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Experimental investigation of shear deformation in laboratory prepared layered soil specimens

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EXPERIMENTAL INVESTIGATION OF SHEAR DEFORMATION IN LABORATORY PREPARED LAYERED SOIL SPECIMENS

by

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A dissertation submitted in partial fulfillment of the requirements for the

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ABSTRACT

Experimental Investigation of Shear Deformation in Laboratory Prepared Layered Soil Specimens

by

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The purpose of this study was to identify and describe the shear deformation mechanisms and structures of laboratory prepared layered soil specimens. Soil specimens made of alternating layers of sand and clay were produced in the laboratory with different layering schemes and layering geometries. Layering schemes are groups of specimens with similar layering geometries. Layering geometries refer to the number of layers of sand and clay, thicknesses of the layers and the layer positions within the specimen. The specimens were sheared perpendicular to layering using a specially designed deformation apparatus and their deformation mechanisms and deformation structures were identified and described. The descriptions of the deformation structures were used to compare the deformation of specimens within and between layering schemes.

The study showed that as the sand layer thickness of the specimens increased, the sand deformation structures became more complex. The sand
deformation structures, shear bands, did not appear to form in specimens with very thin sand layers, but, as the sand layer thickness increased, secondary shear bands, primary shear bands and tertiary shear bands formed.

As the clay percentage of the specimen increased, the clay deformation structures became more complex. In specimens with a low clay percentage, slip lines and step structures were formed. As the clay content increased, clay smears and double clay smears were formed. Specimens with higher clay contents generally required more local strain to form clay deformation structures and have narrower shear zones than specimens with a lower clay content.

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INTRODUCTION

Soil deformation is usually studied using one of two approaches: a mechanistic approach or a phenomenological approach. A mechanistic approach measures stresses and strains required to deform a soil specimen. This information is then used to produce a constitutive model to mathematically describe soil behavior.

A phenomenological approach describes what happens to a soil specimen while it is being deformed. Deformation processes, deformation mechanisms and deformation characteristics are identified and verbally described. This information may be used to improve the constitutive models.

The purpose of this study is to identify and describe the shear deformation processes and deformation structures formed in artificially layered soil specimens deformed in direct shear. Soil specimens made of alternating layers of sand and clay were produced in the laboratory. The specimens were produced with different layering schemes and layering geometries. Layering schemes are groups of specimens with similar layering geometries, and layering geometries refer to the number of layers of sand and clay, thicknesses of the layers and the layer positions within the specimen. The specimens were sheared perpendicular to layering using
a deformation apparatus which was designed, developed and manufactured for this study. The descriptions of the deformation structures were then used to compare the deformation of specimens within and between layering schemes.

This dissertation is divided into seven chapters. Chapter Two is a background chapter which contains a literature review of topics relevant to this study, namely, the motivation for this study, producing layered soils in the laboratory, previous studies using phenomenological approaches to study soil deformation and a list of terms used throughout this dissertation.

Chapter 3, Methodology, describes how this study was conducted. It describes how the study was divided into three tasks and details the purposes of each of the tasks.

Chapter 4 describes the first task, developing a test procedure. Developing a test procedure consisted of designing, developing and manufacturing a deformation apparatus, developing a technique to produce layered soil specimens and data collection. These sub-tasks were conducted in five developmental design cycles. In each of the developmental design cycles, layered specimens were deformed in various deformation apparatuses but the results of the specimen deformation in the first four developmental design cycles were deemed unacceptable. Chapter 4 is devoted to describing the first four developmental design cycles. This description includes the deformation apparatus, specimen layering schemes and geometries which were deformed, the data which was collected and why the results were unacceptable.

Chapter 5, Test Matrix and Data Collected, describes developmental design cycle five. Developmental design cycle five was the final design cycle. The
deformation apparatus, specimen layering schemes and layering geometries and data collected are all described.

Chapter 6, Analysis, addresses Objective 2 and Objective 3. The purpose of Objective 2 was to describe the shear deformation processes which were observed in the deforming specimens and describe the deformation structures which were formed in the specimens. The purpose of Objective 3 was to compare specimen deformation within and between specimen layering schemes.

Chapter 7, Summary, Conclusions And Recommendations For Future Work, summarizes the work performed, the conclusions reached and possible areas for future work.
CHAPTER 2

BACKGROUND

The Background Chapter contains a literature search which investigates topics relevant to this study. This Chapter provides information on the motivation for this study, producing artificially layered soils in the laboratory, previous studies using phenomenological approaches to study soil deformation and a list of terms and definitions used throughout this dissertation.

Study Motivation

Geotechnical engineers typically classify soils into three categories: granular, cohesive and intermediate soils. As their names imply, granular soils are comprised of gravel, sand and silt and cohesive soils are comprised of clay minerals. Intermediate soils are made up of both granular and cohesive materials. Within the category of intermediate soils, there are two types of soil formations: massive soils and layered soils. Massive soils consist of a non-structured homogeneous mixture of both granular and cohesive materials. Layered soils consist of alternating layers of granular and cohesive materials.

One type of naturally layered soil deposit, varved clays, are known to be the cause of many geotechnical related problems in northern North America and
northern Europe. Varved clay deposits were formed in glacial lakes. They consist of alternating layers of light and dark layers or varves. The light varves were deposited in the summer months and consist of fine sands and silts. The dark varves were deposited in the winter months and consist of silts and clays (Terzaghi, Peck and Mesri, 1996).

Many engineering studies have been performed on varved clays. These studies have focused on composition of the varves (for example, Baracos, 1976), engineering properties of varved clays (for example, Tschebotarioff and Bayliss, 1948, Baracos, Graham and Domaschuk, 1980, and Eigenbrod and Burak, 1991), sampling problems (for example, Colon and Isaacs, 1971 and Saxena, Hedberg and Ladd, 1978) and geotechnical problems associated with varved clays (for example, Milligan, Soderman and Rutka, 1962, Lo and Stermac, 1965, and van Genuchten, 1988).

One city with many geotechnical problems associated with varved clays is Winnipeg, Manitoba, Canada. Baracos, Graham and Domaschuk (1980) state these problems as being: natural riverbank slopes being marginally stable at slopes as flat as 8:1, compacted clay fills failing in shallow planar slides at moderate inclinations and excavation stability is much less than implied by measured unconfined compressive strengths. They further add that the behavior of the varved clays is complex and deserves further attention.

This work will not attempt to solve the geotechnical problems associated with varved clays. The purpose of this study was to identify and describe the shear deformation mechanisms and structures of laboratory prepared layered soil specimens. This may provide some insight into the behavior of naturally layered soils.
Producing Artificially Layered Soil Specimens

Producing soil specimens in the laboratory is a common practice among geotechnical engineers. In order to study the effects of different parameters on soil behavior, a large number of specimens must be produced with identical features. These features may include: mineralogic composition, consolidation history, soil fabric, initial water content and initial void ratio. It is often impossible to obtain natural specimens with such a set of identical features; therefore, many times soil is remolded to produce specimens for laboratory testing. Typically, remolded specimens are prepared at or near optimum water contents and contain a wide variety of material sizes.

Numerous researchers have prepared homogeneous and stratified clay specimens in the laboratory using various techniques which include, but are not limited to remolding, sedimentation, and consolidation and compaction (Krishna Murthy et. al., 1974). One example of producing specimens in the laboratory was performed by Maltman (1987). Maltman was interested in investigating deformation microstructures in water-rich sediments. For his investigations, he produced clay specimens by firstly preparing a slurry of clay and sea water in a ratio of 1 to 2 and then allowing the slurry to settle either under its own weight in settling tanks, under an applied load on the base of a triaxial cell or under an applied load in a consolidation apparatus. Stratified clay specimens were produced by introducing different clay slurries on top of already settled clay slurries.

One set of researchers who were interested in producing layered specimens containing dissimilar materials were Krishna Murthy et. al. (1979). For their work, the authors excavated a square pit 1.25 m wide by 1.5 m deep and constructed a
brick well within the pit. A clay slurry with a water content of 200% was produced using commercially available kaolin and transferred into the well. Once the slurry had settled under its own weight, a sand layer was deposited through a column of water on top of the clay layer. This process was repeated until the desired height was reached.

After depositing all of the required material, a load was applied to the top of the well using concrete blocks and cast iron weights. The sediments were consolidated to a pressure of 78.4 kPa (approximately 12 psi) and primary consolidation was completed in one year. The specimens had a final layering sequence of alternating clay layers 7 mm (0.28 inch) thick and sand layers 4 mm (0.16 inch) thick. The only drawback to this process is the time required to essentially complete the consolidation process.

Townsend and Gay (1964) also prepared artificially layered specimens in the laboratory using reconstituted natural materials. They introduced a thick slurry into a settling tube with a perforated base which allowed for drainage of the specimen. Air pressure was applied to the top of the slurry to decrease the sedimentation time. Once the sedimentation was completed, the air pressure was removed and the sample was further consolidated under a known load. Layered specimens were made by introducing additional slurries of different materials after sedimentation of previous layers was completed.

**Phenomenological Techniques in Deformation Studies**

There are two phenomenological techniques which are often used in deformation studies: analog modeling and imaging. These techniques are often
used together to investigate the evolution and formation of deformation structures. The two techniques are described below.

Analog Modeling

Analog modeling is one of the most well known techniques to study deformation using a phenomenological approach. Analog modeling is a tool which is used to simplify nature; natural deformation structures are modeled and investigated in a 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 (Koyl, 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 to study the deformation of layered materials. Koyl (1997) provides 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.

