International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics

1995 - Third International Conference on Recent Advances in Geotechnical Earthquake Engineering & Soil Dynamics

06 Apr 1995, 10:30 am - 12:30 pm

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Recommended Citation

Holchin, J. D. and Vallejo, L. E., "The Liquefaction of Sand Lenses Due to Cyclic Loading" (1995). *International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*. 14.
https://scholarsmine.mst.edu/icrageesd/03icrageesd/session03/14

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

The Liquefaction of Sand Lenses Due to Cyclic Loading

Paper No. 3.30

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SYNOPSIS Many studies have been conducted on the effects of cyclic loading on homogeneous saturated deposits of sand, and to a lesser extent on silt and clay. In contrast, very little research has been performed on the effects of cyclic loading on saturated sand lenses located within clay masses. Sand lenses and thin discontinuous layers of loose sand are frequently encountered in saturated clay or silt deposits located in areas of the United States prone to earthquakes. Sand lenses are also frequently associated with hydraulic fill structures, which are known to perform poorly during earthquake loading. The liquefaction and failure of sand lenses has been identified as a major factor in the Turnagain Heights Landslide during the 1964 Alaska Earthquake and lateral spreading landslides in the 1906 San Francisco Earthquake, among others.

A major obstacle to laboratory testing of sand lenses is the modeling of a sand lens or lenses within a clay deposit or block, and finding equipment that can subject the sample to cyclic loading. Until now, only theoretical analyses of sand lens failure have been performed, with the most promising method utilizing the principles of Linear Elastic Fracture Mechanics (LEFM) theory. This study developed a method of constructing one or more sand lenses within a block of clay and then applying a uniform cyclic loading with a shaking table. For clay blocks with a single sand lens and with two sand lenses, behavior was closely monitored during the cyclic loading to the point of failure. The results of the testing verified that the principles of the LEFM theory can be used to determine the mode of failure of a sand lens or lenses due to cyclic loading.

INTRODUCTION

Lenses and thin discontinuous layers of loose sand are frequently encountered in saturated clay deposits located in areas of the United States prone to earthquakes (1,2,4,9,11,12,13,14). These sand lenses are features that are difficult to locate even when many test borings are conducted. Because they are difficult to detect and because they are, according to Terzaghi (12) "minor geologic details," they are not often considered in liquefaction studies of potential sites for engineering structures. Thus, very few studies have been conducted to date concerning the effects of the liquefaction of sand lenses on the ground surrounding them as well as on any overlying structures. Nonetheless, long-standing speculation has suggested that in the event of an earthquake, the response of saturated clay deposits containing sand lenses can be greatly affected by the behavior of these lenses.

For example, liquefaction of saturated sand lenses embedded in sloping clay masses has been thought to be the principal cause of major slide movements (4,10,11). If an earthquake takes place in an area of saturated flat clay deposits containing loose sand lenses, the sand lenses may liquefy. If liquefaction takes place, the cavities in the clay originally occupied by the solid sand will now be filled by liquid sand. The combined effect of the earthquake induced shear stress, the overburden pressure, and the pressure developed by the liquefied sand may cause the cavity that contains the liquefied sand to fail. According to Vallejo (13), failure takes place in the form of tensile and shear cracks that propagate from the tips of the cavity in the direction of the ground surface. The liquid sand uses these cracks to move toward the surface and form sand craters. The empty cavity that contained the sand lens closes as a result of the existing overburden pressure. The closing of the empty cavity will cause not only the collapse of the clay above it, but the generation of a large basin depression on the ground above the cavity (Fig. 1). If a structure is located on the depression basin, it could experience damage from the differential settlements that are the result of the slope changes in the ground surface.

From numerical analysis of the response to cyclic shear deformations of horizontal clay deposits containing discontinuous weak layers, Ambraseys (1,2) established that the yielding of the weak layers causes the overlying soil to oscillate freely, and introduces a higher frequency modulation in the response. These high frequency oscillations could affect the stability of structures located on these soils. In addition, the yielding of weak layers were found to cause slow and erratic attenuation patterns of peak accelerations at the ground surface.

