04 Apr 1995, 10:30 am - 12:00 pm

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Proceedings: Third International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, April 2–7, 1995, Volume I, St. Louis, Missouri

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Paper No. 1.62

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SYNOPSIS There are a tremendous studies in literature about the earth pressure,most of them are concentrated on the static loading conditions.The problems of earth pressure under dynamic loadings are still the case of studies. In this paper the results of an experimental studies about variations of earth pressure at rest under different vertical cyclic loadings are presented. Cubical soil samples of 15 cm. dimensions were subjected to vertical cyclic stresses and induced lateral pressure behind the rigid side walls of the soil were measured accurately. A dry and uniform sand was used and the samples were prepared by the raining technique. A kind of true triaxial apparatus was used and different samples in the quite dense and loose conditions were tested. The variations of lateral pressure versus vertical stress and number of load cycles are plotted and discussed. In the concluding section a recommendation is made for designing retaining walls under cyclic surcharges.

INTRODUCTION

The relation between vertical and lateral stresses in a soil element has been studied experimentally and theoretically by many researchers. In the early stages the application of elasticity theory to soil elements under small strains seemed to be reasonable. As a result the lateral stresses could be calculated under a known vertical stress by having the soil modulus of elasticity and poisson's ratio. But the dependency of the soil constants($E,\nu,..$) to the stress level, stress path, constraint conditions and many other factors made it clear that in spite of simplicity, the elasticity is not an acceptable approach to this problem. The elasto-plastic behavior of the soil elements diverted the studies towards plasticity approaches. Nevertheless, to obtain the relationship between vertical and lateral stresses before failure conditions remained a problem.Since then to get more realistic information about variations of the soil lateral pressure extensive experimental studies have been carried out. Many of them have been focussed on the soil samples or site models under monotonic vertical loadings,and some valuable empirical equations were obtained to express the lateral pressure coefficient under different conditions accordingly. The relation between the vertical and lateral stresses becomes more complicated when the vertical stress changes cyclically. In this paper the method and results of an experimental study of soil samples subjected to cyclic vertical stress are presented and discussed. A special testing apparatus and sample preparation technique were used to control the conditions and to measure the lateral stresses accurately.

THE TESTING APPARATUS

The apparatus used to measure lateral stresses of soil samples under different loading conditions is a type of true triaxial apparatus called SCTA (simple cubic true triaxial apparatus). The SCTA consists of three different parts. The first and the main part is the sample container which can accommodate the cubical soil samples by 15 cm. dimensions.It has six metal faces which initially provide a rigid boundary for the soil samples. There are four lateral walls two of which are fixed and bolted to the base of the container and the other two are moveable.Any desired lateral strain can be applied to the sample by these walls. The amount of inserted strains can be controlled by two dial gauges mounted behind these walls and the values of induced lateral stress on each wall are measured accurately by two sensitive load cells. Therefore any constraint condition(ie; confined, plane strain and triaxial strain) can be applied to the soil sample by the moveable walls quite easily.

The second part is the loading system which consists of a pneumatic cylinder controlled by a digital-analogue pneumatic converter linked to a micro computer. Any type of the vertical stress (monotonic and cyclic) with different amplitude(up to 450 kN/m^2), frequency (up to 0.1 Hz) and number of load cycles can be applied to the soil samples.

The third part of the apparatus is the data acquisition system which consists of a four channels data logger connected to a micro computer. The two lateral stresses (σ_2& σ_3) and the vertical stress and strain (σ_1& ε_1) are measured and recorded automatically by this system.The general plan of the SCTA is shown in figure 1.