**Imaging Techniques**

Imaging goes hand-in-hand with analog modeling. Since the deformation of the analog model can be seen, it follows that photographs or video recordings should be taken at various intervals throughout the deformation process. The imaging techniques cited below are applied throughout the deformation of the specimen. Imaging techniques such as scanning electron microscopes, thin section analysis, CAT scans and MRI imaging are typically conducted on a specimen once deformation is complete, not while deformation is ongoing.
Radiography was introduced into soil mechanics by Gerber in 1929. Much of the pioneering work using radiography to determine strain distributions in soil samples was developed by Roscoe and his co-workers at Cambridge in the early 1960's. They placed a grid pattern of lead shot or tungsten spheres in the central plane of the specimen. As the specimen deformed, the spheres would move and a radiograph would be taken. Strain distributions could be determined by comparing radiographs from the undeformed specimen to radiographs of the deformed specimen. The x-ray equipment used to produce the radiographs is very expensive so other techniques, most notably photographic techniques, have been developed to observe deformation structures and to compute strain distributions in soil specimens (Wong and Arthur, 1985).

Photographic techniques are much more limited than radiographic techniques. The photographic techniques use strain markers placed against a transparent plane strain surface. No information is obtained on the strain distributions inside the specimen. Rodriguez del Camino (1977) used photographs to compute strains in specimens of loose sand and compared the photographic results with radiographic results. He found that consistently smaller strains were found on the plane strain surfaces than those in a central plane. Wong and Arthur (1985) found that smaller strains were observed on the plane strain surface of dense sands (Wong and Arthur, 1985).

Tamate et. al. (1994) used a photographic technique to compute strain distributions of dense sand specimens in a direct shear device. The sand sample was held in place behind a perspex plate by a latex sheet. The latex sheet had a grid imprinted on it, consisting of 5 mm squares. During the shearing process, photos were taken of the specimen. These photos were then digitized and
displacements of the grid's intersections with reference to the undeformed sample were measured (Tamate et. al., 1994).

Yoshida et. al. (1994) also used a photographic method to observe the deformation of dense sand specimens in plane strain compression. They also used a latex sheet imprinted with a grid and photographs were taken during compression of the specimens. The photos were digitized and strain fields were computed by a photogrammetric system.

Digital imaging techniques were first introduced into geotechnical engineering in the early 1990's. Acosta et. al. (1992) used digital imaging techniques to evaluate pavement surface distress and Gustafsson and Knutsson (1994) used digital imaging techniques to study the motion of granular materials (Liang et. al, 1997).

Laing et. al. (1997) used digital imaging techniques to observe the formation of shear bands in hollow cylinder sand specimens. Video images and photographs were taken during the test using four video cameras and a photographic camera. The video images were sent to a PC where the images were captured using a video capture board. An ink grid was imprinted on the sand specimen to provide a reference grid during the test.

Macari et. al. (1997) used digital imaging techniques to measure the volume change of deforming specimens in triaxial compression tests. They used two standard composite color cameras placed at 90° to each other to video tape the deforming specimen. In turn, the signals were sent to a frame grabber installed in a PC to capture the video signals (Macari et. al., 1997).
List of Terms and Definitions

Throughout this dissertation, numerous terms are used to describe the specimens, shear deformation processes and deformation structures. These terms may be foreign to many readers and therefore, a list of terms and definitions is presented.

General Terms

These general terms are used throughout all Chapters of this dissertation.

Direct Shear

This is how the specimens are deformed. One half of the cylindrical specimen is held rigidly in place (passive side) and the other half of the specimen (active side) is subjected to the force of a semi-cylindrical shaped plunger and forced past the passive side.

Developmental Design Cycle

During a developmental design cycle a deformation apparatus is designed and used to deform layered soil specimens. The results of the deformation are analyzed to determine if the results are satisfactory. If the results are not satisfactory, the deformation apparatus and specimens are redesigned and the types of data collected is changed and the process is repeated.
Primary Shear Direction
This is the direction in which the plunger moves. For this study, the primary shear direction is vertical.

Secondary Shear Direction
This is the direction which deformation occurs, which is not parallel to the primary shear direction. Secondary shear has been observed to take place at an angle of approximately 40° to the primary shear direction.

Specimen Terms
Specimen terms are commonly used terms used to describe specimens.

Passive Side
This is the side of the cylindrically shaped specimen which is held rigidly in place.

Active Side
This is the side of the cylindrically shaped specimen which is subjected to the force of the semi-cylindrical shaped plunger. The active side is forced past the passive side.

Layering Scheme and Layering Geometries
A layering scheme is a group of specimens with similar layering geometries. Layering geometries refer to the number of sand and clay layers, thicknesses of the layers and position of the layers within the specimens.
Deformation Terms

These are terms which are used to describe the specimen deformation.

Shear Deformation Processes

The specimen is undergoing direct shear deformation, however, during deformation, three processes have been observed. These processes have been termed interparticle movement, drag and slip.

Interparticle Movement

This is the process of particles moving past each other either in the primary shear direction or the secondary shear direction. Interparticle movement is a local phenomenon.

Drag

This is the process of the plunger or soil layers forcing lower layers to change orientation because of frictional forces. Drag is identified by the type of deformation structures which are formed within the deforming specimen. Drag is a local phenomenon.

Slip

This is the process of the active side moving past the passive side as one block would move past another block. Slip is a global phenomenon. Drag and interparticle movement may occur in the active portion of the specimen while slip is occurring.
Shear Zone

A shear zone is an area of localized deformation contained within narrow, sub-parallel sided zones (Ramsay, 1979).

Deformation Structures

Deformation structures are easily identifiable features contained within deformed specimens. Seven deformation structures have been identified.

Drag Structure

Friction between the plunger and soil or between two soil layers causes soil layers to change in orientation without becoming segmented. These structures have been termed drag structures.

Shear Bands

Shear bands are well defined, narrow regions of intensely sheared granular material in which significant decreases in density have taken place (Scarpelli and Wood, 1982 and Vermeer, 1990). This study has identified three types of shear bands: primary shear bands, secondary shear bands and tertiary shear bands. Primary shear bands form in the direction of primary shear, secondary shear bands form in the direction of secondary shear and tertiary shear bands form off of primary or secondary shear bands in the direction of primary shear.
Slip Lines
Slip lines are the clay equivalent to shear bands (Vermeer, 1990). In this study, slip lines have only been observed in the direction of primary shear.

Step Structures
Step structures or segmented clay layers are formed when movement takes place on one or more slip lines within a clay layer.

Sand Pockets
Sand pockets are small portions of sand layers which have been cut off from their parent sand layers by clay. They are formed by movement along slip lines in clay layers.

Clay Smear
A clay smear is a thin layer of clay which separates sand layers juxtaposed across a fault (Lindsay et. al., 1993).

Double Clay Smear
A double clay smear is two clay smears side by side within a deformed specimen. Between the two clay smears are sand pockets.
CHAPTER 3

METHODOLOGY

The Methodology Chapter describes how this study was conducted. The purpose of this study is to identify and describe the shear deformation processes and deformation structures formed within artificially layered soil specimens. Soil specimens made of alternating layers of sand and clay were produced in the laboratory. The specimens were produced with different layering schemes and layering geometries. Layering schemes are groups of specimens with similar layering geometries. Layering geometries refer to the number of layers of sand and clay, thicknesses of the layers and the layer positions within the specimen. The specimens will be sheared perpendicular to layering using a deformation apparatus which was designed, developed and manufactured for this study. The descriptions of the deformation structures were then used to compare the deformation of specimens within and between layering schemes.

The study is divided into three tasks. Each of the tasks contain sub-tasks which must be accomplished before each task is met. Once all the tasks have been met, all the components of the study will have been performed and the study will be complete. The three tasks are:
- develop a test procedure,
- observe and describe shear deformation processes and deformation structures, and
- compare specimen deformation within and between layering schemes.

**Develop a Test Procedure**

Task 1, Develop a Test Procedure, has been divided into three sub-tasks. The sub-tasks have been named: Apparatus Design, Specimens, and Data Collection. The function of the Apparatus Design sub-task is to answer questions regarding the deformation apparatus. The choice of deformation apparatus dictates the size and orientation of the specimens, how the specimens are deformed and what measurements can be made during testing. If an existing deformation apparatus, a direct shear or triaxial apparatus is chosen, the size and orientation of the specimens, how the specimens are deformed and what measurements can be made during deformation are set. However if a new deformation apparatus is to be designed and manufactured, questions regarding specimens, deformation and measurement devices must be addressed during the design of the deformation apparatus.

The function of the Specimens sub-task is to answer questions regarding the type of specimens which will be used. If it is decided that natural specimens will be used, a naturally layered soil deposit must be found and a technique to sample the deposit must be decided upon or developed. If artificially layered soil specimens will be used, materials to manufacture the specimens must be identified and a technique to produce the specimens must be developed. Regardless of the type
of specimen which will be used, the specimen size and shape must be determined in conjunction with the Apparatus Design sub-task.

The function of the Data Collection sub-task is to answer questions regarding the types of data which will be collected. If it is decided that an existing deformation apparatus will be used, the type of data collected during deformation is set. If a new apparatus is to be designed and manufactured, the types of data collected during testing must be decided upon. Data may also be collected before and after testing. This type of data is independent of the type of apparatus which is chosen to deform the specimens.

The three sub-tasks from Task 1 are so closely linked that each of the sub-tasks depends on one another for completion. In order to complete Task 1, the three sub-tasks are performed simultaneously rather than independently.

Once all the sub-tasks in Task 1 have been completed, tests are performed and the results are analyzed. If the results are satisfactory, the study moves on to Task 2 and then to Task 3. If the results are not satisfactory, the sub-tasks from Task 1 are modified. The loop comprised of performing the three sub-tasks from Task 1, performing tests and analyzing the test results and modifying the Task 1 tasks is called a Developmental Design Cycle. The three tasks and their order are shown in a flow chart in Figure 3-1.