Thus, when saturated clay deposits containing lenses of loose sand predominate, the ground displacements and the pattern of surface ground motion in areas subjected to earthquakes could, to a large extent, be governed mainly by the dynamic behavior of the sand lenses. The purpose of the investigation was to study the effect that the liquefaction of the sand lenses has on clay deposits containing these lenses, and to use a shaking table to substantiate the theoretical (LEFM) analysis of the causes and effects of sand lens liquefaction.

BACKGROUND OF THE PROBLEM AND ITS SIGNIFICANCE

Areas With Natural Sand Lenses

Lenses of loose, saturated sand are frequently encountered in natural clay deposits located in areas of the United States prone to earthquakes. These areas are among those specifically identified as regional focus sites by the 1993 USGS National Earthquake Hazards Reduction Program.

Downtown San Francisco Area

During the 1906 San Francisco earthquake, failures attributable to liquefaction occurred at many locations within the San Francisco area. Lateral-spreading landslides occurred in three separate zones within the city of San Francisco. These three zones are:

- The Foot of Market Zone.
- The South of Market Zone.
- The Mission Creek Zone.

The geologic composition of all three zones involve the presence of saturated sand lenses embedded in a matrix of silty clay or homogeneous clay deposits. According to Youd and Hoose (14), the lateral spreading and slumping ground failures that took place in these three areas during the 1906 San Francisco earthquake has as a probable cause the liquefaction of the saturated sand lenses embedded in the clay deposits.

San Francisco Bay Region

This area features the geological composition of an alluvial valley fill located in the northern part of the Santa Clara Valley, California (9). The region contains locations with many sand lenses of varying cross sectional areas embedded in a clay matrix. The groundwater level is very close to the surface. Thus, the sand lenses are saturated. In the event of an earthquake, the sand lenses could liquefy as well as interact with one another. The liquefaction of the sand lenses can cause settlements and ground failures.

Alaska

Figures 2 & 3 depict the geology as well as the geometry of a slope along the shoreline in the Turnagain Heights area in Anchorage, Alaska that slid into the ocean during the 1964 earthquake. Seed (10,11) advanced the theory that the landslide was caused by the liquefaction of the saturated sand lenses embedded in the sloping clay mass. Very little is known, however, about the mechanics of liquefaction and interaction of the sand lenses that formed the continuous layer on which the slide supposedly took place.

Areas With Man-Made Sand Lenses

Sand lenses can be found in certain man-made deposits of clay or silt in cases where some type of hydraulic filling process was used for soil placement. Many hydraulic fill dams were built from the late 1800's to about 1940 in this country, before heavy compaction and earthmoving equipment were available for the construction of large dams. Although hydraulic fill dams can be found all over the world, many in the United States are located in seismically-active regions such as the west coast, near California, or the southeast, near South Carolina (7).

The major zones of a hydraulic fill dam include the unwashed, dumped fill that forms the shells of the dam, washed fill at the outer edges of the core area, and the center core. The general construction process for a hydraulic fill dam was to build increasingly-closer levels of dumped fill for the shells of the dam, while pumping fluid soil (sand, silt and/or clay) to the outside edges of the pool area. The intent was for the larger, course-grained soil (sand) to drop out of suspension first as the fluid soil migrated to the center area of the pool, leaving the fine-grained soils (silt and/or clay) to form the "impermeable" core of the dam (8).

Unfortunately, many deficiencies were noted in hydraulic fill dams and this construction process was generally discontinued in the United States by the late 1940's. The earliest deficiency to arise was that many hydraulic fill dams began to leak almost immediately upon filling of the reservoir. This was attributed to the presence of thin sand lenses and layers within the core which simply could not be prevented during construction. Indeed, the authors' experience with geotechnical investigations of hydraulic fill dams revealed the frequent presence of such features. A more serious deficiency was discovered when these dams were eventually subjected to major earthquakes. In many cases, performance was less than satisfactory. The upstream failure and near disaster of the Lower San Fernando Valley Dam during the 1971 San Fernando Earthquake served as a dramatic warning of the weakness of hydraulic fill dams during earthquakes, and prompted the state of California to evaluate and strengthen, if necessary, all such dams in operation.

