Investigation of clay smear formation in laboratory-prepared layered soil specimens

Glen Edwin Maxwell
University of Nevada, Las Vegas

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INVESTIGATION OF CLAY SMEAR FORMATION IN LABORATORY PREPARED LAYERED SOIL SPECIMENS

by

Glen Edwin Maxwell

Bachelor of Science
Mechanical Engineering
University of California, San Diego
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A thesis submitted in partial fulfillment of the requirements for the

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Master of Science

Examination Committee Chair

Dean of the Graduate College

Examination Committee Member

Examination Committee Member

Graduate College Faculty Representative
ABSTRACT

Investigation of Clay Smear Formation In Laboratory Prepared Layered Soil Specimens

by

Glen Edwin Maxwell

Dr. Moses Karakouzian, P.E., Examination Committee Chair
Professor of Civil Engineering
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The purpose of this study was to investigate the impact of layering geometry on the formation of clay smears in laboratory prepared soil specimens. Digitized video clips of specimen deformation under vertical shear were reviewed. New conventions and definitions were developed to describe and measure the onset of clay smear. Measurements for a variety of sample layering geometries were taken. Specimen geometry was compared with its respective smear development properties to derive general relationships.

The study showed that as the sand thickness within a specimen increased, the required amount of vertical displacement and sand layer displacement prior to smear also increased. Ratios of sand to clay within a specimen did not alone provide a consistent indicator on the development of smear. However, by normalizing the sand layer displacement required for smear, a nearly constant value for all samples was achieved.
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CHAPTER 1

INTRODUCTION

Modeling and predicting sub-surface fluid flow is vital in many fields. Petroleum and reservoir engineers constantly attempt to further understand sub-surface flow fields. In a faulted layered soil or rock deposit, one structure that inhibits the flow of fluid is known as a clay smear. Clay smears are thin veneers of clay that separate two permeable layers, juxtaposed across a fault, which results in the restriction of fluid flow through that particular strata (Lindsay et al, 1993).

Classic theoretical and analytical models used to describe and predict sub-surface flow fields in stratified or layered deposits must be modified in faulted layered deposits. The presence of clay smears within these faulted strata greatly affect the ability to accurately predict fluid transport. This work does not explore the modification of classical sub-surface fluid transport theory for a medium containing clay smears. Rather, the purpose of this study was to explore the effect of layering geometry on smear formation in laboratory prepared faulted soil specimens. This study may provide insight on predicting the presence of sub-surface flow restrictions in naturally formed, faulted layered deposits and thereby guide the adaptation of classical theoretical models to broader types of subsurface conditions.
For this work, layering geometry refers to the thickness of individual sand and clay layers as well as the ratios of clay to sand in different sections of the specimens. Digital video recordings of specimen deformation under shear were reviewed. Specimens that formed clay smears during deformation were selected for further investigation. A new procedure for identifying and measuring the onset of smear was developed. For each specimen, the onset of clay smear was measured and the influence of the layering geometry was then investigated. A relationship between the specimen layering geometry and the onset of clay smear was developed.
CHAPTER 2

BACKGROUND

The background chapter includes an investigation on the deformation processes involved in the formation of clay smear. A discussion about analog modeling is included, as is a literature review of other work relating to the investigation of clay smears. This chapter also outlines techniques used in the laboratory for investigation and measurement of clay smear.

Origin of Layered Soils

Layered soils are comprised of alternating layers of granular and cohesive materials. An example of layered soil deposits in northern North America and northern Europe are known as varved clays. An example of these deposits is shown in Figure 2-1. These clay deposits were formed in glacial lakes by alternating seasonal deposits in the lake beds. The fine sand and silt varves are deposited during the spring and summer seasons and the silt and clay varves are deposited during the fall and winter seasons (Terzaghi, Peck and Mesri, 1996). Another naturally formed layered soil deposit is deltaic deposits. In simple geologic terms, as a river approaches a delta, the water velocity slows and coarser material is deposited. As the sediment load is carried further into the delta, finer and finer material is deposited as the river velocity continues to decrease. Over time, the
build up of the delta causes finer material to be deposited on top of the coarser materials. This results in a soil deposit containing distinct soil layers composed of different sized material. This processes is responsible for the layered soil deposits in the petroleum-rich Gulf of Mexico (Blatt, Middleton and Murray, 1980).

Figure 2-1. Varved Clay Deposit. (Terzaghi, Peck and Mesri, 1996).

Shear Deformation Processes

The formation of clay smears are the result of displacement deformation. These displacement deformations result from multiple shear deformation processes induced by faulting. In nature, gravity (Maltman, 1994) or tectonic phenomenon provide the forces necessary to create faulting. In the laboratory, these natural forces are modeled with mechanical systems that impart deformation to a layered specimen of soil. Typically, the study of laboratory induced clay smear has been performed using an apparatus that imparts movement of one part of a specimen along a stationary part of the specimen. This technique creates a hanging wall/foot wall interface inside the specimen (Figure 2-2).
During this "faulting" process, a clay layer is displaced along the interface of the hanging wall / foot wall. This plane is defined as the active/passive interface, and at this interface, a thin veneer of clay separates two (or more) granular (sand) layers. This smear phenomenon ultimately inhibits fluid flow within the sand layers across the interface.

