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Liquefaction properties and initial structure of a loose sand

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ABSTRACT

The influence of initial sand structure on the liquefaction properties of a reference French sand is studied based on the use of two modes of reconstitution of specimens, namely dry pluviation and wet tamping. Undrained compression tests carried out in the triaxial apparatus for the same initial void ratio of specimens show well-differentiated behaviors as a function of the mode of reconstitution used. Wet tamping favors the initiation of a static liquefaction type of phenomenon (unstable behavior), whereas dry pluviation favors a dilating type of response characterized by a strain-hardening type of behavior (stable behavior). Electron microscope observations have allowed to identify two different sand structures corresponding to the two types of reconstitution methods: an aggregates and macropores type of structure is observed for specimens prepared using wet tamping method whereas a more regular single-grained arrangement is observed for specimens prepared using dry pluviation. The differences in behavior observed are then interpreted in terms of volumetric behavior of the sand (contractancy and dilatancy), which depends on the initial sand structure.

Introduction

It is well recognized that the mechanical behavior of sands strongly depends upon their initial state , in terms of density index and consolidation state. The influence of the initial sand structure, in the sense of the geometrical arrangement of the grains within the material is not as clearly known, understood and quantified. Different authors have already shown, even indirectly, the influence of this factor on the behavior of sands, by using differentiated modes of reconstitution of specimens, but without explicitly making reference to the sand structure. In particular, Mulilis et al. (1977) as well as Tatsuoka et al. (1986) show that the mode of reconstitution of a sand specimen has a significant influence on its resistance to cyclic shear and liquefaction properties. Been and Jefferies (1985) show different responses upon drained shear according to the mode of reconstitution of specimens (dry pluviation or wet tamping). As far as liquefaction instabilities are concerned, Canou (1989) present preliminary results showing that wet tamping seems to favor the initiation of liquefaction instability under monotonic shear, with respect to dry pluviation. Vaid et al. (1999) confirm this result, showing that wet tamping favors the initiation of liquefaction with respect to water pluviation. Zlatovic and Ishihara (1997) present results obtained on a Nevada sand, showing that dry pluviation would favor the initiation of liquefaction with respect to wet tamping, which is contrary to the conclusions reached by the previous authors.

Within this context, the objective of the experimental research presented in this communication

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was, based on the use of wet tamping and dry pluviation techniques for triaxial specimens reconstitution, in order to carefully quantify the influence of sand structure resulting from these preparation methods, on the static liquefaction properties of a reference French sand, Hostun sand RF (Benahmed, 2001, Benahmed et al., 2004). Another objective was to try to characterize the sand structures obtained with the two preparation techniques based on electronic microscope observations (MEB).

Description of the static liquefaction phenomenon

The phenomenon of sand liquefaction under monotonic shear, classically called "static liquefaction", has been first evidenced by Castro (1969). It is characteristic of loose contracting sand structures, shearing in undrained conditions, and must be distinguished from the cyclic mobility phenomenon, which may only develop, for dilating material, under cyclic loading, whereas liquefaction may occur under both monotonic and cyclic loadings. Since the work of Castro (1969), this phenomenon, which corresponds to a specific instability of the material, has been the object of tremendous amount of research, up to now. Figure 1 presents a typical result of static liquefaction obtained in a compression test carried out in the triaxial apparatus, on Hostun sand RF (Canou et al., 1991). This sand is a silica sand (Flavigny et al., 1990), with sub-angular grains (D_{50} = 350 µm ; C_U=1.57 ; e_{min} = 0.656 ; e_{max} = 1.000, ρ_s =2.65 t/m^3, $\rho_{d,min}$ = 1.33 t/m^3 ; $\rho_{d,max}$ = 1.60 t/m^3). The shear curve (q, ε_a) is characterized by a sharp peak of resistance, obtained at a low level of axial deformation (about 1 % in this case) followed by a rapid strain softening and final stabilization around an ultimate very low stationary value. The rapid initial increase of excess pore water pressure with progressive stabilization around a very high level value accounts for the very contractive nature of the material. The corresponding effective stress path, shown in figure 1-b presents the typical shape characteristics of the static liquefaction phenomenon, with progressive decrease of effective mean stress p' and migration of the state of effective stresses towards the (q, p') axis origin, with stabilization, at the ultimate state, on an accumulation point, called steady state by different authors (Castro and Poulos, 1977; Poulos, 1981), which is comparable, in first approximation, to the critical state of the soil. The stress ratio, η_{inst}, reached at the peak of resistance, corresponds to a mobilized friction angle significantly lower than the friction angle mobilized at the ultimate state (η_{crit}, critical state), accounting for the specificity of the liquefaction instability.

