# THE GENERATION OF PORE PRESSURES IN CLAYEY SOILS DURING EARTHQUAKES

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## SYNOPSIS

Recent construction tendency in the world has obliged several major structures to be built on cohesive soils. Thus, structures on clayey soils, undergoing repeated stresses from earthquakes, have been subject to consequences of porewater pressure increase resulting in large deformations and failure.

In order to investigate the dynamic behavior of cohesive soils under earthquake loads, samples from a kaolin clay produced in the laboratory, under carefully controlled conditions were tested under stress controlled cyclic loading. The slurry consolidation technique provided the production of reasonably homogeneous and reproducible bulk samples, thus enabling to study the dynamic properties of cohesive soils independent of the variation in their index properties.

Different samples consolidated under isotropic triaxial conditions were subjected to cyclic loading under undrained conditions and the generation of pore water pressure, with number of cycles, has been determined.

The effects of different cyclic strain rates, on pore water pressure generation in clayey soils have been thus assessed experimentally. This behavior is attempted to be evaluated in terms of strain dependent character of cohesive soils.

## INTRODUCTION

Recently major structures, such as off-shore gravity oil tanks, nuclear power plants and pipelines etc., are being built on cohesive soils and soft clayey marine deposits, with certain undesirable properties. Thus, structures on clayey soils, undergoing vibrations from earthquakes and wave action, were subject to the consequences of soil failure due to pore pressure increases and large deformations.

Results of the intensive research activities in the past decade have shown that a decrease in strength and moduli properties is observed when cohesive soils are subjected to cyclic loading. Accumulation of plastic strains and pore pressure build-up with increasing number of repetitive load cycles, has been subject of extensive experimental investigation.

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However, we are still far away from reaching to a clear understanding on the dynamic behavior of cohesive soils in general, and building up of excess pore pressures under cyclic stresses, in particular. Among the results reported in literature there are several seemingly divergent and sometimes contradictory conclusions. This is probably due to the fact that individual test programs are normally restricted to one soil tested in a specific manner over a limited range of variables, and the reconciliation of these apparently contrasting conclusions may often be found in the rate (frequency) of loading, heterogeneity of samples tested, method of sample preparation, pore pressure measurement technique, or some other analogous factor.

In this paper, results of some stress controlled cyclic triaxial tests on samples of laboratory prepared kaolin clay are reported and the effect of frequency of cyclic loading on the generation of excess pore pressures has been investigated.

## SAMPLE PREPARATION

In order to minimize the effects of factors such as heterogeneity, stress history, moisture-content variation, initial fabric, pore fluid chemistry etc., the soil specimens tested under cyclic loading were trimmed from laboratory prepared kaolin samples. Such factors are usually recognized to be of prime importance in the expected dynamic behaviour of clayey soils, and in order to be able to investigate frequency dependence, for instance, one should use test specimens in which all these factors are either kept constant or independently measured. Even if such measurements were made, the analysis of test results with so many variables will be greatly difficult and a large number of test results will be required. Where as, when the side factors are kept constant, the effect of the factor under investigation will be more clearly pronounced and meaningful conclusions may be reached (with a much less number of tests).

In this investigation, clay samples were produced by consolidating high water-content slurries in a special slurry consolidometer (1). The initial water content of the slurries were chosen to be same at $w_i$=250%, a clean kaolin clay powder and distilled water was used in the preparation of the slurries, and same incremental loading path was applied during consolidation. This sample preparation technique provided the production of reasonably homogeneous and reproducible bulk samples. At this stage of the investigation, the final consolidation pressure was chosen to be 1.0 $kg/cm^2$ and kept constant for all samples. The final water content of the bulk samples were about $w_f$ = 36 % (± 1.0 %) and they were highly saturated ($S_{ave.}$ = 95 % ± 2.0 %). Triaxial test specimens of 5.0 cm. diameter and 10.0 cm. height were trimmed from the bulk samples with great caution and reconsolidated in the triaxial chamber under 1.0 $kg/cm^2$ effective consolidation pressure. The average undrained shear strength of the samples were found to be $S_u$ = 0.40 $kg/cm^2$ (± 0.02 $kg/cm^2$). The index properties of Kaolin clay used are,

