4th International Conference on
Earthquake Geotechnical Engineering
June 25-28, 2007
Paper No. 1131

CRACK FATIGUE IN CLAYS MODELED USING DEM

Luis VESGA[1]

Over-consolidated clays and shales forming part of the core section of earth dams, natural slopes, and clay deposits undergoing desiccation, can develop cracks that may propagate as a result of changes in the state of stresses produced by earthquakes. Repetitive and very high stress concentrations around the crack tips cause the cracks to propagate. The pre-existing and the new cracks can produce severe weakness of the soil which can produce damaging or failure of structures along with an increase in the hydraulic conductivity of the clay. In the existing studies, the crack propagation in clays under dynamic loading has not been analyzed. In this study, the crack propagation in fissured prismatic samples of clay subjected to uniaxial dynamic loading was tested in the laboratory and analyzed numerically using the Discrete Element Method (DEM). The DEM was developed originally to represent groups of individual particles, but can also be used to represent continuum materials if bonding is applied between particles. The DEM modeling permitted to obtain a relationship between the dynamic stress applied and the number of cycles needed to cause crack propagation. The number of cycles required to cause crack propagation in fissured samples prepared in the laboratory corresponds the DEM modeling results.

Keywords: dynamic loading, crack propagation, clays, fatigue, Discrete Element Method.

INTRODUCTION

Over-consolidated clays and shales forming part of the core section of zoned earth dams and natural slopes have been found to exist in the fissured state (Bishop, 1967; Covarrubias, 1969; Duncan and Dunlop, 1969; Marsland, 1972; Morgenstern, 1977; Peterson et al. 1966; Rizkallah, 1977; Sherald, 1973; Skempton, 1964; Skempton and LaRochelle, 1965; Terzaghi, 1936; Vallejo, 1985; Williams and Jennings, 1977). According to Covarrubias (1969), fissures or cracks exist in the core section of earth dams as a result of deformation of the materials in the dam or in the foundation due to their weight; abrupt changes in the cross section of a valley; large deformations ca[1]used by saturation of the materials in the dam; excessively rapid filling of the reservoir that causes high rates of strain, especially of the materials undergoing substantial movement upon saturation; large transient stresses caused by earthquakes; large differences in stress-strain properties of materials in adjacent zones or layers. In the case of stiff clays forming natural slopes, Williams and Jennings (1977) found that fissures develop as a result of a variety of processes, the most important of which are: consolidation, swelling of the clay as a result of a decrease in overburden pressure, chemical reactions in the clay that induce volume distortions, tectonic stresses, desiccation of the clay, weathering process inherited from bedrock, and large lateral stresses.

Clay deposits subjected to desiccation often develop intense cracking that extends deep below the surface. Arizona, Mexico City, and Bogota are examples of areas particularly affected by such deep cracking. Vesga et al. (2003) found intensive deep cracking in the high plastic Bogota (Colombia) clay deposit that affects a flat area of 90000 ha located in a zone characterized by high seismic hazard: hundreds of kilometers of roadways and hundreds of small buildings in this area have been severely damaged or collapsed as a result of deep cracking caused by desiccation.

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[1]Domeight Research Institute, Pittsburgh, PA, USA. vesgaluis@domeight.org

The present research addresses the question of what happens to fissured soils when they are subjected to dynamic loading such as that generated by earthquakes, wave action, traffic load, or machinery vibration. Laboratory and numerical analyses using DEM (Discrete Element Method) were performed in order to study the fatigue in fissured clay specimens subjected to dynamic uniaxial loading.

PREVIOUS RESEARCH

Previous Related Research on Crack Propagation in Clays

Vallejo (1985, 1987, 1989, 1994), Vallejo et al. (1994), and Vallejo and Shettima (1995) report several important findings related to the behavior of clays with pre-existing cracks. Vallejo and co-workers did several tests using rectangular kaolinite specimens with single or multiple cracks prepared in accordance with a special process that he developed; cracks of different orientations and specimens with different water contents were used. The specimens were subjected to monotonic uniaxial, biaxial, triaxial and shear stress fields. The researches used Linear Elastic Fracture Mechanics (LEFM) extensively to theoretically study the tension and compression stress concentrations around the cracks.

Four important conclusions can be derived from their findings as follows. (1) The critical pre-existing crack inclination, which corresponds to the condition of the lowest compression strength for crack propagation, varies between 45º and 60º with respect to the direction of the applied principal stress. (2) The maximum tangential stress criterion for a sharp crack of the type earlier proposed by Erdogan and Sih (1963) was used to predict the angle between the pre-existing crack plane and the crack propagation direction; this criterion was selected by Vallejo et al. (1995) as the closest to their findings between of all the criteria that were applied; (3) Fissures propagate as a result of constant compressive stresses (creep), which are much less than the crack-propagation compression strength of monotonically loaded clays (Vallejo and Shettima, 1997). (4) Multiple cracks will make the clay weaker, especially if superposition of tensile-stress concentration zones develope (Vallejo, 1993).

