

Evaluation of a liquefaction criterion for a loose sand

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ABSTRACT : Based on a series of static and cyclic liquefaction tests performed on a sand in the triaxial apparatus, an evaluation of the collapse surface concept, proposed by Sladen and co-authors in 1985 is presented in this communication. The collapse surface represents the location in the (q, p', e) space where liquefaction is initiated under undrained conditions. This concept, initially developed in relation with static liquefaction behaviour, is evaluated for cyclic liquefaction tests, and it seems to be also well-adapted to this type of behaviour. The concept could then allow, based on further experimental validation, to unify both phenomena (static and cyclic liquefaction) under the same criterion describing the location of points in (q, p', e) space where collapse is initiated.

1 INTRODUCTION

The phenomenon of static liquefaction is a particular mechanical instability which is characteristic of loose sands. It corresponds to an important and rapid decrease of the resistance of the material submitted to undrained shear, related to a generation of high excess pore pressures. This phenomenon has already been responsible for sometimes very large flow slides (Hazen, 1920 ; Koppejan et al., 1948 ; Terzaghi, 1956), but has only recently been reproduced in the laboratory, in the triaxial apparatus (Bjerrum, 1961 ; Castro, 1969). In particular, Castro (1969) clearly shows the influence of the density of the sand and of the type of sand on the development of static liquefaction. The influence of the isotropic consolidation stress has also been studied by others (Sladen et al., 1985 ; Canou, 1987), showing a quasi-proportional relation between the isotropic consolidation stress and the peak resistance obtained before collapse. In 1985, Sladen et al. (1985) have presented an interesting method of analysis for the prediction of the initiation of static liquefaction based on the concept of collapse surface. The purpose of the present communication is to evaluate the concept of collapse surface on a series of static liquefaction tests carried out on a specific sand, and to evaluate the applicability of the concept in the case of cyclic liquefaction tests.

2 EXPERIMENTAL SET-UP AND PROCEDURE

Both monotonic and cyclic tests have been

carried out. For monotonic tests, a classical triaxial cell is used, allowing to test samples with a diameter of 70 mm and a length to diameter ratio of 2. Electrical transducers (pressure, force and displacement) are used, allowing an automatic data acquisition during the test for subsequent processing of the data. The procedure involves the classical steps needed to perform a triaxial test on sand (saturation, consolidation), and special care is given to the measurement of void ratio, very delicate to obtain accurately, this parameter having a great importance in liquefaction studies. In order to obtain loose enough material, susceptible to liquefy ($I_d < 0,5$ or $D_R < 50\%$), the sand is placed in a wet state ($w \approx 27\%$), and compacted layer by layer. This procedure, already described by Bjerrum et al. (1961) as well as by Castro (1969), allows to obtain very loose sand structures. After saturation and consolidation, the shear test is then carried out at controlled strain rate ($\dot{\epsilon}_a = 1\%$ per minute) up to 10 or 15 % axial strain.

For cyclic tests, a different set-up is used, allowing to apply, through a servo-controlled system, a cyclic solicitation according to a preselected program (signal shape, amplitude and frequency). Except for specific details characteristic of cyclic loading, the general procedure used for sample preparation is very close to the one used for monotonic testing. The test is a force-controlled test, in which the cyclic deviator force is applied in a sinusoidal manner with a period of 60 seconds. Therefore, no dynamic effects are taken into account.

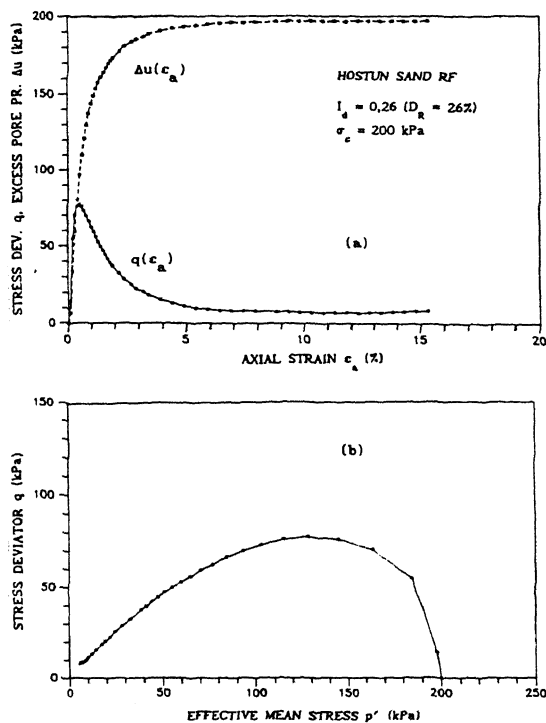


Figure 1. Typical result of static liquefaction obtained on Hostun sand RF : (a) (q, ϵ_a) and $(\Delta u, \epsilon_a)$ curves; (b) stress path in (q, p') plane