The results of the tests are categorized as being satisfactory based on the following criteria:

- constancy of passive side geometry,
- deformation repeatability,
- ease of obtaining or producing layered specimens, and
- usefulness of data in describing specimen deformation.
Figure 3-1. Study Methodology and Tasks
Constancy of passive side geometry within the deformed specimen refers to how the specimen deformed. For this investigation, the goal is to shear the specimen perpendicular to the layering with one side, the passive side, having little or no deformation vertically, horizontally or radially and the other side, the active side, sliding past the passive side, deforming vertically and horizontally but not deforming radially. This stress condition is referred to as a $K_0$ stress condition, which is the predominant state of stress of sediments undergoing burial in the presence of uniform gravitational loading (Maltman, 1994).

Deformation repeatability refers to obtaining similar results from testing identical specimens. The repeatability concept may apply to forces measured during shearing or the deformation seen in the specimens.

The other two criteria are much less quantifiable. The criteria, ease of obtaining or producing specimens and usefulness of data in describing how specimens deform are rather relative and are meant to improve the specimens and types of data collected throughout the Developmental Design Cycles.

**Observe and Describe Deformation Mechanisms and Deformation Structures**

Once Task 1 has been satisfactorily completed, Task 2 begins. The goal of Task 2 is to observe and describe the shear deformation processes and the deformation structures found in the deformed specimens. Shear deformation processes take place in the deforming specimen resulting in specimen deformation. The deformation mechanisms were identified and described for all specimens, regardless of layering geometry and clay/sand content. Deformation structures are
identifiable features which are formed in the specimens as a result of deformation. Once again, the deformation structures were described for all specimens, regardless of layering geometry and clay/sand content.

**Compare Specimen Deformation Within Layering Schemes**

The final Task for this study is to compare the deformation for specimens within and between the various layering schemes. The artificially layered specimens were produced with different layering schemes and layering geometries. Layering schemes are groups of specimens with similar layering geometries. The shear deformation processes and deformation structures described in Task 2 were be used to compare how specimens with different layering geometries within and between the same layering scheme deform.
CHAPTER 4

DEVELOPING A TEST PROCEDURE

Developing a test procedure is the first Task which must be completed in order to complete this study. This task was been divided into three sub-tasks: Apparatus Design, Specimens and Data Collection. Once a test procedure was developed, tests are performed and the results analyzed. If the results were not satisfactory, Task 1 and its three sub-tasks were modified and the process was repeated. Satisfactory test results were based on four criteria: constancy of passive side geometry, deformation repeatability, ease of obtaining or producing layered specimens and usefulness of data in describing specimen deformation. These criteria are described in Chapter Three. The process of developing a test procedure, testing specimens, analyzing results and determining if the results are satisfactory is known as a Developmental Design Cycle. It took four Developmental Design Cycles before satisfactory test results were achieved. Chapter 4 describes the four cycles.
Developmental Design Cycle 1

Developmental Design Cycle 1 used naturally layered soil specimens. Due to the specimen size and orientation, it was decided that a deformation apparatus should be designed and manufactured to shear the specimens. No data was collected during specimen shearing, but X-ray photographs of the specimens were taken before shearing and thin sections were made from the sheared specimens.

Specimens

The specimens which were used in Cycle 1 were obtained from a naturally layered soil deposit. Samples were obtained by driving a foot-long piece of opaque PVC tubing into the soil deposit. Two foot long samples were obtained in this manner. The PVC tubes which contained the layered soil were cut into sections between 76.2 mm and 101.6 mm in length to make specimens.

The specimens consisted of very thin (on the order of 1 to 2 mm thick) layers of fine sand/silt and clay. Since the specimens were contained in opaque PVC tubing, X-ray photographs of the samples had to be taken to show the layering within the samples. Figure 4.1 contains an X-ray photograph of one section of one of the specimens. The dark layers are fine sand/silt layers and light layers are clay layers.

Deformation Apparatus

The deformation apparatus used in Cycle 1 consisted of an outer aluminum tube which was 400 mm long with a wall thickness of 4.8 mm. The specimen, PVC tubing and soil, was placed at the bottom of the tube, against a bottom plug which
X-ray photograph of naturally layered soil specimen
Dark layers are fine sand/silt and light layers are clay
Scale shown is in tenths of a foot

Figure 4-1. X-ray Photograph of Naturally Layered Soil Specimen
was welded to the outer tube. The bottom plug was semi-circular in shape and extended from the outer edge to the center of the outer aluminum tube. A top plug was then placed on top of the sample and secured in place with a screw. A semi-cylindrical shaped aluminum plunger was placed on the soil portion of the specimen and forced through the specimen using a machine press. A drawing of the Cycle 1 deformation apparatus is shown in Figure 4.2.

The deformation apparatus is similar to a direct shear apparatus. The direct shear test is a well established test which is routinely used in geotechnical engineering to determine the shear strength of soil specimens. It was determined that a typical direct shear apparatus would be inappropriate to shear the naturally layered soil specimens. When performing a typical direct shear test, a soil sample is placed in a shear box. The shear box may be either circular or square. The naturally layered soil samples obtained for the first cycle were cored vertically from a soil deposit with horizontal layering. The specimens were to be sheared perpendicular to layering, which ruled out using a direct shear apparatus with a circular box. A square shear box could be used but the specimens would have to be trimmed from the circular specimens. Trimming the specimens would have caused a large amount of specimen disturbance.

The deformation apparatus designed for Cycle 1 has several advantages over the direct shear apparatus. Soil specimens taken from the field are placed and deformed directly into the apparatus without removing the specimens from the core barrel (PVC tube). This reduces the amount of specimen disturbance. Secondly, the deformation apparatus designed for Cycle 1 allows less radial expansion of the specimen than a direct shear apparatus. In a direct shear test, a normal load is
Figure 4-2. Cycle 1 Deformation Apparatus
placed on the specimen and during shearing, the specimen is allowed to contract and/or dilate. Using the apparatus designed for the first cycle, Apparatus 1, little or no radial expansion takes place during deformation.

Data Collected

During Cycle 1, two types of data were collected. X-ray photographs were taken of the samples before they were deformed. Since the soil was cored in an opaque PVC tubing, it was impossible to see the soil layering and the X-ray photographs were used to show the specimen layering. The second type of data which was collected for this investigation was thin section photographs. Two thin sections were made from the deformed specimens. The thin sections showed microscopic deformation features from within the specimens.

Results

Only two thin sections from the tested specimens could be made because the deformed specimens were very fragile when removed from the protective PVC tubing. However, the thin sections provided valuable information on the deformation within the layered specimens. They showed that the layers within the soil specimen were sheared. Figure 4.3 contains a small portion of one of the thin sections showing the sheared soil layers.

Even though the layered soil specimen was successfully sheared, the results of Cycle 1 were not satisfactory. Naturally layered soils are usually highly variable with respect to composition and layering geometry and they are difficult to sample and handle without inducing large amounts of specimen disturbance (Tschebotarioff

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Figure 4-3. Portion of Thin Section Showing Sheared Clay Layer
and Bayless, 1948 and Saxena et. al., 1979). The X-ray photographs of the samples from Cycle 1 show that this is true for this study. Figure 4-4 contains two X-ray photographs of portions of the specimens from Cycle 1. Figure 4-4a shows that some of the sand layers are not continuous through the sample. The other photograph, Figure 4-4b, shows that during sampling, the sample split at the interface between a clay layer and a sand layer. This is known as a bedding plane part.

The deformation apparatus which was designed and manufactured for Cycle 1 was very long and thin, making it very unstable. Another drawback of the Cycle 1 deformation apparatus is that the specimen is placed at the bottom of the tube. Once the specimen was sheared, the active side of the specimen dropped to the floor. It would be beneficial to have the active side of the specimen remain within the deformation apparatus.

The only data collected from Cycle 1 was X-ray photographs and thin sections. X-ray photographs require very specialized equipment and are expensive to produce. Thin sections are expensive to make and difficult to analyze. Ideally the data should be easy to collect and relatively easy to analyze.

Lessons Learned

Even though the test results from Cycle 1 were not satisfactory, several important lessons were learned from this cycle.

■ Specimens
  • Sampling problems restrict the use of natural specimens.
  • Specimen layering and composition are highly variable with natural specimens.
Figure 4-4. Two Difficulties Encountered When Using Natural Specimens
• Specimen layering was too thin to easily distinguish with the unaided eye.

• Opaque PVC tubing prevented visual inspection of specimens.

■ Data Collected

• X-ray photographs require very specialized equipment and are expensive to produce.

• Thin sections are expensive to make and difficult to analyze.

• Data should be obtained using simpler techniques.

■ Deformation Apparatus

• The deformation technique worked satisfactorily for deforming the specimens.

• Deformation apparatus must be modified to make it more stable.

• Deformation apparatus must be modified so that active portion of specimen will remain in the apparatus.

■ Repeatability

• Thin sections show that deformation results are repeatable.

Developmental Design Cycle 2

Developmental Design Cycle 2 tested artificially layered soil specimen which were produced in the laboratory. Two layering schemes and seven specimen layering geometries were developed for Cycle 2. The deformation apparatus was modified and a small load frame provided the force to shear the specimens.
Several types of data were collected during this Cycle: force required to shear the specimen, displacement of the plunger into the specimen and photographs of the undeformed and deformed specimens.

Specimens

Cycle 2 used artificially layered soil specimens which were produced in the laboratory. Before any specimens could be produced, materials to produce the specimens had to be identified and a technique to produce the specimens had to be developed. Ideally, the method of producing specimens should require no specialized equipment and it should not take a great length of time to produce the specimens.

