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# Shear strength degradation of vibrated dry sand

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ABSTRACT

The present paper first provides a state-of-the-art review of experimental researches characterizing the shear strength degradation of vibrated dry sand. Once subjected to vibrations, the shear strength of dry sand exponentially decreases with the acceleration amplitude of vibration to reach a particular state wherein dry sand behaves like a complex fluid: this is the vibrofluid behavior. In the present paper, fundamentals equations and criteria governing the shear strength degradation of vibrated dry sand are summarized. A revisited intrinsic Coulomb criterion, taking into account the absence of pore pressure to explain the shear strength degradation, is discussed and explained considering the existence of a corresponding "shaking" pressure. A "general" Critical State Soil Mechanics, including the effect of the acceleration, is introduced. Finally, a rapprochement with the fundamental researches of the physicists involved in the study of granular matter is proposed allowing the identification of the governing dimensionless parameters and the different dynamic regimes encountered by vibrated dry sands once subjected to shearing.

## 1. Introduction

Because of its granular nature, cohesionless soil is difficult to categorize. It is a geometrically complex assemblage of grains of various sizes and shapes resulting in a particular grain-size distribution. Also the way the particles are in contact, the orientation and the distribution of these contacts, called the fabric of the assemblage, certainly play a role in its behavior. In addition, the sand is characterized by a presence of voids defining its porous character. This pore space can possibly be filled with some liquid according to its degree of saturation.

Up to now, many researches have been dedicated to investigate the shear strength degradation of cohesionless soils in saturated condition, mainly under large cyclic strains resulting in the increase of the pore pressure (Seed and Lee [1] and [2]; Casagrande [3]; Ishihara and Li [4]; Castro [5]; Castro and Poulos [6]; Seed [7]; Dobry et al. [8]; Figueroa et al. [9]; Youd et al. [10]; Seed et al. [11]; De Alba and Ballestero [12]; Jefferies and Been [13]). As a result, the two phenomena of liquefaction flow and cyclic mobility have deeply been highlighted.

If under saturated conditions, the "fluidization" of the sand can be explained by these two phenomena (liquefaction flow and cyclic mobility), it is not clear which parameters play a role in the shear strength degradation of dry sand when it is subjected to vibrations. An interest is shown in this topic because of its importance in several industrial processes such as the vibrocompaction and vibrodriving. In spite of some research works performed in this field of geotechnical engineering, physical mechanisms in play in these processes remain poorly understood. In order to investigate this question, the authors have performed a large literature study to highlight the effects of the vibrations on the volume change and shear strength of dry sand on the basis of early experimental and numerical works.

## 2. Effects of vibrations on volume change of dry sand

In the past, Mogami and Kubo [14], Barkan [15] and [16], Selig [17], Prakash and Gupta [18], D'Appolonia and D'Appolonia [19], Greenfield and Misiaszek [20], Ermolaev and Senin [21], D'Appolonia et al. [22], Kolmayer [23] and Dobry and Whitman [24] have conducted a variety of noteworthy experiments with the aim to study the effects of vibrations on the volume change of dry granular soils. They considered the influence of the following variables on the dynamic behavior of the dry sand: the direction of the vibrations, the harmonic vibration parameters (acceleration amplitude, a [$m^2/s$], frequency, fr [Hz], and displacement amplitude, A [mm] of motion), the duration of the vibrations, the size of the container, the grain-size distribution of the sand and the static surcharge applied to the sample. Report on those results was performed in details by Denies et al. [25] whom

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*Abbreviations:* EVR, vibratory equilibrium void ratio; CVR, critical void ratio; DEM, discrete element modeling

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complete their review by the presentation of original experiments revealing that volume change arising during vibration cannot be explained without addressing related phenomena such as the motion pattern displayed by individual sand particles and vibrofluidization.

According to the previous studies, the acceleration amplitude of the vibrations is the governing motion parameter of the vibrocompaction of dry granular soils for horizontal and vertical vibrations.

For the sake of concision, in the continuation of this article, the term “acceleration amplitude” will be used as a substitute for “dimensionless acceleration amplitude”, defined as the ratio of the amplitude of the acceleration [$m^2/s$] to the gravitational acceleration ($g$). $\mathit{\Gamma}$ will symbolize that key variable, and will be indexed with $h$ for horizontal vibrations and with $v$ for vertical vibrations. Moreover, unless otherwise noted, all vibrations are considered to be sinusoidal.

### 2.1. Experimental observations for horizontal vibrations

The application of horizontal vibrations leads to the densification of dry sand.

For horizontal vibrations, Barkan [16] has early suggested a relationship describing the evolution of the void ratio of the dry sand in function of the duration of the vibrations:

$$e(t) = e_{\mathit{\Gamma}} + (e_{init} - e_{\mathit{\Gamma}})\exp(-\beta_t t) \tag{1}$$

where $e$ [-] is the void ratio, $e_{init}$ the initial void ratio resulting from dry pouring and $t$ the vibration time [min]. $\beta_t$ [$min^{-1}$] is an empirical coefficient depending on the nature of the soil and on the acceleration amplitude: it characterizes the rate of vibrocompaction. $e_{\mathit{\Gamma}}$ is the minimum void ratio that can eventually be reached under the imposed acceleration amplitude $\mathit{\Gamma}_h$. It can also be defined as the vibratory equilibrium void ratio (EVR): the stable void ratio for a sample being densified at particular acceleration amplitude, $\mathit{\Gamma}_h$.