THE LIQUEFACTION OF SAND LENSES--THEORETICAL STUDIES

Very little is known about the liquefaction mechanics of sand lenses and the effect of this liquefaction on the ground surrounding the lenses. Vallejo (13), using the principles of Linear Elastic Fracture Mechanics theory, has conducted one of the few theoretical studies designed to understand the effects of the liquefaction of horizontal sand lenses on the ground that contains them. Vallejo (13) determined that:

(a) When one horizontal saturated sand lens liquefies, the liquefied sand exerts pressure on the cavity that contains it. This pressure, acting together with an earthquake shear stress and overburden pressure, causes large tensile and compressive stresses in the clay regions surrounding the liquefied sand lens (Fig. 4).

(b) The tensile stresses in the clay cavity surrounding the liquefied sand causes the extension of the cavity. This extension is in the form of a secondary tensile crack that develops at one of the tips of the cavity. The tensile crack propagates at an angle of 70.5 degrees with respect to the plane of the cavity (Fig. 1). This tensile crack propagates toward the ground surface with the help of the pressures developed in the liquid sand. The tensile crack serves as a drainage path for the liquefied sand.

(c) The overburden stresses close the horizontal cavity that contained the sand lens and cause the collapse of the ground above it as well as the formation of a basin of depression at the ground surface level. The collapse zone above the cavity is delimited by the tensile crack that extends from one of the tips of the cavity (Fig. 1) and by a shear plane that extends from the other tip of the cavity. The shear plane is inclined at $(45-\phi\backslash 2)$ with respect to the vertical. ϕ is the angle of shearing resistance of the clay. Any structure located on the depression basin could experience damage as a result of differential settlements (Fig. 1).

(d) If more than one horizontal sand lens exists in a clay deposit (Fig. 3), the liquefaction of sand lenses causes the clay between the sand lenses to develop large zones of tensile stresses. These tensile stresses cause the clay to develop tensile cracks that connect the cavities containing the liquefied sand (Fig. 5). The joining of the cavities by the secondary tensile cracks, produces a continuous failure surface like the one that probably caused the Turnagain Heights landslide in Alaska (Fig. 2).

LIQUEFACTION OF SAND LENSES--LABORATORY STUDIES AND THEIR SIGNIFICANCE

After an extensive literature search related to sand lenses, it was found that no laboratory study on the mechanics of liquefaction of saturated sand lenses embedded in clay deposits has been conducted to date. Most of the laboratory studies that make use of either dynamic triaxial or simple shear apparatuses as well as shaking table tests have been designed to investigate the liquefaction behavior of homogeneous sand samples or the development of pore water pressures in homogeneous clay samples.

The only laboratory testing found which could be considered similar involved testing of layered sandy soils. Liu and Qiao (6) performed shaking table tests on layered sands, using uniform cyclic loading, while Fiegel and Kutter (3) performed centrifuge tests on sands confined by a low-permeability silt layer using both uniform cyclic loading and actual earthquake time histories. Both studies found that the presence of a lower-permeability layer above the sand layer made liquefaction more likely than if the sand was a uniform deposit, because dissipation of excess pore water pressures was restricted. In the case of a sand lens, a quick dissipation of excess pore water pressures due to cyclic shear strains is nearly impossible, making the occurrence of liquefaction even more likely.

Laboratory Equipment

A shaking table made by the All-American Tool & Manufacturing Co., model No. 10 HA, was used in this study. It is a simple apparatus that produces one-dimensional cyclic movement of a flat metal plate, or table (Fig.6). The movement was produced by an 1/2 hp electric motor hooked up to dual system of adjustable pulleys and belts. The rate, or frequency, of the cyclic movement was controlled by adjusting the diameter of the adjustable pulleys. The amplitude of the movement was fixed at 0.15 inch. The range of cyclic movement available with this apparatus was from 6 cycles per second to 35 cycles per second (Hz). An electric gauge was available to monitor the frequency of the cyclic movement. The accuracy of this gauge was checked by careful examination of plots of the acceleration of the container at different frequencies, and was found to be satisfactory.