Experimental procedures

The compression triaxial tests have been performed on 70 mm diameter and 140 mm high specimens of Hostun sand RF, which characteristics have been given before. Two well-differentiated reconstitution techniques have been used, namely wet tamping and dry pluviation. Wet tamping procedure consist in mixing the dry sand with a small quantity of water (w=2%), in order to obtain a very loose material thanks to the capillary cohesion thus created. This material is then compacted layer by layer (2 cm thickness layers) into the fabrication mold of the specimen. Dry pluviation consists in filling up the fabrication mold in a continuous steady state process using a pluviation device (Dupla, 1995, Benahmed, 2001). The dry density obtained in this case depends on both massic flow rate of the sand and pluviation height, both being controlled during the process. Figure 2 presents the principle used for pluviation as well as a photograph showing the pluviator developed for the triaxial test (Benahmed, 2001).

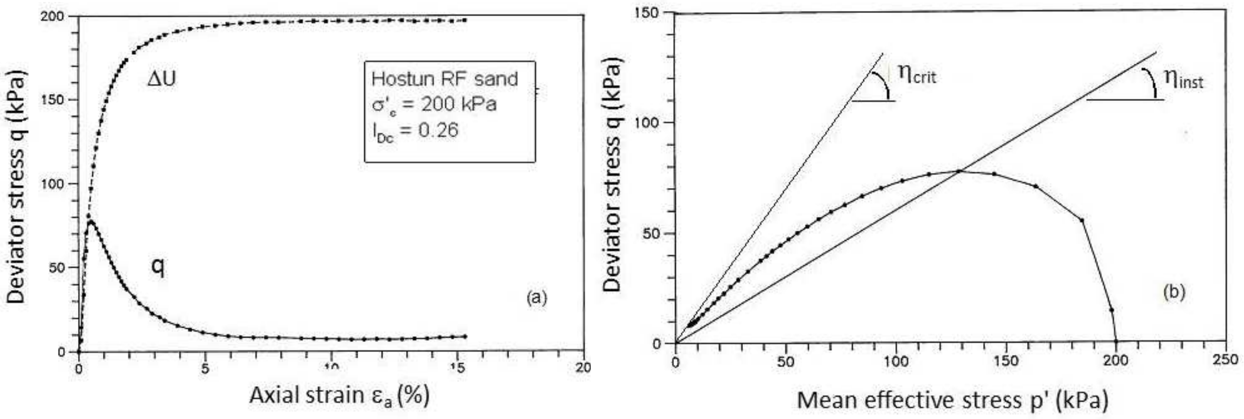

Figure 1. Typical result of static liquefaction test carried out on Hostun sand RF : (a) shear curve and excess pore water pressure curve ; (b) effective stress path (Canou et al., 1991)

Both methods (wet tamping and dry pluviation) allow to obtain loose sand structures, which allows to make comparisons between both reconstitution modes for a same given void ratio or density index.

Presentation of results obtained

Figure 3 presents a comparison between the behaviors observed for two specimens prepared according to the two previously described procedures. The sand is in a loose state in both cases, corresponding to a void ratio, after consolidation, equal to 0.946 (density index I_D equal to 0.16). The shear curves shown in figure 3 allow to observe very differentiated behaviors between wet tamping procedure and dry pluviation. As far as wet tamping is concerned, a static liquefaction type of behavior is observed with a low level peak of resistance followed by strain-softening (even if not as sharp as the one shown in figure 1). As far as pluviation is concerned, a significant strain-hardening phase is observed, characteristic of a dilating response in undrained conditions. The corresponding effective stress paths are also shown in figure 3, allowing to