3 DESCRIPTION OF THE TESTED SAND

The sand used in this study is Hostun sand (RF), which is a silica pit sand (mostly quartz) ($D_{50} = 0,38$ mm, $e_{min} = 0,656$, $e_{max} = 1$) with relatively angular grains and with a relatively uniform grain size distribution ($C_v = 2$). This sand is a reference sand used in different french laboratories (Flavigny et al., 1990).

4 TYPICAL TEST RESULTS

A typical result of static liquefaction carried out on Hostun sand at a density index I_D of 0,26 ($D_R = 26\%$) and for an isotropic consolidation stress of 200 kPa, is presented on figure 1.

The static liquefaction behaviour is characterized by a marked low level peak of resistance ($q_p \approx 80$ kPa on the figure), obtained at low strain ($\epsilon_a \approx 1\%$), followed by a rapid decrease of the sand resistance (softening) until a residual state is reached at large strains ($\epsilon_a > 7$ to 8%), where the material keeps deforming without further noticeable evolution of its state of stress (perfect

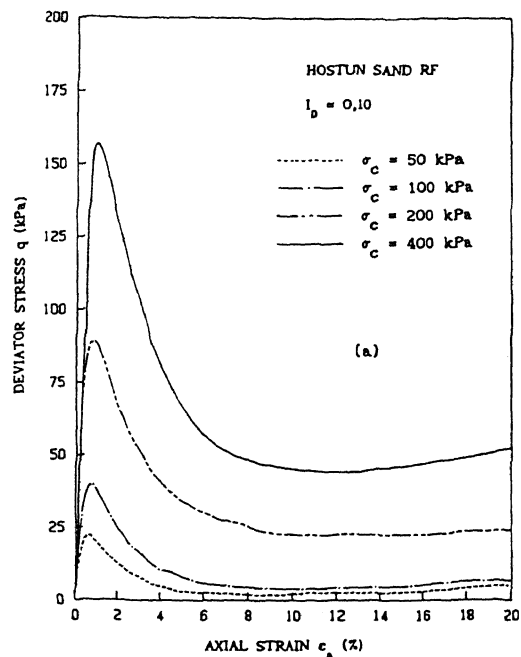


Figure 2. Influence of isotropic consolidation stress on static liquefaction development

plasticity). This particular state of the material has been called steady state by Poulos (1981), and is similar, in the case of sands, to the more classical critical state concept (Casagrande, 1976). The corresponding excess pore pressure curve presents a high initial generation rate, accounting for the highly contracting behaviour of the sand, which slowly decreases until complete stabilization is reached at the steady state.

5 INFLUENCE OF THE ISOTROPIC CONSOLIDATION STRESS ON STATIC LIQUEFACTION

The liquefaction behaviour of a sand strongly depends upon a combination of both void ratio (or density) and isotropic consolidation stress. The influence of both parameters is taken into account through the concept of state parameter ψ in the $(e, \ln p')$ plane (Been and Jefferies, 1985). Concerning the isotropic consolidation stress, figure 2 shows the influence of varying σ_c from 50 to 400 kPa on the behaviour observed.

It is interesting to note that the peak resistance obtained is quasi-proportional to the isotropic consolidation stress applied, with a proportionality coefficient of about 0,4. Also, the axial strain when the peak occurs increases with σ_c , varying from about 0,5% for $\sigma_c = 50$ kPa to 1,5% for $\sigma_c = 400$ kPa. Thus, the increase of σ_c globally decreases the risk of liquefaction

and collapse of the material. According to critical state concepts, the residual state obtained at large strains (steady state) should only depend upon the initial void ratio of the samples. From the experience gained, it is believed that the differences observed and visible on the figure must, to a great extent, be related to differences in the void ratio of the different samples tested. It is indeed very difficult to precisely anticipate the actual void ratio that will be obtained after saturation and consolidation of the samples.

