Vibratory driving and segregation in granular matter

Denies, N. & Holeyman, A.
Université catholique de Louvain-la-Neuve

Keywords: vibrodriving, granular matter, discrete element method

ABSTRACT: Vibrodriving is used more and more to insert piles or sheet-piles into the soil. However the required acceleration and frequency to enforce penetration still remain difficult to estimate. It is not always necessary to operate the hydraulic group at the maximum energy consumption to obtain the maximum penetration velocity. In the present study, a case history of vibratory driven pile is first analysed. Then, the discrete element method (DEM) is applied to establish a link between the processes of vibratory driving and segregation in granular matter by analysing the sinking of a disk in a vibrated granular medium. Numerical simulations were conducted to investigate the "vibro-viscous" character of the sand and the response mechanisms of the granular medium when subjected to a vertical dynamic excitation. The influences of density ratio and object size ratio are firstly analyzed. Then, the coupled influence of acceleration and frequency imposed at the medium boundaries on the sinking velocity is studied for disks of different densities. These simulations are compared to Barkan's (1963) initial work on vibrodriving. Finally, an analogy between vibrodriving and segregation phenomena is established.

1 INTRODUCTION

Many researchers are still looking for a deeper understanding of the soil response to earthquakes with a view to protect structures and human lives. But others have succeeded in harnessing soil degradation as a result of cyclic straining. Pavyluk (URSS), 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 (1963). Vibrodriving is a technique that uses vibrations to insert a profile into the soil. This process is faster than impact driving and consumes less energy, in particular in soils such as dry or saturated sands. Fig. 1 illustrates the vibrodriving of a steel pile. Three major actors play a role in the mechanics of the vibratory driving process: the pile to be driven, the selected vibrator, and the imposed soil conditions (Holeyman 2002). If great progress has been made in the use of this process, the driving velocity of the profile in the soil and its long-term bearing capacity still remain difficult to estimate. It is really difficult to understand the behaviour of the soil under large cyclic strains. Once the soil along the profile is vibrated with sufficient energy, the soil structure degrades and the use of continuum modelling becomes less suited. One cannot neglect the fact that soil is a granular medium. As a consequence, it exhibits a non linear behaviour and requires a multiscale computational framework. The present paper is based on a discrete analysis of the soil behaviour. It considers the problem at microscopic-scale of contact, at grain-scale and at flow-scale. Indeed, sheared sand presents flow characteristics that can be approached by a rheological study. If the sand exhibits fluidity, it could be of interest to consider its potential viscous character and to characterize the coupled influence of acceleration and frequency upon this fluidified behaviour.

2 A HISTORY CASE OF VIBRODRIVING

Within the framework of a European research project (BBRI 1994) and a national research project (BBRI 1995–1997), the Belgian Building Research Institute investigated the vibratory driving technique for installing steel (sheet) piles. Analytical models were developed in order to predict the penetration velocity of profiles in the soil. The purpose of the research project was notably to establish comparisons between predicted and observed installation times for piles on different sites. Most of the results confirmed the validity of the HIPERVIB1 simplified model based on the work of Holeyman (1993a and 1993b) but in other cases, differences were observed. The case history chosen herein is the vibratory driving of a steel pile at a site located in Kortrijk (Belgium). As reported by Holeyman et al. (1996), it was a 20.6 m

Figure 1. Steel pile driven with vibrator in Belleville (F) (http://www.leductp.com/).

long tubular steel pile with a diameter of 1 m and a thickness of 9.5 mm. Fig. 2 presents the characteristics of the site and the pile driving. The refusal was estimated by the aforementioned model to a depth of 18.2 m but was actually obtained at a depth of about 11 m. The instrumented pile was installed with a PTC 30HFV vibratory hammer (static moment, me, of 26 kg.m) with a frequency of 37 Hz leading to vibration amplitude at the pile top (0.65 mm) which was found to be lower than the nominal vibration amplitude (2.3 mm). Weakness of the power pack was identified by Holeyman et al. (1996) as the most probable explanation for the small observed amplitude. Finally to reach a depth of 18 m, the PTC 30HFV was replaced by a PTC 110HD (me = 105 kg·m) vibratory hammer. With that second vibrator, the frequency was decreased and the pile displacement amplitude increased with a view to obtain an optimum elasto-plastic penetration. As a result, one did observe a real increase of the penetration velocity (Fig. 2). It should be noted that in that case the available power was significantly increased with the second vibratory hammer. Recent in situ tests by the BBRI tend to display that an optimal adjustment of the frequency can lead to a decrease of the power consumption (Whenham et al. 2006). It is one example among others of the misuse of operational parameters of a vibratory hammer. The maximum penetration velocity does not always correspond to the maximum value of the frequency. The control of the energy consumption of the hydraulic group requires a better understanding of the response of the soil to the frequency-displacement parameters imposed to the pile. How does the granular medium react to dynamic loading? To answer this question, the present study attempts to draw a parallel between the processes of vibratory driving and segregation in granular matter by analysing the sinking of a disk in a vibrated granular medium.

3 EXPERIMENTAL PROTOTYPE

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 velocity dependant viscous friction. Barkan (1963) showed that internal friction resistance tends to vanish and that a granular soil starts behaving like a viscous fluid when subjected to intense vibrations.