A rectangular-shaped container with the dimensions of 14 in.x 4 in.x 12 in. (length x width x height) was constructed of 3/16 inch-thick clear plexiglass, with the joints carefully glued together. This container was securely fastened to the metal plate of the shaking table for the duration of the study. Clear plexiglass was selected to allow observation of the sample during testing.

An accelerometer was attached to the base of the container by a threaded bolt, as measurements of the acceleration of the sample and/or the container during cyclic loading were desired. However, incorrect operating procedures for use of the accelerometer resulted in inaccurate acceleration data during testing.

A Druck model PCDR 81 miniature pore water pressure transducer was very useful during other parts of the liquefaction study, due to its very small size (less than 1/2 inch-long and 1/4 inch in diameter) and water-tight design, which was intended to allow it to be submerged in the saturated sample, and a very rapid data recording rate. Unfortunately, we could find no effective way to enclose the transducer inside of the sand lens without either smearing the transducer surface and thereby impairing the pore water pressure readings, or sacrificing the impermeability of the clay plug above the sand lens with the cable. Therefore, no pore water pressure readings were obtained during testing.

Soils Used in the Study

The clay used was commercially available china koalinite clay, which came in a dry powder form. This clay was hand-mixed with water to a uniform consistency. The clay was classified as CL (clay with low plasticity) by the USCS, with a liquid limit of 38 % and a plastic limit of 20 %.

The Ottawa sand was selected because of its unusually round uniform grains and was classified as SP (poorly graded sand) by the USCS. Notable gradation characteristics included a D_{10} of 0.27 mm, a D_{50} of 0.43 mm, and a D_{max} of 0.90 mm. In addition, the C_C (coefficient of curvature) was calculated as 0.92 and the C_u (coefficient of uniformity) was calculated as 1.70, indicating poor grading of the sand.

Sample Preparation

The kaolinite clay was mixed with water to a uniform consistency and placed in a 6 inch x 4 inch x 14 inch (width x height x length) plexiglass consolidation form. The sample was consolidated by approximately 60 pounds under saturation conditions and then removed from the form. At this point, the location of the sand lens or lenses was selected. The cavity for the lens or lenses was then carved out using an oval-shaped metal form. After several unsuccessful attempts at filling the cavity with sand and saturating the sand prior to placement of the sample within the plexiglass container, it was decided to instead place the clay sample inside the plexiglass container on the shaking table first and then fill the cavity with sand. This was done by drilling a 1/4 inch diameter hole from the top of the sample down to the cavity, and dropping the sand into place through a straw until the cavity was full. The cavity was shaken slightly to completely fill it with sand, while remaining in a relatively loose condition. Water was then added to the sand through the straw until the sample was saturated. The final step was to place a clay plug, which was a mixture of kaolinite and swelling bentonite, into the 1/4 inch diameter hole in order to seal the sand lens within the clay mass. Two configurations of lenses were tested; the first being one lens nearly centered within the clay block and the second being two lenses spaced about 1.5 inches apart near the center of the clay block.

Testing Procedure

The testing procedure was simply to initiate cyclic loading on the sample and to observe and record changes to the size and shape of the lens or lenses as the testing progressed. The testing was stopped when a final size and shape of the lens or lenses was achieved, i.e. no further changes were occurring. Because of the limited amplitude possible with this particular shaking table, the higher frequencies of shaking were used to induce cyclic strains to the sample. As previously detailed, no measurement of excess pore water pressures was made.