Three shear deformation processes have been identified in the formation of clay smears in laboratory specimens. These processes are known as: interparticle movement, drag and slip (Hudyma, 1999).

Interparticle movement is a localized phenomenon. This process occurs when individual particles of sand and clay move past one another in the active/passive interface. This phenomenon occurs in both the granular and cohesive layers. McKinstry (1953) defined two types of interparticle movement: primary shear and secondary shear. Primary shear is an experimentally induced shear and is defined as shear deformation in a plane within the active/passive interface. The development of secondary shear in a specimen is dependent upon its material properties. This phenomenon occurs in the
passive side of the laboratory specimen and is oriented at an angle to the primary shear plane.

Drag is another localized phenomenon defined in the area of the active/passive interface. Drag, however, is a direct result of the experimental procedure used to investigate shearing artificial specimens. This process is governed by frictional forces between the soil and the mechanical system used in the production of the faulting. It occurs when the mechanical system forces the specimen to deform by dragging the active side of the specimen past the passive side soil layers. This process results in many changes and anomalies near the interface with the particular mechanical system, including: changes in layer orientation and changes in layer thicknesses. Specific changes to the orientation of specimen layers and interruption of these soil layers near the mechanized/soil interface were not investigated in this work.

Slip is a global phenomenon that occurs within the active/passive interface of the layered soil specimen. This process is defined globally as an active block moving en-mass along a passive block—rather than as an individual particle movement process. Both interparticle movement and drag processes always precede slip. Its use as a definition in this work is limited to a general description of the global phenomenon occurring between the active and passive sides of a particular soil specimen.

The previously described deformation processes combine to create two types of macroscopic deformation: strain deformations and displacement deformations (Morgenstern and Tchalenko 1967). Figure 2-3 outlines these differences.
Figure 2-3. Strain and Displacement Deformation. (Morgenstern and Tchalenko, 1967).
Strain deformation is evidenced by lack of displacement after deformation. Displacement deformation, conversely, involves movements of the structure. In the reviewed smear areas, the representative layers within the specimens initially undergo strain deformation at the early stages of loading and then progress into displacement deformation.

Analog Modeling

Analog modeling is one of the most well known techniques to study deformation using a phenomenological approach. Analog modeling is a tool that is used to simplify nature; natural deformation processes are modeled and investigated in a controlled laboratory setting. A scale model of undeformed material is produced and deformed in such a way that deformation structures seen in the field are reproduced in the laboratory. The deformation of the model usually takes place in a vessel in which the progressive deformation can be seen. The goal of analog modeling is to gain an understanding of the formation and evolution of the deformation structures (Koyi, 1997).

Researchers from the fields of civil engineering, petroleum engineering and structural geology have used materials such as natural geologic materials, wood, cheese, putty, paraffin wax and plasticine as analog materials. Koyi (1997) provided an excellent overview of analog modeling from its first use in 1815 to present day analog modeling techniques. The studies cited below provide an overview of analog models used to investigate the deformation of layered materials.

Ramberg (1955) performed a series of experiments to study the deformation structures which formed when a specimen was compressed perpendicular to the layering.
His specimens consisted of a competent elastic layer sandwiched between two incompetent viscous layers. The competent layers were made up of modeling clay, plasticine or cheese and the incompetent layer was made up of putty. The specimens were deformed by pressing on them with his hand.

Mandl et. al. (1977) performed tests on layered specimens within a torsional shear apparatus. The specimens consisted of vertical bands of sand alternating laterally with bands of clay. The specimens were sheared along a median slip plane under various simulated overburden pressures. After shearing, the researchers noticed that where shear zones intersect clay beds, sand wedges are formed with their apexes pointing in the direction of shear motion. Along the wedges, clay from unsheared portions of the clay beds is forced into the shear zone. Microscopic examination of the shear zone showed that the granular material dilated on the active portion of the specimen and the granular material compacted on the stationary portion of the specimen. The shear zone produced in the laboratory closely resembled shear zones in naturally layered materials the researchers had seen in nature (Weber et. al., 1978).

Aydan et. al. (1994) deformed layered slate specimens and oak specimens to study the deformation and initiation of kink bands. Both the rock and wood specimens were cut so that the cleavage and wood fibers were orientated parallel to compression direction. Several of their findings showed kinking always initiated from either a material or imposed mechanical singularity and grew into a band in which the strain localized, visible kinking developed after peak strength was exceeded and the inclination of kink bands was different from that of shear fractures which was predicted using Mohr-Coulomb compression yield criterion.
Kobberger and Zulauf (1995) performed tests on layered specimens to produce and describe the formation of folds and other deformation structures under constrictional conditions. Their specimens were made from plasticine. The cylindrical specimens consisted of a longitudinally oriented competent red layer sandwiched between two incompetent white layers. The specimens were deformed by compressing the specimens around their circumference and allowing the specimens to expand at the top and bottom.