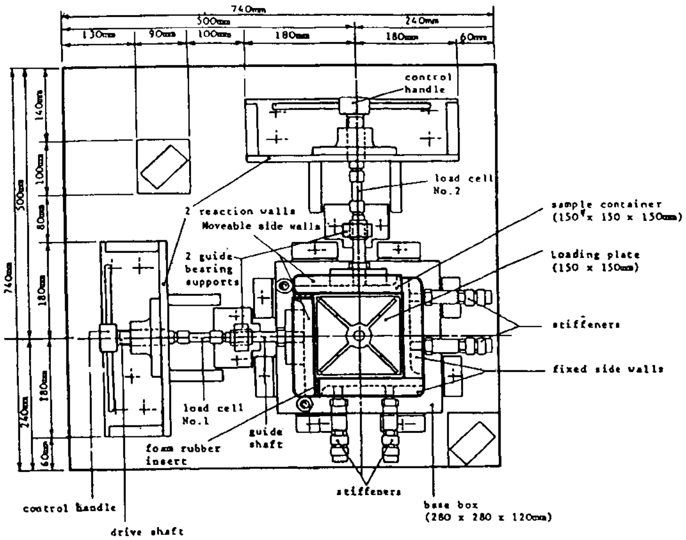

Figure 1- The general plan of the testing apparatus

THE TESTING MATERIAL AND PREPARATION TECHNIQUE

To eliminate the effect of particles degradation while preparing several identical samples, a uniform Leighton Buzzard sand with subangular particles of medium size D_{50} =0.40 mm,and specific gravity of 2.65 was used. The maximum and minimum porosities of this sand were 44% (e=0.79) and 33%(e=0.49) respectively. The particle size distribution of the material is shown in figure 2.

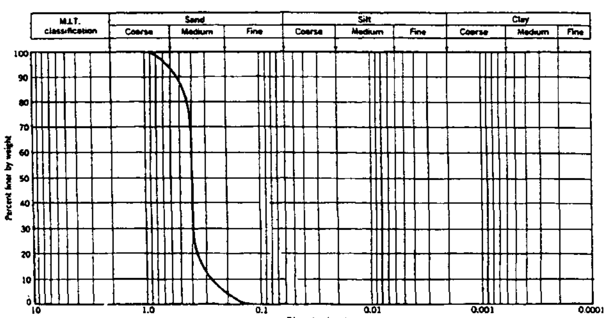

Figure 2- The particle size distribution of the sand

To prepare the soil samples under desired and controlled conditions, the raining technique developed by J. J.,Kolbuszewski was used. By this method the soil sample could be prepared with different density uniformly. The prepared samples by this technique are quite repeatable.A special device developed and mounted on the top of the sample container by which the sand can be poured to the container from different heights. Calibration graphs were provided and used to determine the required height of pouring for a desired porosity. They are shown in figure 3.

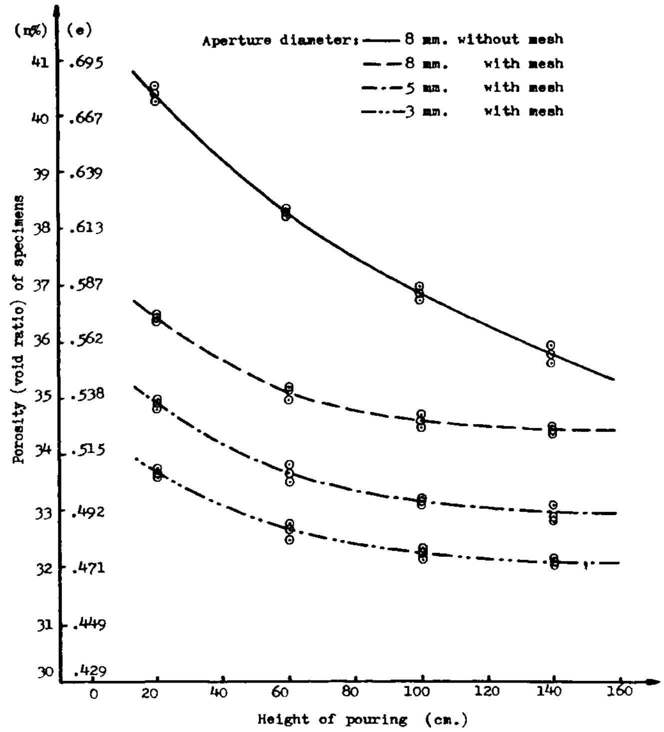

Figure 3- The calibration graphs of the testing sand

THE METHOD OF TESTING

The sample container was initially set in a position that a space of 15x15x15 cm was provided. The sand was then poured from the raining device fixed at a specific height to fill the sample container. The loading plate was then put on the top of the sample. To provide the Ko condition, the two moveable walls were kept fixed in their initial positions. The vertical load was applied to the sample and the induced lateral pressures were measured by the two load cells located behind the moveable walls.