$$w_L = 60\ \%,\ w_p = 25\ \%,\ I_p = 35\ \%$$

$$\gamma_s = 2.68\ gr/cm^3, \qquad \text{clay fraction} = 32\ \%$$

## CYCLIC TRIAXIAL TESTS

Stress controlled cyclic triaxial tests were carried out on specimens crimmed from slurry prepared kaolin samples. Tests specimens were 5.0 cm. in diameter and 10.0 cm. in height. Drainage from both top and bottom was provided, and vertical filter drains surrounding the specimen were used. After isotropic consolidation was completed and full saturation ensured, undrained cyclic triaxial tests were carried out with pore pressure measurements from the bottom of the specimen. During the cyclic loading applied dynamic stresses, axial deformations and pore pressures were continiously recorded. Tests at several dynamic stress ratios ($\sigma_d/S_u$) with two different loading frequencies (f= 0.10 Hz and 0.01 Hz) were carried out using sinusoidal cyclic loading.

## EXPERIMENTAL RESULTS

The results of the cyclic triaxial are usually represented with cyclic strength curves as shown in Figure 1 (2, 4, 6). Points along these strength curves show the dynamic stress ratios causing a predetermined strain level to be reached after the corresponding number of cycles of stress repetitions.

The solid line in Figure 1 is obtained from tests with 0.10 Hz frequency, and the broken line from tests with 0.01 Hz frequency. Both strength curves correspond to 10 % peak-to-peak axial strain level ($\varepsilon_a$=10 %). It is observed from Fiqure 1 that there is a strong frequency dependency in accumulation of strains under cyclic loading. Longer the duration of loading per cycle (lower the frequency) it is sooner that a certain strain level is reached.

In Figure 2, the generation of pore water pressures as observed in the cyclic triaxial tests, are given. Again, the solid lines represents the results of tests with 0.10 Hz frequency, and broken lines show the results of tests with 0.01 Hz frequency. In the generation of pore pressures the frequency dependency is even more pronounced.

In the lower frequency tests the rate of increase in the pore water pressure with number of cycles is much larger than in the higher frequency tests. In a few pilot tests run on samples of same kaolin clay with 1 Hz frequency, the generation of pore water pressures did amount to only a small fraction of the values observed in slower tests.

## EVALUATION OF EXPERIMENTAL RESULTS

Experimentally observed behavior of the clay samples tested in this investigation were consistent with the expectations and with the results of certain other investigators (4,6,7). Because of their strain dependency, and that clayey soils do exhibit creep behavior under loads, cyclic loading conditions that produce the longer duration of sustained load per cycle is expected to lead to accumulation of strains more rapidly.

Since the generation of excess pore pressures is fundamentally a strain dependent phenomena rather than a stress dependent process, cyclic loading with lower frequency will also generate excess pore pressures in fewer cycles than higher frequency loadings. The experimentally determined frequency dependency both in strain accumulation and pore pressure generation is very clear and it is free of almost all other side factors such as loading history, sample heterogeneity, method of sample preparation, soil fabric, etc.

It is observed that a series of low frequency stress pulses which is only a small fraction of the undrained shear strength of a clay soil, may induce a substantial increase in pore water pressures. The accompanying reduction in the effective stresses may cause a resumption of creep movements in a soil which was formerly in equilibrium,

The rate of increase in the pore water pressure (u) with number of cycles (N) of loading, might be expressed with a phenomenological relationship of the type:

$$\dot{u} = \frac{du}{dN} = A'k(t)\ e^{\alpha S}$$

where, k(t) is a time (frequency) dependent coefficient,
A and $\alpha$ are constants,
S is the stress level.

Similar relationship have been used in the past to express time rate of deformations in undrained creep tests, and when the coefficient k(t) is defined as $k(t) = (t_1/t)^m$, the experimentally observed time dependency is shown to be in good agreement with the behavior predicted by this expression (3,5). The exact from of the coefficient k(t) to be used in defining the frequency dependency in the rate of increase in pore pressure under repetitive loading is currently under investigation.

## CONCLUSIONS

Accumulation of plastic strains and pore pressure build-up in cohesive soils with increasing number of repetitive load cycles is quite a complex phenomena and there is still need for further experimental and theoretical research to thoroughly understand the effect of several different factors. In this experimental investigation, the effect of frequency of cyclic loading on the generation of pore pressures in cohesive soils has been studied. Dynamic triaxial compression tests are carried out on specimens trimmed from laboratory prepared kaolin samples. The slurry consolidation technique is used to prepare reasonably homogeneous samples with controlled clay mineral, pore water chemistry, loading history and initial fabric. The cyclic triaxial samples at several stress ratios, with two different loading frequencies, provided the means to investigate the frequency dependent behavior.