Kidan and Cosgrove (1996) formed layered specimens consisting of plasticine and paraffin wax. The purpose of their study was to investigate initiation and amplification of structures which form when a multilayered specimen is deformed perpendicular to layering. The specimens were made up of horizontal layers 15 cm long, 5 cm wide and thicknesses ranging between 1 and 10 mm. The specimens were deformed in compression perpendicular to layering and the edges were confined while the front and back of the specimen were free to deform. They determined that the structures formed may be controlled by the properties of single layers within the specimen or by the mechanical anisotropy of the multilayered specimen as a whole.

Hudyma (1999) developed a new apparatus to model shear deformation processes in layered soil specimens. This device offered a completely different approach to modeling shear processes in that it simulated a natural $K_0$ stress condition—a naturally occurring model of layered deposits. Shear forces were applied perpendicular to soil strata, while the entire specimen is constrained radially. Real-time deformation of this specimen was recorded via video camera. Bulk stress and strain properties are not directly measured, however, detailed qualitative information is available for any point during the deformation process.
Historical Methods of Modeling Clay Smear

The most commonly used apparatus to model and study the formation of clay smear in the laboratory has been the ring shear apparatus. Mandl et al. (1977) developed a ring shear device to study the formation of shear zones in granular materials. An annular specimen is laterally confined between two pairs of rings and is vertically confined with annular platens. Drainage is achieved by means of porous annuli screwed to the platens. A normal force is applied vertically on the top ring while the lower ring is rotated. This rotation creates a shear plane through the median of the specimen where clay smears may develop. These studies also included experiments on specimens of layered specimens with alternating vertical strata of sand and clay. Again, the specimens were sheared along the central slip plane while being subjected to various levels of overburden pressures. Their experiments produced a multi-layered clay smear through the median slip plane. Figures 2-4 and 2-5 show a typical ring shear apparatus.

Sperrevik et al. (2000) utilized this specialized geotechnical testing apparatus to investigate the development of clay smear along faults in sand-clay sequences. They investigated the application of varying levels of overburden pressures, sensitivity of varying clay properties and varying levels of clay percentages in the formation of clay smears. Their results showed that clay smear formation was governed by the competence contrast between the clay and sand. As the competency of the clay relative to the sand increased, the less likely there was any formation of clay smear.

Clausen and Gabrielsen (2001) used the ring shear apparatus to explore relationships between normal stress, varying numbers of clay layers, deformation rates, fault/throw
Figure 2-4. Typical Ring Shear Apparatus.

Figure 2-5. Ring Shear Specimen Chamber. (Clausen and Gabrielsen, 2001).
distances, clay water content and the formation of clay smears. The ring shear apparatus was in fact the same one as used in the tests conducted by Sperrevik et al. (2000). Their findings indicated that deformation rate has a moderate effect on the clay smear potential, as does the number of clay layers and the fault/throw displacements.

Hudyma (1999) developed an alternate apparatus to investigate shear deformation in laboratory specimens. This vertical deformation apparatus (shown schematically in Figure 2-6 (a-c)) differed from the ring shear apparatus in that the soil specimens are sheared perpendicular to layering. Half of the specimen is held in place during the shearing operation (hanging wall) and the side subjected to the vertical force is allowed to travel vertically (footwall) through the bottom of the specimen chamber. Additionally, a camera stand was constructed and attached to the load frame platen to allow recording of the actual deformation process and its corresponding deformation displacements.

Karakouzian and Hudyma (2002) used this apparatus to concentrate on the analog modeling of formation of clay smears.

As explained in Karakouzian and Hudyma (2002), two major differences exist between the ring shear apparatus and the vertical shear device. The first is the stress conditions experienced by the soil specimens during shearing (Figure 2-7 (a-b)). While the ring shear apparatus imparts an overburden force to the soil specimen, the only applied force acting on the specimen in the vertical shear apparatus is the shearing force. The ring shear device imparts this normal force parallel to the layering strata. The vertical shear device imparts its loading perpendicular to the specimen layers. Along with the configuration of the specimen chamber and the layering orientation, the vertical
Figure 2-6. Vertical Shear Apparatus. (Karakouzian & Hudyma, 2002).
shear device approximates a $K_o$ stress condition – the usual state of stress for sediments being layered under uniform gravitational forces (Maltman, 1987). The second difference between the two devices is manifested in the type and method of data collected. The ring shear apparatus is routinely used to measure bulk stress-strain behavior, displacement and specimen heights from instrumentation. There is no ability to measure or identify the beginning or “onset” of development of smear in a tested specimen. Conversely, the vertical shear apparatus was designed to allow continuous viewing and recording of the entire deformation process within a layered specimen. No stress-strain information is measured. This process viewing allows the repeated examination of shear zones and clay smears at varying states of deformation – not just the final state as one is confined in the use of the ring shear apparatus.
Figure 2-7. Ring vs. Vertical Shear Apparatus Model Schemes
CHAPTER 3

METHODOLOGY

This chapter outlines the methodology involved in developing a procedure for the quantifiable investigation of clay smear with the vertical shear device. A brief discussion of the physical properties of the materials used and the preparation of the test specimens is presented. A synopsis of the actual specimen deformation process and data collection procedure is included. Finally, the detailed method of analysis and definitions that were developed to analyze clay smear formation with this apparatus are detailed.