Previous Related Research on Stability Threshold

Lefebvre et al. (1988) studied the cyclic undrained resistance of non-fissured, intact saturated Hudson Bay clay and described the threshold as the stress level below which the soil suffers no failure regardless of the number of applied cycles. The researchers used the term *cyclic stress ratio* to describe this stress level which relates to both the applied triaxial cyclic stress and the triaxial compression strength of the intact clay. They found that for the saturated Hudson Bay clay, the stability threshold is defined by a cyclic stress ratio of between 0.60 and 0.65. In similar way, the *cyclic stress ratio* (r_d) is applied in this research to the study of crack propagation in clays under dynamic loads.

CYCLIC STRESS RATIO AND FATIGUE APPLIED TO FISSURED CLAYS

The laboratory tests for this research focused on specimens of fissured clays that were subjected to cyclic loads; the loads applied were just a fraction of the static loads that caused the failure of the clay (Vesga, 2005). The research investigated the influence of the resulting fatigue on the propagation of cracks in an unsaturated kaolinite clay and on the threshold stress with respect to cyclic loads levels below which the cracks do not propagate. Samples of fissured clays were subjected to uniaxial cyclic stress conditions. The cyclic stress ratio was defined as the ratio between the applied deviator dynamic vertical stress (σ_d) on a fissured specimen and the monotonic compression strength (σ_u) of a similar specimen having the same water content and crack geometry. The cyclic stress ratio is given as:

$$r_d = \frac{\sigma_d}{\sigma_u} \tag{1}$$

The purpose of the dynamic-load testing was to find the fatigue curve and the threshold load (fraction of the static load), expressed as the cyclic stress ratio r_d, at which, regardless of the number of cycles applied, there is no crack propagation in kaolinite clay having a constant moisture content of 18% and subjected to dynamic loading conditions.

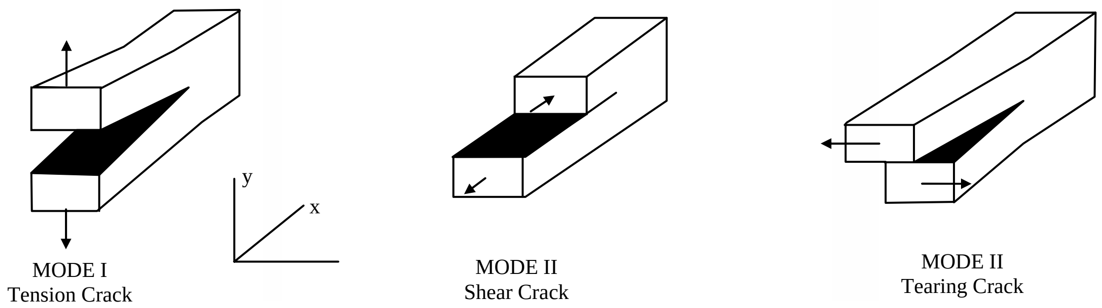

Figure 1. The three modes of cracking (Adapted from Vallejo, 1994).

LEFM THEORY AS APPLIED TO THE ANALYSIS OF CRACK PROPAGATION

Linear Elastic Fracture Mechanics Theory (LEFM)

According to LEFM theory, a crack or fissure in clay can be stressed in three different modes illustrated in Figure 1 (Vallejo, 1994). With Mode I, the stress normal to the crack walls produces a different type of cracking in which the disarrangements of the crack surfaces are perpendicular to the plane of the crack. With Mode II, a type of cracking is produced by shear stresses along the crack plane causes the walls of the crack to slide with the crack plane. With Mode III, a tearing and cracking is caused by out of-plane shear stresses. Cracks can propagate in materials as a result of one or more of these modes (Vallejo, 1994). Covarrubias (1969) used the three modes of fracture to investigate the propagation characteristics of cracks in cohesive materials used in earth barriers. The propagation of the cracks was found by Covarrubias to be result from the tensile stresses normal to the plane of the cracks (mode I type of loading). More recently, Lee et al. (1988), Fang et al. (1989), and Morris et al. (1992) have used LEFM theory to analyze the crack propagation in solids that result from tensile stresses (mode I type loading).

Vesga (2007) presents some basic concepts of LEFM in an article included in this Conference Proceedings.