6 APPLICATION OF THE COLLAPSE SURFACE CONCEPT TO STATIC LIQUEFACTION

The concept of collapse surface, introduced by Sladen et al. (1985), allows to predict the location of points in the (q, p', e) or (t, s', e) space where sample collapse will be initiated. This concept is based on the following experimental observation, done by these authors: if different samples of loose sand with the same void ratio after consolidation e_1 , are sheared in undrained conditions, starting from different levels of isotropic consolidation stress, the points representing the maxima of stress paths for the different tests, are aligned, and the straight line D_1 joining them passes through the steady state point common to the different tests (fig. 3). For another series of tests, carried out with another consolidation void ratio e_2 , a new straight line D_2 would be obtained, passing through the steady state point corresponding to e_2 , and parallel to D_1 . Therefore, when the initial void ratio of the sand varies, a set of parallel straight lines will be obtained, describing in the (q, p', e) or (t, s', e) space a cylindrical surface passing through the steady state line, and generated by all the parallel straight lines. This surface, called collapse surface by Sladen et al. (1985), represents the location of material states for which the collapse mechanism will be initiated. The slope (supposed constant) of the collapse straight lines in (t, s') plane is called α_L , their intercept with t axis being called a_L (fig. 3). Based on these characteristics, it is possible to define, in a similar way as for Mohr-Coulomb failure characteristics ϕ' and c' , two collapse parameters ϕ_L and c_L in the following manner (Sladen et al., 1985):

$$\sin \phi_L = \text{tg } \alpha_L, \quad c_L = \frac{a_L}{\cos \phi_L}$$

Sladen et al. (1985) present a relatively narrow range of variation of ϕ_L for different types of sands (14° to 18°).

The interest of the collapse surface concept is that it could allow to predict, once the surface parameters have been determined, the state of effective stresses in (q, p') or (t, s')

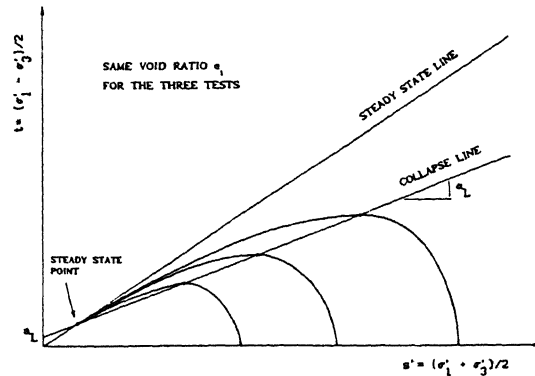


Figure 3. Schematic definition of the collapse line in (t, s') plane (after Sladen et al., 1985).

planes for which static liquefaction will be initiated. Another interest is to allow to define a zone of potentially stable initial states of the material (below the collapse surface) for which the consolidation stress is close to isotropic, and a zone of highly unstable initial states of the material, located above the collapse surface, and for which even very small increments of deviator stress applied in undrained conditions could initiate the collapse mechanism (Castro, 1969 ; Seed, 1983 ; Schlosser, 1985 ; Blondeau, 1986 ; Kramer and Seed, 1988 ; Canou et al., 1991).

Since the collapse surface concept is still relatively new, appears interesting, and has only been evaluated so far on a limited number of experimental data, we have applied this concept to the experimental program carried out on fine Hostun sand RF. Figure 4 (a and b) shows the stress paths in (t, s') plane obtained for two series of static liquefaction tests carried out at different isotropic consolidation stresses. The collapse lines have been represented for each test, passing through the maximum of the stress path, and through the corresponding steady state point. It may be observed that, for the tests considered, ϕ_L is reasonably constant, with a value of about 13°. The average value obtained, based on a relatively important experimental program carried out on Hostun sand, is 14°, which is in close agreement with the range of variation proposed by Sladen et al. (1985). The values of ϕ_L obtained for Hostun sand RF tend to confirm the interest of the collapse surface concept, on a certain range of initial void ratios (or densities), corresponding to loose states of the sand.