Specimen Physical Properties and Construction

The layered soil specimens created to model clay smear formation were comprised of alternating strata of granular and cohesive soils. Figure 3-1 shows a typically constructed soil specimen used within the vertical shear test apparatus.

The granular material used was Ottawa Foundry Sand F-110 obtained from the U.S. Silica Company. The grains are rounded and have a specific gravity of 2.65. The USCS classification of the sand is SP, poorly graded (well sorted) sand. To aide in visualization, the sand was dyed pink, gray or blue using stamp pad ink.

The cohesive material used was a specially blended clay. This material was a mixture of 50% kaolin clay, 20% pyrophyllite clay, and 30% feldspar particles blended together
at a water content of approximately 23%. This clay mixture had a liquid limit of 42% and a plastic limit of 22%. The mixture produced an off-white colored cohesive material that could be easily trimmed with a wire saw.

Using these granular and cohesive soils, layered test specimens were constructed in a clear acrylic tube that was 102 mm in length and 50.8 mm in diameter. A bottom layer of clay was inserted into the acrylic tube and was then covered with a layer of colored sand. The sand was inundated with water and densified by repeatedly striking the sides of the
tube with a rubber mallet. Alternating layers of clay and sand were then placed inside the tube to a specific geometric layering scheme.

Deformation Apparatus and Process

As shown previously (Figure 2-6 (a)), the clear acrylic specimen tube was inserted into a cylindrical steel sleeve. This steel sleeve is 230 mm long, 57.2 mm in diameter and 10 mm thick. A bottom stage is connected to a semi-cylindrical plunger to ensure synchronous, uniform, planar deformation of the specimen. The steel sleeve contains a centered, elliptical viewing window measuring 50.8 mm and 102 mm on its widest and longest axis, respectively. A digital dial indicator is connected to the load platform to measure deformation displacement. An 8-mm video recording camera with a polarizing filter is mounted on a stand attached to the load platform. This camera was directed at the elliptical viewing window and recorded the continuous deformation history and the corresponding deformation displacement of the plunger displayed on the dial indicator.

As the plunger advanced, the specimen was sheared perpendicular to layering. The fixed half of the specimen (hanging wall) was termed the passive side, while the side subjected to the plunger force (foot wall) was termed the active side. Deformation was achieved with a small load frame to which the deformation apparatus was mounted and was controlled with a variable rate motor operating at a constant 1.6 mm per minute. Measurement of the deformation was achieved with the use of the above mentioned digital dial indicator attached to the load frame to which the plunger was indirectly mounted. Maximum plunger travel into the specimens was 50 mm. For each specimen test, the video record of that particular test was digitized and saved in MPEG format.
Figures 3-2 and 3-3 show a representative specimen prior to and after deformation in the apparatus.

Figure 3-2. Specimen ESLT 10 Prior To Deformation.

Method of Analysis / Definitions

As described earlier, prior to the development of the vertical shear apparatus, all modeling of clay smears in laboratory prepared soil specimens had been performed with the ring shear apparatus. The ring shear machine, while allowing precise quantitative measurements of soil properties, does not lend itself practically to the qualitative
examination of the development of smear. In contrast, the ability to visually examine and re-examine any point(s) of smear development via the vertical shear apparatus enables the collection of a vast amount of qualitative information quickly. To perform quantitative analysis on the impact of layering geometry on the formation of clay smear, standard procedures, conventions and definitions for measurement of smear were developed.

Nine digitized deformation clips created by Hudyma (1999) were used as the specimen base for the development of these procedures. These specimens, and their respective layering properties are outlined in Table 3-1.
Table 3-1. Specimen Names and Properties.

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>Clay Layer Thickness (mm)</th>
<th>Sand Layer Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESLT 1</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>ESLT 4</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>ESLT 6</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>ESLT 10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>ESLT 15</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>ESLT 23</td>
<td>10</td>
<td>23</td>
</tr>
<tr>
<td>SLT 10-10-10-30</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>SLT 10-10-50</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>CSR 5</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

As described in Hudyma (1999), the naming convention of the soil specimens relates to its layering geometry. Specimens with the prefix “ESLT” indicate that these specimens contained Equal Sand Layer Thicknesses for all layers. This corresponding thickness (in mm) is the suffix of the specimen name. All ESLT specimens contained alternating clay layers of 10 mm. Specimens “SLT” had varying Sand Layers of varying Thicknesses, designated by the numerical values following this prefix. Specimen SLT 10-10-10-30 had sand layer strata measuring 10 mm, 10 mm, 10 mm, and 30 mm, respectively. Again all SLT specimens contained alternating clay layers of 10 mm. Specimen CSR 5 contained equal and alternating clay and sand layers of 5 mm each. Screen captures from the digitized video clips showing the above nine specimens (in their undeformed states) are shown in Figures 3-4 through 3-12.
Figure 3-4. Specimen ESLT 1

