Application of strain approach for investigation of post-initial liquefaction behaviour of soils

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ABSTRACT: The problem of liquefaction of soils has been, generally, investigated applying the so-called stress approach, so far. The laboratory tests, by this approach, enable investigation until the occurrence of initial liquefaction, while, after that, the investigation of the problem is limited. However, the problem of soil liquefaction can be, as well, investigated by the so-called strain approach. The objective of this paper is to consider the possibilities for application of this approach for investigation of the complete process of liquefaction, including the post-initial liquefaction part.

1. INTRODUCTION

For determination of the liquefaction potential by laboratory tests it is regular practice to use a cyclic excitation with constant stress amplitudes. The dynamic strength of soil is usually expressed in terms of stress $\tau$ or stress ratio $R_T = \tau/\sigma_0'$ and the number of cycles $N$ producing initial liquefaction. In the expression for $R_T$, $\sigma_0'$ is the initial stress. The details for this kind of tests, defined as tests with stress approach, can be frequently found, particularly in Seed (1979), Ishihara (1985) and Committee (1985).

It is a rare practice the laboratory tests for determining of the liquefaction potential to be performed by application of cyclic excitation with constant strain amplitudes $\gamma$. By this approach, defined as strain approach, the liquefaction parameters are expressed in terms of $\gamma$ and the number of cycles $N$, producing characteristic state in the liquefaction process. The approach and result details can be found in Fann (1981), Dobry (1982), Committee (1985) and Talaganov (1986).

It is a regular practice to determine the initial liquefaction state, defined as first occurrence of $U = \sigma_0'$ ($U$ is pore pressure), when testing by both approaches. Very rarely, tests continue until the occurrence of a certain shear strain level.

But, it is evident that all investigations carried out until the occurrence of initial liquefaction do not encompass the liquefaction process completely. The process continues after the occurrence of the initial liquefaction and can be defined as post-initial liquefaction process. Due to the relation of this process with the liquefaction consequences, it is considered to be of special importance. Because of that, and due to the need to investigate the liquefaction phenomenon completely, it is necessary that the laboratory tests include the post-initial liquefaction part as well.

It seems that by application of the shear strain approach the investigation of the whole liquefaction process, which means the post-initial liquefaction part as well, can be successfully performed. For that purpose herein are analysed the possibilities and the advantages of investigations with shear strain approach and are presented the results of performed investigations within a longterm research project, realised in the Institute of Earthquake Engineering and Engineering Seismology in Skopje.

2. CHARACTERISTICS OF CYCLIC STRESS TESTS

In the cyclic stress tests, water saturated and undrained sand samples are subjected to cyclic excitation with controlled shear stress amplitude $\tau$, which is varied from test to test. As a result of the cyclic excitation the pore pressure $U$ increases, while, equivalent to that, the initial effective stress decreases.

Usually, the tests are performed until the first occurrence of $U = \sigma_0'$ (or $\sigma' = 0$, where $\sigma'$ is effective stress) defined as initial liquefaction. The number of cycles $N_i$ for occurrence of initial liquefaction depends on the relative density of the sample $D_r$.

Typical results from this kind of tests...
for two different $D$, for loose and dense sands are shown in Fig.1 and Fig.2. The results present the given cyclic excitation $\tau$, the development of the shear strain $\gamma$ and the development of the pore pressure $U$.

If we analyze the obtained results, especially those close to the occurrence of the initial liquefaction, certain characteristic phenomena can be observed. The pore pressure appears to be cyclic. In further considerations the maximal value of the pore pressure in each cycle will be marked with $U$, and the minimal one with $U_{\text{min}}$. Consequently $\sigma'$ is cyclic as well.

Due to the fact of $U$ being cyclic, the first appearance of $\sigma = \sigma_0$ is only for one moment of the time, so after that the pore pressure falls to $U_{\text{min}}$. In the next cycle appearance of $\sigma = \sigma_0$ is repeated, and so on.

![Fig.1: Records of Cyclic Stress Tests of Loose Sand](image)

![Fig.2: Records of Cyclic Stress Tests of Dense Sand](image)

...grows moderately. It is characteristic that in this case the difference between $U$ and $U_{\text{min}}$ is rather big in comparison to the one in the case of loose sands, which directly influences the relationships $\tau - \gamma$ as well. In this case they are with very much expressed hardening effects.

3. CHARACTERISTICS OF CYCLIC STRAIN TESTS

In the cyclic strain tests, water saturated and undrained sand samples are subjected to cyclic excitation with controlled shear strain amplitude $\gamma$, which is varied from test to test.