DESCRIPTION OF LABORATORY TESTS PERFORMED

Preparation of Samples

Prismatic kaolinite specimens were prepared for the tests. The liquid, plastic and shrinkage limits of the kaolinite are 44, 26 and 24 respectively and the specific gravity is 2.59. The specimens for the direct and indirect tensile tests had moisture contents between 3% and 32%, with intervals of around 3%. The sample preparation was done with the following process:

a) Mixing the dry powdered kaolinite with distilled water to moisture content of 40% and until a smooth and uniform paste was obtained.
b) Casting the paste into molds (prismatic of 7.5 cm x 7.5 cm x 2.5 cm or cylindrical 6.35 cm in diameter and 2 cm thick).
c) Applying a vertical pressure of 30 kPa for consolidation during 24 hours in a closed environment with 75% of relative humidity (*RH*).
d) Extracting the specimens and subjecting them to a drying process into an environment with a *RH* ~30%.
e) Cracks with inclination angle 45º with respect to the horizontal were made in the prismatic specimens; samples were still saturated during this stage. Each crack was made using a blade which produced a crack having a length of 25 mm and a thickness of 1 mm. Figure 4 shows the crack geometry.
f) After each specimen reached the desired moisture content (around 18%) it was stored into a plastic membrane during a minimum 24 hour period in order to obtain equilibrium through the sample. All the specimens were tested at this mositure content level.

Uniaxial Compression Tests

Uniaxial constant water content tests were done using both intact and pre-cracked specimens. Each sample tested was maintained inside a plastic membrane in order to prevent water content changes during the tests.

Dynamic Loading Tests

A MTS hydraulic compression machine was used for the dynamic loading tests. The purpose of these tests was to find the number of cycles needed to produce crack propagation under dynamic loading represented by the cyclic stress ratio r_d. The cyclic stress ratio is defined as the ratio between the applied dynamic vertical stress and the ultimate monotonic compression strength of a similar specimen having the same water content and the same crack inclination. Thus, the cyclic axial load was a fraction of the static load at which the specimen failed.

A sine wave loading type with a frequency of 1 Hz was applied to the specimens. The data acquisition system DATAQ ID-194 (Dataq Instruments, 2003) recorded the load and deformation of the samples occurred during the tests. The level of the cyclic stress ratio r_d was changed in order to determine the number of cycles to produce crack propagation (fatigue).

RESULTS FROM LABORATORY TESTS

Uniaxial Ultimate Compression Strength σ_u

The ultimate uniaxial compressive strength σ_u is the stress required to produce failure of the specimens as Figure 5 shows. The ultimate compression strength for intact specimens and for specimens with a crack is very close. For intact specimens having a moisture content of 18% the ultimate uniaxial compressive strength is σ_u=1130 kPa and for specimens having a crack is σ_u=1118 kPa. This indicates that the presence of the primary crack has no effect on the ultimate uniaxial compressive strength of the tested specimens. As Figure 5 shows, a shear failure plane was observed in the lateral face of all of the specimens.

Stress level at Crack Propagation σ_c

Two stress levels were registered for each uniaxial compression loading test performed on the fissured specimen. With the stress level of σ_c, crack propagation occurred in the front and rear faces of the specimen (see Figure 2 below). With the stress level of σ_u – which is the maximum stress specimen was able to withstand – a shear failure plane appeared in the lateral faces of the specimen. The stress level at crack propagation is σ_c=792 kPa for a water content of 18%. Vesga (2007) presents results from similar tests using specimens having different water contents.

