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Analysis of thick cylinder cavity expansion tests in relation with sand liquefaction properties

J.C. DUPLA and J. CANOU
Soil Mechanics laboratory (CERMES, ENPC/LCPC)
Central II, La Courtine, 93167 Noisy-le-Grand Cedex

ABSTRACT

The purpose of this communication is to present the results of a study concerning the applicability of the pressuremeter loading (cylindrical cavity expansion test) to the evaluation of the liquefaction risk of a sandy mass submitted to a cyclic loading (earthquake). An experimental program has been carried out on thick cylinder samples for both monotonic and cyclic loadings and the results show that the cylindrical cavity expansion sollicitation could allow to obtain quantitative characteristics related to liquefaction potential of a sand.

KEYWORDS

cavity expansion; thick cyclinder; monotonic loading; cyclic loading; pressuremeter; liquefaction, sand

INTRODUCTION

The pressuremeter test, widely used in France for various applications in geotechnical engineering, is one of the in situ tests which is best fitted to theoretical interpretations, based on cylindrical cavity expansion theories (Baguelin et al., 1978)

The purpose of this investigation is to study the volumetric behaviour of the material under stress conditions similar to stress conditions existing around a pressuremeter cell. The thick cylinder is a laboratory set-up which allows to simulate a cylindrical cavity expansion test in a cylindrical sample, and which reproduces loading conditions close to the pressuremeter loading, with slightly different boundary conditions. This test is therefore very useful to conduct fundamental studies (Fahey, 1986; Juran and Bensaïd, 1989; Alsiny et al., 1992) in order to assess the influence of various parameters on the results obtained (such as sand density, level of consolidation, loading characteristic).

EXPERIMENTAL SET-UP AND TESTING PROCEDURE

Fig. 1 shows a schematic view of the thick cylinder cell. The sand specimen has an external diameter of 100 mm and it is 140 mm high. The central cavity has an initial diameter of 10 mm (or 20 mm). The specimen is maintained by an inner (cavity) and an outer latex membrane 0.3 mm thick.

As far as the cavity expansion test is concerned, two different devices are used according to the selected type of loading (monotonic or cyclic). For monotonic expansion tests, a digital volume-pressure controller (GDS type) is used allowing to perform pressure-controlled or volume-controlled expansion tests with a very precise regulation. For cyclic tests, an electro pneumatic servovalve connected to microcomputer wich allows to run pressure-controlled cyclic tests at relatively low frequency (quasi-static range).

The experimental set-up is fully instrumented with pressure transducers (cell pressure, cavity pressure and pore pressure), volume measurement devices for the cavity, and a displacement tranducer to measure possible vertical displacement of the sample. All transducers are connected to the microcomputer through a data acquisition card, the test being entirely controlled by the computer through an appropriate computer program (control of the test, data acquisition and data processing, real-time visualization of the test results, etc.)

As far as the specimen preparation procedure is concerned, two techniques are used, function of the state of density to be reached: for medium to dense structures, the sample is prepared using dry deposition and light compaction layer by layer; for loose structures, however, a wet tamping technique is used, which allows very loose material to be obtained (Castro, 1969; Canou, 1989). The subsequent saturation and consolidation of the samples are based on regular triaxial techniques.

EXPERIMENTAL PROGRAM

The sand used in this study is Hostun sand RF. This sand is a reference sand widely used in France for research purpose, and it has been described by Flavigny et al. (1990). This material is a medium size silica sand with subangular grains and an average grain size D_{50} of 0.38 mm (e_{max}=1, e_{min}=0.656).

Both monotonic and cyclic tests have been performed on this sand for fully drained and fully undrained conditions. Most monotonic tests were volume-controlled expansions (after checking that pressure-controlled and volume-controlled tests give the same results). Cyclic tests were carried out pressure-controlled, in a way similar to cyclic stress-controlled triaxial tests performed for liquefaction potential evaluation.

We present in the following section typical results obtained.

