Conditions for isotropic liquefaction of model granular materials

T. Doanh[a], A. Le Bot[b], N. Abdelmoula[a], S. Hans[a], C. Boutin[a]

a. Ecole Nationale des Travaux Publics de l'Etat. LGCB, LTDS (UMR 5513). Vaulx en Velin. France.
b. Ecole Centrale de Lyon. LTDS (UMR 5513). Ecully. France

Résumé :

En mécanique des sols, la liquéfaction est pratiquement synonyme à l'annulation des contraintes effectives intergranulaires. Elle n'est possible que pour les milieux granulaires lâches, complètement saturés et cisaillés en volume constant. Dans cet article, nous présentons un comportement inattendu en compression isotrope des matériaux granulaires modèles dans un prototype expérimental très simple. Les assemblages granulaires lâches ont de multiple effondrements instantanés, accompagnés d'une compaction volumique et d'une contraction axiale. Finalement, la liquéfaction spontanée avec de très large déformation n'est observée qu'au-dessus d'un seuil de l'indice des vides e_{30}^{liq}*. Nous détaillons les trois conditions d'apparition de liquéfaction isotrope des matériaux granulaires modèles.*

Abstract :

In the current understanding of soil mechanics, the liquefaction phenomenon is almost synonymous to the vanishing of the effective intergranular stress. It occurs only for fully saturated granular media deviatorically sheared in constant volume. In this article, we present an unexpected isotropic compressibility behaviour of model granular materials with a very simple experimental set-up. Loose granular assemblies experience multiple sudden collapses associated with volumetric compaction and axial contraction. Ultimately, spontaneous liquefaction is observed above a threshold void ratio e_{30}^{liq}*. We detail the three conditions for isotropic liquefaction of model granular assemblies to occur.*

Keywords : Liquefaction, Model granular materials, Isotropic consolidation, Friction, Dynamic

1 Introduction

Soil liquefaction is one of the most devastating phenomenon in civil engineering with dramatic consequences, including the loss of human lives. Liquefaction events often occur during earthquake, or even during the quasi-static shearing of loose granular materials. In these events, termed as dynamic and static liquefaction in soil mechanics [6], the soils completely lose their strength and behave like a liquid with no or little shear strength. The sinking of intact buildings into the soil during earthquake remains one of the most recognizable image leaving behind these liquefaction events. Consequently, a large number of intensive theoretical and experimental studies has been devoted to the understanding of this particular phenomenon.

However, despite this large body of accumulated knowledge, the physical significance behind liquefaction is far from fully understood. According to the simplification made in soil mechanics to understand first qualitatively the soil behaviour during liquefaction, two requirements are needed for a fully saturated granular media to liquefy. The first requirement refers to the presence of an external shearing source in order to activate the dilatancy mechanism or the ability of saturated loose soils to contract. The second requirement links to the transient nature of the liquefaction event, giving no time for the interstitial fluid to flow freely, or to be sufficiently drained; hence the constant volume or undrained condition during which the granular compaction is translated into an increase of the interstitial pore pressure. This excess pore pressure can rapidly end up equalling the external shearing pressure, i.e reducing the effective stress on the granular structure down to zero. The grains are no longer in contact with each other; the needed intergranular structure disappears and the soil, unable to sustain the still existing external imposed force, behaves like a fluid. It collapses with very large deformation or simply liquefies.

Basically, liquefaction occurs when the a fully saturated granular medium is sheared in constant volume. More precisely, with the two above requirements satisfied i.e. shearing in undrained condition, static liquefaction happens for loose granular materials above a threshold void ratio e_c, representing the transition from liquefaction behaviour in undrained shearing to non-liquefaction behaviour characterized by the steady state of deformation [3]. This threshold e_c is fully identified for Toyoura sand [11, 4], a well-known sand for laboratory studies. In soil mechanics, the current understanding almost relates the liquefaction phenomenon to the vanishing of the effective stress with no shear resistance under undrained conditions.

Our previous work assesses that the requirement of an imposed external shearing source is not a necessarily one. Spontaneous compaction and ultimately liquefaction can be induced by *isotropic* compression in *drained* condition on model granular materials [5]. Insotropic liquefaction happens for loose assemblies above a threshold void ratio e_{30}^{liq}. In the present work, we push a step further and detail the three conditions for isotropic liquefaction of model granular materials to occur.