In order to study the variations of lateral pressure at rest, under different cyclic vertical loads, 44 tests were carried out in which the porosity of the samples,the amplitude, frequency and number of cyclic loads were altered in the range given in the following table;

No.of cycles (N)	frequency (Hz.)	amplitude (KN/m^2)	porosity (%)
up to 360	up to 0.10	up to 212	33 & 41

In all tests and during application of cyclic vertical stress the two moveable walls were fixed and no lateral strain was permitted. Although the apparatus is able to provide other constraint conditions, and many tests were carried out in those conditions, but the results of those tests are not presented here, and in the following sections the changes of lateral pressure under confined condition is described only.

THE TEST RESULTS

Variations of lateral stress in both sides ($\sigma h1 = \sigma 2$ & $\sigma h2=\sigma 3$) under cyclic vertical stress ($\sigma v= \sigma 1$) versus number of load cycles for loose (n=41%) and dense (n=33%) samples are shown in figures 4 and 5 respectively. To compare the relation between vertical and lateral stress, the applied cyclic load are shown in the same plot.It is quite clear that as σv cycles between its minimum and maximum values, The lateral stresses ($\sigma h1$ & $\sigma h2$) vary between some minimum and maximum values as well. Although the amplitude of the vertical stress is constant (212 KN/m^2), the amplitude of lateral stresses changes as the number of load cycles increases. The maximum values of lateral stresses in each cycle decrease while their minima increase as the loading continues .Since the lateral conditions of the samples are quite identical in both lateral sides, the recorded lateral pressures are almost equal and show a small difference which is negligible.

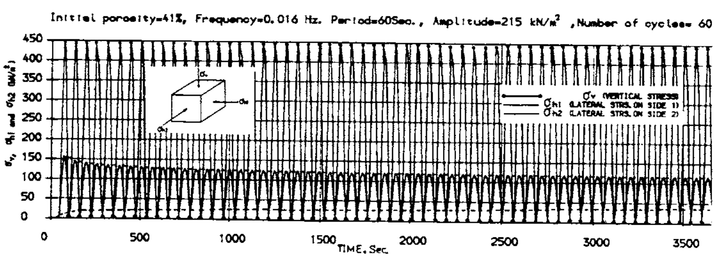

Figure 4- The variations of lateral stresses versus number of cycles for loose samples.

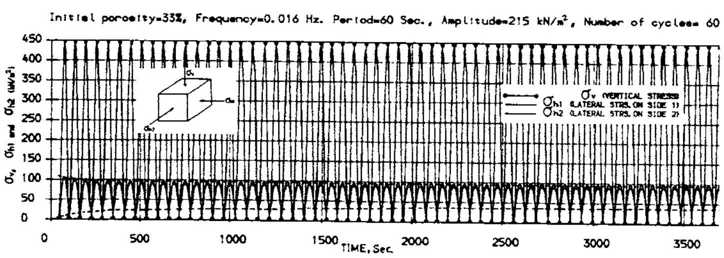

Figure 5- The variations of lateral stresses versus number of cycles for dense samples.

To show variations of lateral stress more clearly, and discuss about their relations with vertical stress, the lateral stress versus vertical stress at different number of cycles for loose and dense samples are shown in figures 6 and 7 respectively.As there were small differences between $\sigma h1$ and $\sigma h2$, their average values are plotted in these graphs. In order to show the trend of the results, the curves after each 5 cycles up to 50th cycle are plotted.

It can be seen from the figures that for both loose and dense samples the loading portion of the graphs are almost linear and similar to the results of monotonic tests, while the unloading portions are curves which are concave downwards. As a results, from the first cycle of load, hysteresis loops are developed which are initially large but they become smaller as the loading continues.

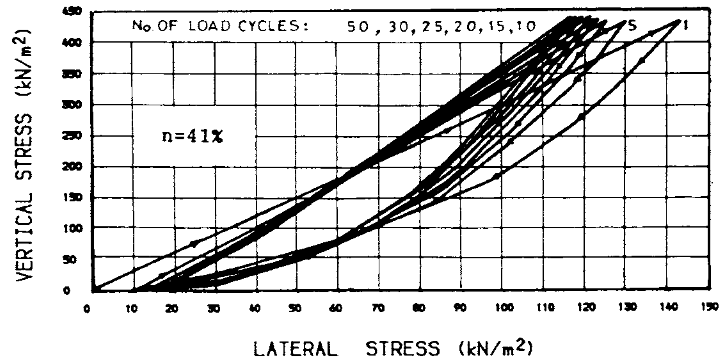

Figure 6- The variations of lateral stresses versus vertical stresses for loose samples.