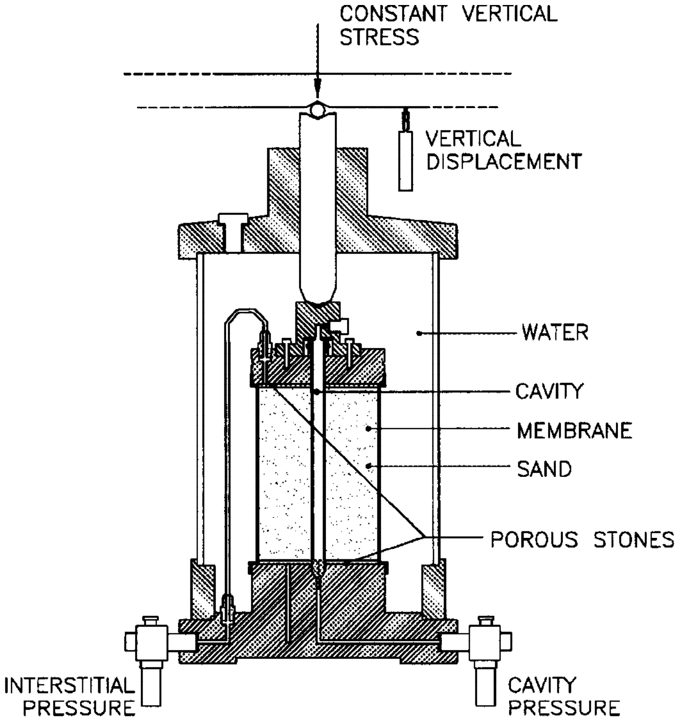

Fig. 1. Thick cylinder apparatus

PRESENTATION OF TYPICAL RESULTS

In this paragraph, typical results are shown for both monotonic and cyclic cavity expansion tests under drained and undrained conditions.

Monotonic tests

Fig. 2 shows a typical result obtained for a strain-controlled cavity expansion test carried out under drained conditions. We may remark that the behaviour observed is qualitatively very close to the behaviour observed during an homogeneous triaxial test. In particular, the volumetric behaviour of the sample ($-\varepsilon_v=\Delta V_{sam}/V_{sam,0}$) in a cavity expansion test is very similar to the one observed in triaxial tests, since we see a contractant behaviour followed by a dilatant behaviour. Based on the strong similarities existing between both experiments, the cavity expansion test may be analysed on the basis of a test parameter $\alpha=(\Delta p_{cav}/p'_c)$ ($p'_c=p_{c0}-\Delta u_s$) introduced by Schwab and Dormieux (1985). As for the triaxial test, we can define a characteristic state, α_c (similar to $\eta_c=q/p'$ defining the phase transformation line or characteristic state in a triaxial test) , in order to describe the transition from the contracting to the dilating domain. For the test presented, the value of α_c is 4. An important point to note here is that, if relative radius of the cavity r_e/r_i is changed from 10 to 5, the value of α_c varies from 4 to 2. Schwab and Dormieux (1985) have obtained for the same geometrical conditions, a value of α_c equal to 1.9 which is very close to the value obtained. Therefore the (Δp_{cav}, p'_c) plane is equivalent to the (q, p') plane , and the "generalized" stress path obtained is vertical (fig. 2 c), because $p'_c=p_{c0}$ ($\Delta u_s=0$).

A typical result of a strain-controlled cavity expansion test carried out under undrained conditions is shown in fig. 3. Again, we may observe strong similarities with the result of a regular undrained triaxial test. The excess pore water pressure curve (fig. 3-b) reveals a contractant behaviour ($\Delta u>0$) in the first part of the test, followed by a dilatant behaviour ($\Delta u>0$). We may define the "generalized" characteristic state as the state for which $\Delta u=0$. The parameter α, introduced above, may be defined in the same way, and the value of α_c is identical to the value obtained for the drained case.

