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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 applaing 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 τ or stress ratio $R_\tau = \tau/\sigma_o'$ and the number of cycles N producing initial liquefaction. In the expression for R_τ , σ_o' 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 γ . By this approach, defined as strain approach, the liquefaction parameters are expressed in terms of γ and the number of cycles N, producing characteristic state in the liquefaction process. The approach and result details can be found in Finn (1981), Dobry (1982), Committee (1985) and Talaganov (1986).

It is a regular practice to detetmine the initial liquefaction state, defined as first occurrence of $U=\sigma_o'$ (U is pore pressure), when testing by both approaches. Very rearly, 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 postinitial 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 weel, 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 τ , 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 $U=\sigma_o'$ (or $\sigma'=0$, where σ' is effective stress) defined as initial liquefaction. The number of cycles N_L for occurrence of initial liquefaction depends on the relative density of the sample Dr.

Typical results from this kind of tests

for two different D_r, for loose and dense sands are shown in Fig.1 and Fig.2. The results present the given cyclic excitation τ, the development of the shear strain γ and the development of the pore pressure U .

If we analize 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_{min}. Consequently σ' is cyclic as well.

Due to the fact of U being cyclic, the first appearance of $U = \sigma'_0$ is only for one moment of the time, so after that the pore pressure falls to U_{min}. In the next cycle appearance of $U = \sigma'_0$ is repeated, and so on.

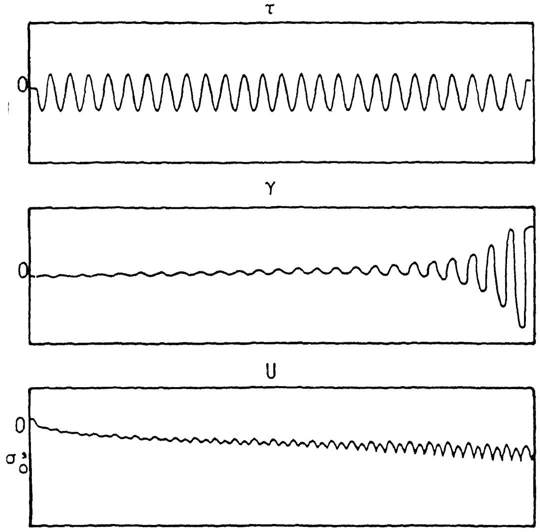

Fig.1 Records of Cyclic Stress Tests of Loose Sand

In the case of loose sands as in Fig.1, with the occurrence of initial liquefaction γ starts to grow rapidly with tendency to reach uncontrolled values. For that reason the experiment, practically, cannot continue. This is especially evident from the relationships $\tau - \gamma$. They show that with the occurrence of the initial liquefaction the shear resistance of the material reduces to a great extent. Under such conditions the excitation amplitude τ appears to be too big and the experiment must be stopped. In many cases, after the occurrence of initial liquefaction, the full value of τ cannot be practically applied any longer.

In the case of dense sands as in Fig.2, with the occurrence of initial liquefaction, γ does not grow rapidly, but it still

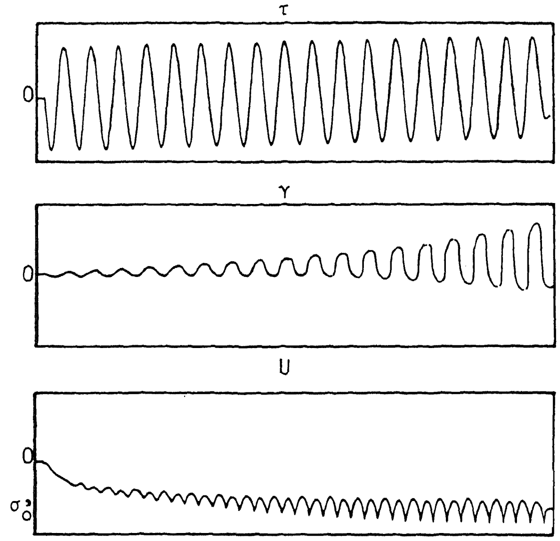

Fig.2 Records of Cyclic Stress Tests of Dense Sand

grows moderately. It is characteristic that in this case the difference between U and U_{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 γ , 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 σ'_0 decreases, so that the effective stress σ' gets lower and lower values. As a result of that the initial shear stress τ_0 , as well starts to decrease getting smaller values τ That means that the application of the shear strains with constant amplitudes γ causes shear stresses which are in accordance with the characteristics of the material. Equivalently to the softening of the material the τ 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 of 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