He designed the sphere penetration experiment (SPE) to analyse these phenomena (Fig. 3). Barkan recorded the sinking velocity of a dense sphere in a vertically vibrated container (1) of sand with a square base of 30 cm×30 cm and with a height of 40 cm.

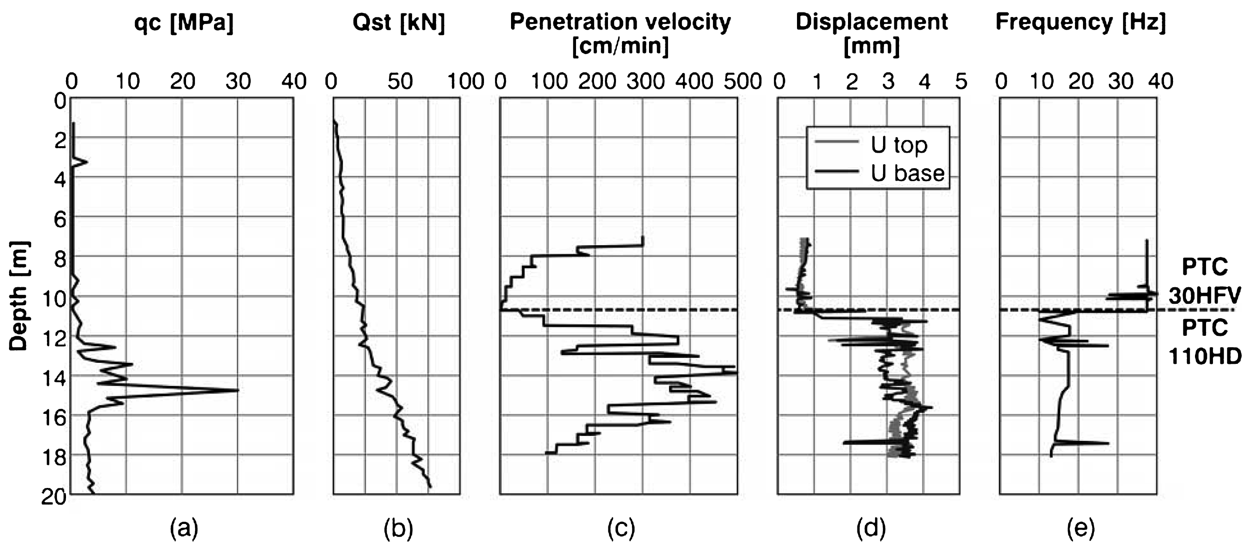

Figure 2. Subsoil profile and pile driving at Kortrijk site (B) (BBRI 1995-1997 and Holeyman 1996) : (a) CPT cone resistance, (b) CPT friction resistance, (c) penetration log, (d) profile vibration level, (e) vibration frequency.

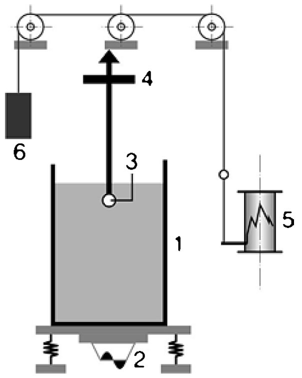

Figure 3. Experimental prototype of Barkan (1963).

Fig. 3 also presents the vibrating plate (2), the sphere (3), the loading system (4), the recorder (depth versus time) (5) and the counterweight (6) which allowed him to apply various ‘‘bias’’ loads on the sphere. The sand used was white quartz sand with a granulometry of 0.2–0.5 [mm] placed in the container at an initial void ratio of 0.5. The intended harmonic movement actuating the container was characterised by an acceleration ranging from 0.34 g to 3.4 g [m·sec^{-2}] where g is the earth gravity acceleration and by a constant frequency of 31.7 [Hz].

4 SOLID PHASE MODELLING

In the present analysis, soil is considered exclusively as a granular medium while the soil particles are individually modelled as discrete elements or ‘‘DEM’’ (Cundall and Strack 1979). The particles are considered like distinct rigid bodies. In the present case, all particles are circular. The present model is the PFC2D model (Itasca 2004). It consists in a two-dimensional representation of circular particles. One might consider that the program simulates a collection of variable-radius cylinders with a unit thickness. Two force components and one moment component are considered for each disk within this model. The method successively uses laws of motion and contact force-displacement laws. Contacts occur over a vanishingly small area. An overlap is allowed between different particles: its magnitude is function of the contact force via a force-displacement relationship. Overlaps are small in comparison with the particle size. The contact law is directly depending on grain stiffness and relative movement at the contacts.

Fig. 4 presents the linear contact model. The inter-particles force vector can be calculated such as the sum of the normal component and the shear component of contact force. A slip Coulomb model (Itasca 2004) is introduced to allow slippage to occur upon reaching a limiting shear force. It is defined by the dimensionless friction coefficient at the contact μ, where μ is the minimum friction coefficient of the particles in contact. If the shear contact force attempts to exceed $\mu|F_i^n|$ where F_i^n is the normal force component, then slip is allowed to occur.