Fig. 3-c presents the corresponding stress path in the (Δp_{cav}, p'_c) plane, which shape is very similar to the undrained stress path obtained for a regular triaxial test. This would allow to think that, as for the triaxial test, the "characteristic state" defined for cavity expansion tests is intrinsic to the material, for a given value of the ratio r_i/r_e. In the (Δp_{cav}, p'_c) plane we see very clearly the failure of the material, like for triaxial test in the (q, p') plane. In the same way as above we can define a value α_r, corresponding to the failure of the material. In drained test, the failure is reached at the maximum of the stress path, that is for the limit pressure. In undrained test, the failure is defined in the second part of the test (dilating zone) when the stress path follows a straight line (≈constant value of α). However, this value depends on sand density, level of consolidation, type of sollicitation (drained or undrained) and on the ratio r_e/r_i. This evolution is identical to the evolution of M_R ($=q/p'$ at failure in a triaxial test).

Cyclic tests

Fig. 4 presents the result of a cyclic pressure-controlled expansion test carried out under undrained conditions. Cyclic tests are characterized by a cyclic loading ratio $R_c=\Delta p_{c,cyc}/p_{c0}$. For the test presented in fig. 4, $R_c=0{,}7$. We can see that a phenomenon very similar to the classical cyclic mobility (or liquefaction phenomenon), observed in the triaxial apparatus, may also be reached with thick cylinder tests. Once again, we obtain the value of α_c that we already had. In the (Δp_{cav}, p'_c) plane, we can clearly see (fig. 4 c) the characteristic state. During the first part of the test, the soil shows a contracting behaviour with a regular increase of residual excess pore pressures. Then the « stress path » reaches the characteristic state and a typical cyclic mobilty phenomenom is initiated.

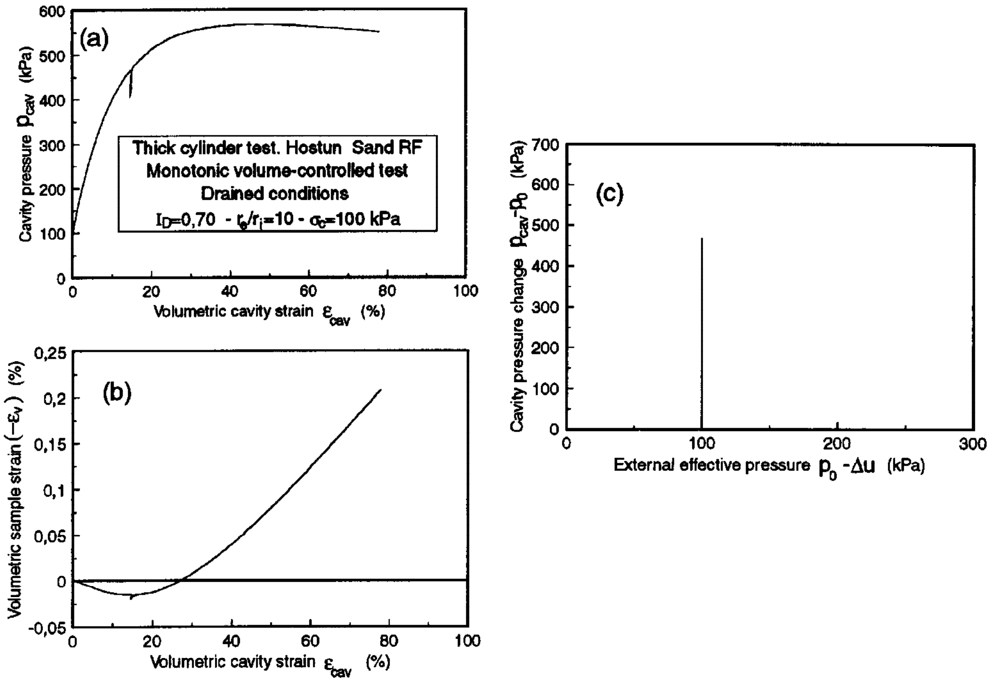

Fig. 2. Typical result of a monotonic strain-controlled thick cylinder test carried out under drained conditions : (a) (p_{cav}, ε_{cav}) ; (b) ($-\varepsilon_v$, ε_{cav}) ; (c) (Δp_{cav}, p'_c)