Artificially layered specimens have many advantages over natural specimens: the percentages of the various materials in the specimens is known, any layering geometry can be produced and any layering thickness can be used.

The specimens produced for Cycle 2 were cylindrical in shape. Specimens were produced in clear acrylic tubes so the specimen layering could be seen. The acrylic tubes were 152.4 mm in length, had an inside diameter of 50.8 mm and had a wall thickness of 3.3 mm. The acrylic tubes support the fragile specimens and provide a means to view, photograph and store the deformed specimens for later use.

The layered portion of the specimens was 100 mm in length. In addition to the 100 mm layered length, Cycle 2 specimens had a bottom support clay layer which was 25.4 mm thick.
The specimens were sheared perpendicular to layering. The side of the specimen which is held in place during shearing is referred to as the passive side and the side which is subjected to the force of the plunger and moved during shearing is referred to as the active side. After the specimen is sheared, it is labeled and the ends are sealed with a mixture of paraffin wax and petroleum jelly to prevent drying and damage.

Specimen Materials

The granular material which was chosen to produce the layered soil specimens was Ottawa Foundry Sand F-110. It is a silica sand which is commercially available from the U.S. Silica Company. The physical characteristics of the sand are presented in Table 4.1.

<table>
<thead>
<tr>
<th>Table 4.1. Physical Characteristics of F-100 Silica Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sieve Analysis (Percent Retained)</strong></td>
</tr>
<tr>
<td>No. 40</td>
</tr>
<tr>
<td>No. 50</td>
</tr>
<tr>
<td>No. 70</td>
</tr>
<tr>
<td>No. 100</td>
</tr>
<tr>
<td>No. 140</td>
</tr>
<tr>
<td>No. 200</td>
</tr>
<tr>
<td>No. 270</td>
</tr>
<tr>
<td>Pan</td>
</tr>
</tbody>
</table>
The first specimen which was produced used the granular material with its natural color. All of the other specimens were produced with colored sand. The sand was dyed using stamp pad ink. The colored sand provided a means to easily identify various sand layers in the deformed specimens. The sand was dyed pink, grey and blue.

The cohesive material which was used to produce the layered soil specimens was a specially blended clay. The specially blended clay was a mixture of 50% kaolin clay, 20% pyrophyllite clay and 30% feldspar particles. These materials were mixed together at a water content of approximately 23%. The mixture produced an off-white colored cohesive material which could easily be trimmed with a wire saw.

Producing Specimens

The specimens were produced in a clear acrylic tube which provided support and protection to the fragile specimens and also allowed the specimen layering to be viewed. The sand layers within the specimen were saturated and densified to their maximum density.

The specimens are produced in the following manner.

1. A beveled edged sampling tube is used to obtain a clay sample. The blended clay mixture comes in 25 pound blocks. The sampling tube, which is 150 mm in length, is pushed into the clay block and a sample is obtained. The sampling tube has the same inside diameter as the specimen tube (the tube in which the specimen is made).
2. A specimen tube is placed on a flat surface and wood and/or aluminum spacer disks are placed inside the specimen tube. The spacer disks are used to raise and lower the working surface within the specimen tube.

3. A portion of the clay sample is extruded from the sampling tube. The extruded portion is trimmed to the desired thickness and is placed in the specimen tube. This is the bottom clay layer of the specimen.

4. Several spacer disks are removed from the specimen tube to lower the working surface. The bottom clay layer adheres to the sides of the specimen tube so it must be pushed further into the tube to ensure that it rests on the working surface. Next, a sand layer is deposited on the clay layer.

Repeated trials of compacting the sand into the desired layer thicknesses revealed that each 5 mm thickness of sand layering required 17.5 grams of sand.

The required amount of sand is placed on the clay layer, inundated with water and densified. The sand is densified by repeatedly striking the sides of the specimen tube with a small rubber hammer.

5. A portion of the clay sample is again extruded from the sampling tube, trimmed to the desired thickness and placed in the specimen tube on the
sand layer. The upper portion of the densified sand layer must be kept slightly below the top of the specimen tube when placing a clay layer. If not, air may be trapped between the sand and clay layers. This process is repeated until the desired layering geometry of the specimen is produced.

Layering Schemes

Two layering schemes were developed for Cycle 2. Layering schemes are groups of specimens with similar layering geometries. The layering schemes are Repeating Sand and/or Clay Sequences and Special Design Layering. The Repeating Sand and/or Clay Sequences scheme contains three layering geometries. Layering geometries refer to the number of layers of sand and clay, thicknesses of the layer positions within the specimen. These geometries are shown in Figure 4-5.

The 2mm S/C layering geometry is composed of alternating layers of sand and clay which are 2 mm thick. This layering geometry does not have a bottom support clay layer.

The 8mm S layering geometry is composed of 12 alternating layers of blue, pink and grey sand which are 8 mm thick. The top sand layer is only 4 mm thick. The bottom support clay layer is 25.4 mm thick.

The 24mm C layering geometry consists of 5 clay layers which are 24 mm thick with 3 mm thick sand layers between the clay layers. The top clay layer is 17 mm thick. There is no bottom support clay layer.
Design Name: 2mm S/C
Specimen consists of alternating layers of 2 mm thick sand and clay.
The top layer is a sand layer. The bottom layer is a clay layer.
Specimen length is 152.4 mm

Design Name: 8mm S
Specimen consists of 12 alternating layers of blue, red and grey sand which are 8 mm thick. The top sand layer is 4 mm thick. The bottom clay layer is 50.8 mm thick. Specimen length is 152.4 mm.

Design Name: 24mm C
Specimen consists of mostly clay with thin sand layers which act as markers.

Figure 4-5. Repeating Sand and/or Clay Specimens
The Special Design Layering scheme has four layering geometries: Design 1 (D1), Design 2 (D2), Design (D3) and Design 4 (D4). The layering geometries are shown in Figure 4-6. Each of the layering geometries has a bottom support clay layer which is 25.4 mm thick.

The naming of the specimens within the Special Layering Designs incorporates the specimen layering geometry (D1, D2, D3 or D4) and the subsequent deformation (slip) regime. Slip refers to the amount of movement of active side past the passive side. For example, D4SL+20 indicates specimen layering geometry D4 and a maximum deformation (slip) of 20 mm after localization. Localization is taken as the point of strain-softening or a decrease in the load bearing capacity of the specimen (Hobbs et. al., 1990). It is thought that through-going shear zones are formed after localization.

Deformation Apparatus

The deformation apparatus which was used in Cycle 1 was redesigned to correct the deficiencies and problems associated with the apparatus. A sketch of the Cycle 2 deformation apparatus is shown in Figure 4-7. The outer tube is a steel cylinder which is 230 mm in length and 10 mm thick. To assemble the apparatus, the bottom plug and semicircular spacer are first connected to the outer tube. The layered soil specimen, which is contained within a clear acrylic tube, is placed into the outer tube and pushed in until the bottom of the acrylic tube makes contact with the semicircular spacer. The top plug and plunger guide are then secured in place. The semicircular spacer, which was attached to the bottom plug, extended 25.4 mm into the acrylic tube.
Figure 4-6. Special Design Specimens
Figure 4-7. Cycle 2 Deformation Apparatus
The specimen is sheared perpendicular to the layering. The side of the specimen which is held in place during the shearing is referred to as the passive side and the side which is subjected to the force of the plunger referred to as the active side. After the specimen is sheared, it is labeled and the ends are sealed with a mixture of paraffin wax and petroleum jelly to prevent drying and damage.

Figure 4-8 contains sketches of Cycle 1 and Cycle 2 deformation apparatuses for comparison purposes. The Cycle 2 deformation apparatus has been shortened to provide a much more stable apparatus. The plunger has been shortened and a plunger guide has been introduced at the top of the outer tube to reduce the chance of the plunger not remaining vertical as it shears the soil specimen. The specimen has been moved to the center of the apparatus. This will keep the active portion of the specimen within the deformation apparatus.

A small load frame was used in Cycle 2 to provide the force used to deform the specimens. The deformation apparatus was placed on the platen of the load frame. The platen is moved up and down by a variable rate motor which kept the rate of movement of the platen constant. The plunger was placed against a proving ring which indicated the force required to shear the specimen. The rate at which the platen moved was kept constant at 1.6 mm/min. The load frame and deformation apparatus set up is shown schematically in Figure 4-9. The plunger displacement was not corrected to include the deformation of the proving ring.

Data Collected

Three types of data were collected during this investigation: photographs, the force required to shear the specimen and the displacement of the plunger in the
Figure 4-8. Comparison Between Cycle 1 and Cycle 2 Deformation Apparatuses
Figure 4-9. Schematic Drawing of Load Frame and Deformation Apparatus
specimen. Photographs were taken of the specimens before and after deformation. The after deformation photographs show the active side, passive side, the interface between the passive and active sides and the interface between the active and passive sides. The force required to deform the specimens was collected manually by reading the dial gage on the proving ring. Readings were taken every five seconds for the first minute and every thirty seconds thereafter.

Results

Seven specimens were deformed in Cycle 2. The specimen names, layering, test conditions and total deformation are outlined in Table 4-2.