7 COLLAPSE SURFACE AND CHARACTERISTIC STATE

The characteristic state (Luong, 1980) or phase transformation line (Ishihara et al., 1975) represents the location, in the (q, p') or (t, s')

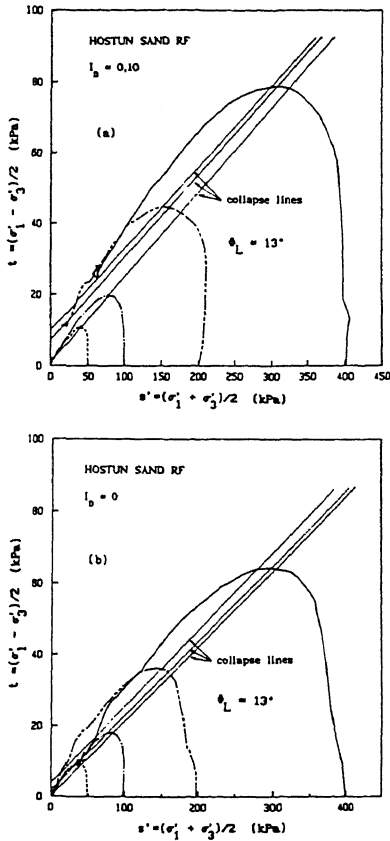


Figure 4. Evaluation of the collapse surface concept for two sets of data : (a) $I_D \approx 0,1$ ($D_R = 10\%$) ; (b) $I_D \approx 0$ ($D_R = 0\%$).

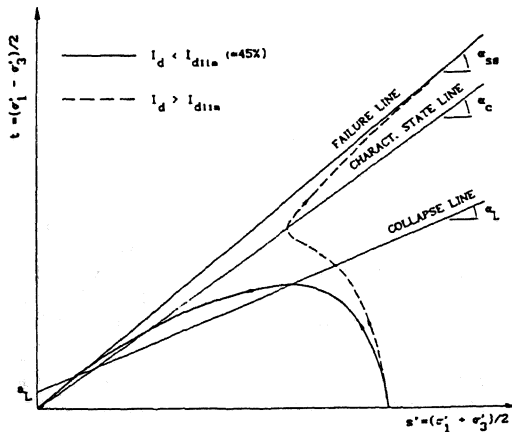


Figure 5. Complementarity of characteristic state and collapse surface concepts (schematic).

s') plane, of the material states for which the volumetric behaviour changes from contractance

to dilatance. The characteristic line allows to predict the type of behaviour that will be observed, in particular in the case of cyclic solicitations (adaptation, accommodation or ratchet), in relation with the position of the point representative of the material state with respect to the characteristic line. The concept of characteristic state is therefore applicable to sands presenting first a contractant phase followed by a dilatant phase, i.e. medium to high density materials ($I_D > 0,5$ or $D_R > 50\%$). In the case of loose or very loose sands ($I_D < 0,4$), the structure only contracts when sheared, and the characteristic state does not exist anymore (or may be considered as superposed with the failure line). For these loose sands, the mechanical behaviour in undrained conditions is essentially controlled by the collapse (at low strains) and by the constant residual state obtained at large strains. The notions of steady state (or critical state) and of collapse surface appear therefore well-adapted to the description of the behaviour of such loose sands.

The characteristic state and the collapse surface concepts thus appear as complementary concepts, allowing to describe the undrained mechanical behaviour of a sand over the whole range of possible densities for this sand. The first concept is valid for medium to dense sands ($I_D > 0,5$), the second concept being valid for loose states of the material for which the density index I_D is less than 0,4 (fig. 5). There will still exist a range of densities ($0,4 < I_D < 0,5$), for which both a slight softening of the sand, and a characteristic state (at large strains) may be observed. This transition zone corresponds to a specific behaviour called limited liquefaction (Vaid and Chern, 1985).

8 COLLAPSE SURFACE AND CYCLIC LIQUEFACTION

Cyclic undrained triaxial tests have been run on loose Hostun sand to reach liquefaction of the samples under this type of loading conditions. The samples were prepared in a similar way as for monotonic test, in order to obtain loose structures. Both isotropic and anisotropic consolidation stress states were applied to the samples. The anisotropic consolidation state is characterized by the K_c ratio, equal to : $(\sigma'_c + q_c) / \sigma'_c$, σ'_c and q_c being respectively the isotropic and deviatoric parts of the consolidation stress. The amplitude of the cyclic solicitation is characterized by the cyclic stress ratio $R_{cyc} = \Delta q_{cyc} / \sigma'_c$. The cyclic load is only compressional (no "extension" phase applied).