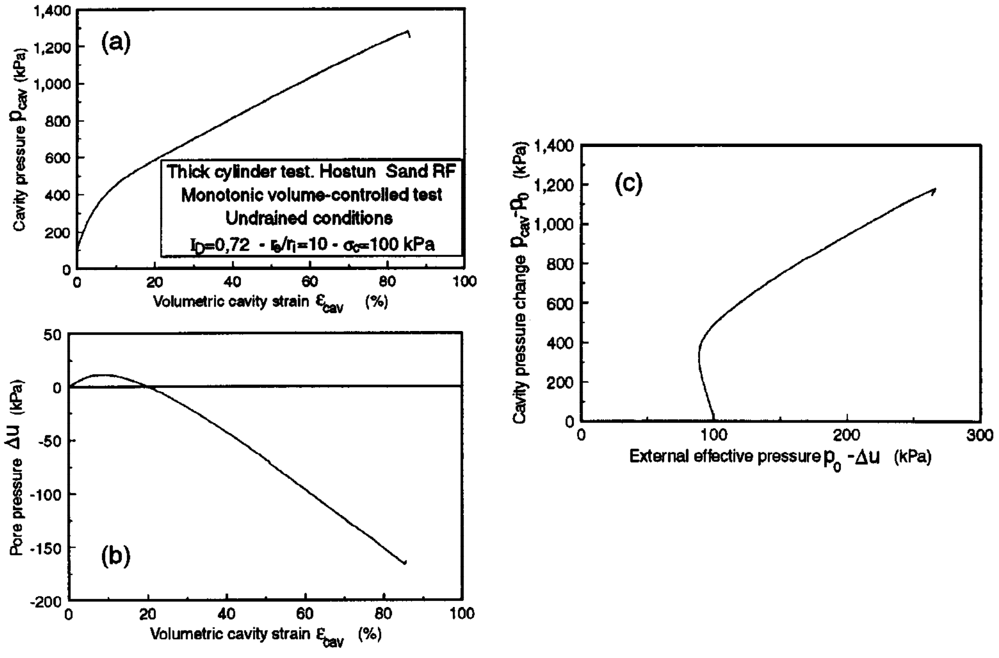

Fig. 3. Typical result of a monotonic strain-controlled thick cylinder test carried out under undrained conditions : (a) (p_{cav}, ε_{cav}) ; (b) (Δu_s, ε_{cav}) ; (c) (Δp_{cav}, p'_c)