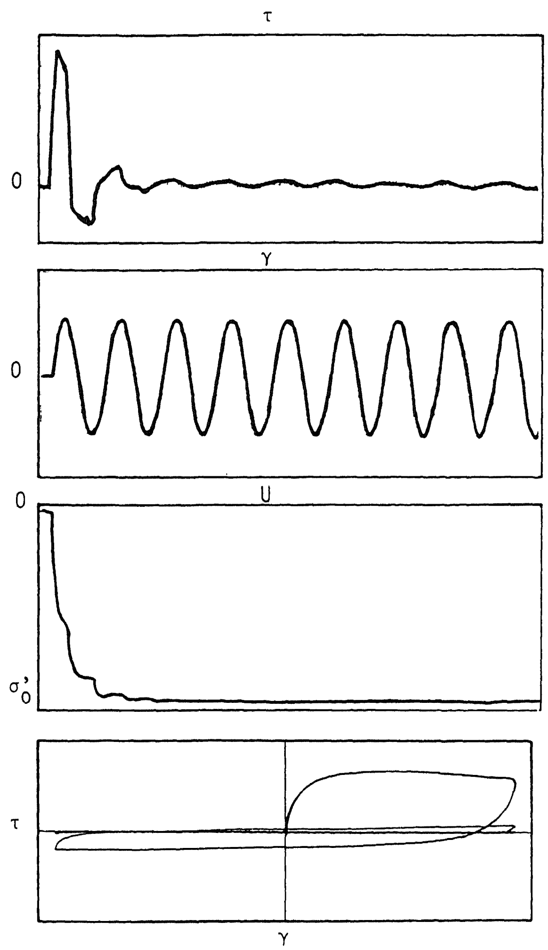

Fig.3 Records of Cyclic Strain Tests of Loose Sand

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 σ_0', i.e. of σ'. This decrease of σ' 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 τ, γ 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_{min} and with a double frequency in comparison to the excitation frequency. But, the difference between U and U_{min} for loose sand is mush smaller then the one for dense sand. The excitation amplitude γ in both cases is equal and is γ = 1%. The initial liquefaction for both kinds of sand becomes for $N_L = 2 \div 3$. After the occurrence of initial liquefaction at loose sand the cyclic nature of the pore pressure rapidly weakens and U_{min} reaches the value of σ_0'. The pore pressure transforms itself into a constant one with value equal to σ_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_{min} gradually but permanently approaches that value. Almost after more than 50-60 cycles U_{min} it practically reaches the value of $U_{min} = \sigma_0'$, while the pore pressure from cyclic transforms 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 τ decrease from cycle to cycle.

For losse 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 τ 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 histeretic damping of the soil from cycle to cycle. The decreasing continues even after the initial liquefaction with a tendency towards complete reduction.

From the viewpoint of the possibilities of testing by cyclic strain approach, based on the discussed characteristics of the results it can be concluded that the tests can be performed in the post initial liquefaction phase when the $\tau - \gamma$ transformations and increase of U_{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_L. The second one is the moment when the pore pressure from cyclic transforms into a constant one. That hapens in the cycle N_{LL}, when U_{min} reaches the va-