2 Isotropic consolidation and experimental method

2.1 Measurement principle

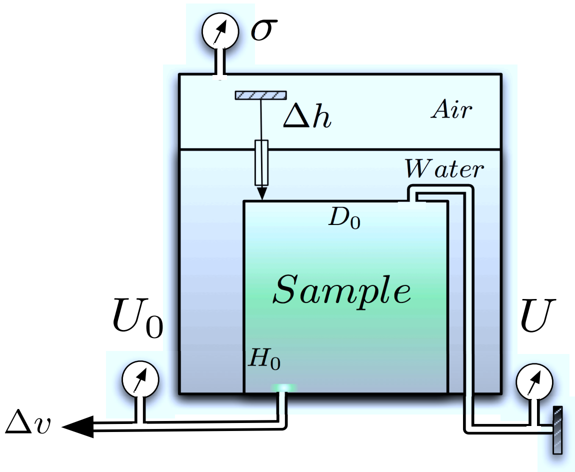

Figure 1: (Color online) Sketch of the experimental setup for isotropic consolidation.

In granular mechanics, three macroscopic parameters characterize the isotropic consolidation. The main parameter is the compression index $C_c = \Delta e/\Delta log\sigma^{'}$ indicating the ability of granular media to compact continuously under increasing effective isotropic stress $\sigma^{'}$ or under loading stress path. The volumetric compaction is usually translated into a continuous decrease of void ratio e. The swelling index $C_s = \Delta e/\Delta log\sigma^{'}$ is the second parameter describing the expansion tendency under decreasing effective isotropic stress or under unloading stress solicitation. The preconsolidation stress $\sigma^{'}_p$ is the last parameter pointing to the maximum effective isotropic stress in the past history of a particular soil. These parameters constitute currently a widely accepted idealization of the mechanical consolidation behaviour of granular materials in the compressibility diagram Δe vs $log\sigma^{'}$ [12].

Isotropic consolidation is also characterized by a nil interstitial pore pressure U throughout the test duration, giving $\sigma^{'}$ = σ, following the effective stress principle formulated by Terzaghi [10], $\sigma = \sigma^{'} + U$, σ is the total isotropic stress.

2.1 Experimental device and protocol

The simple experimental set-up, presented in Fig. 1 is a classical one for triaxial testing. It consists in an isotropic drained compression of a short cylindrical granular sample of initial height H_0 and diameter D_0 inside a triaxial cell. The sample was enclosed inside a cylindrical and open-ended latex membrane of thickness 0.3 mm. The back pressure U_0 needed for a full saturation was applied at the bottom of the sample. The pore-water pressure U was recorded outside the triaxial cell using a very thick plastic tube connected to the top cap of the granular sample, at a distance of about 60 cm. The total isotropic stress σ was manually imposed using compressed air and slowly increased while keeping the excess pore pressure $\Delta U = U - U_0$ small to respect the requirement of full drainage for a consolidation testing or a fully drained isotropic compression. The axial displacement Δh was measured by a linear variable differential transformer sensor mounted directly on the top platen to estimate the global axial strain $\varepsilon_a = \Delta h/H_0$. The water volume Δv expelled from or moving into the sample was measured a volume sensor and the global volumetric strain deduced from $\varepsilon_v = \Delta v/V_0$, where V_0 is the initial sample volume.

3 Isotropic consolidation on model granular materials
3.1 Materials and preparation

The model granular material used was made of monodisperse and spherical soda lime glass beads (CVP Sil-glass) of mean diameter of 0.723 mm. Some complementary tests were performed on alternated glass beads (Sili beads by Sigmund-Lindner) of mean diameter of 0.675 mm. To avoid possible wearing effects, only virgin glass beads were used.

The sample, H_0 = 70 mm and D_0 = 70 mm, was prepared using a modified moist tamping and under compaction method [2, 7]. Predetermined quantities of moist glass beads, mixed with 2 % of distilled water in weight, were placed and gently compacted in five layers of prescribed thickness using a flat-bottom circular stainless steel tamper of 20 mm in diameter. To obtain a fully saturated state, we used the CO_2 method [8] with de-aired distilled water, and a constant back pressure U_0 of up to 200 kPa was applied. Prior to each experiment, we increased the net total stress $\Delta\sigma = \sigma - U_0$ and measured the excess pore pressure ΔU in undrained condition. The resulting Skempton's coefficient B = $\Delta U/\Delta\sigma \geq$ 0.95 indicates a quasi-saturated sample [9]. The void ratio e_{30} at confining pressure of 30 kPa was carefully evaluated from the water content obtained at the end of the isotropic compression [11], and also from the usual procedure of measuring the sample dimensions during different fabrication stages.