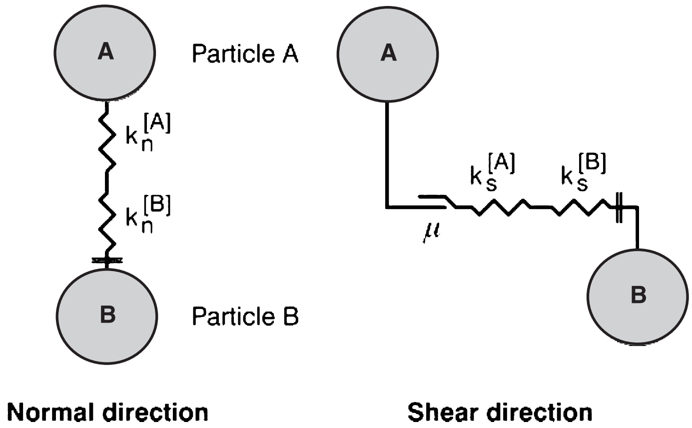

Figure 4. Normal and shear contact forces between two particles.

5 NUMERICAL MODEL

5.1 *Introduction*

The SPE is modelled in this study by its more manageable 2D counterpart. Its size is also reduced. Indeed, Barkan’s prototype contains more than 200 millions grains and cannot be solved in a reasonable time with DEM. About 1 day of calculation on Pentium (R) D CPU 3.20 GHz is required to simulate a 2000 particles problem during 5 minutes. Hereafter, the parameters associated with the prototype and the model will be identified by the indices p and m, respectively. It seems that increasing gravity allows one to conserve a lot of similarity ratios. There is only one requirement which is not fulfilled concerning the grain size. Actually, the gravity is increased by a factor N to conserve stress values in the model. Gravity amplification is widely used in centrifuge modelling practice (Taylor 1995, Zeghal and El Shamy 2004). The scaling laws developed for dynamic models imply that the frequency of the vibrating container and its acceleration are increased by a factor N while time is divided by N.

Tables 1 and 2 provide a summary of mechanical properties of the SPE and its reduced model. Barkan’s grain sizes are multiplied by a factor 5 to reduce the

Table 1. Experimental prototype parameters

BARKAN PROTOTYPE (3D)
Particles
Granulometry ϕ : fixed, 0.2 → 0.5 [mm]
Density ρ : fixed, 2641.79 [kg/m³]
Friction coefficient μ_P : not available
Number of sample particles: about 200 millions
Initial porosity: fixed, 0.33 [-] (void ratio e: 0.5 [-])
Height: fixed, 0.4 [m]
Width: fixed, 0.3[m]
Normal and shear stiffness k_n and k_s: not available
g-level: fixed, 1
Sphere
Diameter ϕ_s : fixed, 28 [mm]
Equivalent density: variable ρ_s [kg/m³]
Friction coefficient μ_s : not available
Normal and shear stiffness k_{sn} and k_{ss}: not available

Table 2. Numerical model parameters

DEM MODEL (2D)
Particles
Granulometry ϕ : fixed, 1 → 2.5 [mm]
Density ρ : fixed, 2641.79 [kg/m³]
Friction coefficient μ_P : fixed, 0.5 [-]
Number of sample particles: fixed, 2222
Initial porosity: fixed, 0.33 [-] (void ratio e: 0.5 [-])
Height: fixed, 0.1 [m]
Width: fixed, 0.075[m]
Normal and shear stiffness k_n and k_s: 10^8 [N/m]
g-level: fixed, 4
Sphere
Diameter ϕ_s : fixed, 38.4 [mm] (22 ϕ_{avgr})
Equivalent density: variable ρ_s [kg/m³]
Friction coefficient μ_s : fixed, 0.5 [-]
Normal and shear stiffness k_{sn} and k_{ss}: 10^8 [N/m]

number of particles. The object size ratio, r_d, defined here as the ratio of the large disk diameter to the average grain diameter, is 22 for the numerical 2D model against 80 for Barkan's 3D prototype.

Fig. 5 shows the numerical granular model with black lines indicating the contact force intensities at a particular calculation step of the vibrating simulation.

5.2 *Creation of the reduced model*

The numerical sample is first created, in order to obtain the desired grain size distribution with a void ratio about 0.5 using an iterative procedure. That procedure consists in a combination of two methods. In the first one, the grains are created one by one, randomly in the sample, until the desired porosity is obtained. In the second one, the radii of all the particles are adjusted to reach the desired dimensions. The two methods are repeated until the porosity and the grain sizes of the model are satisfactory. Then, the large disk is created and lowered onto the sample. The sinking is continuously recorded. The quasi-static lowering of the sphere is followed until the ratio of the maximum unbalanced force over the maximum contact force is lower than 0.003. Indeed, it has been shown that the model is in equilibrium when the maximum (or average) unbalanced force is sufficiently small compared to the maximum (or average) contact force in the model for a packed assembly of particles (Itasca 2004). Once this equilibrium state has been reached, vibration of the container is started according to the prescribed velocity amplitude and frequency.

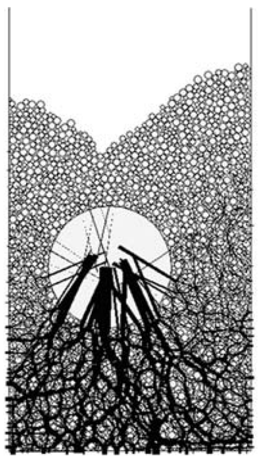

Figure 5. Reduced numerical model of Barkan's experiment.