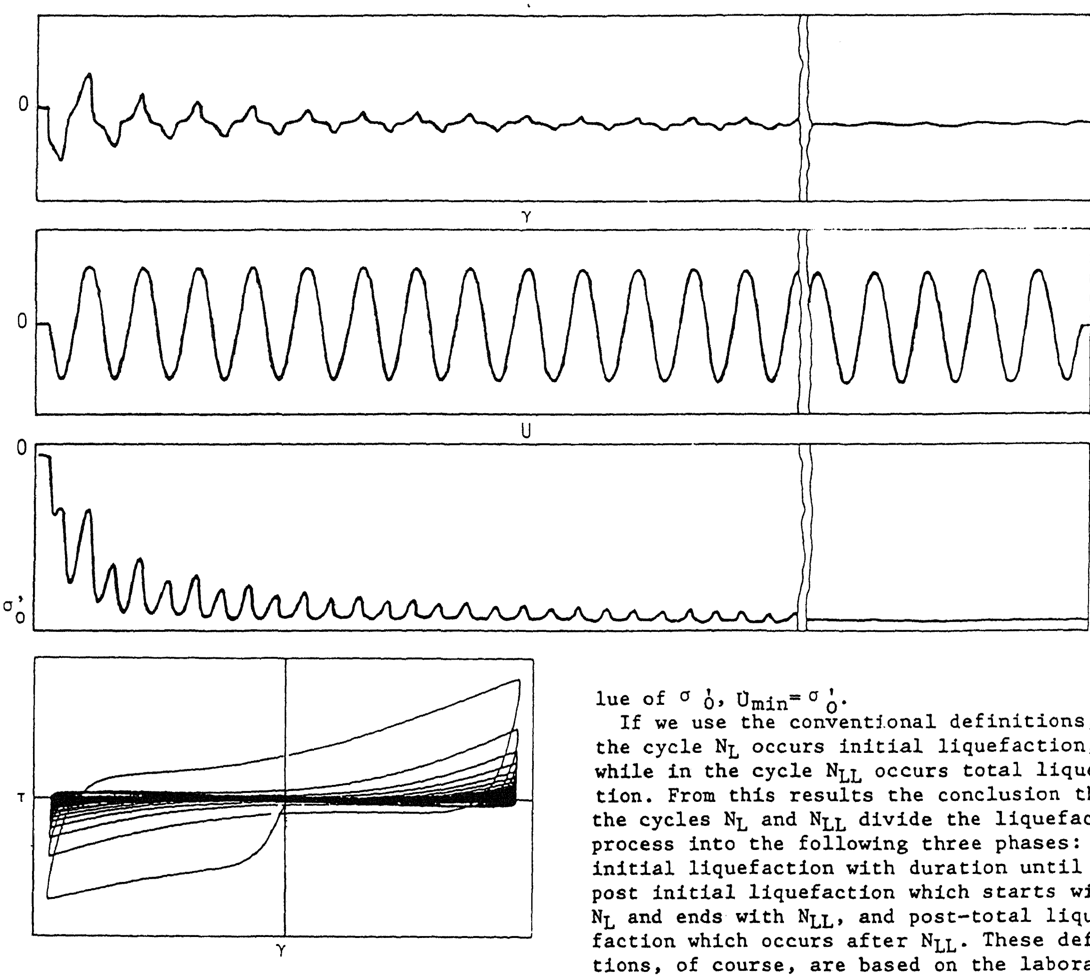

Fig.4 Records of Cyclic Strain Tests of Dense Sand

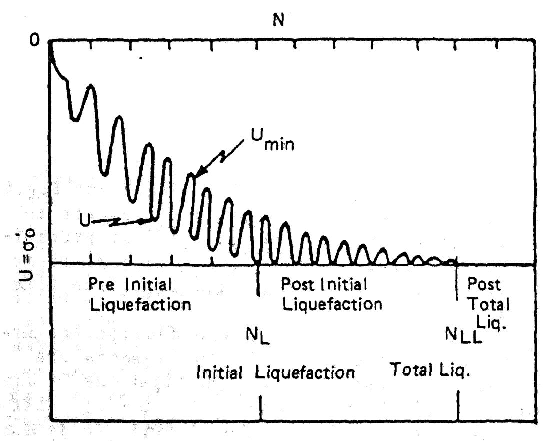

Fig.5 Commens of the Results of the Cyclic Strain Tests

lue of σ'_0, $U_{min}=\sigma'_0$.

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_L=3, N_{LL} > 50-60). The duration of the post initial liquefaction phase is much bigger in comparison to the pre-initial 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 τ decrease from cycle to cycle. If we mark with τ_L the value of τ in the cycle N_L, then, although greatly reduced, $\tau_L \neq 0$. As boundary case appears very loose sand, for which τ_L tends towards 0. In the post initial liquefaction phase τ continues to decrease. If with τ_{LL} we mark τ in the cycle N_{LL}, then τ_{LL} tends towards 0.

The effective pressure σ' 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 σ' and the maximal one with σ'_{max}, then in the cycle N_L are $\sigma'_L = 0$ and $\sigma'_{max,L} \neq 0$. In the cycle N_{LL} the $\sigma'_{max,LL}$ tends towards 0. Again at very loose sand $\sigma'_{max,L}$ tend towards 0.

The relationships $\tau - \gamma$, as well, reflect the discussed characteristics, i.e. definitions. From cycle to cycle they transform, when permenant "rotation" with approaching towards the γ-axis appears. But, in the cycle N_L still exists non-linear relationship $\tau - \gamma$. In the post initial liquefaction phase the transformation continues with tendency the $\tau - \gamma$ to transform in a horizontal line in the cycle N_{LL}. 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 $\tau - \gamma$ results, as well, equivalent transformation of the secant shear moduli G and the histeretic 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_{LL} 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 Talaganov (1989) and Talaganov (1991). In Fig.6, for illustration, is presented the relationship between the amplitudes γ and the number of the cycles N_L which cause initial liquefaction. Different from the relationships R_τ and N_L of the cyclic stress tests, which also depend on D_r, the relationship between γ and N_L is not mush sensitive to D_r.

5. CONCLUSIONS

From the laboratory results obtained from cyclic strain test it folows 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 $U = \sigma'_0$, 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 cyn be successfully investigated including the post initial liquefaction phase.

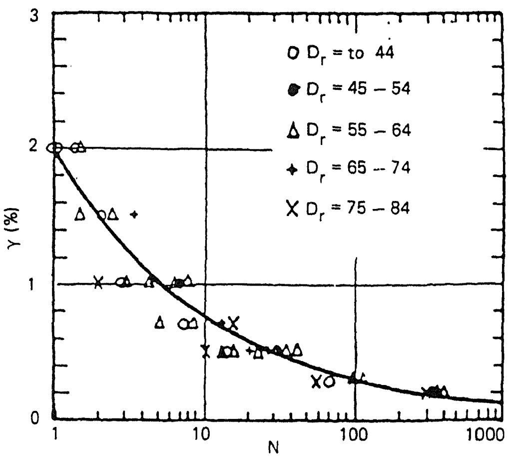

Fig.6 Relationship of Shear Strain Amplitude γ and Number of Cycles NI Producing Initial Liquefaction

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