3.2 Results and analysis

Typical isotropic consolidation results show that the experimental set-up yields a very different compresssibility behaviour in Fig. 2a. Granular media such as sand, exhibit normally a continuous increase of density [12, 1]. For model granular materials, instead of the usual smooth and continuous decrease of e with increasing σ', event of large unexpected drop Δe in void ratio can be seen at undermined triggering isotropic stress σ'_{trig}. Between two events, the normal continuous decrease of e is observed during the loading phase. Surprisingly, a large drop in e for the last event occurring at $\sigma'_{trig} = 276$ kPa. This large volumetric compaction is accompanied with an equally very large axial strain in Fig. 2b; and the granular sample collapses instantaneously onto the pedestal base of the triaxial cell in a spontaneous liquefaction. The cylindrical form of the specimen is totally destroyed. For this sample, the vertical compression indicates

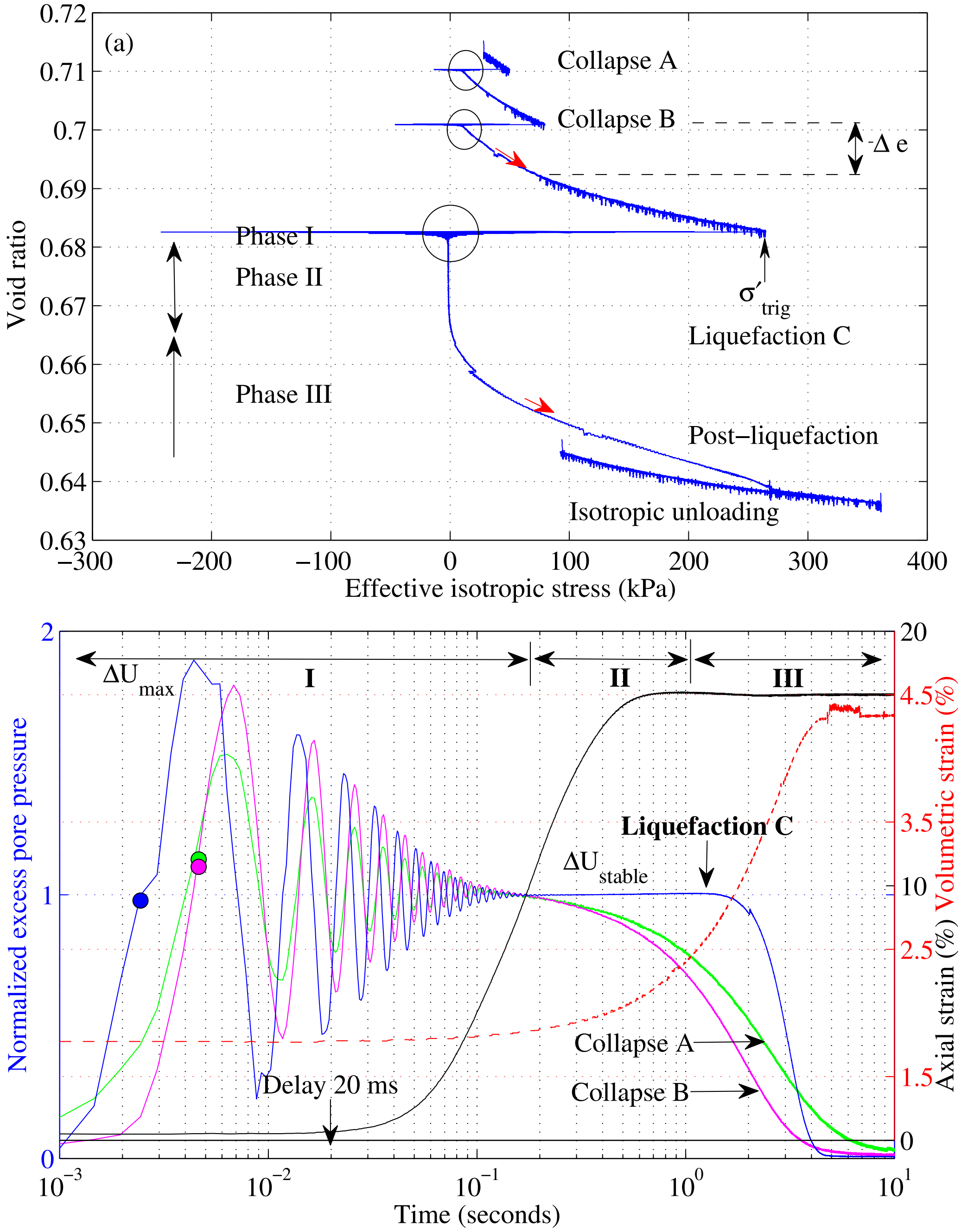

Figure 2: (Color online) (a) Isotropic liquefaction at 267 kPa. (b) Three phases of pore water pressure development : I fast and transient development, II constant stable (liquefaction) value and III dissipation (post-liquefaction). The axial strain (black) and volumetric strain (red) refer to the liquefaction event. Referred liquefaction levels (solid circles) are indicated on the pore pressure evolution.

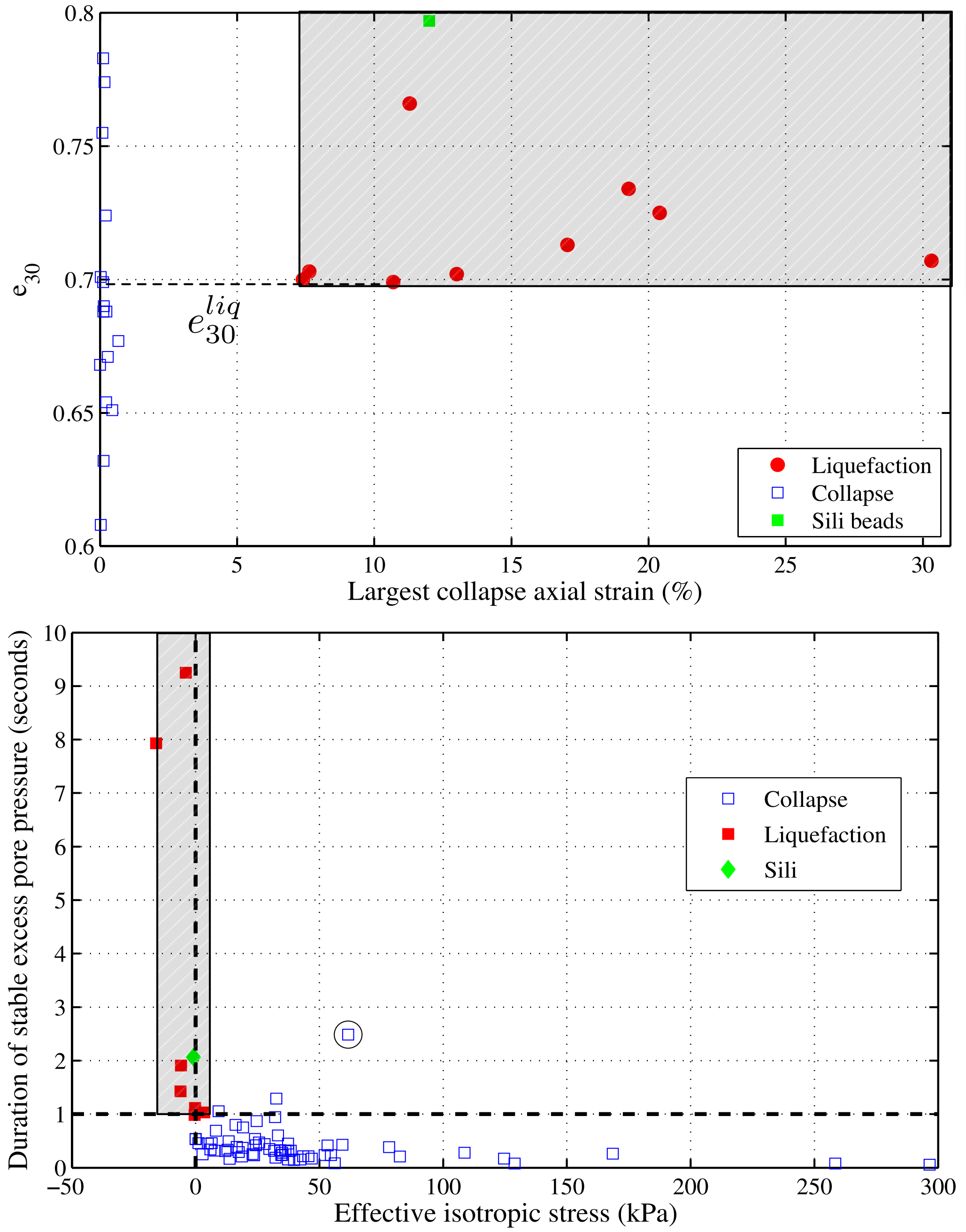

Figure 3: (Color online) Conditions for liquefaction event. (a) loose enough above a threshold void ratio e_{30}^{liq}, (b) the effective stress state small enough approaching the zero value for at least one second.

an axial strain rate $\dot{\varepsilon_a}$ of about 35 %/s. It clearly indicates a dynamic regime of the liquefaction phenomenon happening within less than one second.