Figure 3-5. Specimen ESLT 4
Figure 3-6. Specimen ESLT 6

Figure 3-7. Specimen ESLT 10
Figure 3-8. Specimen ESLT 15

Figure 3-9. Specimen ESLT 23
Each digitized video recording of the specimen deformation (hereinafter, clip) was reviewed. The time-lapse display for each digitized clip was cycled through. The clip was reviewed on an IBM PC, with a 17 inch tube monitor. The clip (provided in MPEG format) was opened in Windows media player viewer and maximized to fit the screen. The clip's aspect ratio remained constant within the player, allowing the specimen's video projection to be scaled as large as the reviewing screen would allow. Clay smear occurs when a thin layer of clay separates sand layers across a fault (Lindsay et. al. 1993). The visual interpretation of this occurrence in the subject specimens was observed for many tests.
As the clips were replayed, the plunger travel induced a vertical shear plane between the hangingwall and footwall interface of the specimen. This interface was defined in Hudyma (1999) as the active/passive interface. As the specimen was sheared, strain deformation produced drag structures in the sand/clay layers in the immediate vicinity of the active/passive interface.

To quantitatively correlate plunger displacement to the onset of smear, a reference grid system was superimposed over the specimen on the video monitor. A clear Mylar sheet was attached to monitor screen and the projection of the undisturbed test specimen was transferred to this sheet. The undisturbed specimen layers were carefully traced onto the film, and a notation was made at the far left of the film to differentiate sand and clay layers. This grid system provided a frame of reference from the specimen’s undisturbed state.

Repeated cycling of the displacement test and close observation of the deformation structures in the middle third of the test specimen were performed. Based upon this review method, a particular sand/clay layer combination was selected to represent the test specimen geometry for clay smear onset. This representative combination was always located at least one layer below the maximum depth penetration of the plunger into the specimen. As expected, the determination of the exact point of onset of smear was not completely objective. The onset of smear for the representative sand/clay layer combination in focus was generally determined to be within 5 mm of plunger travel immediately preceding the point at which a complete truncation of the sand layer occurred.
Subsequent to the definition and visual determination of the point of discontinuity, the cumulative corresponding plunger displacement at this point was recorded. The deformation activity in the specimen sand/clay layer in the 5 mm of plunger travel immediately preceding the truncation point was more closely inspected. Based upon extensive review of the test specimens, this distance of plunger travel prior to the point of discontinuity was found to contain the onset of smear. This distance bounded all cases reviewed for the onset of smear and was taken to be the guideline from which to measure from. Clearly, some specimens exhibited smear formation that developed more rapidly than 5mm prior to the point of discontinuity, however, all specimens reviewed developed smear within 5 mm.

To determine the measured point of the onset of smear, the definition given by Lindsay et. al. (1993) was continuously applied to the subject sand layer until the first state of the active/passive interface of the sand layer under review conformed. Forward and reverse frame review of the video specimen was performed to isolate this point of faulting across the sand layer. Figure 3-13 depicts the specimen prior to onset of smear, at onset of smear, and after truncation of sand layer.

Once the onset of smear has been identified, the image of the subject sand layer was transferred to the Mylar film on the video screen. This deformed state of the entire sand layer is traced in an alternating color from the original grid. Plunger displacement at the point of smear was also noted. Using a scale, a horizontal reference line was extended across the Mylar film at the point of smear of the sand layers. The distance between the undisturbed starting point of the sand layer and this point of smear is measured on the Mylar film to 1.10 of an inch. This distance was defined as $X_u$ (Travel distance of sand to
Figure 3-13. Onset of Smear Determination.
onset of smear (screen scale)). The corresponding plunger displacement was noted and defined as $X_{pl}$ (Travel distance of plunger to onset of smear (local scale)). Utilizing the known geometry of the subject specimen layers, a scale transformation was performed to transfer the sand travel distance from screen scale to local scale.

A scale transformation coefficient was determined for each specimen test studied and was defined as: $C_{s-l}$ (Transformation coefficient from screen to local scale) and was computed as:

$$T_{sl} / T_{ss} = C_{s-l}$$

where $T_{sl}$ is the local (actual) thickness of the subject sand layer (in mm).

and $T_{ss}$ is the thickness of the sand layer as projected from the screen to the Mylar film (in inches).

This coefficient was then used to transform the onset of smear distance from screen scale to local scale as:

$$X_{sl} = X_{ss} \times C_{s-l}$$

Where $X_{sl}$ is the travel distance of sand to the onset of smear (in mm).
CHAPTER 4

DATA ANALYSIS

The goal of this work was to investigate the relationship between the layering geometry of stratified soil specimens with the development of clay smear. The premise of this investigation is that the layering composition or geometry of a specimen influences the amount of shear a particular specimen requires prior to the formation of clay smear. In this chapter, the identification and quantification of some proposed relationships is presented.