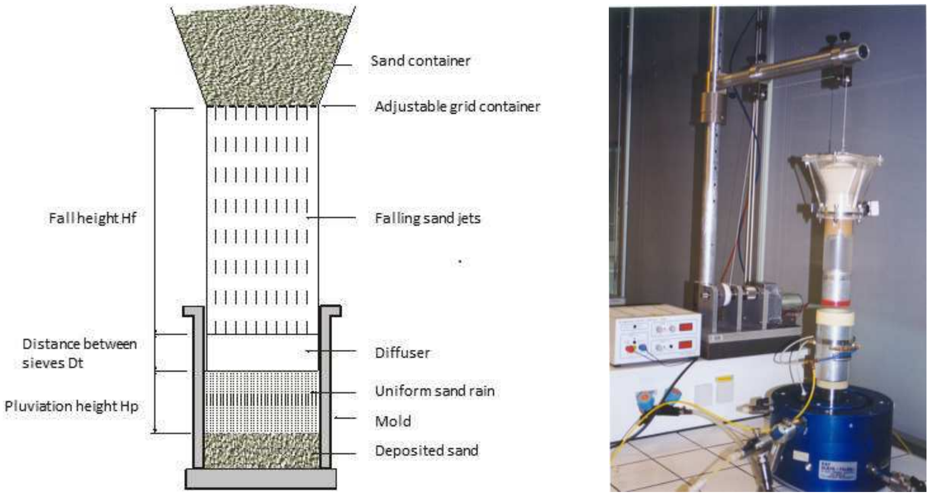

Figure 2. Pluviation process principle and view of the pluviator used in this study

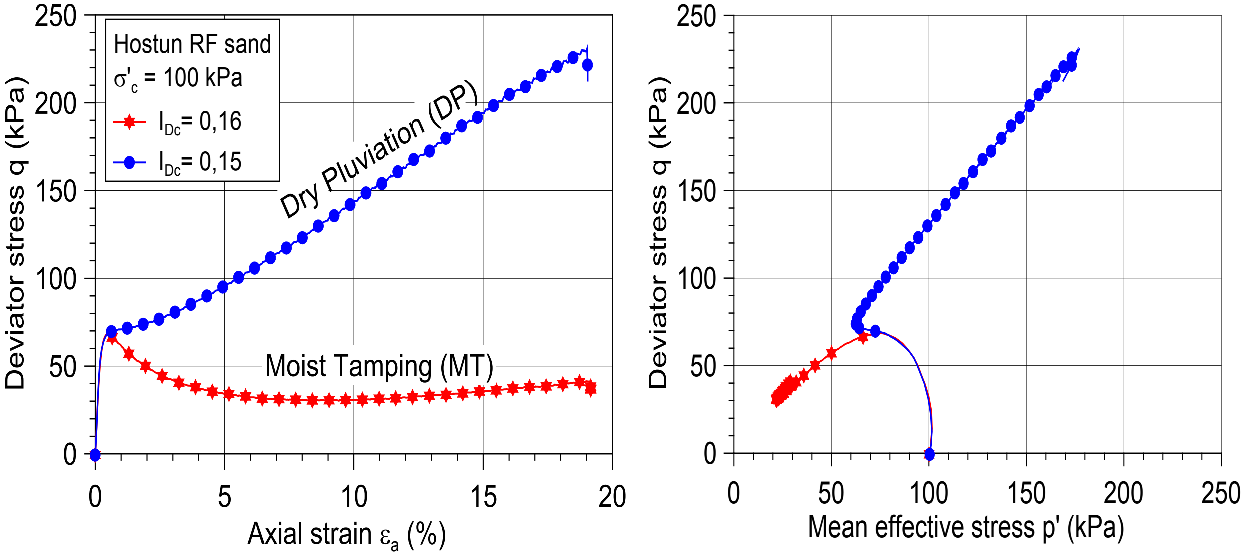

Figure 3. Influence of the mode of reconstitution of specimens on the behaviors observed : shear curves (left) ; effective stress paths (right)

observe the typical shapes corresponding to static liquefaction behavior for wet tamping reconstitution and, for dry pluviation, the typical shape corresponding to a material first contracting and then dilating after crossing the phase transformation threshold or characteristic state (Tatsuoka and Ishihara, 1974, Luong, 1980).

Similar observations have been done for other initial void ratios of the sand, which confirm the differences observed, with a tendency to attenuation of differences when the initial void ratio of the sand increases (Benahmed, 2001).