Figure 6 shows a typical result of cyclic liquefaction obtained for a sample consolidated

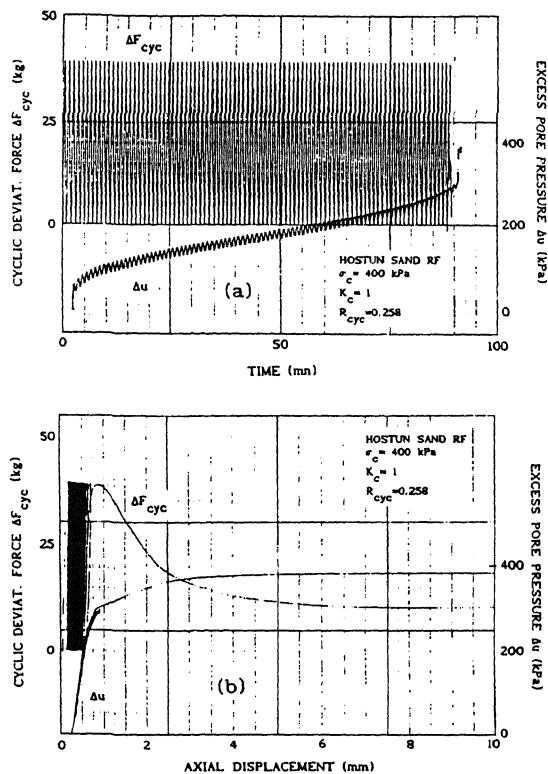


Figure 6. Typical result of cyclic liquefaction test on Hostun sand RF : (a) $\Delta F_{cyc}(t)$ and $\Delta u(t)$ (b) ΔF_{cyc} and Δu as function of deformation of sample.

Table 1. Characteristics of the cyclic liquefaction tests performed.

Test	e	I_D	σ'_c (kPa)	K_c	R_{cyc}	ϕ_L^*
C1	0,93	0,20	400	1	0,395	16,5
C2	0,86	0,39	400	1,25	0,245	17
C3	0,88	0,35	400	1,38	0,133	18,5
C4	0,90	0,29	400	1,50	0,123	16,5
C5	0,87	0,37	400	1,50	0,063	17
C6	0,90	0,29	200	2	0,100	21

Table 2. Characteristics of static liquefaction tests performed with anisotropic consolidation.

Test	S1	S2	S3	S4	S5	S6	S7
I_D	0,26	0,22	0,28	0,20	0,19	0,35	0,29
σ'_c (kPa)	200	200	200	200	200	200	200
K_c	1	1,27	1,54	1,85	1,93	2,34	2,65
ϕ_L^*	15	15,3	15,5	18,3	19,6	21,2	24,6

under an isotropic stress of 400 kPa. It can be seen that the excess pore pressure gradually increases with the number of cycles, and reaches a level at which the sample suddenly collapses. It is interesting to note that the phenomenon observed at the "critical" cycle (cycle n°89 in this case) is very similar to static liquefaction, with a sharp softening of the sample until a residual state (steady state) is reached. Such behaviour was already observed by Castro (1969), after a small number of cycles (5 to 10 cycles). Based on this observation, the idea would be to evaluate the validity of the collapse surface in the case of cyclic liquefaction. If the location of collapse points is similar for cyclic and static liquefaction, the collapse surface concept could allow to predict both types of phenomena, which would be very interesting.

Table 1 summarizes the results obtained for the cyclic tests performed. It can be seen that for isotropically consolidated samples (test n°1), ϕ_L is reasonably close (16,5°) to the value obtained for static liquefaction (14°). When the K_c coefficient increases (increase of consolidation stress anisotropy), ϕ_L seems to increase gradually, which is in good agreement with other data obtained for static liquefaction tests carried out on Hostun sand for different values of K_c (CANOU et al., 1991, see table 2), where it may be observed that ϕ_L increases from 15° to 24,6° when K_c increases from 1 to 2,65.