Data

In review of the specimen tests, Table 4-1 outlines the raw data observed at the onset of smear (if present).

Utilizing the procedures previously described, 9 specimen test videos were reviewed and analyzed. Of these, 7 tests involved symmetric geometry of specimen construction - the sand layers thickness and clay layers thickness were constant throughout the specimen. This type of specimen geometry was referred to as homogeneous. The 2 remaining specimen tests reviewed had non-symmetric geometry of sand and clay layers. This type of specimen construction was referred to as non-homogeneous.
Table 4-1. Specimen Clip Raw Data

<table>
<thead>
<tr>
<th>Test #</th>
<th>Sample Name</th>
<th>Smear Y/N</th>
<th>Homogeneous/Non-Homogeneous Layering</th>
<th>Clay Layer Thickness (mm)</th>
<th>Sand Layer Thickness (mm)</th>
<th>Sand Layer Displacement to Smear (mm)</th>
<th>Plunger Displacement to Smear (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ESLT 1</td>
<td>Y</td>
<td>H</td>
<td>10.0</td>
<td>1.0</td>
<td>3.3</td>
<td>16.14</td>
</tr>
<tr>
<td>2</td>
<td>ESLT 4</td>
<td>Y</td>
<td>H</td>
<td>10.0</td>
<td>4.0</td>
<td>9.5</td>
<td>19.98</td>
</tr>
<tr>
<td>3</td>
<td>ESLT 6</td>
<td>Y</td>
<td>H</td>
<td>10.0</td>
<td>6.0</td>
<td>15.6</td>
<td>25.90</td>
</tr>
<tr>
<td>4</td>
<td>ESLT 10</td>
<td>Y</td>
<td>H</td>
<td>10.0</td>
<td>10.0</td>
<td>26.7</td>
<td>50.00</td>
</tr>
<tr>
<td>5</td>
<td>CSR 5</td>
<td>Y</td>
<td>H</td>
<td>5.0</td>
<td>5.0</td>
<td>12.5</td>
<td>22.84</td>
</tr>
<tr>
<td>6</td>
<td>SLT 10-10-10-30</td>
<td>Y</td>
<td>NH</td>
<td>10.0</td>
<td>10.0</td>
<td>25.4</td>
<td>50.00</td>
</tr>
<tr>
<td>7</td>
<td>SLT 10-10-50</td>
<td>N</td>
<td>NH</td>
<td>10.0</td>
<td>10.0</td>
<td>50.0</td>
<td>50.00</td>
</tr>
<tr>
<td>8</td>
<td>ESLT 15</td>
<td>Y</td>
<td>H</td>
<td>10.0</td>
<td>15.0</td>
<td>29.3</td>
<td>42.04</td>
</tr>
<tr>
<td>9</td>
<td>ESLT 23</td>
<td>N</td>
<td>H</td>
<td>10.0</td>
<td>23.0</td>
<td>43.8</td>
<td>50.00</td>
</tr>
</tbody>
</table>

As can be seen from Table 4-1, smear occurred in both homogeneous and non-homogeneous specimens. With only 2 non-homogeneous specimen geometries for review, a definitive hypothesis on the effect of this influence alone was premature.

To investigate the possible dependence between the overall volume of sand as compared to that of clay contained within a particular specimen on the development of smear, the ratio of sand layer thickness to clay layer thickness was computed for each specimen. This parameter, known as the "Sand/Clay Ratio" (SCR), for each specimen is shown in Table 4-2.

For non-homogeneous specimens, since the sand layer thicknesses varied (by definition), the computation of SCR for these specimens is somewhat ambiguous. Not enough specimen data was reviewed for non-homogeneous layering geometry to form hypothesis. Given the data in Table 4-2, the SCR alone does not appear to be a sole basis
Table 4-2. Sand/Clay Ratio for Each Specimen.

<table>
<thead>
<tr>
<th>Test #</th>
<th>Sample Name</th>
<th>Smear Y/N</th>
<th>Homogeneous/Non-Homogeneous Layering H / NH</th>
<th>Sand/Clay Ratio (SCR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ESLT 1</td>
<td>Y</td>
<td>H</td>
<td>0.1</td>
</tr>
<tr>
<td>2</td>
<td>ESLT 4</td>
<td>Y</td>
<td>H</td>
<td>0.4</td>
</tr>
<tr>
<td>3</td>
<td>ESLT 6</td>
<td>Y</td>
<td>H</td>
<td>0.6</td>
</tr>
<tr>
<td>4</td>
<td>ESLT 10</td>
<td>Y</td>
<td>H</td>
<td>1.0</td>
</tr>
<tr>
<td>5</td>
<td>CSR 5</td>
<td>Y</td>
<td>H</td>
<td>1.0</td>
</tr>
<tr>
<td>6</td>
<td>SLT 10-10-10-30</td>
<td>Y</td>
<td>NH</td>
<td>1.0</td>
</tr>
<tr>
<td>7</td>
<td>SLT 10-10-50</td>
<td>N</td>
<td>NH</td>
<td>1.0</td>
</tr>
<tr>
<td>8</td>
<td>ESLT 15</td>
<td>Y</td>
<td>H</td>
<td>1.5</td>
</tr>
<tr>
<td>9</td>
<td>ESLT 23</td>
<td>N</td>
<td>H</td>
<td>2.3</td>
</tr>
</tbody>
</table>

For predicting the development of clay smear. Variations by more than one order of magnitude in SCR still exhibit smear.