6 VIBRATED GRANULAR MATTER AND RESULTS OF THE DEM SIMULATIONS

6.1 *Segregation in vibrated granular matter*

In granular media such as sand, particles are not similar: they differ from one another in size, density, rigidity and others physical properties. These differences often result in segregation processes (Kudrolli 2004). Within the context of vibrated systems, Brown is one of the early scientists interested by the impact of vibrations on granular assemblies (Brown 1939). He identified that the geometrical heterogeneities in a local assembly around a larger particle can result in an increase of its degrees of freedom and imply the rising of the larger piece even if its density is greater than that of the small particles. This type of behaviour was largely described (Williams 1963) and explained via geometrical models such as the void-filling model (Rosato et al. 1987) or arching models (Jullien et al. 1992). If the contact forces are eliminated, then the dense particles can sink. This mobility condition is reached once the vibro-fluidized state limit of the soil is reached. In spite of the high number of experiments and simulations performed at that limit, its definition, implying larger acceleration, is not precisely defined at this time (Hong et al. 2001, Breu et al. 2003). The behaviour of the large sphere depends on the object size ratio, r_d, on the ratio of the large sphere density to the small particles density, r_ρ, on the amplitude of vibrations, frequency, boundaries conditions, including roughness, interstitial fluid, humidity, magnetic phenomena and certainly on the particles nature (Kudrolli 2004).

6.2 *Influence of density*

6.2.1 *Single larger disk*

Shishodia and Wassgren (2001) utilized two-dimensional discrete element computer simulations to investigate the equilibrium position of an "impurity" large disk in a vibrofluidized bed of 300 homogeneous, frictionless circular disks with coefficient of restitution of 0.95.

If one considers the impact of two bodies, the coefficient of restitution can be expressed as the ratio of the relative velocity of rebound to the relative velocity of impact. This coefficient depends not only on material property but also upon the severity of impact. At low velocities, the coefficient of restitution is nearly equal to unity and the contact deformation is therefore elastic. Increasing the relative velocity of impact results in the fall of this coefficient (Johnson 1985).

In the Shishodia and Wassgren simulations, the large disk, after an initial transient phase, rose approximately linearly to an equilibrium level and fluctuated about that point. This equilibrium is a function of the oscillations of the container and the impact of the surrounding disks. They considered a model where the impurity weight was balanced by a buoyant force due to the collisions with the surrounding disks, and its stability around that equilibrium.

Fig. 6 presents our calculated sinking of disks of different relative densities as functions of time. The results of our DEM simulations have been obtained for an acceleration amplitude of 0.42 g [m·sec^{-2}] and a frequency of 7.75 [Hz]. Disk specific weight is expressed in terms of relative density, r_ρ, by comparison with the soil specific weight. It seems that the sinking of the disk follows Stokes law: after an initial transient phase the sinking velocity decreases and becomes quasi-constant. The sinking velocity increases with the disk density. If the disk relative density is lower than 1, it is observed that, after the disk has found its equilibrium state in the assemblage, there is no more sinking. The weight of the disk would be, under that condition, balanced by an equivalent buoyancy force proportional to the weight of the displaced soil volume combined with the penetration resistance of the soil.

Fig. 7 presents the relation between sinking velocity and equivalent bias load for our DEM simulations. DEM simulations tend to show that for this important size ratio ($r_d = 22$), there is no difference between applying a load on the disk and increasing its density. The equivalent bias load s has been calculated with equation (1) considering the drag force expression for immersed disks:

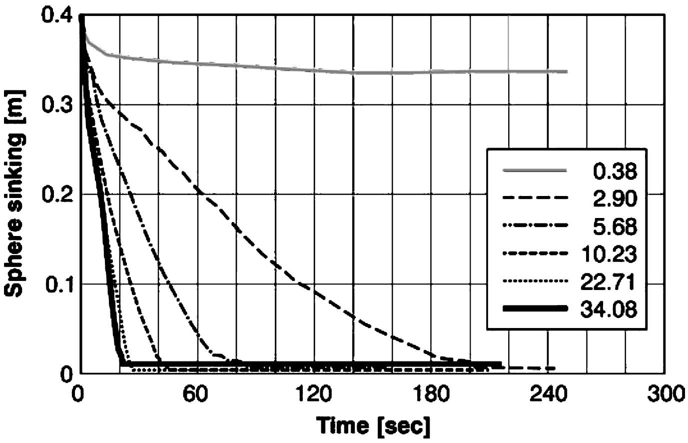

Figure 6. Sphere sinking versus time for different sphere density ratios, r_ρ [0.38–34.1], (a = 0.42 g and f = 7.75 [Hz], $r_d = 22$).