Observation of sand structure – Interpretation of differences in behavior observed

The initial state of the specimens being practically the same in terms of void ratio and effective stress state, the differences in behavior observed are *a priori* related to the two different modes of reconstitution of the specimens used, that may result in differences in the resulting sand structures formed. Electron microscope (MEB) observations have therefore been performed on small samples obtained from specimens prepared using the two procedures. Figure 4 presents typical photographs obtained for Hostun sand. The photographs allow to identify two well differentiated sand structures, as a function of the mode of fabrication of the specimens : for wet tamping reconstitution mode (Fig. 4.a and 4.b), a rather irregular structure, dominated by an arrangement formed by aggregates and macropores, is observed; for pluviation, a more regular "single-grained" sand structure may be observed, without macropores. With respect to the liquefaction phenomenon, one may therefore introduce the concept of unstable or metastable structure, organized in aggregates and macropores, which favors the initiation and development of the phenomenon of liquefaction and of stable structure, formed by a regular packing of grains, much less susceptible to liquefy. Figure 5 presents similar photographs obtained on Fontainebleau sand, which has also been studied in a similar way as Hostun sand. This silica

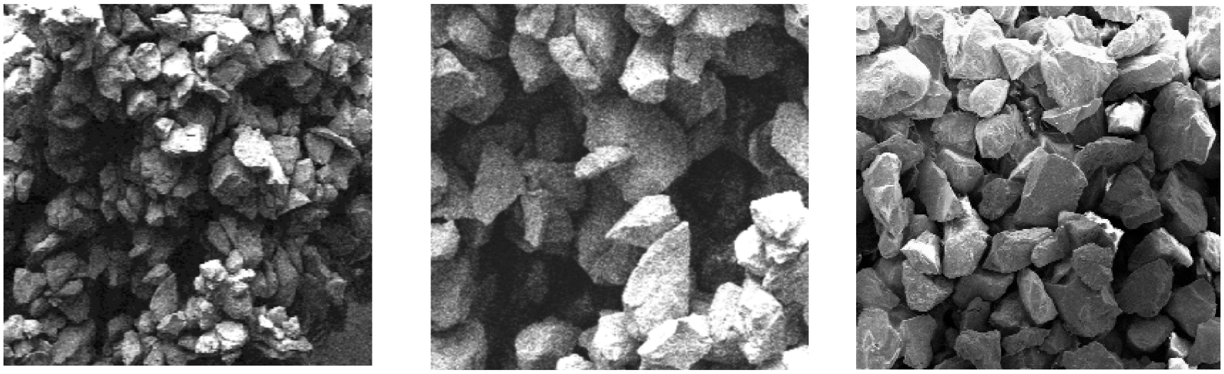

Figure 4. Microphotographs of Hostun sand RF showing two well differentiated structures : aggregates and macropores structure (wet tamping, left); aggregates and macropores structure (zoom, middle); regular single-grained packing (dry pluviation, right)

sand is composed of sub-rounded grains and it is finer than Hostun sand (D_{50} = 200 µm). The photographs shown in figure 5 allow again to clearly see the sand aggregates and macropores structure, well-differentiated from the single-grained structure. Undrained triaxial tests carried out on Fontainebleau sand, which are not reported here, have shown that this sand was even more liquefiable than Hostun sand (comparison made for the same density index).

The differences in behavior observed between the two types of structures may be interpreted in terms of volumetric behavior, contractancy and dilatancy. The average void ratio being the same for both types of structures, the intra-aggregate void ratio is lower than the average void ratio in the aggregate-macropore structure. If one considers that the aggregate behaves, at least during initial shearing phase, as a "macrograin" of low deformability, the volumetric deformation of sand will essentially result from the collapse of macropores and will be essentially of the contracting nature and will favor, upon undrained conditions, the development of high excess pore water pressures. In the case of the single-grained structure, the volumetric strain may only occur by modification of the intergrain porous space, which does not allow for a macropore collapse similar to what may occur for macropores, which may explain a volumetric behavior globally less contracting in the second case. Figure 6 presents a bidimensional conceptual scheme corresponding to both types of structures for equal diameter disks (case of a uniform material). The two types of configurations have been represented for the same average void ratio.