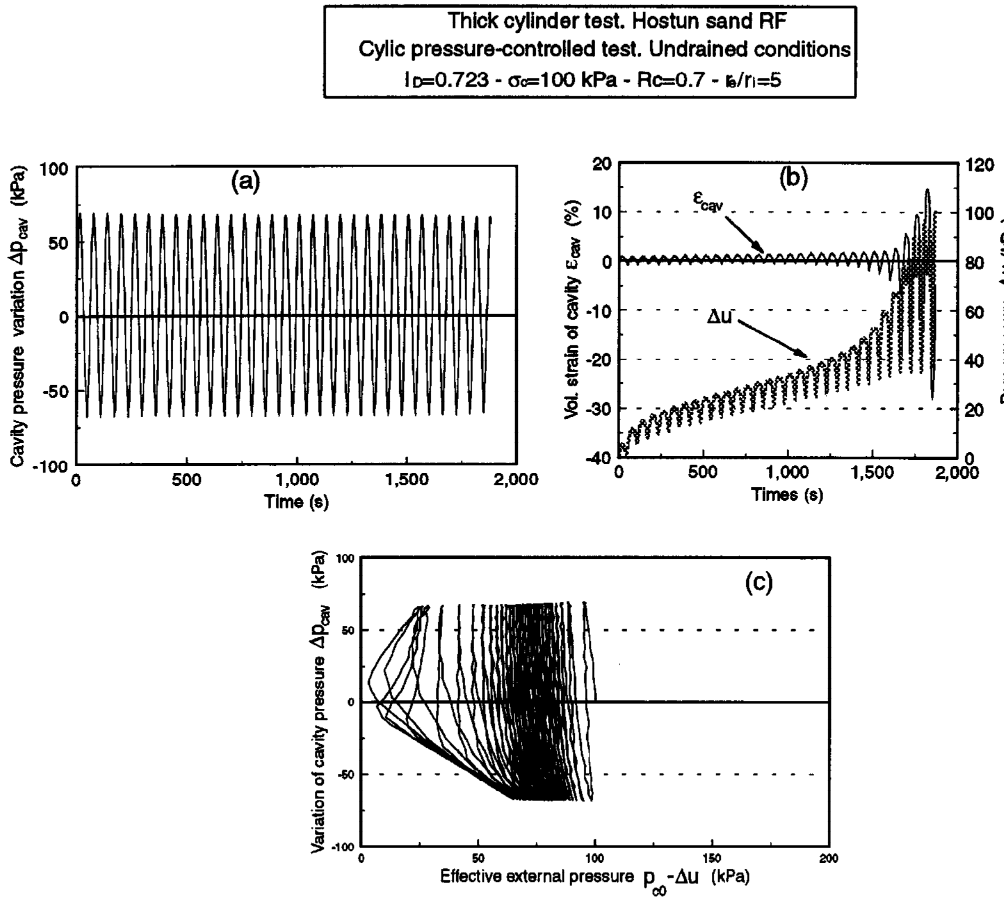

Fig. 4. Typical result of a cyclic stress-controlled undrained test in the thick cylinder : (a) (Δp_{cav}, t) ; (b) (ε_{cav}, ε_{sam}, t) ; (c) (Δp_{cav}, p'$_c$)

The pore pressure reaches the consolidation pressure (momentary liquefaction points), twice per cycle (one time in compression and one time in extension) and we observe large strains at the cavity wall. The strenght of the material at these points is very reduced, and this explains the important accumulation of volumetric strain of the cavity. It is important to note that the "characteristic state" is first reached during an extension phase, because the material is weaker in extension than in compression. This result is similar to cyclic mobility triaxial tests.

Fig. 5 shows the result of a cyclic stress-controlled cavity expansion test carried out under drained conditions. characterized by a cyclic loading ratio R_c=0.8, and in this case the loading is non alternated (no stress-reversal). We notice an initial high rate of volumetric strain accumulation, which progressively decreases to remain approximtaly constant after about 50 cycles. The same observation may be done for the volumetric strain of the sample.

Fig. 6 presents the accumulation of volumetric strain of cavity and sample. On this figure, the volumetric strain of the sample is defined as: $\Delta V_{sam}/V_{cav,0}$. In that way, we can compare the two accumulation curves showing that the levels of volumetric strain of the cavity and of the sample reached after 40 cycles are almost the same. Other cyclic drained tests, for r_e/r_i=5, show identical curves of accumulation of the volumetric strain of the cavity and of the sample (Dupla, 1994).