Testing Results

1. Effect of One Sand Lens Within a Clay Sample: Figure 7 shows the general arrangement of the clay sample with one saturated sand

lens before shaking was initiated, while Figure 8 shows the same sample at the end of shaking. The testing was initiated at a shaking frequency of 10 Hz, but no reaction of the sand lens was noted until the shaking frequency reached 30 Hz, at which point the sand began to move around within the lens and the lens cavity itself began to thin and extend itself horizontally at both ends. This began to occur about 5 minutes after initiation of the test. After approximately 25 minutes of shaking at 30 Hz frequency, the sand lens appeared to stabilize and no additional changes were noted. At this point, the sand lens had thinned from 1.25 inches initially to 0.75 inches, and had extended from 2.75 inches initially to 3.5 inches. Also, a crack was visible in the clay sample that extended from the right tip of the sand lens to the sample surface, at a measured angle of 70 degrees, which is very close to the value of 70.5 degrees predicted by Vallejo (13).

It should be noted that no sand was ejected to the sample surface in the classical "sand boil" mode that is commonly noted at earthquake sites. Although sand volume reduction occurred due to consolidation and densification, some sand and water may have been forced into the crack because the volume of the cavity was reduced by about 25 %. Some sand was observed in the crack during removal of the sample from the plexiglass container, but the extent was could not be determined due to disturbance.

2. Effect of Two Sand Lenses Within a Clay Sample: Figure 9 shows the general arrangement of the clay sample with two saturated sand lenses before shaking was initiated, while Figure 10 shows the same sample at the end of shaking. The testing was initiated at a shaking frequency of 30 Hz and a reaction of both sand lenses was noted almost immediately. The first indication of liquefaction was the random movement of sand in both lenses, followed closely by a change in shape of both lenses. Both sand lenses underwent a change in shape nearly identical to that noted in the previous test of the clay sample with one sand lens. Both lenses thinned from 1.25 inches initially to 0.75 inches and extended horizontally from 2.75 inches initially to 3.5 inches. In this case, no crack was observed to extend upward from either sand lens, as was noted during the testing of the clay sample with one sand lens. However, a crack did develop between the two lenses that effectively connected both sand lenses. The duration of shaking was about 30 minute.

CONCLUSIONS

The results of the shaking table laboratory testing verified that the principles of the LEFM theory as proposed by Vallejo (13) can be used to determine the mode of failure of a sand lens or lenses due to cyclic loading. The results also showed that sand lenses can in fact be tested in the laboratory under cyclic loading. Indeed, when cyclic loading was induced upon a clay block with a single sand lens, the sand within the lens liquefied and exerted pressure on the cavity walls. The cavity then deformed and forced a tensile crack in the clay block at an angle of nearly 70.5 degrees to horizontal. Since the liquefied sand was not ejected entirely along the crack to the clay surface, the cavity itself could not collapse, but it is thought that this would have occurred if the shaking table could have inparted a higher level of cyclic strain.

Similarly, when cyclic loading was induced upon a clay block with two aligned sand lenses, the sand within both lenses liquefied and again exerted pressure on the cavity walls. Both cavities deformed and forced a tensile crack between the two cavities, which effectively joined the cavities, as predicted by LEFM theory again. This failure mechanism demonstrates how the liquefaction of sand lenses within a clay embankment can produce a failure plane which ultimate leads to slope failure.

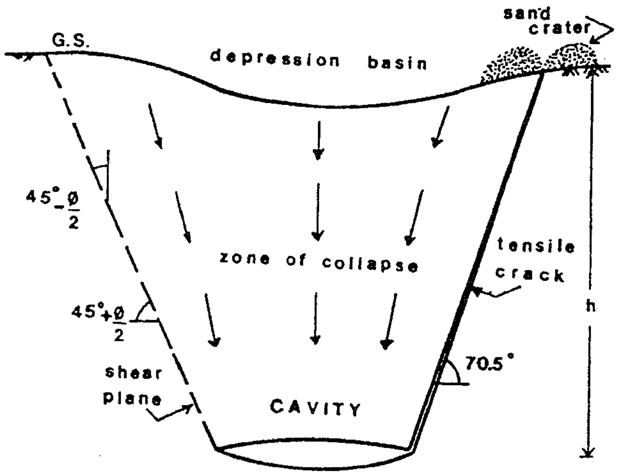


Fig. 1. Effects of the liquefaction of a sand lens on the ground surrounding it. (13)