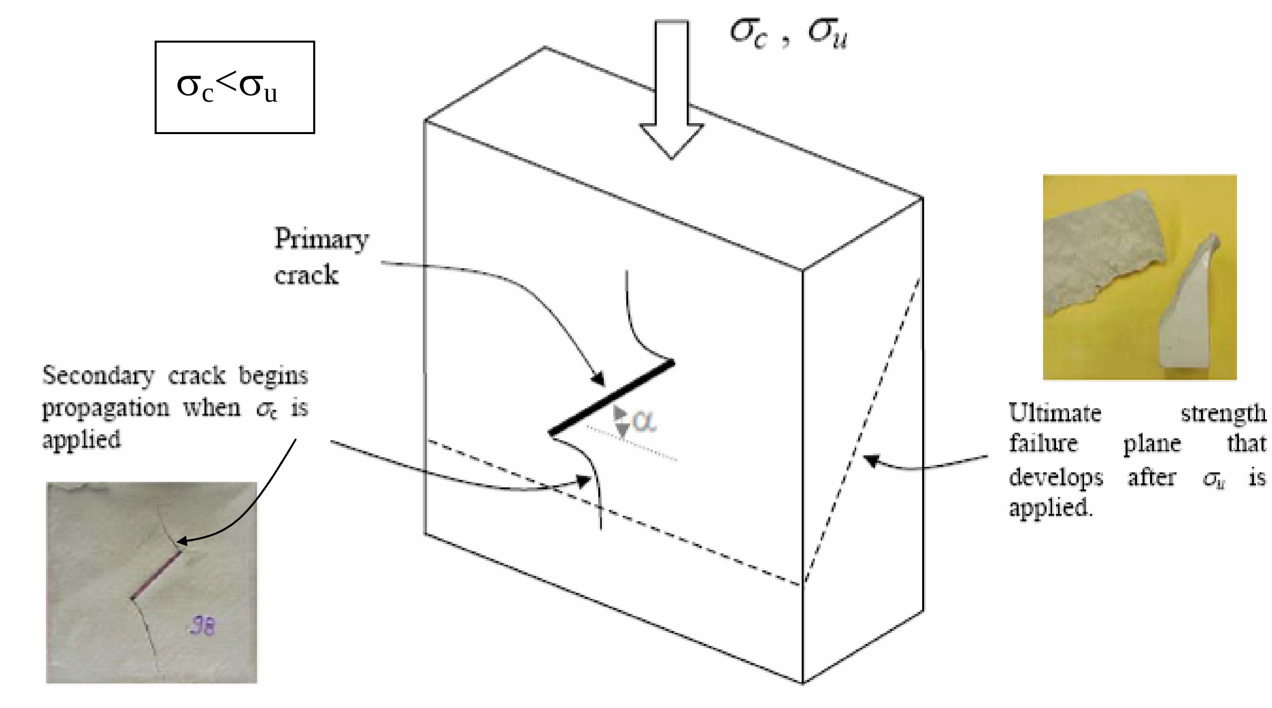

Figure 2. Crack propagation and failure plane observed from the uniaxial compression tests.

Crack Propagation angle and Crack Propagation Path

Figure 2 (left, lower corner) and Figure 6 show the condition of samples after crack propagation. The specimen had a typical brittle behavior characterized by a primary crack that remains open after the secondary crack propagates. The crack propagated at an angle of 88º with respect to the plane of the primary crack. After the secondary crack started the propagation, the crack curved towards the vertical direction as Figure 5 shows. The MTS criterion proposed by Erdogan and Sih (1963) for the prediction of the crack propagation angle predicts very well the angle δ for primary crack inclination angle α of 45º.

Fatigue derived from Dynamic Loading Tests

The cyclic stress ratio was earlier defined as the ratio between the applied dynamic vertical stress and the ultimate monotonic compression strength of a similar specimen (with the same water content and the same primary crack inclination). The purpose of the dynamic loading test was to find the relationship between the cyclic stress ratio r_d (fraction of the static load) and the number of cycles which produced fatigue in the specimens. The dynamic load was decreased until no crack propagation occurred under dynamic loading conditions regardless of the number of cycles applied.

Figure 3 shows the obtained results; in this figure, the cyclic stress ratio that produced fatigue is expressed as a function of the number of cycles applied. All the specimens developed a secondary crack caused by fatigue of the clay. The dynamic numerical analyses with DEM were calibrated using this curve.

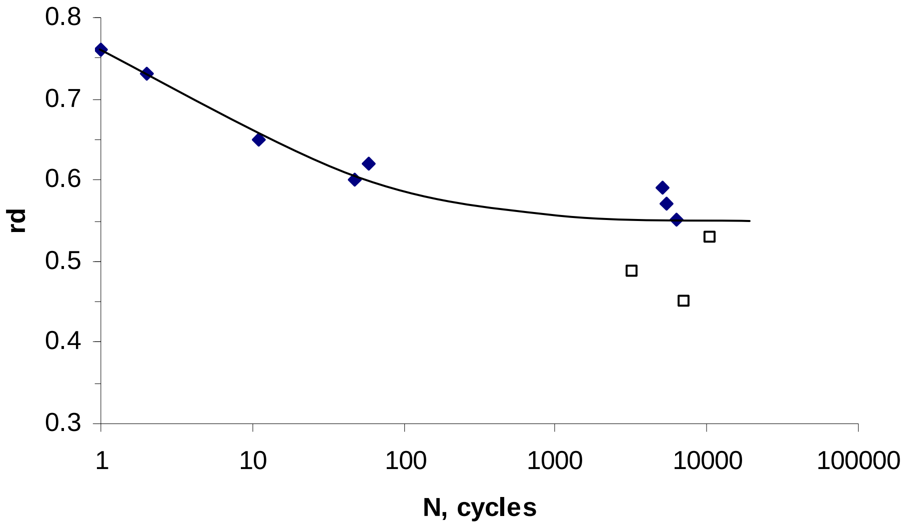

Figure 3. Relationship between cyclic stress ratio r_d and number of cycles applied to produce crack propagation by fatigue of the clay for a primary crack inclination angle α=45º. Clear points show results from specimens which crack did not propagate.

DISCRETE-ELEMENT METHOD FOR ANALYSIS OF CRACK PROPAGATION

In addition to the theories available for the analysis of crack propagation in clays, the Discrete Element Method (DEM) developed by Cundall and Strack (1979) was applied to analyze fatigue of the specimens having cracks. The method was implemented using the computer program PFC^{2D} supplied by the Itasca Consulting Group (2002).

DEM has been used extensively to study of the behavior of materials such as granular soils and rocks when they are subjected to static or dynamic loads. This method has also been used to simulate continuum materials such as rocks and clays if contact bonds between the DEM particles are implemented (Itasca Consulting Group, 2002).

DEM was used in this research in the study of crack propagation in stiff fissured clays considering this material as a continuum. For each bond, PFC^{2D} uses normal tensile and shear maximum loads as well as normal and shear stiffness, as it is shown in Figure 4 below (Itasca, 2002).