In this case as well, the pore pressure starts to grow as a result of the cyclic excitation, while the initial effective stress $\sigma'_0$ decreases, so that the effective stress $\sigma'$ gets lower and lower values. As a result of that the initial shear stress $\tau_0$, as well starts to decrease getting smaller values $\tau$. That means that the application of the shear strains with constant amplitudes $\gamma$ causes shear stresses which are in accordance with the characteristics of the material. Equivalently to the softening of the material the $\tau$ decreases. Due to that, close to the moment of the initial liquefaction occurrence, which in this case as well can be defined as first occurrence of $\sigma' = 0$ (or $U = \sigma'_0$), no dramatic phenomena take place, so that the test can normally be continued in the post-initial liquefaction part.

For illustrating these characteristics of the cyclic shear strain tests in Fig.3 and Fig.4 are presented typical results. The results were obtained from the tests performed on
equipment for cyclic simple shear tests. The tests were performed on dry sand with a procedure of constant volume. In this procedure, due to the constant volume and the application of cyclic shearing, appears a decrease of $\sigma_0'$, i.e. of $\sigma'$. This decrease of $\sigma'$ can be taken as equivalent to the increase of $U$ in water saturated undrained tests.

In Fig. 3 and Fig. 4 are shown the time histories of $\tau$, $\gamma$ and $U$, as well as the relationships $\tau - \gamma$, for loose and dense sands. It can be noted that the increase of the pore pressure is cyclic, with occurrence of maximal amplitudes $U$ and minimal $U_{\text{min}}$ and with a double frequency in comparison to the excitation frequency. But, the difference between $U$ and $U_{\text{min}}$ for loose sand is much smaller than the one for dense sand. The excitation amplitude $\gamma$ in both cases is equal and is $\gamma = 1\%$. The initial liquefaction for both kinds of sand becomes for $N_f = 2x3$. After the occurrence of initial liquefaction at loose sand the cyclic nature of the pore pressure rapidly weakens and $U_{\text{min}}$ reaches the value of $\sigma_0'$. The pore pressure transforms itself into a constant one with value equal to $\sigma_0'$. In a case of dense sand after the occurrence of initial liquefaction the pore pressure is still cyclic and keeps the value of $U = \sigma_0'$, while $U_{\text{min}}$ gradually but permanently approaches that value. Almost after more than 50-60 cycles $U_{\text{min}}$ practically reaches the value of $U_{\text{min}} = \sigma_0'$, while the pore pressure from cyclic transformations into constant.

The discussed characteristics of the pore pressure increase reflect the characteristics of the $\tau - \gamma$ relationship. It can be seen that the amplitudes $\tau$ decrease from cycle to cycle.

For loose sand the $\tau - \gamma$ relationships are of softening type. Almost immediately after the occurrence of initial liquefaction the $\tau - \gamma$ transforms into horizontal line, expressing a complete reduction of the shear strength in the soil.

For dense sands the $\tau - \gamma$ relationships are of the hardening type. After the occurrence of initial liquefaction the shear resistance of the soil is considerably decreased, but it still exists. The cyclic shearing in the post initial liquefaction phase causes further reduction of the shear resistance of the soil. The shear stress amplitudes $\tau$ continue to decrease. The relationship $\tau - \gamma$ approaches to horizontal line. That means that there is a tendency for complete reduction of the shear strength of the soil.

These transformations of the $\tau - \gamma$ relationships results in decreasing of secant G moduli and the hysteretic damping of the soil from cycle to cycle. The decreasing continues even after the initial liquefaction phase when the $\tau - \gamma$ transformations and increase of $U_{\text{min}}$ can be observed.

4. COMMENTS OF THE RESULTS

From the results presented in Fig. 3 and Fig. 4 we shall first comment the pore pressure increase. For that purpose in Fig. 5 is presented an idealized picture of the pore pressure development which corresponds to midium dense sand.

It can be noted that in the development process of the pore pressure, two moments are specially characteristic. The first one is the moment of the first occurrence of $U = \sigma_0'$. That happens in the cycle $N_f$. The second one is the moment when the pore pressure from cyclic transformations into a constant one. That happens in the cycle $N_{\text{LL}}$ when $U_{\text{min}}$ reaches the va-
If we use the conventional definitions, in the cycle $N_L$ occurs initial liquefaction, while in the cycle $N_{LL}$ occurs total liquefaction. From this results the conclusion that the cycles $N_L$ and $N_{LL}$ divide the liquefaction process into the following three phases: pre initial liquefaction with duration until $N_L$, post initial liquefaction which starts with $N_L$ and ends with $N_{LL}$, and post-total liquefaction which occurs after $N_{LL}$. These definitions, of course, are based on the laboratory results obtained by undrained tests (constant volume tests), when a dissipation of the pore pressure was prevented.