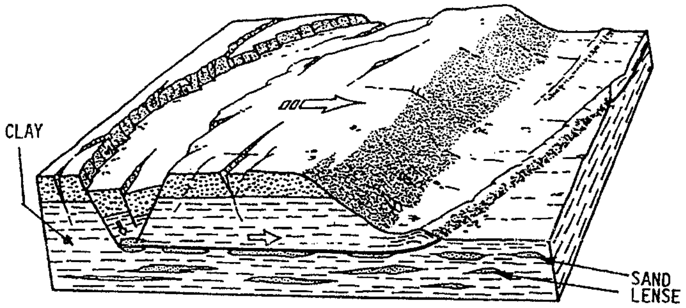
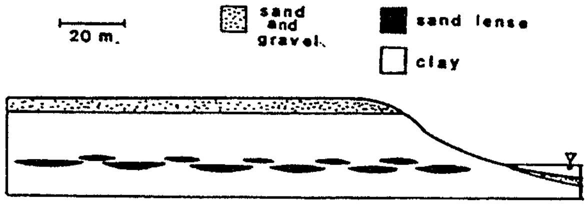
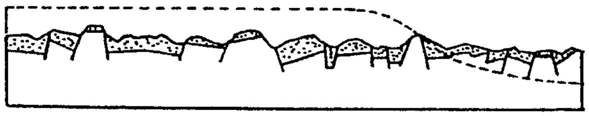


Fig. 2. Schematic diagram of characteristics for the 1964 Anchorage, Alaska, landslides. (4)



(A) Before Earthquake



(B) After Earthquake

Fig. 3. Sand lenses and the development of the Turnagain Heights landslide in Anchorage, Alaska. (11)

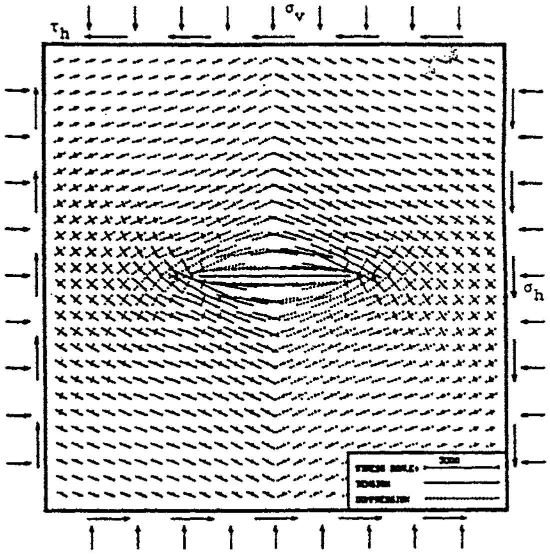


Fig. 4. Principal stresses around a liquefied sand lens (dottted lines represent compression, solid lines tension). (13)

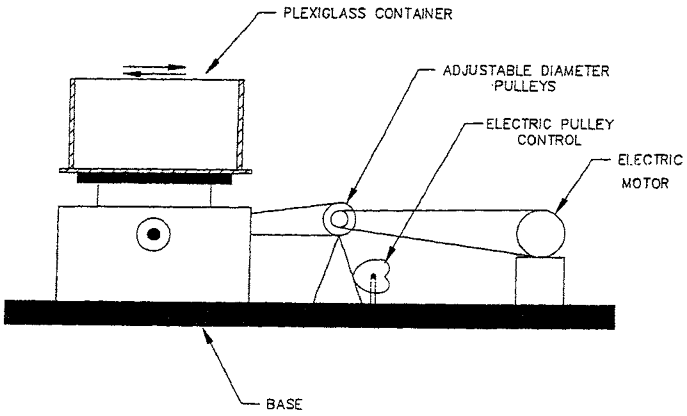


Fig. 6. Shaking table arrangement. (5)