Next, the deformation distance experienced by a representative sand layer to the onset of smear was compared for all specimens. This distance is known as “throw” and is defined in this context as the distance from the top of the sand layer at zero displacement to the top of the sand layer at the onset of smear. This measurement represents the distance the sand layer traveled during shear to the onset of smear. To examine the influence of layering geometry on this distance, the ratio of sand thickness to clay thickness for each specimen was computed. Table 4-3 shows the specimen comparison of Sand/Clay Ratio and distance to onset of smear for all specimens. Figure 4-1 shows this comparison for all 9 specimens graphically.
Table 4-3. SCR and Displacement to Smear for Each Specimen

<table>
<thead>
<tr>
<th>Test #</th>
<th>Sample Name</th>
<th>Smear Y/N</th>
<th>Homogeneous/ Non-Homogeneous Layering</th>
<th>Clay Layer Thickness (mm)</th>
<th>Sand Layer Thickness (mm)</th>
<th>Sand/Clay Ratio (SCR)</th>
<th>Sand Layer Displacement to Smear (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ESLT 1</td>
<td>Y</td>
<td>H</td>
<td>10</td>
<td>1</td>
<td>0.1</td>
<td>3.3</td>
</tr>
<tr>
<td>2</td>
<td>ESLT 4</td>
<td>Y</td>
<td>H</td>
<td>10</td>
<td>4</td>
<td>0.4</td>
<td>9.5</td>
</tr>
<tr>
<td>3</td>
<td>ESLT 6</td>
<td>Y</td>
<td>H</td>
<td>10</td>
<td>6</td>
<td>0.6</td>
<td>15.6</td>
</tr>
<tr>
<td>4</td>
<td>ESLT 10</td>
<td>Y</td>
<td>H</td>
<td>10</td>
<td>10</td>
<td>1.0</td>
<td>38.3</td>
</tr>
<tr>
<td>5</td>
<td>CSR 5</td>
<td>Y</td>
<td>H</td>
<td>5</td>
<td>5</td>
<td>1.0</td>
<td>12.5</td>
</tr>
<tr>
<td>6</td>
<td>SLT 10-10-10-30</td>
<td>Y</td>
<td>NH</td>
<td>10</td>
<td>10</td>
<td>1.0</td>
<td>38.5</td>
</tr>
<tr>
<td>7</td>
<td>SLT 10-10-50</td>
<td>N</td>
<td>NH</td>
<td>10</td>
<td>10</td>
<td>1.0</td>
<td>50.0</td>
</tr>
<tr>
<td>8</td>
<td>ESLT 15</td>
<td>Y</td>
<td>H</td>
<td>10</td>
<td>15</td>
<td>1.5</td>
<td>29.3</td>
</tr>
<tr>
<td>9</td>
<td>ESLT 23</td>
<td>N</td>
<td>H</td>
<td>10</td>
<td>23</td>
<td>2.3</td>
<td>43.8</td>
</tr>
</tbody>
</table>

Influence of SCR on Sand Throw to Smear

![Graph showing the relationship between Sand/Clay Ratio (SCR) and Sand Throw to Smear (mm).]

Figure 4-1. SCR vs. Sand Throw To Smear

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For the specimens reviewed that exhibited smear, the throw required for a particular sand layer at the onset of smear appears fairly linearly related to SCR. The two specimens (ESLT 23 and SLT 10-10-50) that did not exhibit smear do not appear to conform to this relationship. A possible explanation may involve the large sand layer present at the bottom of both of these specimen. Given the maximum plunger penetration of 50 mm, it is believed that the length of the sample chamber is interfering with the normal shear deformation development of the sample. It is interesting to note that specimens ESLT 10 and SLT10-10-10-30 have nearly identical throw distances to onset of smear, even though the later contains non-homogeneous layering strata.

In a similar fashion, the travel distance experienced by the plunger to onset of smear in the specimen was recorded. Table 4-4 shows this value, while Figure 4-2 depicts this graphically.