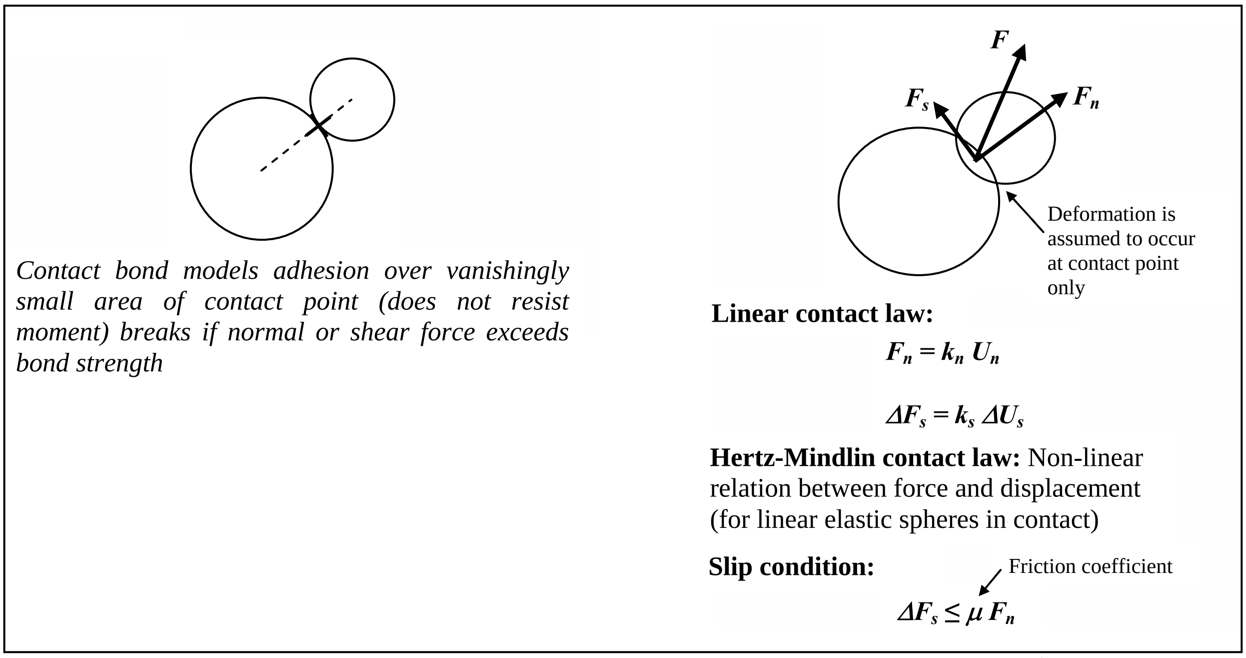

Figure 4. Contact forces and bonding simulation between particles in the PFC^{2D} Discrete Element Method (DEM) program (Adapted from Itasca Consulting Group, 2002).

In general when a contact bond breaks, a separation between particles develops. This breakage takes place when the induced tensile force exceeds the tensile force that the bond can tolerate and a crack forms. If this bond is near the original crack in a simulated crack specimen, the original crack propagates in the location of the broken bond.

PFC^{2D} comes with a library with several functions that are very useful not only for solving specific problems but also for deriving new functions using the computer language FISH. In this study several subroutines were developed using FISH for the generation of the specimens with cracks and to simulate the dynamic loading of the specimens.

PARAMETER	VALUE
Particles:	
Type of Particles	Disks
Number of Particles (excluding the ones from the crack)	9851
Normal Contact Stiffness	$1x10^8$ N/m
Shear Contact Stiffness	$1x10^8$ N/m
Normal Bonding Force	$1x10^3$ N
Shear Bonding Force	$2x10^3$ N
Density	1000 kg/m^3
Walls:	
Normal Contact Stiffness	$1x10^8$ N/m
Shear Contact Stiffness	0
Velocity of the top horizontal wall	$1x10^{-6}$ m/s
Velocity of the bottom horizontal wall	0

Table 1. Parameters used in DEM's simulations

DEM's Model Calibration

A single primary crack at inclination of 45º with respect to the horizontal was implemented for calibration of the model using the laboratory tests results. The results of both, the numerical and theoretical analysis, correspond very well with the laboratory tests results. The DEM parameters used for the computer simulations are shown in Table 1. Ten thousand disks were used to simulate the samples as Figure 5 shows. All disks have the same size and are arranged at a coordination number of 6. The parameters in the model were changed by trial and error until similar results were observed compared with the static laboratory tests on the fissured specimen. The results compared were the stress applied at crack propagation and the secondary propagation path followed through the specimen.