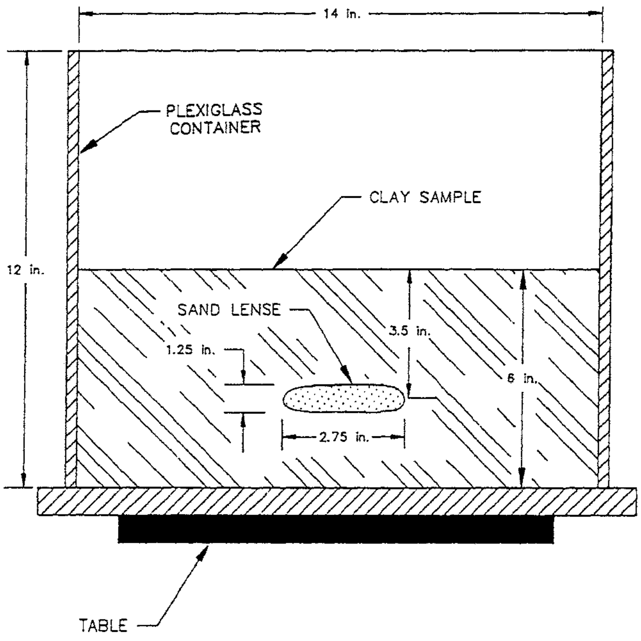


Fig. 7. Clay sample with one sand lens before testing. (5)

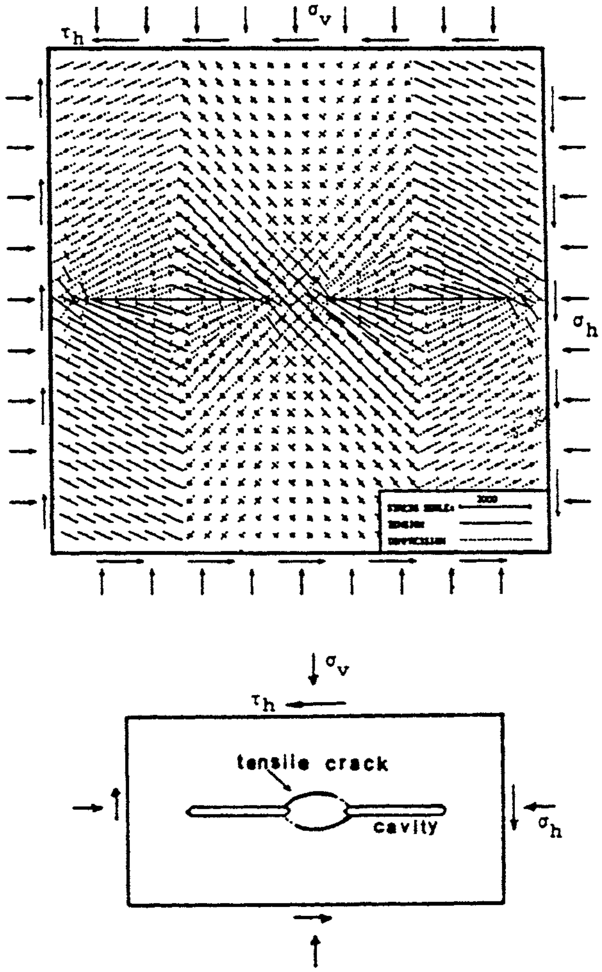


Fig. 5. Principal stresses and cavity interaction for the case of two alligned lenses (dotted lines represent compression, solid lines tension). (13)