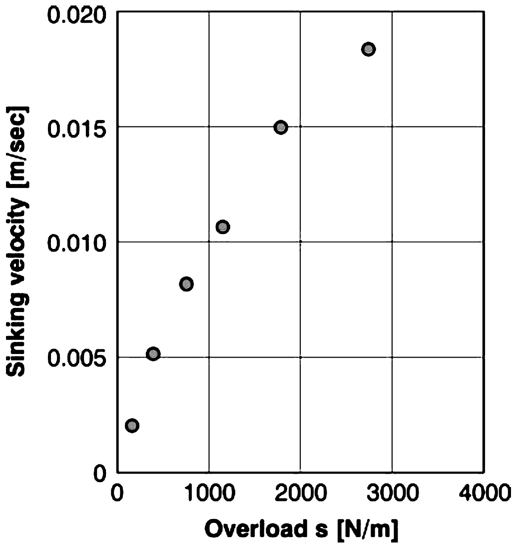

Figure 7. Sinking velocity variations versus equivalent bias load s (a = 0.42 g and f = 7.75[Hz], $r_d = 22$).

$$s = \frac{\pi}{12} r^2 g(\rho_S - \rho) = v \cdot V \qquad (1)$$

where v [Pa.sec] is the "liquid" medium viscosity, V [m·sec^{-1}] is the steady driving or penetration speed, ρ_S [kg·m^{-3}] is the sphere density, ρ [kg·m^{-3}] is the liquid density and s is the overload or "bias" load [N·m^{-1}]. The constant velocity V is assessed based on the linear portion of the sphere sinking logs. The relation is not truly linear as indicated by equation (1), but rather conforms to a power function.

6.2.2 Vibrated binary mixtures

In a vibrated binary granular medium, it is complex to determine the sinking or the rising of the large particles. There is a coupled influence of the size ratio and the density ratio of the particles.

For binary hard spheres under gravity, Hong et al. (2001) proposed a crossover condition, based on 3D molecular dynamics simulations, given by the simple relation

$$\frac{d_l}{d_s} = \left(\frac{\rho_l}{\rho_s}\right)^{-1} \qquad (2)$$

where l relates to large spheres and s to small ones. The coefficient of restitution of the hard spheres is close to unity. When the diameter ratio is smaller than the inverse of the density ratio the particle mixture should show the so-called Brazil nut effect (BNE) i.e. large spheres segregate to the top. In the contrary case, the binary mixture should show reverse Brazil nut effect (RBNE). Fig. 6 presents DEM simulated penetration logs for the different density ratios used. The criterion (2) becomes $r_d = r_\rho^{-1}$. The object size ratio is fixed, $r_d = 22 = 0.045^{-1}$. All these simulations are in agreement with the criterion (2) except the simulation with the density ratio 0.38. According to criterion (2), the large sphere should sink. Indeed, the size ratio in the DEM simulations is larger than the inverse of the density ratio, $(0.38)^{-1}$. But it is important to question the validity of this comparison. The granular medium considered in our DEM simulations has a more varied granulometry that the binary mixture considered by Hong et al. (2001). Moreover, our DEM simulations are defined to determine a sinking criterion more than a crossover condition between BNE and RBNE.

6.3 Influence of the nature of the particles

Breu et al. (2003) made observations on vertically shaken binary granular mixtures: 82% of the tested combinations of beads used in their experiments (145 out of 178) were in agreement with (2). Fig. 8 presents the results of these experiments. The prediction can fail due to the rigidity of the particle. The criterion (2) was not verified in the experiments of Breu et al. (2003) when one particle type was made of aluminium or polyurethane. The criterion (2) was proposed for hard spheres with coefficient of restitution of 0.9999 for the particles and 0.98 for the walls, values where the system did not suffer from inelastic collapse leading to cluster formation, decreasing the momentum (Hong et al. 2001).

Ohtsuki et al. (1995) conducted numerical simulations to assess the effects of particle size and density on the segregation in cohesionless granular mixtures. The particles were modelled as inelastic hard discs with a coefficient of restitution of 0.95.

In this case, the density ratio seems to be more determining probably due to the influence of the inertial effects combined with the contact force. On the other hand, it is vital to consider simultaneously the nature of the granular medium and the imposed movement of the boundaries.

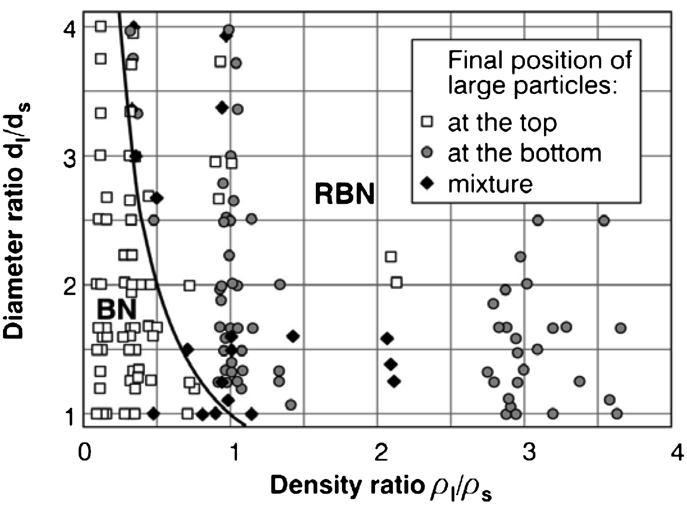

Figure 8. ''Phase space'' for particle properties. The solid line separating both areas is given by expression (2). Each symbol represents one experiment. Symbols on top of each other represent two different particle mixtures with the same diameter and density ratio, but showing different behaviors (Breu et al. 2003).

