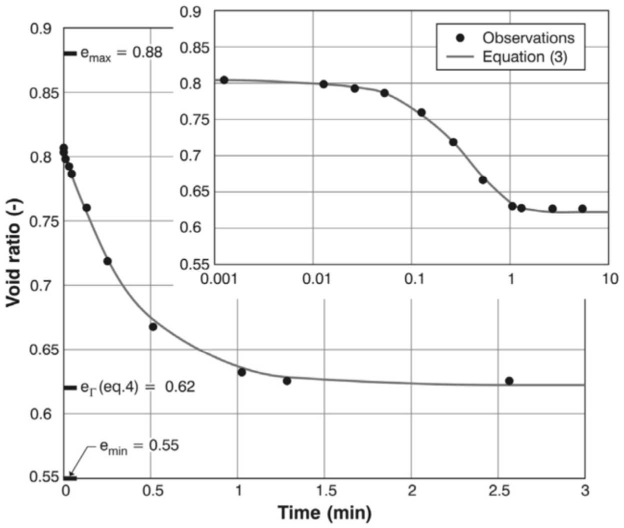

Figure 4. Void ratio-time curve.

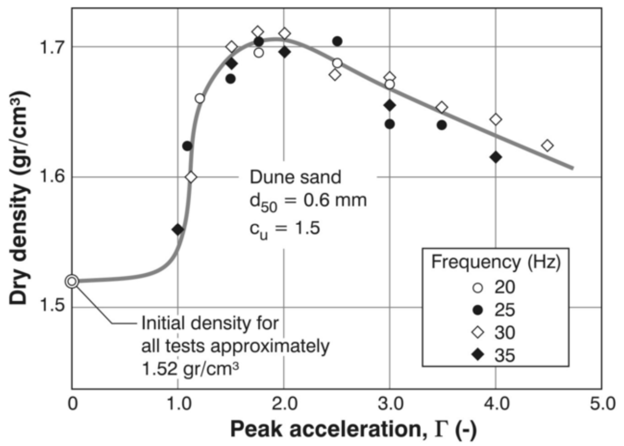

Figure 5. Dry density of dune sand vs. acceleration amplitude (D'Appolonia D. J. and D'Appolonia E., 1967).

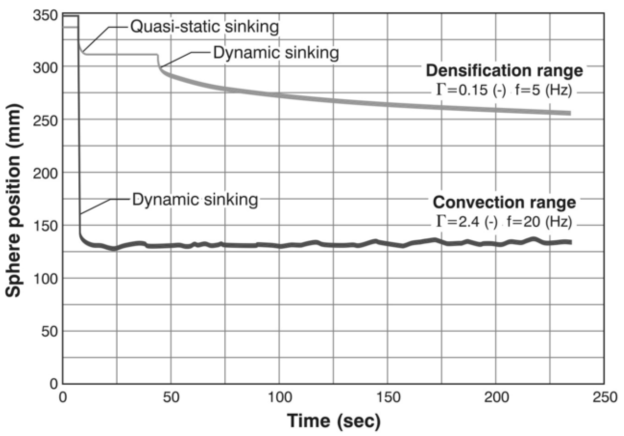

Figure 6. Sphere penetration logs.

displacement amplitude and f = 20 (Hz) within the convection range. Sphere position is defined as the vertical distance between the lower part of the sphere and the bottom of the container.

At low acceleration amplitude, the viscous properties of the soil are smaller than its elasto-plastic character. The sinking log seems to follow an exponentially decreasing profile and the rate of penetration depends on the vibration parameters and on the initial void ratio of the sample. The motion of the sphere is sinusoidal and presents a frequency of 5 (Hz) and a displacement amplitude about 1.5 (mm) close to the imposed motion of the container with a residual sinking component.

At high acceleration amplitude, after a short transient sinking phase resulting from its initial position (lowered onto the highly tumultuous free surface), the sphere reaches an equilibrium height. The fluctuations, around this equilibrium position, are due to the variation of the collisions and dry frictions with the upward convection flow of surrounding particles. Hence, it seems that, at the equilibrium height, there is vertical force, due to the convection, which balances with the weight of the sphere and this height of equilibrium does not depend on the initial void ratio of the sample.

6 CONCLUSIONS AND PERSPECTIVES

This study concerns experiments on vertically shaken dry cohesionless soils. Three types of behaviour of the vertically vibrated sand are identified, depending on the acceleration amplitude : the densification behaviour, the surface instability behaviour, and the convection behaviour. The volume change with time can be approximated by an exponential relationship in the densification range. Additional investigations are required to define more precisely the boundaries between the behaviour types.

Concerning the SPE results, two kinds of sinking curves are displayed. An exponentially decreasing profile is observed in the densification range whereas in the convection range, the sphere quickly sinks in the vibrated medium and finds an equilibrium penetration. The weight of the sphere penetrometer is balanced by a "buoyant" force augmented by the flow of surrounding sand grains. Additional experiments will further characterize the influence of vibration parameters on sinking log in the densification and convection ranges.

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