Considering the densification of dry sand under horizontal vibrations, one can consider a sand mass lying in a stable configuration (at rest, without vibration). Nevertheless, this initial configuration already corresponds to a vibratory equilibrium void ratio (EVR). Only the application of an acceleration amplitude larger than the threshold amplitude necessary to obtain this initial configuration will allow further densification.

Barkan [15] has proposed the following equation to estimate the EVR:

$$e_{\mathit{\Gamma}} = e_{\min} + (e_{init} - e_{\min})\exp(-\alpha_t \mathit{\Gamma}_h) \tag{2}$$

where $e_{min}$ is the minimum void ratio and $\alpha_t$ [-] the index of vibratory compaction.

Subjected to horizontal vibrations, a global settlement of the dry sand is always observed in spite of the level of the acceleration amplitude, $\mathit{\Gamma}_h$. The behavior of the sand mass can therefore be assessed with the help of Eqs. (1) and (2). No particular behavior or motion patterns (size-segregation, convection, particle recirculation…) are observed during horizontal shaking.

For horizontal vibrations, no decompaction was reported by any authors in the literature (even for $\Gamma_h$ values larger than 1) which is not the case with vertical direction of vibration.

### 2.2. Experimental observations for vertical vibrations

When cohesionless soil, placed in a cylindrical container without static surcharge, was vertically vibrated under the gravitational field, experiments performed on dry Fontainebleau sand have allowed to Denies et al. [25] to distinguish three types of dynamic behaviors, depending on the acceleration amplitude, $\mathit{\Gamma}_v$:

- the densification behavior ($\mathit{\Gamma}_v < 1$),
- the instability surface behavior ($\mathit{\Gamma}_v \approx 1$), and
- the vibrofluid behavior ($\mathit{\Gamma}_v > 1$).

In the densification range, the sand monotonously densifies, according to the same relationships as obtained for horizontal vibrations (Eqs. (1) and (2)) but with smaller values of $\alpha_t$ and $\beta_t$. Optimum acceleration amplitude close to $1g$ is then observed where a minimum void ratio can be approached. When the acceleration amplitude is increased beyond $1g$, granular convection is observed and instability develops in the sand mass leading to the emergence of an inclined free surface. Finally, if the acceleration is further increased, the free surface progressively flattens. There is an impressive dilatation of the whole sample accompanied by the development of a bulge and grains saltation is noticed. The sand becomes fully vibrofluidized (Denies et al. [25]). The convection phenomenon will be later discussed in Section 6.1.

### 2.3. Effect of the normal pressure on the volume change during vibrations

It is to note that the previous results have been obtained for dry sands vibrated with a free surface condition (without static surcharge applied to the sample). There are few experimental data characterizing the influence of the normal pressure applied to the sample on its behavior during vibration. As explained in Denies et al. [25], the application of a static surcharge to the surface of the sample or the increase of the depth of the sand deposit (corresponding to the application of an overburden pressure) could have the same effect: limiting densification of the sample. Additional vibration energy would then be required to overcome the resistance to density change as a result of the reinforcement of intergranular force chains in the sample, increasing in turn internal friction forces. These friction forces are increased by both static surcharge and added weight of sand (overburden pressure). These observations are valid for vertical (Ermolaev and Senin [26], D'Appolonia and D'Appolonia [19], and Kolmayer [23]) as well as for horizontal (Youd [27]) vibrations. The vibratory equilibrium void ratio (EVR) increases with an increase of the normal pressure applied to the sample.

A formula is proposed in Kolmayer [23] to take into account the influence of the static surcharge applied to the sample on the parameters of Eq. (1) for vertical vibration experiments:

$$\beta_t = f\left(\frac{\mathit{\Gamma}_v^{\xi}}{\sigma}\right) \tag{3}$$

where $\xi$ is called the “static surcharge coefficient” by Kolmayer and $\sigma$ is the static surcharge applied to the sample. The experiments of Kolmayer [23] are described in the Section 4 of the present paper.

Ermolaev and Senin [26] illustrates the relationship between the index of vibratory compaction ($\alpha_t$), introduced in Eq. (2), and the static surcharge applied to the sample with the help of the following formula:

$$\alpha_t = \alpha_0 \exp(-K_2\sigma) \tag{4}$$

where $\alpha_O$ is the index of vibratory compaction without static surcharge (for $\sigma$=0) and $K_2$ [-] is an empirical coefficient dependent on the soil type according to the authors. Their experiments were conducted on some specimen of sandy loam, with water content close to 16.5%, subjected to vertical vibrations. Unfortunately, no precise description of their experimental set-up and procedure is available in the literature.

Finally, Youd [27] studied the influence of the static surcharge applied to the sample on the parameter $\alpha_t$ for horizontal vibration. The experiments of Youd [27] are described in the Section 5 of the present paper. On the basis of his experimental results, the following empirical relationship can be proposed:

$$\alpha_t = 0.174\exp(-0.003\sigma) \tag{5}$$

The previous relationship was established considering the experimental results of Youd [27] with a R-squared value close to 0.99 [-] and with $\sigma$ in [kPa]. The similarity between Eqs. (4) and (5), respectively for

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