6.4 Influence of acceleration amplitude

Fig. 9 presents a comparison between Barkan's results and the results of our DEM simulations. Three different DEM simulations are presented. There are two simulations with the same initial void ratio but with different initial geometric configurations. The vibro-viscosity of soil is calculated considering an adequate sinking phase following Stokes' law (Denies and Holeyman 2007). The imposed acceleration amplitude is scaled by the gravity acceleration to obtain a non dimensional parameter, Γ. One can observe that the principal differences arise at low accelerations. In that regime, local geometries of the assembly influence on the vibro-viscosity value. Once the acceleration reaches a threshold amplitude, the vibro-viscosity reaches an asymptotic value and there is no more difference between the samples of different initial configurations. At this moment, the soil reaches its vibro-fluidized limit and behaves like a viscous liquid.

If low acceleration amplitude is applied on the granular assembly, there is no relative movement between the large and the small particles. Barkan proposed an acceleration threshold Γ of 1.5 to trigger some sinking movement of the large sphere. Beyond this value, the sinking velocity increases linearly with the acceleration. Clément et al. (1992) propose a minimum value of Γ about 1.1 considering vibrated sand-heap. In Breu et al. (2003), for acceleration larger than 3.5 g, large particles can sink. Moreover, if the density ratio increases, that facilitates a sinking behaviour, in our DEM simulations, the sinking of the large sphere is already observed for $\Gamma = 0.34$ and $f = 7.75$ Hz. Is it sufficient to consider the acceleration amplitude to characterize the movement of the large disk?

6.5 Influence of the displacement amplitude

Actually, the displacement amplitude of the vibrations must be sufficient to allow the relative movement of particles in the sample. Thus, it is necessary to consider the coupled influence of the acceleration and the frequency on the sinking of the large particle.

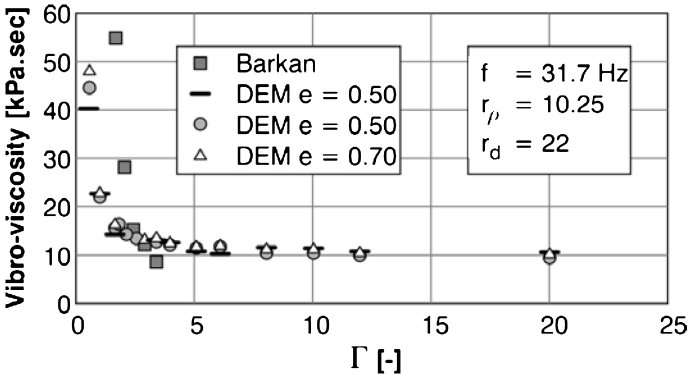

Figure 9. Comparison between Barkan's results and DEM simulations results.

Recently, Ellenberger et al (2006) proposed a study about experiments on vertically shaken binary mixtures. The experiences of Ellenberger et al concern the behaviour of one large disk in a pseudo-2D column full of polystyrene beads and close to our conditions of simulations. Fig. 10 illustrates the coupled influence of acceleration and frequency via the displacement amplitude λ (Ellenberger et al. 2006). If one considers a fixed value λ, decreasing acceleration corresponds to decreasing non linearly the frequency of the vibrations. One can observe that there is no motion below a certain level of acceleration. Then, the small beads begin to fill the voids of the assembly. There is some rearrangement in the granular structures. The principal conclusion can be drawn from the influence of the frequency: upon decreasing, the disk can transit from a rising mode to a sinking mode.

Fig. 11 presents the influence of the frequency on the vibro-viscosity coefficient in the case of our DEM simulations. If the boundaries frequency is decreased, the vibro-viscosity is decreased and thus the sinking velocity increases.

A probable explanation could be found in the fact that it is necessary to have maximum displacement amplitude to obtain a maximum impact to induce (elasto-plastic) penetration. The high amplitude displacement is necessary to obtain fluidization. It implies a progressive rearrangement of particles around the sinking large disk.

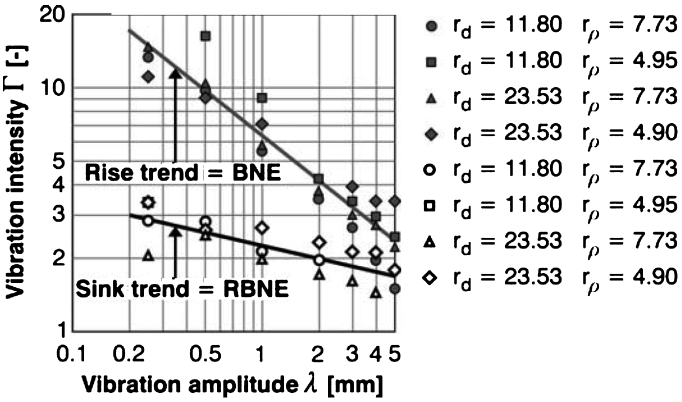

Figure 10. The minimum vibration intensity, Γ, as a function of amplitude, λ, at which an intruder rises from the bottom to the top of the granular bed (crosshaired symbols); sinks from the top to the bottom of the granular bed (open symbols). Trend lines are drawn to guide the eye (Ellenberger et al. 2006).

6.6 *Analogy between vibrodriving and segregation process*

There are obvious differences between the vibrodriving process in granular media and segregation phenomena. In the first case, the pile or sheet-pile is vibrated into the sand which is at rest. In the second one, the vibrations are applied on the granular medium and the disk or sphere is lowered onto the medium.