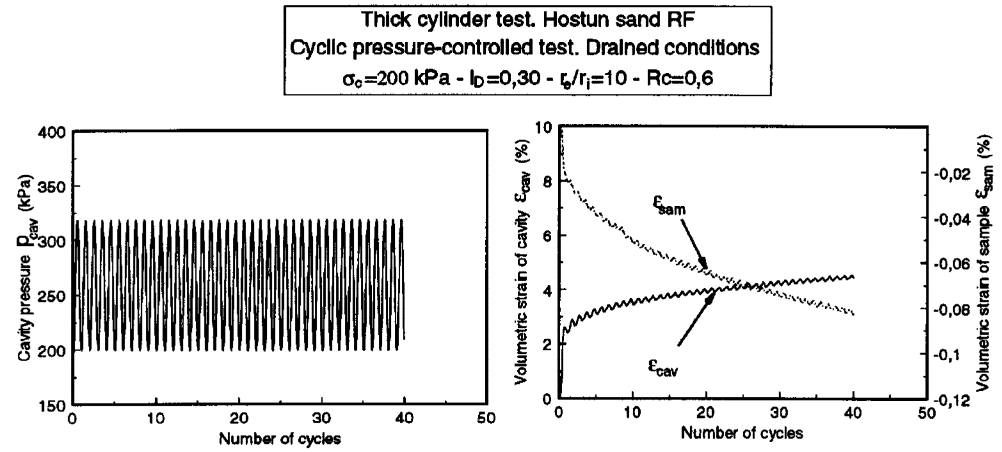

Fig.5. Typical result of a cyclic stress-controlled drained test in the thick cylinder

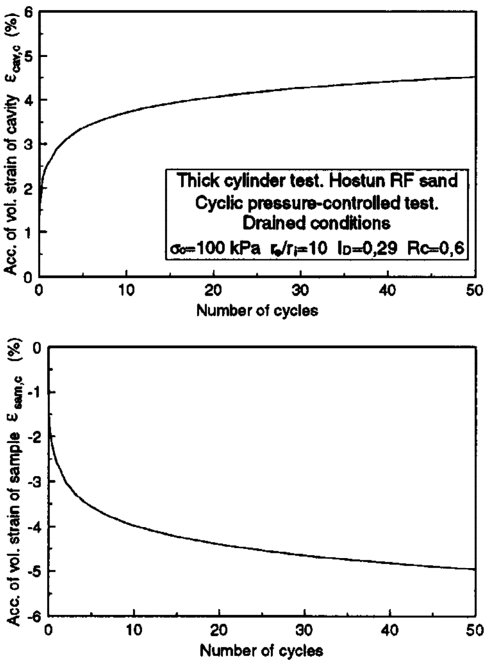

Fig. 6. Accumulation of volumetric strains of the cavity and the sample.

The level of accumulation of volumetric strain of the cavity (or of the sample) reached during the stabilization phase, gives important information about the volumetric behaviour (contractancy or dilatancy) of the material (see next section).

INFLUENCE OF DENSITY INDEX ON RESULTS OBTAINED

The density index I_D (or relative density $D_R = I_D$ x 100 %) has a major influence on the mechanical behaviour of a sand, in particular in terms of volumetric behaviour (contractancy or dilatancy), with important consequences in terms of liquefaction potential of the material: the looser the material and the higher its susceptibility to liquefy. Therefore, the first parameter to be investigated in this study was the density index of Hostun sand RF, for both monotonic and cyclic loadings.

Drained tests only were carried out for both monotonic and cyclic tests with measurement of volumetric strains, the idea being to subsequently correlate the volumetric strain to excess pore water pressure generation observed in undrained triaxial tests.

As far as monotonic expansion is concerned, fig. 7 shows the results of three tests carried out for three densitiy indexes of the material (I_D=0.29, 0.48 and 0.79). The results obtained are in good agreement with what could be expected. In terms of expansion curve, increasing the density results in a more rigid response with higher initial moduli and higher limit pressures. In terms of volumetric behaviour, the higher the density and the more dilatant the response. For very loose sand structure, the volumetric response is only of contractant nature. Those results are in good agreement with elementary behaviour observed in the triaxial apparatus.

As far as cyclic expansion is concerned, fig. 8 shows the results of 3 stress-controlled cyclic tests for which the density index only has been varied (I_D=0.29, 0.60 and 0.90), all other parameters being the same. The results are presented in terms of the envelope curves for the volumetric strain accumulation of the cavity versus the number of cycles applied. Again, the results obtained are in good agreement with the results that would be obtained in undrained cyclic triaxial tests in terms of excess pore water pressure generation: the looser the material and the higher the accumulation of volumetric strain obtained (similar to the accumulation of excess pore water pressure).