It has been experimentally observed that, the longer the duration of sustained load per cycle, the higher is the rate of increase of pore pressure with number of cycles of repetitive loading. This behavior is thought to be similar to creep type behavior observed in cohesive soils under sustained loading.

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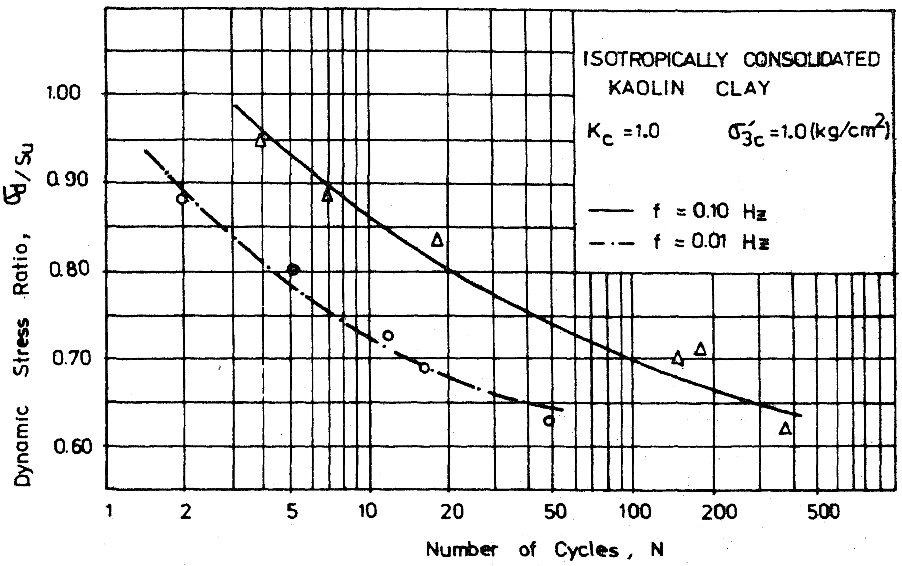


FIGURE: 1 - EFFECT OF FREQUENCY OF LOADING ON CYCLIC STRENGTH OF KAOLIN CLAY

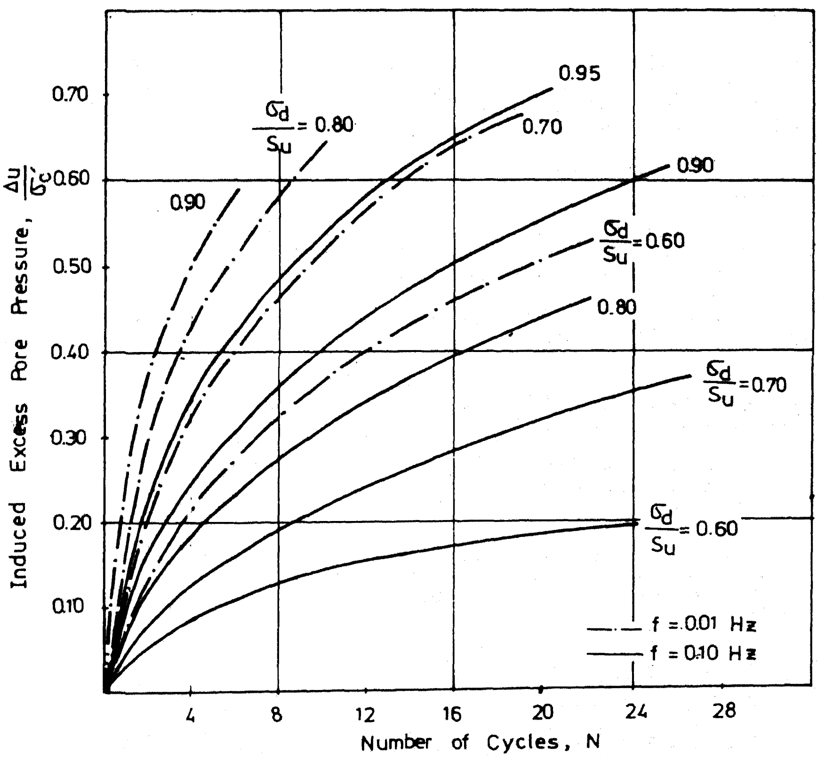


FIGURE: 2 - EFFECT OF FREQUENCY OF LOADING ON PORE PRESSURE GENERATION IN KAOLIN CLAY