But in both cases, the loading parameters include the acceleration amplitude, the frequency, the weight of the large body and the "bias" load. Finally, the result concerns the sinking of an element in a vibrated granular medium.

Considering the coefficient of vibro-viscosity, *v*, it is defined to describe the difficulty to insert piles or sheet-piles into the soil using vibrations. If one compares Fig. 9 and Fig. 12, it is possible to understand the analogy between the segregation process and the vibrodriving process. Fig. 12 presents the influence of the acceleration amplitude on the soil friction forces, measured on the lateral surfaces of plate or U-shaped sheet-piles during vibro-extracting process (performed by Preobrajenskaïa and reported by Barkan 1963). Increasing acceleration excitation probably allows in both cases to decrease the effective friction applying to the sinking element and one observe in both cases the existence of a vibro-fluidized state in which the acceleration has no more

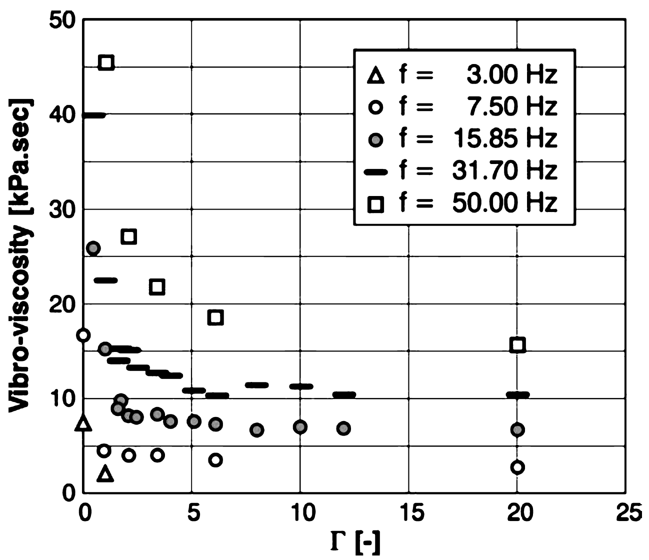

Figure 11. Influence of the frequency on the DEM vibro-viscosity coefficient for $e_{initial} = 0.5$, ($r_\rho = 10.25$ and $r_d = 22$).

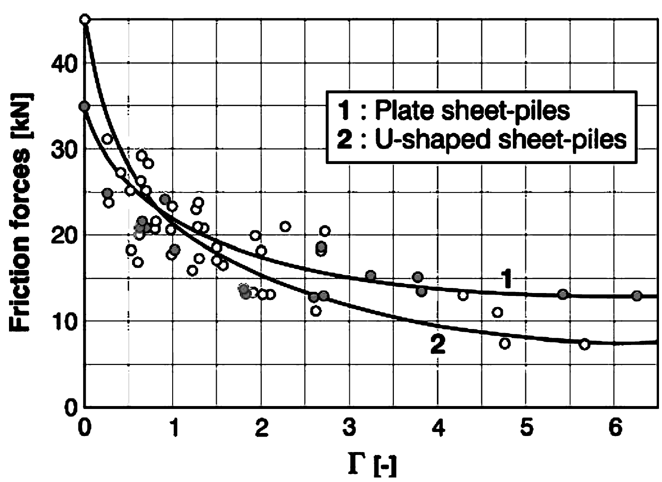

Figure 12. Influence of acceleration amplitude of the oscillations imposed by the vibratory hammer on the friction forces of the soil on lateral surface of two types of sheet-piles (after Barkan, 1963).

influence on the sinking velocity. In this way, experiments are necessary to better determine the vibro-fluidized limit and the coupled influence of acceleration amplitude and frequency considering the power consumption of the power pack.

7 CONCLUSIONS AND PERSPECTIVES

In this study, the discrete element method (DEM) is applied to establish a link between the processes of vibratory driving and segregation in granular matter by analyzing the sinking of a disk in a vibrated granular medium. A two-dimensional reduced model was used to analyze the viscous characteristic of the soil subject to a vertical dynamic excitation. The numerical model was based on Barkan's conceptual sinking sphere experiment (SPE). The 3D experiment was modelled by a 2D DEM counterpart of reduced dimensions in order to solve the problem in a reasonable time. The gravity was increased to conserve stress values in the model.

The influence of density sphere was first investigated. The calculated penetration logs are in general agreement with Stokes law while buoyancy effects could be suspected for a relative density smaller than 1. The relation between sinking velocity and bias load does not follow a linear trend but seems to be better described by a power function.

In comparison with Barkan's results, the calculated soil vibro-viscosity is of the same order of magnitude but its trend versus acceleration is not similar. If numerical results initially present a linear decrease, soil reaches a fluidized state beyond a value depending on the imposed frequency (Fig. 11) where the vibro-viscosity coefficient seems to be independent on the acceleration level. An analogy is then established with the process of vibrodriving using a comparison with the Preobrajenskaïa in situ tests.

There are a lot of studies concerning vibrated binary mixtures but there are few analyses about shaken sand of wider granulometry.

In the future, new SPE experiments will be carried out to confirm or refute the DEM numerical trend of acceleration influence and to explore more fundamentally the influence of the frequency on vibrated sand process such as vibrodriving.