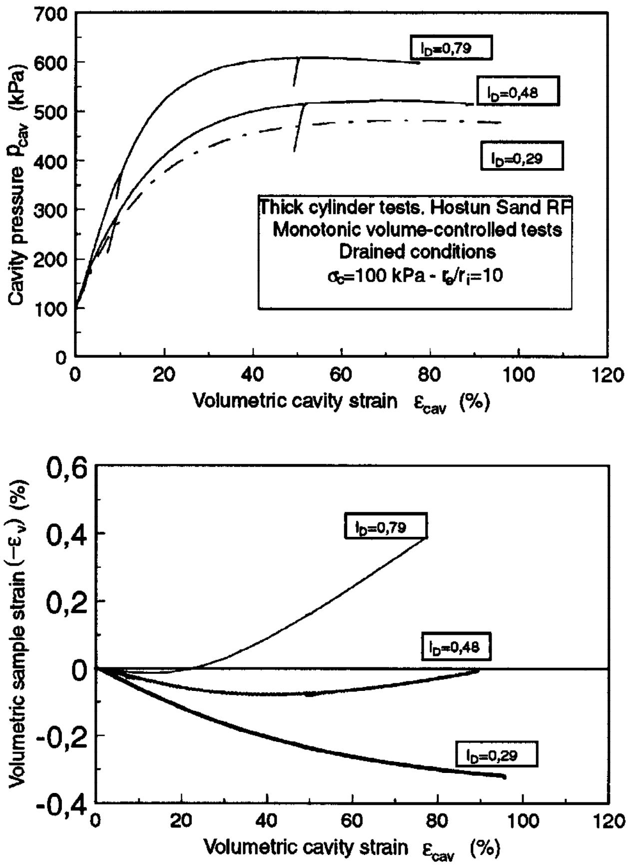

Fig. 7. Influence of relative density on monotonic thick cylinder tests

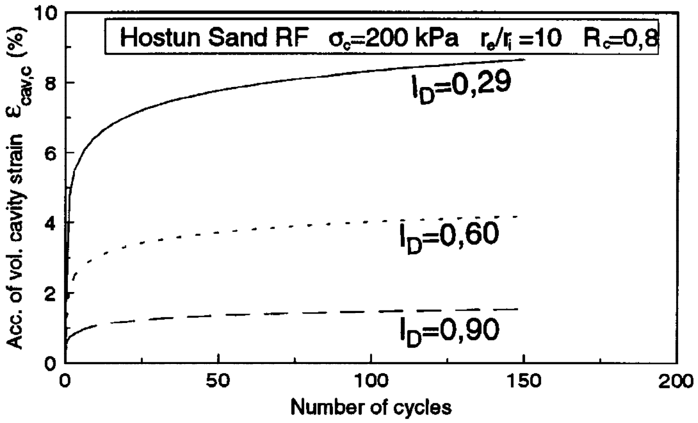

Fig. 8. Influence of relative density on cyclic drained thick cylinder tests

CONCLUSIONS

Based on the results of the thick cylinder tests presented, the following conclusions may be given:

-Strong similarities exist between the thick cylinder expansion test (non-homogenous test) and the classical triaxial test (homogenous test) in particular in terms of volumetric behaviour. The basic parameters involved in both tests, and in particular the sand density, have similar influences on the test results, which is an important point for the possible establishment of correlations between both types of tests.

-An important point concerns the increase of cavity volume during a cyclic test, which is representative of the global volumetric strain of the material around the probe. This result is interesting because it could be extended to real pressuremeter test in a sand mass, therefore allowing to develop correlations between the cyclic pressuremeter test and the liquefaction characteristics of the same material, which constitutes an intersting perspective.

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