The tests are analyzed by looking at both the photographs of the deformed specimen and the force-displacement curves. A photograph of the deformed specimen 2mm S/C is shown in Figure 4-10 and the force displacement curve is shown in Figure 4-11. The photograph shows that the deformation of the specimen is very complicated. The majority of the deformation is concentrated at the active/passive interface. The force displacement curve shows an initial seating portion, a linear portion, a definite yield point, a definite peak and a zone of strain softening or reduction in force with increasing displacement. This is the type of curve which would be expected when testing a dense sand or an over-consolidated clay.
Note: Scale Units Are Inches

Figure 4-10. Specimen 2mm S/C
Figure 4-11. Force-Displacement Curve For Specimen 2mm S/C
Table 4-2. Summary of Specimen Deformation - Cycle 2

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>2mm S/C  *</td>
<td>Total Deformation = 50.8 mm</td>
</tr>
<tr>
<td>D4SL+20mm †</td>
<td>Localization at 23.2 mm deformation</td>
</tr>
<tr>
<td>D4SL+10mm †</td>
<td>Localization at 28.4 mm deformation</td>
</tr>
<tr>
<td>D4SL+5mm †</td>
<td>Localization at 14.2 mm deformation</td>
</tr>
<tr>
<td>D3SL+20mm †</td>
<td>Proving ring capacity exceeded at 30.4 mm</td>
</tr>
<tr>
<td>D3SL+10mm †</td>
<td>Localization at 22.8 mm deformation</td>
</tr>
<tr>
<td>D3SL+5mm †</td>
<td>Localization at 15 mm deformation</td>
</tr>
</tbody>
</table>

Note: * Specimen layering geometry 2mm S/C layering geometry is composed of alternating layers of sand and clay which are 2 mm thick † Indicates Special Layering Design geometry (D3 or D4) and maximum deformation (slip)

Photographs for the three Design 4 specimens are shown in Figure 4-12. Once again, the deformation seems concentrated at the active/passive interface but the deformation appears less complicated.

The force-displacement curves for the three Design 4 specimens are presented in Figure 4-13. The curves follow the same trend up to approximately 13 mm but after that, there is little similarity in the curves. The curve for specimen D4SL+5mm shows a definite peak at approximately 14 mm displacement. The other two specimens, D4SL+10mm and D4SL+20mm, show a small peak, but at displacements of approximately 28 mm and 23 mm respectively. The specimen geometries are the same but the force-displacement curves are much different. This indicates that the force-displacement results are not repeatable.

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Figure 4-13. Force-Displacement Curves For Design 4 Specimens
Photographs of the three Design 3 specimens are shown in Figure 4-14 and the force displacement curves for the Design 3 specimens are shown in Figure 4-15. The photographs show little deformation in the specimens. During the test, the specimens were deformed to displacements of 30.4 mm (D3SL+20mm), 32.8 mm (D3SL+10mm) and 20 mm (D3SL+5mm). However, the movement of the active side relative to the passive side does not match the displacement recorded during the test. Table 4-3 contains the test displacement and measured specimen displacement for the three specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Displacement Measured During Test</th>
<th>Displacement Measured From Photographs</th>
</tr>
</thead>
<tbody>
<tr>
<td>D3SL+20</td>
<td>30.4 mm</td>
<td>16 mm</td>
</tr>
<tr>
<td>D3SL+10</td>
<td>32.8 mm</td>
<td>20 mm</td>
</tr>
<tr>
<td>D3SL+5</td>
<td>20.0 mm</td>
<td>10 mm</td>
</tr>
</tbody>
</table>

There is an obvious discrepancy between the specimen deformation recorded during the tests and the specimen deformation measured from the photographs of the deformed specimens. The specimens were only deformed to approximately half the displacement which was recorded during the test. However, the force-displacement curves show significant forces were recorded throughout the test.

Two possible explanations for the discrepancies have been identified. The plunger may not have been seated on the specimen at the start of the test. If this was the case, the frictional forces acting on the plunger from the plunger guide are large and may mask the force required to shear the soil.
Figure 4.14. Design 3 Specimens
Figure 4-15. Force-Displacement Curves For Design 3 Specimens
The second explanation is the semi-cylindrical spacer was rotating clockwise while the specimen was shearing. After the test was complete, the spacer rotated back to its original position, dragging the specimen up to the top of the specimen tube.

Lessons Learned

Even though the test results were not satisfactory, several important lessons were learned from this cycle.

■ Specimens

• Specimen preparation technique which was developed worked very well and specimens were relatively easy to manufacture.
• Specimen layering was very easy to see with the unaided eye.
• Colored sand helped to identify layers in deformed specimens.

■ Data

• Photographs were clear enough to show specimen deformation.
• Questions were raised about the validity of the force measurements.

■ Deformation Apparatus

• The deformation technique worked satisfactorily for deforming the specimens.
• The bottom portion of the deformation apparatus had to be modified so that there is no need for a spacer on the passive side of the specimen.
Results

- The finer the layering is in the specimen, the more complicated the deformation features.
- Deformation is concentrated at the active/passive interface.
- Colored sand is beneficial for distinguishing and tracing deformed layers across the active/passive interface.

Repeatability

- Force measurements made during shearing were not repeatable.

Developmental Design Cycle 3

In Developmental Design Cycle 3, nine specimens were tested. The nine specimens were from six different layering geometries. The testing of specimens with identical layering geometries helped establish whether or not the specimen deformation was repeatable. The specimens were produced in the laboratory and deformed in a compact deformation apparatus using a small load frame to provide the force to shear the specimens. The only data which were collected during this cycle was photographs of the undeformed and deformed specimens.

Specimens

The specimens used in Cycle 3 were produced in the laboratory using the technique and materials described in Developmental Design Cycle 2. The specimens were cylindrical in shape and produced in clear acrylic tubes with an
inside diameter of 50.8 mm and a length of 152.4 mm. The acrylic tubes support the fragile specimens and provide a means to view, photograph and store the deformed specimens for later use. The layered portion of the specimens was 100 mm in length. In addition to the 100 mm layered length, a support layer made of the clay was introduced at the bottom of the specimen. The thickness of the support layer was 50.8 mm.

Seven artificially layered soil specimens were deformed in Cycle 3. Two Repeating Sand and/or Clay Sequences layering geometries were used and three Special Design Layering geometries were used, Design 1, Design 2 and Design 4. The Repeating Sand and/or Clay layering geometries used in Cycle 3 were 8mm S and 24mm C. The only difference between the Cycle 3 and Cycle 2 specimens is that the bottom support clay layer was increased in thickness from 25.4 mm to 50.8 mm. Sketches of the specimens are shown in Figures 4-5 and 4-6.

Deformation Apparatus

There are only slight modifications to the deformation apparatus from Cycle 2 to Cycle 3. The Cycle 3 deformation apparatus is shown in Figure 4-16 and a comparison between Cycle 2 and Cycle 3 deformation apparatuses is shown in Figure 4-17. From Figure 4-17, it is clear only minor modifications have been made. Most notably, the semicylindrical spacer was omitted from the design and a longer bottom plug was put in its place. In order to accommodate the new bottom an extra 25.4 mm length had to be added to the outer tube. Also, to accommodate for the loss of the semicylindrical spacer, the bottom support clay layer had to be increased from 25.4 mm to 50.8 mm.
Figure 4-16. Cycle 3 Deformation Apparatus
Figure 4-17. Comparison Between Cycle 2 and Cycle 3 Deformation Apparatuses
A small load frame was used in Cycle 3 to provide the force used to deform the specimens. The deformation apparatus was placed on the platen of the load frame. The platen is moved up and down by a variable rate motor which kept the rate of movement of the platen constant. The plunger was placed against a proving ring which indicated the force required to shear the specimen. The rate at which the platen moved was kept constant at 1.6 mm/min.

Data Collected

Only one type of data was collected for this cycle: photographs of the undeformed and deformed specimens. The after deformation photographs show the active side, passive side, the interface between the passive and active sides and the interface between the active and passive sides.

Results

Nine tests were performed in Cycle 3. A summary of the tests performed in Cycle 3 is shown in Table 4-4.

Figures 4-18 to 4-20 contain photographs of undeformed and deformed specimens 8mm S, 24mm S/C, D1S3 in Test 2, D2S3 in Test 2 and D4S55mm. All specimens show the bottom support clay layer decreased in thickness on the passive side of the specimen. If the bottom support clay layer decreased in thickness, the layered portion of the specimen increased in thickness, which is undesirable. It is interesting to note that for the Design 1, Design 2, Design 4 and the 24mm C specimens, the bottom support clay layer shows greater deformation on the active side than on the passive side, which is to be expected. However, the
Figure 4-18. Repeating Sand and/or Clay Sequence Specimens Deformed in Cycle 3
Figure 4-19. Two of the Design 1 and Design 2 Specimens Deformed in Cycle 3
Figure 4-20. Design 4 Specimen Deformed in Cycle 3
Table 4-4. Summary of Specimen Deformation - Cycle 3.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>8mm S †</td>
<td>50.8 mm</td>
</tr>
<tr>
<td>24mm C †</td>
<td>70.0 mm</td>
</tr>
<tr>
<td>D1S3in ° Test 1</td>
<td>76.2 mm</td>
</tr>
<tr>
<td>D1S3in ° Test 2</td>
<td>76.2 mm</td>
</tr>
<tr>
<td>D2S3in ° Test 1</td>
<td>76.2 mm</td>
</tr>
<tr>
<td>D2S3in ° Test 2</td>
<td>76.2 mm</td>
</tr>
<tr>
<td>D4S55mm °</td>
<td>54.0 mm</td>
</tr>
</tbody>
</table>

Notes:  † The 8mm S layering geometry is composed of alternating blue, red and purple colored layers of sand which are 8 mm thick.  
 ° The 24mm C layering geometry is composed of 24 mm thick clay layers interbedded with sand markers which are 3 mm thick.  
 ° Indicates Special Layering Design geometry (D1, D2, D3 or D4) and maximum deformation (slip)  

8mm S specimen shows the same amount of deformation on both the passive and active sides of the specimen.  

These photographs show that the strain is not uniform within the specimen. The goal of the deformation is to keep the passive side of the specimen undeformed while shearing the specimen, which has not occurred.  