We can now comment the results from Fig.3 and Fig.4, from the viewpoint of these definitions. For loose sand ($D_r < 35-40\%$), the difference between $N_L$ and $N_{LL}$ is very small. It means that immediately after the occurrence of initial liquefaction a total liquefaction takes place. The duration of the post initial liquefaction phase is very small. On the contrary, for dense sand ($D_r > 75-80\%$) $N_{LL}$ is many times bigger than $N_L$ ($N_r > 3$, $N_{LL} > 50-60$). The duration of the post initial liquefaction phase is much bigger in comparison to the preinitial liquefaction phase. It can be concluded that in very loose sand there is a tendency of having $N_L = N_{LL}$, while for very dense sand there is tendency of $N_{LL}$ reaching a very big number. It can also be concluded that the difference between $N_{LL}$ and $N_L$ increases with the increase of $D_r$.

Based on the presented definitions can be commented the other parameters as well, shown in Fig.3 and Fig.4.
The shear stress amplitudes \( \tau \) decrease from cycle to cycle. If we mark with \( \tau_L \) the value of \( \tau \) in the cycle \( N_L \), then, although greatly reduced, \( \tau_L \neq 0 \). As boundary case appears very loose sand, for which \( \tau_L \) tends towards 0. In the post initial liquefaction phase \( \tau \) continues to decrease. If with \( \tau_L \) we mark \( \tau \) in the cycle \( N_L \), then \( \tau_L \) tends towards 0.

The effective pressure \( \sigma' \) has characteristic equivalent to the pore pressure. It means that it appears as cyclic one. If we mark the minimal value in one cycle with \( \sigma' \) and the maximal one with \( \sigma'_{\max} \), then in the cycle \( N_L \) are \( \sigma' = 0 \) and \( \sigma'_{\max} \neq 0 \). In the cycle \( N_L \), the \( \sigma'_{\max} \) tends towards 0. Again at very loose sand \( \sigma'_{\max} \) tend towards 0.

The relationships \( \tau \sim \gamma \), as well, reflect the discussed characteristics, i.e. definitions. From cycle to cycle they transform, when permanent "rotation" with approaching towards the \( \gamma \)-axis appears. But, in the cycle \( N_L \) still exists non-linear relationship \( \tau \sim \gamma \). In the post initial liquefaction phase the transformation continues with tendency the \( \tau \sim \gamma \) to transform in a horizontal line in the cycle \( N_L \). An exception are again the very loose sands for which the transformation in a horizontal line happens in the cycle \( N_L \). On the contrary, in the case of very dense sands the transformation in a horizontal line does not come into realization in total.

From the transformation of the relationships \( \tau \sim \gamma \) results, as well, equivalent transformation of the secant shear moduli \( G \) and the hysteretic damping \( D \). They decrease from cycle to cycle, but in the cycle \( N_L \) retain finite nonzero values. The decrease ends in the cycle \( N_L \) in which \( G \) and \( D \) tend towards 0. Again exceptional are the very loose sands, for which that happens in the \( N_L \) cycle, and the very dense sands for which it does not appear in total.

By statistical processing of the results can be defined a number of relationships of the liquefaction parameters in accordance with the previous discussion. Some of those parameters are presented in Talaganev (1989) and Talaganev (1991). In Fig.6, for illustration, is presented the relationship between the amplitudes \( \gamma \) and the number of the cycles \( N_L \) which cause initial liquefaction. Different from the relationships \( R_L \) and \( H_L \) of the cyclic stress tests, which also depend on \( D_L \), the relationship between \( \gamma \) and \( N_L \) is not much sensitive to \( D_L \).

5. CONCLUSIONS

From the laboratory results obtained from cyclic strain test it follows that the process of liquefaction develops even after the occurrence of initial liquefaction. In that phase, which can be defined as post initial liquefaction phase, the pore pressure has a tendency of transforming itself from cyclic into a constant one with a level \( \pi = \sigma'_{\max} \), while the shear resistance of the soil tends towards a complete reduction. Due to that, there is a need of a complete investigation of the liquefaction process, when it should be included the post initial liquefaction phase as well. The results show that by cyclic strain test the complete liquefaction process can be successfully investigated including the post initial liquefaction phase.

REFERENCES