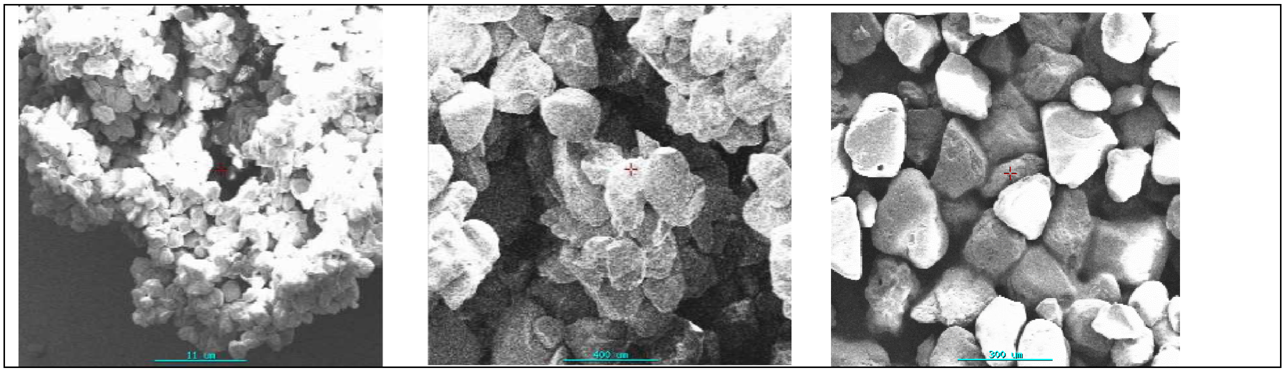

Figure 5. Microphotographs of Fontainebleau sand showing agregates and macropores structure (left and middle (zoom)) and single-grained structure (right)

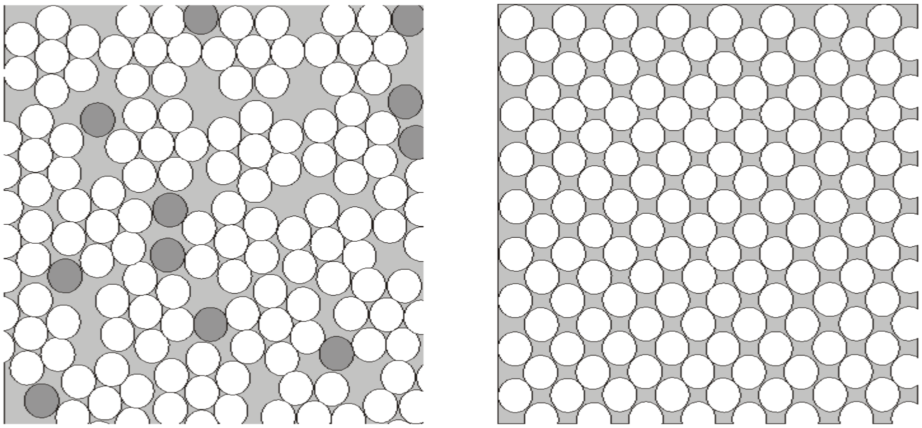

Figure 6. Conceptual bidimensional representation of an aggregates and macropores structure (left) and of a regular single-grained structure (right) for same diameter disks (same global void ratio in both cases)

Conclusions

By using two well differentiated modes of reconstitution of triaxial sand specimens, it has been possible to identify significant differences in behavior for a loose reference French sand with respect to the phenomenon of liquefaction of sand under monotonic shear, called “static liquefaction”. The wet tamping procedure results in the formation of a sand structure dominated by the presence of aggregates and macropores which favors the development of high excess pore water pressures upon undrained loading and the initiation of the liquefaction instability. Dry pluviation results in the formation of a more regular single-grained structure which favors a dilating type of response, more stable. Electron microscope observations have allowed to identify the two structures corresponding to the two specific behaviors observed : the first type, very contracting, may be qualified as a “instable” or “metastable” structure towards the liquefaction phenomenon, the second one may be qualified as a “stable” structure. The differences in behavior observed between both types of structures may be interpreted based on the existence of aggregates and macropores in the unstable structure, which favor contractancy and development of high excess pore water pressures. These results, obtained in the laboratory based on two well-defined reconstitution modes, show that the void ratio alone or density index alone is not enough to characterize the behavior of a sand with respect to liquefaction risk and it is important to also try to characterize the sands structure. For natural sands, it is a priori possible to find very different structures resulting from very different modes of geological formation of the soils (type of sedimentation, wind-deposited soils, presence of fines, possible cementation bonding, , etc.). These results are also related to the problem of characterization of sandy material used for construction, by hydraulic placement, of embankments or artificial islands, earth dams, in water environment (Sladen et al., 1985), without possibility of efficient in situ compaction and that can, therefore, result in the formation of unstable soil structures with respect to liquefaction.

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