Therefore, the range of ϕ_L values obtained in the case of cyclic liquefaction is very consistent with the range of values obtained for static liquefaction, with an apparent influence of K_c on the ϕ_L values calculated.

9 CONCLUSIONS

The concept of collapse surface, proposed by SLADEN et al.(1985) allows with a good precision to predict the location of points in the (q, p') or (t, s') planes where static liquefaction (material collapse) is initiated. When applied to cyclic liquefaction tests, this concept seems to still correctly describe the location of collapse points, with values of ϕ_L very close for static and cyclic loading. The K_c coefficient, describing the consolidation stress anisotropy, seems to have a noticeable influence on ϕ_L values, ϕ_L increasing when K_c increases. More cyclic data will however be necessary, in order to further check the similarities between both types of tests (monotonic and cyclic), and to further validate the concept of collapse surface in an attempt to unify both phenomena (static and cyclic liquefaction).

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REFERENCES

- Been, K. and Jefferies, M.G., 1985. A state parameter for sands. *Geotechnique*, vol. 35, n°2, pp. 99-112.
- Bjerrum, L., Kringstad, S., Kummeneje, D., 1961. The shear strength of a fine sand. *Proc. 5th Intern. Conf. on Soil Mechanics and Found. Engin.*, Paris, vol. 1, pp. 29-37.
- Blondeau, F., 1986. Incidence de l'anisotropie de consolidation sur le potentiel de liquéfaction statique. Application au glissement sous-marin du port de Dunkerque. *Revue Française de Géotechnique*, n°37, pp. 72-80.
- Canou J., 1987. Etude expérimentale de la liquéfaction statique des sables lâches. Rapport de recherche CERMES - STC PMVN, n°278 238 p.
- Canou, J., Thorel, L., De Laure, E., 1991. Influence d'un déviateur de contrainte initial sur les caractéristiques de liquéfaction statique d'un sable. *Proc. 10th ECSMFE, Firenze*, vol. 1, pp. 49-52.
- Casagrande, A., 1976. Liquefaction and cyclic deformation of sands : a critical review. *Harvard Soil Mechanics Series n°88*, Harvard Univers., Cambridge, USA.
- Castro, G., 1969. Liquefaction of sands. Ph. D. dissertation, Harvard Univers., Cambridge, USA, 112 p.
- Flavigny, E., Desrues, J., Palayer, B., 1990. Note technique : le sable d'Hostun "RF". *Revue Française de Géotechnique*, n°53, pp. 67-70.
- Hazen, A., 1920. Hydraulic fill dams. *ASCE transactions*, vol. 83, pp. 1713-1745.
- Ishihara, K., Tatsuoka, F., Yasuda, S., 1975. Undrained deformation and liquefaction of sand under cyclic stresses. *Soils and Foundations*, vol. 15, n°1, pp. 29-44.
- Koppejan, A.W., Wamelen, B.M., Weinberg, L.I.H., 1948. Coastal flow slides in the dutch province of Zeeland. 2nd ICSMFE, Rotterdam.
- Kramer, S.L. and Seed, H.B., 1988. Initiation of soil liquefaction under static loading conditions. *JGED, ASCE*, vol. 114, n°4, pp. 412-431.
- Luong, M.P., 1980. Phénomènes cycliques dans les sols pulvérulents. *Revue Française de Géotechnique*, n°10, pp. 39-53.
- Poulos, S., 1981. The steady state of deformation. *JGED, ASCE*, vol. 107, GT5, pp. 553-562.
- Schlösser, F., 1985. Liquéfaction de veines de sable lâche dans des talus sous-marins. 11th ICSMFE, San Francisco.
- Seed, H.B., 1983. The slide at the Port of Nice. Special lecture. *Offshore Techn. Conf.*, Houston.
- Sladen, J.A., d'Hollander, R.D., Krahn, J., 1985. The liquefaction of sands, a collapse surface approach. *Can. Geot. Journ.*, vol.22, pp. 579-588.
- Terzaghi, K., 1956. Varieties of submarine slope failures. *Harvard Soil Mech. Series n°52*, Harvard Univ., Cambridge, USA.
- Vaid, Y.P. and Chern, J.V. 1985. Cyclic and monotonic undrained response of saturated sands. *Proc. ASCE convention on "Advances in the art of testing soils under cyclic loading"*, pp. 120-147.