Figure 4-21 shows deformed specimens D1S3in Test 1 and Test 2. The two deformed specimens show some degree of deformation repeatability. The clay layers within the specimen appear to have similar deformation structures. The bottom support clay layer has deformed differently for the two specimens. The bottom support clay layer for D1S3in Test 1 has a step-like structure whereas the bottom support clay layer in specimen D1S3in Test 2 is more uniformly deformed.
Figure 4-21. Two Design 1 Specimens Indicating the Degree of Deformation Repeatability
Another deficiency of Cycle 3 is the data collected. The only data which was collected was photographs of the specimens before and after deformation. In order to describe how the specimens are deforming, it would be beneficial to have photographs of the deforming specimen throughout the test, rather than only at the beginning and the end of the test.

Lessons Learned

Even though the test results were not satisfactory, several important lessons were learned from this cycle.

- Specimens
  - The thick (50.8 mm) bottom support clay layer compressed during shearing.

- Data
  - More data needs to be collected during shearing to help describe how the specimens deform.

- Deformation Apparatus
  - The deformation technique worked satisfactorily for deforming the specimens.
Results

- The strain is not uniform within the deformed specimen; the thick clay layer appears to be compressing on the passive side during shearing.
- More information must be collected in order to fully describe how the specimens deform.

Repeatability

- Even though the strain is not uniform within the deformed specimen, the deformation of the specimens is somewhat repeatable; the same deformation generally appears in specimens with identical layering geometries.

Developmental Design Cycle 4

Developmental Design Cycle 4 consists of three tests using two different specimen layering geometries. The deformation apparatus was modified so a camera could take pictures of the deforming specimens. The specimens were produced in the laboratory and deformed in a compact deformation apparatus using a small load frame to provide the force to shear the specimens. The data which were collected consisted of photographs of the specimens before and after deformation and photographs of the specimen during deformation.
Specimens

The specimens used in the Cycle 4 were produced in the laboratory using the technique and materials described in Developmental Design Cycle 2. The specimens were cylindrical in shape and produced in clear acrylic tubes with an inside diameter of 50.8 mm and a length of 152.4 mm. The acrylic tubes support the fragile specimens and provide a means to view, photograph and store the deformed specimens for later use. The layered portion of the specimens was 100 mm in length. In addition to the 100 mm layered length, a support layer made of the clay was introduced at the bottom of the specimen. The thickness of the support layer was 50.8 mm.

Three artificially layered soil specimens were deformed in Cycle 4. One Repeating Sand and/or Clay Sequence layering geometry, 2mm S/C, and two Special Design layering geometry, D3, were used in Cycle 4. These specimens are shown in Figure 4-5 and 4-6. The bottom support clay layer for the D3 specimens was 50.8 mm thick.

Deformation Apparatus

Only one modification was made to the deformation apparatus from Cycle 3 to Cycle 4. In the Cycle 4 deformation apparatus: the outer steel tube was replaced by a clear acrylic tube which was 280 mm long, with an inside diameter of 57.3 mm and a wall thickness of 3.6 mm. A sketch of the Cycle 4 deformation apparatus is shown in Figure 4-22. The clear outer tube allowed the deformation of the specimen to be seen and photographed.
Cycle 4 Deformation Apparatus
Not To Scale

Semi-Cylindrical Plunger

25.4 mm

Top Plug

Clear Acrylic Outer Tube

Clear Acrylic Tube (152.4 mm long)

Bottom Clay Support Layer (50.8 mm thick)

Bottom Plug (76.2 mm long)

28.6 mm

25.4 mm

3.6 mm

64.4 mm Outside Diameter

Section A-A through diameter of deformation apparatus

Figure 4-22. Cycle 4 Deformation Apparatus
A small load frame was used in Cycle 4 to provide the force used to deform the specimens. The deformation apparatus was placed on the platen of the load frame. The platen is moved up and down by a variable rate motor which kept the rate of movement of the platen constant. The plunger was placed against a proving ring which indicated the force required to shear the specimen. The rate at which the platen moved was kept constant at 1.6 mm/min.

The load frame platen which the deformation apparatus sat on had to be modified so a camera could be attached to record the specimen deformation. It was decided that the camera should move with the load frame platen rather than having the camera stationary and the deformation apparatus moving though the camera's field of view. The load frame-deformation apparatus-camera setup is shown in Figure 4-23.

Data Collected

Two types of data were collected for Cycle 4: photographs of the specimens before and after deformation and photographs of the specimen deformation. The specimen deformation was captured by photographing the specimen as it deformed. After the test was finished, the photographs were digitized so they could be analyzed using a personal computer.

Results

Three tests were performed using the Cycle 4 deformation apparatus. A summary of the tests performed in Cycle 4 is presented in Table 4-5.
Figure 4-23. Schematic Drawing of Load Frame, Deformation Apparatus and Camera Set-Up
### Table 4-5. Summary of Specimen Deformation - Cycle 4.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>2mm S/C</td>
<td>50.8 mm</td>
</tr>
<tr>
<td>D3S40mm</td>
<td>38.0 mm</td>
</tr>
<tr>
<td>D3S30mm</td>
<td>29.0 mm</td>
</tr>
</tbody>
</table>

**Notes:**
- *The 2mm S/C layering geometry is composed of alternating layers of sand and clay which are 2 mm thick.*
- " Indicates Special Design Layering geometry (D1, D2, D3 or D4) and maximum deformation (slip).

Figures 4-24 and 4-25 contain photographs of undeformed and deformed specimens 2mm S/C, D3S30mm and D3S40mm. The Special Design Layering specimens show the bottom support clay layer decreased in thickness on the passive side of the specimen. The photographs conclusively shows that the bottom support clay layer is compressing on the passive side of the specimen. Since the bottom support clay layer is decreasing in thickness, the layered portion of the specimen increased in thickness, which is undesirable. The goal of the deformation is to keep the passive side of the specimen undeformed while shearing the specimen.

Interestingly, the 2mm S/C specimen shows uniform strain. This suggests that if the bottom support clay layer was decreased in thickness, the strain would be uniform in the deformed specimens.

The photographs provide new information and can be used to describe how the layered specimens deform. However, there are deficiencies in the photographic technique and apparatus design. The photographs do not indicate the displacement of the plunger. A dial gage should be placed on the load frame platen to indicate plunger displacement. Also, the camera needs to be more focused on...
Figure 4-24. 2mm S/C Specimen Deformed in Cycle 4
Figure 4-25. Design 3 Specimens Deformed in Cycle 4
the specimen. Figure 4-26 contains a photograph from the specimen deformation. Note all of the wasted space which could be used to provide a close-up of the specimen during deformation and a dial gage showing the plunger displacement.

Using the clear acrylic tube for the outer tube did not work as well as expected. The acrylic tube was difficult to work with and drilling holes so the plunger guide and plugs could be mounted on the outer tube cracked the tube. Placing the specimen in the outer acrylic tube produced scratches on the inside of the outer tube. These scratches appear on the photographs as bright vertical bands which means the picture is not as crisp as it should be.

When the acrylic tubes are manufactured, the inside diameter is not manufactured to the same tolerances as the outside diameter. The outside diameter is the control diameter in the manufacturing process. The inside diameter is only a nominal diameter, which means that specimen tubes do not always fit inside the outer acrylic tube of the deformation apparatus.

Lessons Learned

Even though the test results were not satisfactory, several important lessons were learned from this cycle.

- Specimens
  - Thick (50.8 mm) bottom support clay layer was compressed during shearing.
Figure 4-26. Photograph of Deforming Specimen
Data

- Photographs provide enough data to fully describe specimen deformation.
- A visual record of plunger displacement should be visible on the photographs.

Deformation Apparatus

- The outer acrylic tube must be carefully matched with the specimen tubes to ensure that the specimen tube fits inside the outer acrylic tube. This means that some of the specimen tubes cannot be used.
- Placing one acrylic tube inside another caused vertical scratches to be formed on the inside of the outer acrylic tube. These scratches appear on the photographs as vertical bands of light which make the pictures not as clear as possible.
- It is difficult to drill holes in the outer acrylic tube without causing the tube to crack.

Results

- The strain is not uniform within the deformed specimen; the thick clay layer appears to be compressing on the passive side during shearing.
CHAPTER 5

TEST MATRIX AND DATA COLLECTED

Chapter 5 describes the test matrix and data collected for final analysis from Developmental Cycle 5. The Chapter contains sections which describe the final deformation apparatus design, the final specimen layering schemes and the data collected. The specimens deformed in this cycle, Cycle 5, provide satisfactory results based on the four criteria described in the Methodology Chapter. Twenty eight artificially layered specimens were deformed in this Cycle. The specimens were photographed before and after testing and the specimen deformation was recorded by taking pictures at 5 mm intervals during deformation.

Specimens

The specimens used in Cycle 5 were produced in the laboratory using the technique and materials described in Chapter 4. The specimens were cylindrical in shape and produced in clear acrylic tubes with an inside diameter of 50.8 mm and a length of 101.6 mm. The acrylic tubes support the fragile specimens and provides a means to view, photograph and store the deformed specimens for later use. The layered portion of the specimens extends for the full length of the acrylic tube. There is no thick clay support layer present at the bottom of the specimen.
Cycle 5 used the Special Layering Designs layering scheme developed in Cycle 2 and five new layering schemes developed for Cycle 5. The layering schemes developed for Cycle 5 are:

- Bottom Clay Layer (BCL) Specimens
- Clay Sand Ratio 50-50 (CSR 50-50) Specimens
- Equal Sand Layer Thickness (ESLT) Specimens
- Top Sand Layer (TSL) Specimens
- Sand Layer Thickness (SLT) Specimens

These specimens were deformed to a maximum slip of 50 mm or until the capacity of the proving ring was exceeded.