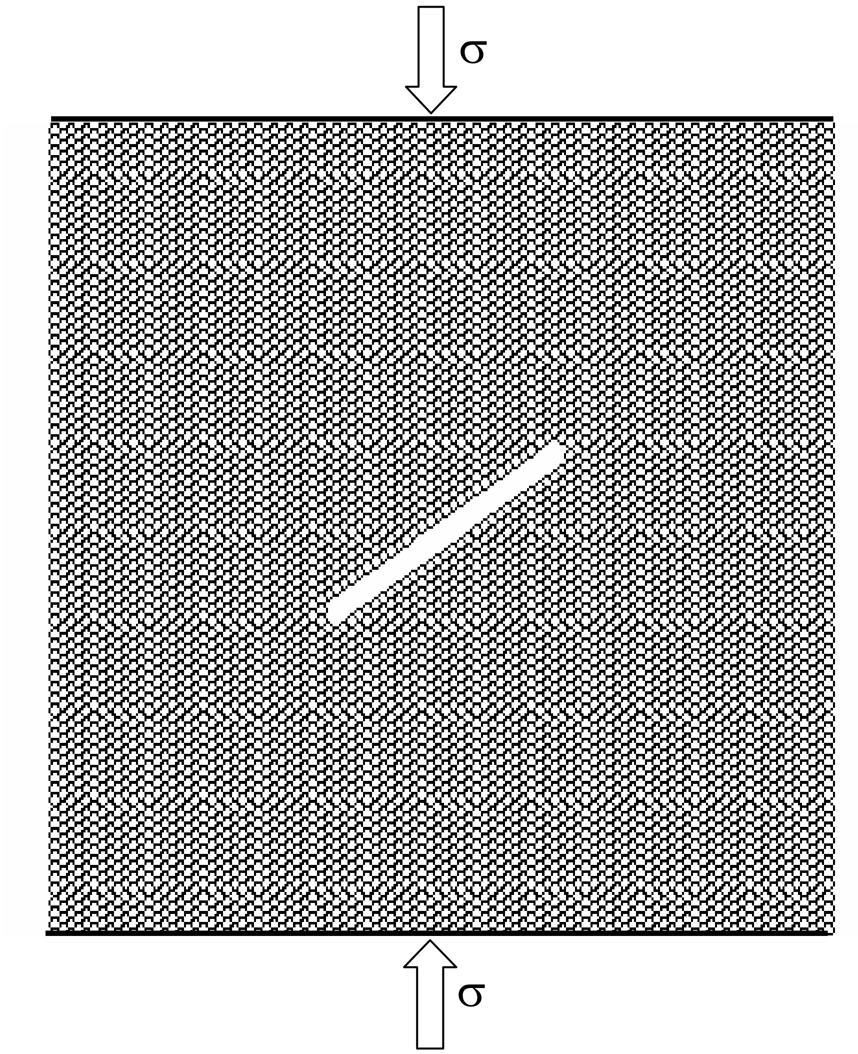

Figure 5. Initial configuration of DEM's specimen for α=45º

Crack Propagation under Static Loading

For primary crack inclination of α=45º, the DEM simulation indicated that crack propagated in the form of secondary cracks that developed at the tips of the primary crack (Figure 6). The new cracks developed from the tips of the pre-existing crack in a direction that could be predicted using the MTS criterion presented by Erdogan and Sih (1963). The secondary cracks curved to a direction

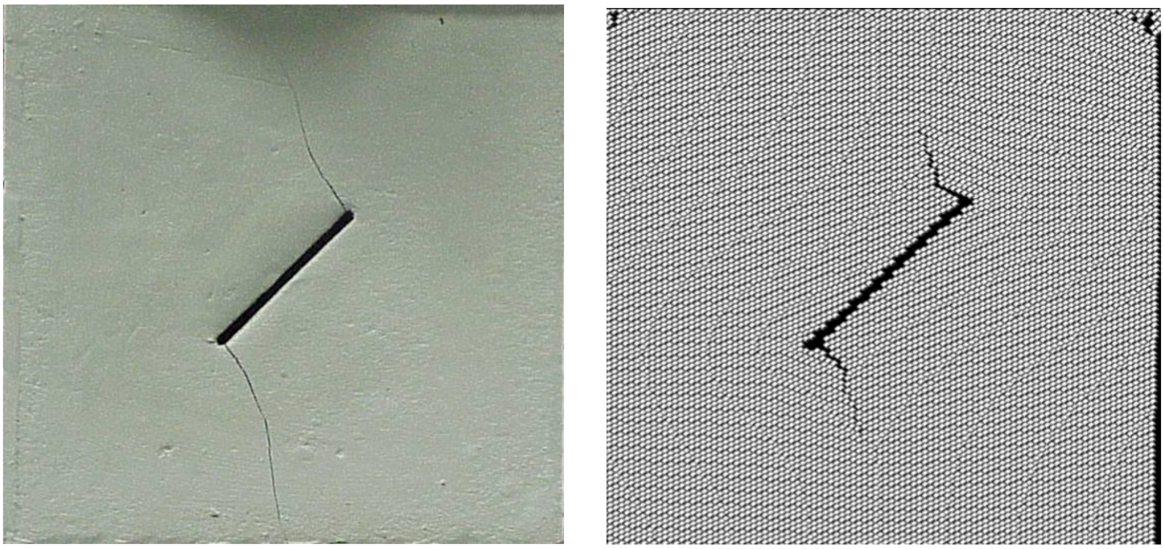

Figure 6. Primary crack and Secondary Tensile cracks in a clay under static loading. Laboratory (left) and DEM (right) results.

that was parallel to the direction of the uniaxial compressive stress, σ_c. Laboratory tests performed as part of this study yielded similar results as shown.