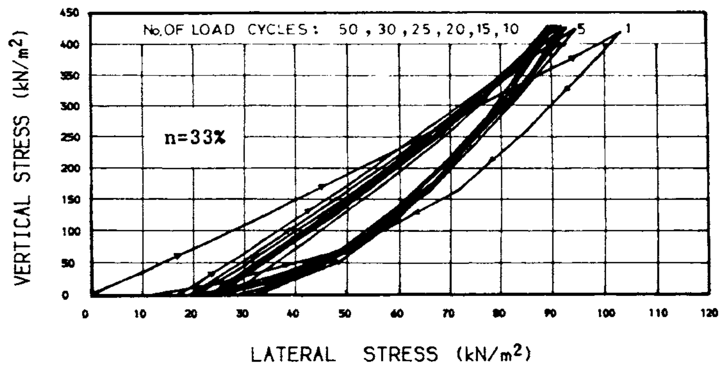

Figure 7- The variations of lateral stresses versus vertical stresses for dense samples.

For the first cycle of loading, on increasing the vertical stress, the lateral stress increases until peak of the loading. When unloading commences, the lateral stress decreases, but at a smaller rate than that happened in loading. After complete unloading ($\sigma v=0$), the lateral stress does not return to zero and some irrecoverable stress remains. In the second cycle,the lateral stress begins to increase linearly again from this point, and after complete unloading, the residual lateral stress is higher than that at the end of the previous cycle. Therefore as the cycling continues, the values of residual lateral stress increase. This means that the minimum values of the lateral stress (ie; the points corresponding to $\sigma v=0$) increase. The rate of increase of the minimum values of the lateral stress decreases as the loading continues. So that after about 30 cycles for dense samples and 40 for loose samples no appreciable changes are observed.

The values of lateral stress corresponding to peak points of the loading cycles decreases on increasing the number of cycles. Again the rate of decrease in the maximum values of lateral stress decreases on increasing the number of cycles. After about 20 cycles for dense and 30 for loose samples, the maximum values become almost constant.

DISCUSSION OF THE TEST RESULTS

The density of the soil plays a major role on the earth pressure. The denser the sample, the smaller lateral pressure developing in a soil sample under the same vertical stress. This fact can be seen in all cyclic test results. Furthermore, the trend of decreasing minimum values of lateral stresses can be attributed to increase in the density of the sample which occurs as the number of load cycles increases.

For increase in the minimum values of lateral stresses by increasing number of cycles, another argument can be used. This may be due to reversal of the direction of frictional forces occurring during unloading at the contact points between particles. As cycling continues the sample becomes denser, as a result the contact areas of grains and the frictional forces increase and the recorded lateral pressure which is mainly due to the frictional forces acting toward the lateral walls, thus increase. However as the potential of densification of the soil samples under vertical cyclic loadings is limited, the rate of increase in the minimum values gradually decreases and after some cycles becomes nearly zero.

From the test results, discussed so far, it is clear that the lateral stress in Ko conditions under cyclic surcharges decreases by increasing the number of cycles, but finally stabilizes. It means that the coefficient of earth pressure at rest for cycling loadings after some changes reaches a new stable value proportional to characteristics of the loading and initial porosity of the material.

SUMMARY AND CONCLUSIONS

The variations of earth pressure at rest under cyclic vertical stresses were investigated experimentally. A uniform sand was used and cubical samples of 15 cm. dimensions were prepared by the raining technique. The samples were tested by a type of true triaxial apparatus (SCTA) developed at Leeds University. The vertical stress was subjected on the soil samples cyclically and the induced lateral stresses were measured accurately.

According to tests results, applying the cyclic vertical stress to the soil will lead to the cyclic earth pressure. While the amplitude of the applied load is constant, the earth pressure amplitude changes between some maximum and minimum values. As the cycling continues, the maximum values of the earth pressure decrease, while its minimum values increase. However, after some loading cycles the amplitude of the earth pressure becomes constant leading to a smaller coefficient of earth pressure at rest proportional to the initial density and loading characteristics.

Based on the above finding, in the range of studied frequencies, the retaining walls constructed to withstand cyclic surcharges in Ko condition, can be designed for a smaller earth pressure than those made for the same intensity but static surcharges, provided the number of cycles is enough to reach the stable condition.

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