Choice of Layering Schemes

The decision to use the layering schemes listed above was based on investigating the relationship between specimen layering and the deformation mechanisms which act to deform the specimens and the deformation structures found within the deformed specimens. This relationship was investigated using Bottom Clay Layer, Clay Sand Ratio 50-50, Equal Sand Layer Thickness, Top Sand Layer and Sand Layer Thickness layering schemes. The layering schemes and their purposes are described below.

The Bottom Clay Layer (BCL) specimens consisted of two layers, a top sand layer and a bottom clay layer, as shown in Figure 5-1. The five specimens in this layering scheme each had a different bottom clay layer thickness. The thickness of the bottom clay layers were 75 mm, 50 mm, 25 mm, 10 mm and 5 mm. These specimens were used to determine the shear deformation processes and
Bottom Clay Layer (BCL) Specimens

BCL refers to the Bottom Clay Layer thickness.

Figure 5-1. Bottom Clay Layer (BCL) Layering Scheme
deformation structures which are formed during deformation of thick sand layers and to determine the influence of the bottom clay layers on specimen deformation.

The specimens from the Clay Sand Ratio 50-50 (CSR 50-50) layering scheme are shown graphically in Figure 5-2. There are four layering geometries in this scheme. Each of the specimens is composed of 50% sand and 50% clay. For each of the specimens, the thickness of the sand and clay layers are the same and the specimen name identifies the thickness of the layers. The layer thicknesses are 50, 25, 10 and 5 mm. These specimens were used to investigate the effect of layer thickness on the deformation of layered specimens while keeping a constant Clay Sand Ratio.

The specimens from the Equal Sand Layer Thickness (ESLT) layering scheme are shown graphically in Figure 5-3. There are seven layering geometries in this scheme. These specimens contain the same number of clay and sand layers. The sand layers are all the same thickness throughout the specimen, but each specimen has different sand layer thicknesses. All of the clay layers are 10 mm thick. The sand layer thicknesses are 40, 23, 15, 10, 7, 4 and 1 mm thick. These specimens were used to investigate the effect of systematically decreasing the sand layer thickness (increasing the Clay Sand Ratio) on the deformation of layered soil specimens.

The specimens from the Top Sand Layer (TSL) layering scheme are presented graphically in Figure 5-4. There are four layering geometries in this scheme. All specimens contain two clay layers, each 10 mm thick. The upper and lower sand layers of the specimens each have a different thickness. The specimen name refers to the thickness of the top sand layer. The top sand layer thickness are
Clay Sand Ratio (CSR) 50-50 Specimens

The specimen name describes the thickness of the sand and clay layers.

Figure 5-2. Clay Sand Ratio (CSR) 50-50 Layering Scheme
Equal Sand Layer Thickness (ESLT) Specimens

Specimen name describes the thickness of the sand layers

All clay layers are 10 mm thick

Figure 5-3. Equal Sand Layer Thickness (ESLT) Layering Scheme
TSL refers to the Top Sand Layer thickness
All clay layers are 10 mm thick

Figure 5-4. Top Sand Layer (TSL) Layering Scheme
40, 30, 20 and 10 mm. These specimen were used to investigate the effect of layer positioning on the deformation of layered soil specimens. The top sand layer was systematically increased by moving the top clay layer from the top to the middle of the specimen. Each of the specimens had the same Clay Sand Ratio.

The specimens from the Sand Layer Thickness (SLT) layering scheme are shown graphically in Figure 5-5. There are four layering geometries to this scheme. The specimens are composed of clay layers which are 10 mm thick and sand layers which are 10 mm thick or greater. Clay layers were systematically added to the top of the specimen, increasing the Clay Sand Ratio. These specimens were used to study the deformation of a specimen with an upper layered portion over a thick sand layer.

The Special Design Layering schemes were used in Cycle 5 to check the repeatability of deformation using the Cycle 5 deformation apparatus. The Special Design Layering specimens are shown in Figure 5-6. These geometries are generally the same as were used in the previous Cycles except that the top and bottom sand layers have been reduced in thickness by 2 mm and a bottom clay layer which is 4 mm thick has been introduced at the bottom of the specimen.

**Deformation Apparatus**

A sketch of the deformation apparatus used in Cycle 5 is shown in Figure 5-7. The outer tube is a steel cylinder which is 230 mm in length and 10 mm thick. The outer steel tube solves the problems associated with using an outer acrylic tube. A bottom stage is connected to the plunger. During shearing, the bottom stage movement is synchronous with the plunger. This helps ensure that there is
Sand Layer Thickness (SLT) Specimens

Specimen name describes the thickness of the sand layers
All clay layers are 10 mm thick

Figure 5-5. Sand Layer Thickness (SLT) Layering Scheme
Special Layering Design Specimens

Design Name: D1

- 20 mm Sand
- 2 mm Clay
- 22 mm Sand
- 4 mm Clay
- 22 mm Sand
- 6 mm Clay
- 20 mm Sand

Bottom Support Clay Layer (4 mm thick)

Design Name: D2

All clay layers are 2 mm thick

- 25 mm Sand
- 10 mm Sand
- 5 mm Sand
- 10 mm Sand
- 5 mm Sand
- 10 mm Sand
- 24 mm Sand

Bottom Support Clay Layer (4 mm thick)

Design Name: D3

All clay layers are 4 mm thick

- 19 mm Sand
- 10 mm Sand
- 5 mm Sand
- 5 mm Sand
- 10 mm Sand
- 5 mm Sand
- 10 mm Sand
- 18 mm Sand

Bottom Support Clay Layer (4 mm thick)

Design Name: D4

All clay layers are 6 mm thick

- 18 mm Sand
- 10 mm Sand
- 5 mm Sand
- 10 mm Sand
- 5 mm Sand
- 10 mm Sand
- 18 mm Sand

Bottom Support Clay Layer (4 mm thick)

Figure 5-6. Special Layering Design Scheme

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Figure 5-7. Cycle 5 Deformation Apparatus
minimal material movement from the bottom clay layer across the potential passive/active interface. There is also an bottom guide which ensures that the bottom stage will remain perpendicular to the shearing direction. The last improvement is that a viewing window has been cut into the outer tube. The window is 50.8 mm wide and 102 mm long. The center line of the window is in line with the potential passive/active interface. The viewing window allows video recording of the specimen deformation.

Figure 5-8 contains sketches of the Cycle 4 and Cycle 5 deformation apparatuses for comparison purposes. The Cycle 5 deformation apparatus has become much more elaborate. A bottom stage is now connected to the plunger and a viewing window has been put into the outer steel tube.

A small load frame was used in Cycle 5 to provide the force used to deform the specimens. The deformation apparatus was placed on the platen of the load frame. The platen is moved up and down by a variable rate motor which kept the rate of movement of the platen constant. The plunger was placed against a proving ring which indicated the force required to shear the specimen. The rate at which the platen moved was kept constant at 1.6 mm/min.

A digital dial indicator has been attached to the load frame. The indicator measures the movement of the load frame platen, which indirectly measures the displacement of the plunger into the soil specimen. The dial indicator was also photographed during the soil deformation so the displacement where deformation events take place could be recorded. A circular-polarizing filter was added to the camera. The filter reduces or eliminates the glare produced by light reflecting from
Figure 5-8. Comparison Between Cycle 4 and Cycle 5 Deformation Apparatuses
the surface and/or scratches of the acrylic specimen tube. Figure 5-9 contains a
drawing of the deformation apparatus, load frame, camera stand and digital dial
indicator.

Data Collected

Two types of data were collected during deformation of specimens from the
Final Phase. Photographs were taken of the specimens before and after
deformation. The after deformation photographs show the active side, passive side,
the interface between the passive and active sides and the interface between the
active and passive sides. During shearing, a camera took photographs at intervals
of every 5 mm displacement. The photographs show both the specimen
deformation and the digital dial indicator which records the plunger displacement.
The photographs were later digitized for analysis using a personal computer.
Figure 5-9. Schematic Drawing of Load Frame, Deformation Apparatus, Camera and Digital Dial Indicator Set-Up

Note: Drawing Not To Scale
CHAPTER 6

ANALYSIS

The Analysis Chapter is divided into five sections: shear deformation processes, deformation structures, uniformity of strain and deformation repeatability, comparison of specimen deformation within layering schemes and comparison of specimen deformation between layering schemes. Shear deformation processes are the ways in which the specimen deforms. Three shear deformation processes have been identified in this study: interparticle movement, drag and slip. Deformation structures are identifiable features which are formed in the specimens as a result of deformation. The identification and descriptions of the shear deformation processes and deformation structures sections fulfill Objective 2. The comparison of specimen deformation within and between layering schemes fulfills Objective 3. Objectives 2 and 3 are described in Chapter 3. The uniformity of strain and deformation repeatability section shows that the strain within the deformed specimens is uniform and the specimen deformation is repeatable. These are two of the criteria by which the results are deemed acceptable.
Shear Deformation Processes

The specimens deformed in this study are undergoing shear deformation, a semi-cylindrical plunger is being forced into one half of a cylindrical specimen while the other half is held in place. During shear deformation, three processes have been observed. They are interparticle movement, drag and slip.

Interparticle movement is a localized phenomenon where particles of clay and/or sand move past one another. Drag is caused by frictional forces between the semi-cylindrical plunger and the soil and also frictional forces between soil layers. The drag process is identified by the type of deformation structure which is formed in the specimen. Drag is also a localized phenomenon. Slip is a global phenomenon. In this study, slip occurs when the active side of the specimen moves as a block past the passive side of the specimen. During slip, interparticle movement and drag may occur in the active side of the specimen.