DEM analysis of dynamic loading of fissured specimens

Using DEM analysis, it was possible to simulate the dynamic loading of fissured specimens. Figure 7, below, shows the stress-strain graph obtained from a DEM simulation of one such specimen. In this case, the dynamic loading was applied by changing the velocity of the top wall of the specimen.

The contact bond option included with the PFC^{2D} computer program presumes that a material is elastic but it breaks when a certain degree of force greater than its contact bond is applied. Consequently, in this research, the bond resistance was reduced by applying an additional bonding-reduction factor (*fd*) to the larger force level in the specimen for each loading cycle (Vesga, 2005).

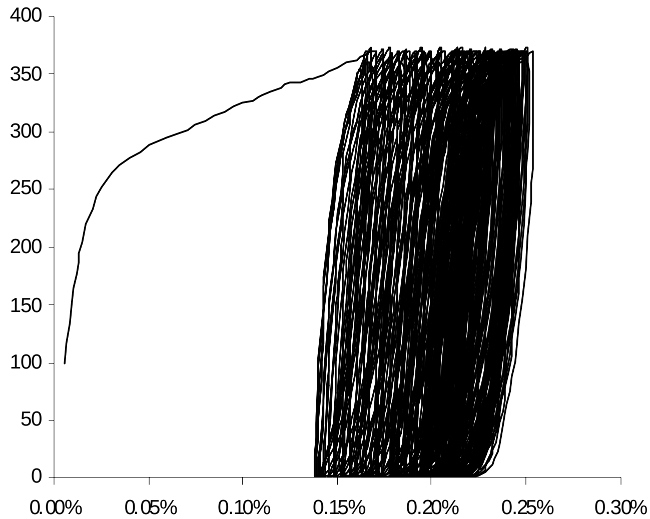

Figure 7. DEM-created stress-strain graph of simulated specimen using DEM and having a primary crack inclined at α=45º.

Various expressions of the bonding reduction factor were then tested until the results from DEM closely matched the laboratory fatigue curve of the specimen having a primary crack inclination angle α=45,° which is shown in Figure 6. The best results were obtained using the bonding reduction factor shown in Figure 8. Here, it can be seen that the residual bonding b_r is the minimum contact bond level in the material below which no additional reduction of strength occurs regardless of the number of cycles applied. The fatigue curve shown in Figure 6 that is derived from the DEM simulation, matches the calibration curve very well.

DEM simulations on specimens having two "left stepping" cracks were also performed using the same function of the bond strength reduction factor described above. Figure 10 shows the results after modeling using DEM.

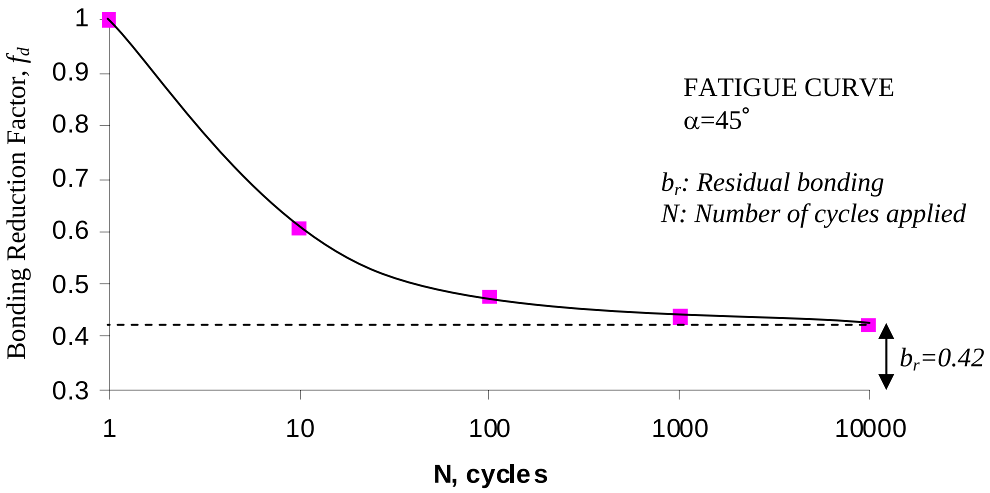

Figure 8. DEM bonding reduction factor for crack fatigue analyses using DEM.