Despite the unexpected events interrupting the smooth compressibility behaviour, the macroscopic incremental parameters C_c and C_s can still be defined in the continuous segments between these events, as well as the average macroscopic parameters $< C_s > \approx < C_c >$ and $\sigma_p^{'}$.

A closer look reveals that each event commences with an instantaneous reduction of $\sigma^{'}$ due to a sudden surge of ΔU, followed by a gradual recover of σ'. In Fig. 2b, ΔU was normalized by the brief stable value ΔU_{stable} between the oscillations and the return to equilibrium $\Delta U = 0$. The time origin is shifted to the beginning of the transient phase $\pm$ 0.5 ms, which is the current time resolution. It should be noted that ΔU was measured simultaneously by two pore pressure transducers using different technologies, a static (piezoresistive) and a dynamic (piezoelectric) one having high resonant frequency of 250 kHz.

The evolution of ΔU can be decomposed reasonably in three phases. First a fast transient phase I occurred within 200 ms at constant volume (hollow circles in Fig. 2a). During this phase, ΔU vibrates like an oscillating underdamped system with a dominant frequency of about 100 Hz in Fig. 2b. Then appears a second phase II only for liquefaction event, characterized by a large increase of volumetric compaction and axial contraction at constant σ' and at stabilizing value of ΔU_{stable} for almost two seconds. It is hypothesized that this duration is enough to create a liquefaction state. Finally a last and longest phase III in which ΔU returns to the initial equilibrium $U = U_0$ at nearly constant axial strain in Fig. 2b. The solid circles on on the rising segment to the first peak ΔU_{max} of different events indicate the null effective stress levels. The blue solid circle on liquefaction event is exactly equal unity, meaning a null effective stress for the whole phase II, hence the liquefaction phase.

By increasing gradually e_o at fabrication state, hence indirectly e_{30}, figure 3a shows the total disappearance of liquefaction of denser samples below a threshold void ratio e_{30}^{liq} = 0.690. Only 8 tests have liquefied out of more than 80 experiments on two types of glass beads. Although being rare, isotropic liquefaction has been repeatedly and consistently observed in two years of work experience. This threshold e_{30}^{liq} represents the condition for a transitional behaviour from full liquefaction or global collapse in isotropic compression to non-liquefaction with the presence of local collapses. However, e_{30}^{liq} is not a full proof guaranteeing the total absence of isotropic liquefaction; it just suggests the possibility to avoid the total failure below e_{30}^{liq} since none of the performed tests below this limit exhibits liquefaction.

Figure 3b gives the two other conditions for liquefaction event inside the shaded rectangle : the usual null effective isotropic stress ($\sigma^{'} \approx 0$) and the maintain of this stress state (i.e. ΔU_{stable}) for at least one second above 95% of ΔU_{stable} (or 5% of pore pressure dissipation). Collapse event can have a relatively longer duration for ΔU_{stable}, as indicated by large blue hollow circle, and not terminate in a full liquefaction due to the presence of positive $\sigma^{'}$.

There are still numerous issues in the measurements of isotropic liquefaction. The most important one is the measure of the dynamic pore pressure generating large negative effective stresses. Currently, no suitable explanation can be found.

4 Conclusions

Isotropic drained compression tests on model granular materials are delicate and relatively difficult experiments. This can explain the total absence of kind of experimental measurements in the granular literature. In this paper, we have presented the possibility of isotropic liquefaction, a phenomenon a priori not possible when compacting in drained condition. Using a very simple experimental set-up, we have been able to liquefy two types of monodispersed glass beads. We have also explicitly detailed the three conditions to have an instantaneous liquefaction on these materials : the granular assembly should be loose enough above the threshold void ratio e_{30}^{liq}, and the effective stress state small enough approaching the zero value for at least one second. Unfortunately, the identification of the triggering mechanisms, responsible for the pore pressure build up in the transient phase, is still not possible and the physical parameters maintaining the pore pressure or the effective stress in the stabilizing phase still unknown.

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