Table 4-4. Plunger Displacement to Onset of Smear

<table>
<thead>
<tr>
<th>Test #</th>
<th>Sample Name</th>
<th>Smear Y/N</th>
<th>Homogeneous/Non-Homogeneous Layering</th>
<th>Plunger Displacement to Smear (mm) (50 mm max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ESLT 1</td>
<td>Y</td>
<td>H</td>
<td>16.14</td>
</tr>
<tr>
<td>2</td>
<td>ESLT 4</td>
<td>Y</td>
<td>H</td>
<td>19.98</td>
</tr>
<tr>
<td>3</td>
<td>ESLT 6</td>
<td>Y</td>
<td>H</td>
<td>25.90</td>
</tr>
<tr>
<td>4</td>
<td>ESLT 10</td>
<td>Y</td>
<td>H</td>
<td>50.00</td>
</tr>
<tr>
<td>5</td>
<td>CSR 5</td>
<td>Y</td>
<td>H</td>
<td>22.84</td>
</tr>
<tr>
<td>6</td>
<td>SLT 10-10-10-30</td>
<td>Y</td>
<td>NH</td>
<td>50.00</td>
</tr>
<tr>
<td>7</td>
<td>SLT 10-10-50</td>
<td>N</td>
<td>NH</td>
<td>50.00</td>
</tr>
<tr>
<td>8</td>
<td>ESLT 15</td>
<td>Y</td>
<td>H</td>
<td>42.04</td>
</tr>
<tr>
<td>9</td>
<td>ESLT 23</td>
<td>N</td>
<td>H</td>
<td>50.00</td>
</tr>
</tbody>
</table>
Influence of SCR on Plunger Displacement to Smear

Figure 4-2. Influence of SCR on Plunger Displacement to Onset of Smear.

To further examine the effect of SCR on the development of smear and to attempt to develop a more general relationship, the throw distance to smear for a particular specimen was normalized with the original sand layer thickness. For relevancy, only homogeneous specimens that exhibited smear were included in this focus. The results of this analysis are shown in Table 4-5 and graphically in Figure 4-3.
Table 4-5. Normalized Throw for Homogeneous Samples

<table>
<thead>
<tr>
<th>Test #</th>
<th>Sample Name</th>
<th>Smear</th>
<th>Homogeneous/ Non-Homogeneous Layering</th>
<th>Sand/Clay Ratio (SCR)</th>
<th>SL Throw/ Layer Thick</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ESLT 1</td>
<td>Y</td>
<td>H</td>
<td>0.1</td>
<td>3.3</td>
</tr>
<tr>
<td>2</td>
<td>ESLT 4</td>
<td>Y</td>
<td>H</td>
<td>0.4</td>
<td>2.4</td>
</tr>
<tr>
<td>3</td>
<td>ESLT 6</td>
<td>Y</td>
<td>H</td>
<td>0.6</td>
<td>2.6</td>
</tr>
<tr>
<td>4</td>
<td>ESLT 10</td>
<td>Y</td>
<td>H</td>
<td>1.0</td>
<td>2.7</td>
</tr>
<tr>
<td>5</td>
<td>CSR 5</td>
<td>Y</td>
<td>H</td>
<td>1.0</td>
<td>2.5</td>
</tr>
<tr>
<td>8</td>
<td>ESLT 15</td>
<td>Y</td>
<td>H</td>
<td>1.5</td>
<td>2.0</td>
</tr>
</tbody>
</table>

After normalizing the throw distance experienced by the sand layer at smear, the value remains fairly constant, independent of SCR. Hypothetically, this normalized value could be used to predict the development or absence of smear in similar specimens. As mentioned earlier, it the larger sample geometries appear to fall slightly off the general relationship supported by the balance of the samples.
Influence of SCR on Normalized Throw at Onset of Smear

Figure 4-3. Normalized influence trend of SCR to smear development
CHAPTER 5

CONCLUSIONS & RECOMMENDATIONS

Several properties of layering geometry were examined for their influence on the formation of clay smear. Symmetric geometry (termed as homogeneity) alone proved inconclusive in its effect on precipitating smear development. Similarly, the Sand/Clay Ratio (SCR) was not found to be a singular determinant for instigating smear.

Comparing the layer thickness reviewed to the necessary displacement to produce smear showed an obvious and linearly increasing relationship. Similar findings were discovered for required plunger displacement to the onset of smear.

When combined together, certain layering geometrical properties seemed to produce less intuitive, general trends for the development of smear. By normalizing the necessary layer throw distance to smear with its own thickness, an approximately constant value was discovered to precipitate smear over all ranges of SCR investigated. While the number of specimens and scope of the study were albeit limited, the geometrical layering dimensions did vary by more than one order of magnitude. The fact that this normalized value varied by such a small margin over this range lends support to the possibility of scaling this phenomenon beyond the specimen sizes reviewed in this study.
In order to more effectively examine this possible global relationship, many more sample geometries would need to be investigated. The thicker layered specimens had sand strata that were greater than 20% (each) of the overall specimen length. To realistically examine smear formation of this type of geometry, a larger test cylinder is probably needed. Size of test vessel limits geometry of specimen layering sizes. Similarly, several more variations of non-homogeneous layered specimens would need to be studied to develop plausible comparisons versus homogeneous specimens.

Another shortcoming of this study was the intrinsic subjectivity introduced in measuring the distances for onset of smear. Eliminating the process of transferring the image to a Mylar film and measuring from that surface would produce much more accurate and repeatable results. Superimposing a grid with a local reference scale over the test vessel would be an easy improvement. This would eliminate the process of scale transformations and produce much more repeatable results.
BIBLIOGRAPHY


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