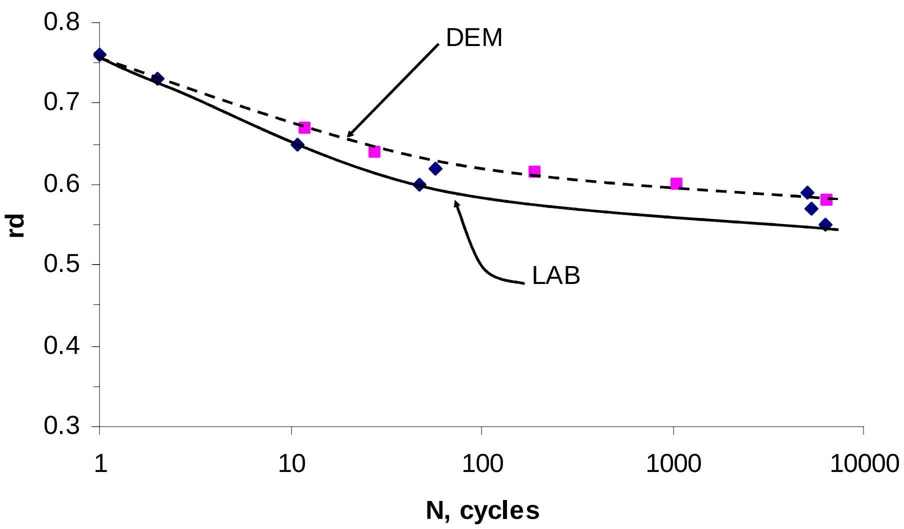

Figure 9. Fatigue curve from fissured specimens under dynamic loading: DEM and laboratory results.

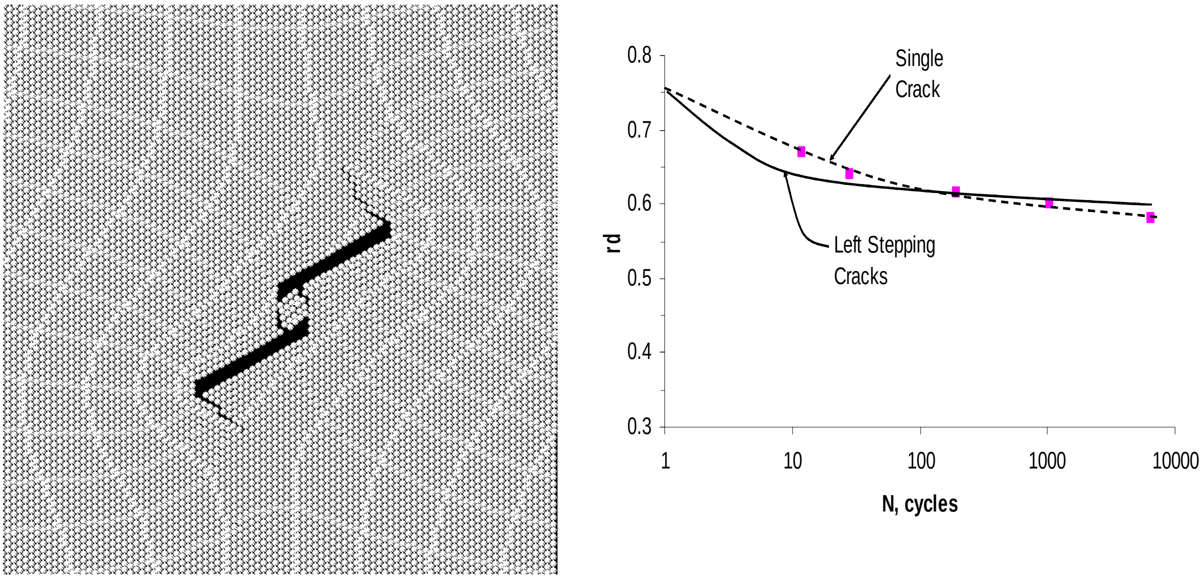

Figure 10. DEM results from specimens having two left stepping cracks.

CONCLUSIONS

Uniaxial static and dynamic laboratory tests were performed in order to determine the fatigue and the crack stability threshold on kaolinite clay specimens having a crack inclined 45° with the horizontal and a moisture content of 18%. Static and dynamic DEM numerical simulations were also performed using specimens having a single crack inclined 45° with the horizontal. The fatigue curve of the numerical model was calibrated using the laboratory tests. A bond-reduction function was derived from the calibration. Additional numerical analyses allowed testing specimens having two cracks in left-step arrangement using the same bond-reduction function.

More research is necessary in order to confirm that using a unique calibration curve of the bond-reduction factor in the DEM analyses produce satisfactory results compared with laboratory tests of similar specimens.

These analyses can be extended to study the influence of the dynamic loading on geotechnical structures having preexisting cracks.

AKNOWLEDGEMENTS

This research was developed by the author as Graduate Student in the School of Engineering in the University of Pittsburgh. The support received from the University is gratefully acknowledged. The author would also like to show his gratitude to his advisor in the University of Pittsburgh, Professor Luis E. Vallejo, and to Edifica Colombia Ltda for the financial support provided through this investigation.

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