ACKNOWLEDGEMENTS

This research was partially supported by the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture, (FNRS-FRIA, Belgium). This support is gratefully acknowledged. The authors wish to acknowledge Valérie Whenham's (BBRI) assistance in documenting the case history.

REFERENCES

Barkan, D.D. (1963). "Méthodes de vibration dans la construction", Dunod, Paris.

BBRI. (1994). "HIgh PERformance VIBratory pile drivers base on novel electromagnetic actuation systems and improved understanding of soil dynamics", Progress reports of the BRITE/EURAM research contract CT91-0561, 1994.

BBRI. (1995–1997). "Heibaarheid van damwanden en diepfunderingen d.m.v. intrillen – ontwerpaspecten en omgevingsaspecten, IWONL-conventie CC CI 253B/6148/CC CIB 253B/6049, IWT – conventie RD/95/05, DGTRE-conventie C.3214-01".

Breu, A. P. J., Ensner, H.-M., Kruelle, C. A., and Rehberg, I. (2003). "Reversing the Brazil-nut effect: competition between percolation and condensation". Phys. Rev. Lett. 90, 014302 (p4).

Brown, R. L. (1939). "The fundamental principles of segregation", J.Inst. Fuel 13, pp. 15–19.

Clément, E., Duran, J. and Rajchenbach, J. (1992). "Experimental Study of Heaping in a Two-dimensional "Sandpile"", Phys. Rev. Lett. 69, pp. 1189–1192.

Cundall, P.A. and Strack, O.D.L. (1979). "A Discrete Numerical Model for Granular Assemblies", Geotechnique 29, pp. 47–65.

Denies, N. and Holeyman, A. E. (2007). "Discrete Element Modelling of sinking sphere in a vibrating granular medium", 18th European Young Geotechnical Engineers Conference, June 17–20, 2007, Ancona, Italy.

Ellenberger, J., Vandu, C.O. and Krishna, R. (2006). "Vibration-induced granular segregation in a pseudo-2D column: The (reverse) Brazil nut effect", Powder Technology 164, pp. 168–173.

Holeyman, A. E. (1993a). "HIPERVIB1, An analytical model-based computer program to evaluate the penetration speed of vibratory driven sheet Piles", Research report prepared for BBRI, June, 23p.

Holeyman, A. E. (1993b). "HIPERVIBIIa, A detailed numerical model proposed for Future Computer Implementation to evaluate the penetration speed of vibratory driven sheet Piles", Research report prepared for BBRI, September, 54p.

Holeyman, A. E., Legrand, C. and Van Rompaey, D. (1996). "A method to Predict the Drivability of Vibratory Driven Piles", Proceedings: Fifth International Conference on the Application of Stress-Wave Theory to Piles, Orlando, pp. 1101–1112.

Holeyman, A. E. (2002). "Soil behavior under vibratory driving", Proceedings: International Conference on Vibratory Pile Driving and Deep Soil Compaction – Transvib 2002, Louvain-la-Neuve, pp. 3–19.

Hong, D.C., Quinn, P.V., and Luding, S. (2001). "Reverse brazil nut problem: competition between percolation and condensation". Phys. Rev. Lett. 86, 3423–6.

Itasca. (2004). "Particle Flow Code, PFC2D, release 3.1", Itasca Consulting Group, Inc, Minneapolis, Minnesota.

Johnson, K.L. (1985). "Contact mechanics", Cambridge University Press.

Jullien, R., Meakin, P., Pavlovitch, A. (1992). "Three-dimensional model for particle-size segregation by shaking". Phys. Rev. Lett. 69, pp. 640–3.

Kudrolli. (2004). "Size separation in vibrated granular matter", Reports on Progress in Physics 67, pp. 209–247.

Ohtsuki, T., Kinoshita, D., Takemoto, Y. and Hayashi, A. (1995). "Segregation by Shaking in Cohesionless Granular Mixtures: Effects of Particle Size and Density", Journal of the Physical Society of Japan, 64, N°2, pp. 430 – 434.

Rosato, A., Stranburg, K.J., Prinz, F. and Swendsen R. H. (1987) ''The fundamental principles of segregation'', J.Inst. Fuel 13, pp. 15–19.

Shishodia, N. and Wassgren, C.R. (2001). ''Particle Segregation in Vibrofluidized Beds Due to Buoyant Forces'', Phys. Rev. Lett. 87, 084302.

Taylor, R. ed. (1995). ''Geotechnical Centrifuge technology'', Chapman and hall, London.

Whenham, V., Huybrechts, N., Legrand C., Bourdhouxhe, M-P, Schmitt, A. (2006). ''Energy consumption during sheet piles vibro-driving : experimental results'', Proceedings of the International Symposium on vibratory pile driving and deep soil vibratory compaction, TRANSVIB 2006, Paris : LCPC, pp. 31–52.

Williams, J.C. (1963). ''The segregation of powders and granular materials'', Fuel Soc.J. 14, pp. 29–34.

Zeghal, M. and El Shamy, U. (2004). ''Dynamic response and liquefaction of saturated granular soils: a micro-mechanical approach'', In Triantafyllidis (ed), Cyclic Behaviour of Soils and Liquefaction Phenomena, Bochum, Germany, March 31–April 02, 2004, London: Taylor and Francis Group, pp. 589–602.