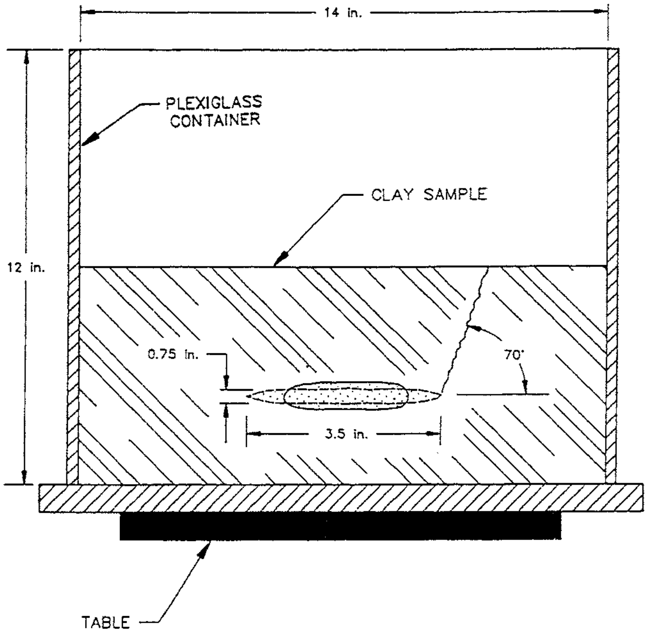


Fig. 8. Clay sample with one sand lens after testing. (5)

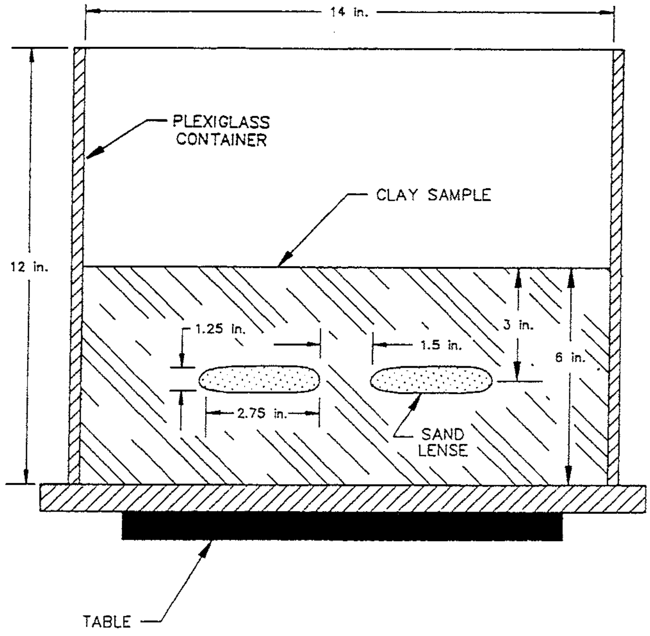


Fig. 9. Clay sample with two sand lenses before testing. (5)

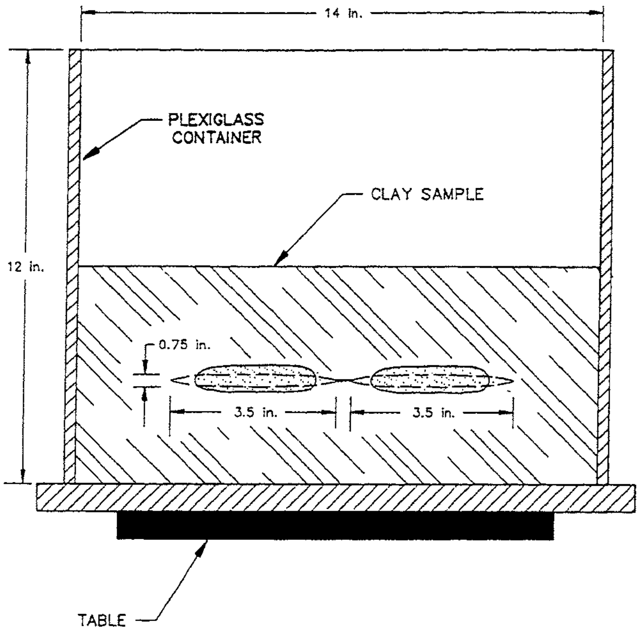


Fig. 10. Clay sample with two sand lenses after testing. (5)

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