These processes, all of which are related to shear deformation, work together to form shear zones and the various deformation structures found within the deformed specimens.

Interparticle Movement

Interparticle movement occurs away from the plunger in both the active and passive sides of the specimen in both the sand and clay layers. Interparticle movement is a localized phenomenon. Two types of interparticle movement have been identified. They have been termed primary shear and secondary shear, following the nomenclature developed by McKinstry (1953). The deformation apparatus is set up to shear specimens on a vertical plane along the center line of
the specimen. Thus, any shear deformation in a vertical plane is termed primary shear. Primary shear is easily identified in specimens by vertical displacement of clay layers at or near the active/passive interface. Figure 6-1 contains two photographs of specimens which show primary shear in clay layers. Specimen ESLT 23 shows the vertical displacement of a clay layer. Specimen ESLT 4 contains thin sand layers. In this specimen, the thin sand layers are truncated at the active/passive interface.

Secondary shear takes place on the passive side of the specimen at an orientation of approximately 40° to the primary shear in specimens with thick sand layers. The acute angle between the primary and secondary shear points in the directions in which the block containing the secondary shears was moving (McKinstry, 1953). Secondary shearing occurs ahead of the horizontal plunger/soil interface. Figure 6-2 contains a photograph of specimen BCL 10mm which shows secondary shears.

Drag

Drag is caused by frictional forces between the semi-cylindrical plunger and the soil and also frictional forces between soil layers. Drag occurs when the plunger forces the specimen to deform by dragging passive side sand and clay layers as it is forced into the specimen. Thick clay layers change in orientation and become progressively thinner as they are dragged into the active/passive interface. The dragging of the clay layers causes the sand layers to also change in orientation, thin and eventually pinch out (finger). Figure 6-3 contains photographs of deformed specimens ESLT 10 and ESLT 4. These photographs show examples of drag from
Figure 6-1. Examples of Primary Shear in Specimens with Thick and Thin Sand Layers

Primary Shear in specimen with thick sand layers

Specimen ESLT 23

Primary Shear in specimen with thin sand layers

Specimen ESLT 4
Secondary Shear

Specimen BCL 10mm

Figure 6-2. Example of Secondary Shear
Figure 6-3. Examples of Drag in Specimens with Thick and Thin Layering

Specimen ESLT 10

Dragged clay layer and pinched sand layer in specimen with thick layering

Specimen ESLT 4

Dragged clay layer and pinched sand layer in specimen with thin layering
specimens with thick sand layers (ESLT 10) and thin sand layers (ESLT 4). Drag is a localized phenomenon.

Drag and primary shear are easily distinguished. Sheared layers are seen in the middle of the specimen, away from the plunger, with sand layers vertically truncated or cut-off on the passive side. Dragged layers are formed at the top of the specimen near the plunger. The layers are thinned and dragged into the active/passive interface.

Slip

Slip takes place at or near the active/passive interface. Slip occurs when the active side moves as a block along the active/passive interface. This shear deformation process is a global phenomenon so during slip, interparticle movement and/or drag may occur in the active side of the specimen. Interparticle movement and drag always occur before slip. Figure 6-4 contains photographs of specimen ESLT 4 at various stages of deformation. Slip is impossible to observe in a single photograph however, showing a progression of photographs, slip deformation or the active side moving as a block past the passive side can be observed.

Shear Deformation Processes Summary

Three shear deformation processes have been identified in this study. They have been named interparticle movement, drag and slip. Interparticle movement in a vertical direction has been termed primary shear. Primary shear occurs vertically at or near the active/passive interface, below the horizontal contact of the plunger and specimen. Interparticle movement in a direction other than vertical has
Figure 6-4. Series of Photographs of Specimen ESLT 4 Showing Progressive Deformation and Slip of the Active Side Past the Passive Side of the Specimen

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been termed secondary shear. Secondary shear occurs at an angle to primary shear below the horizontal contact of the plunger and specimen in the passive portion of the specimen.

Drag occurs at or near the active/passive interface near the plunger soil interface. As the plunger is forced into the specimen, layers are dragged down with the moving plunger. The drag process is identified by the type of deformation structure which is formed in the specimen.

Slip occurs when the active side of the specimen moves as a block past the passive side of the specimen. Slip is impossible to observe in a single photograph but is easily seen in a series of photographs. Interparticle movement and/or drag may occur in the active side as it is slipping past the passive side. Interparticle movement and drag always occur before slip.

**Shear Zones**

Shear zones have been described as areas of localized deformation contained within narrow, sub-parallel sided zones (Ramsay, 1979). In order to identify the boundaries of the shear zone, there must visible deformation of features within the specimen. The layered specimens used in this study provide easily identifiable deformed features.

The definition of a shear zone given above is a geological definition. When shear zones are formed in nature, the shear force is provided by natural forces, such as gravity or tectonic forces, not by a mechanical system. The configuration of the deformation apparatus used in this study imparts some deformation which is unlikely to be seen in nature. The plunger causes the top portion of the specimen
to be dragged whereas the portion of the specimen away from the plunger is sheared, much like what would occur in nature. Thus, two different shear zones can be identified: a shear zone which includes the effect of the plunger dragging material and a shear zone which does not include the effect of the plunger. However, since this is a laboratory investigation, not a field investigation, the definition of a shear zone will include all forms of deformation will included in this study.

For this study, a shear zone can be described as a zone which contains deformed material. The shear zone extends both along side and beneath the plunger within the boundaries of the acrylic specimen tube. The boundaries of the shear zone may coincide with the boundaries of the acrylic specimen tube.

Deformation Structures

Deformation structures are identifiable features contained within the deformed specimen. The structures identified in this study are macroscopic, meaning they can be seen with the unaided eye. Morgenstern and Tchalenko (1967) identified two categories of deformation structures: strain discontinuities and displacement discontinuities. Examples of these discontinuities are presented in Figure 6-5. Strain discontinuities are structures which have deformed, but no movement has taken place. Displacement discontinuities are structures on which movement has taken place. During shearing of the layered specimens, some layers can be initially classified as strain discontinuities and then, with further deformation, become displacement discontinuities.
Strain Discontinuity

Displacement Discontinuity

After Morgenstern and Tchalenko, 1967

Figure 6-5. Strain and Displacement Discontinuities
Drag Structures

Drag structures are classified as strain discontinuities. They are formed along the vertical side of the plunger/soil interface because of frictional forces between the plunger and soil or frictional forces between soil layers. The frictional forces cause the layers to be dragged along side the plunger as it moves into the specimen. Surprisingly, drag structures are not unique to the clay layers within the specimen.

Drag structures are easily identified in clay layers. Dragged clay layers are strung out or stretched with little or no segmentation. An example of clay layer drag in a sandy specimen (specimens with more than 50% sand) is shown in Figure 6-6a. The top clay layer contains a drag structure. The second and third clay layers are not classified as drag structures because the clay layers are segmented. The portion of the top clay layer on the passive side shows little reduction of thickness near the active/passive interface. The clay layer abruptly changes orientation, from horizontal on the passive side to vertical at the active/passive interface and back to horizontal on the active side. From the figure, it appears that the clay on the active side has thinned meaning that the vertical portion must have come from the active side clay layer.

The top sand layer is cut off at the active/passive interface and some of the sand is dragged on the outside of the first clay layer. After enough displacement, there is no more sand to drag along the plunger and the top sand layer ends.

The second sand layer shows a different structure. The sand layer portion in the passive side changes orientation near the active/passive interface and begins to thin and almost pinch out at the active/passive interface. On the active side, the
Figure 6-6a. Drag Structure a in Sandy Specimen

Drag Structure

Segmented Clay Layer
(Not Classified as a Drag Structure)

Specimen ESLT 15

Figure 6-6b. Drag Structures in a Clayey Specimen

Drag Structure

Sand Layer Dipping into Active/Passive Interface

Specimen ESLT 4

Figure 6-6. Drag Structures in Sandy, Clayey and Sand Specimens
Figure 6-6c. Drag Structures in a Sand Specimen

Specimen BCL 10mm-Layered

Figure 6-6. Continued
sand layer has thinned and shows a change in orientation at the active/passive interface.

Drag structures from clayey specimens (specimens with more than 50% clay) are somewhat different that the drag structure described above. Figure 6-6b contains a photograph of specimen ESLT 4 which shows an example of a clay drag structure. The top clay layer looks similar to the clay layer drag structure in Figure 6-6a however, there are differences in the clay layers below the top clay layer. Below the top clay layer, clay layers 2 and 3 appear to be dipping into the active/passive interface. The cause of the change in orientation of the layers is friction from the plunger and/or friction between soil layers.

In Figure 6-6b, the top sand layer is cut off at the active/passive interface. Since the layer is so thin, not much sand is available to drag on the outside of the top clay layer. The second sand layer changes orientation near the active/passive interface and is cut off by the plunger. The third sand layer also changes orientation near the active/passive interface but instead of being cut off, the sand layer fingers or pinches out at the active/passive interface.

In specimens containing only sand, there are also drag structures. However, the specimens must be layered in order to see the structures. Figure 6-6c contains a photograph of BCL 10 Layered. From the photograph, the sand drag structures are clearly seen and they look similar to the structures seen in Figure 6-6a. Looking at the active/passive interface, drag structures from the top three sand layers are present. The zone in which the structures are present is very thin. As with the clay layers, material from the top sand layer is dragged along the active/passive interface until there is no more material to drag. Sand layers two and three on the
passive side show a change in orientation near the active/passive interface and a thinning of the sand layers on the active side.

Shear Bands

Shear bands or rupture surfaces are well defined narrow regions of intensely sheared material in which significant decreases in density have occurred (Scarpelli and Wood, 1982 and Vermeer, 1990). Shear bands are displacement discontinuities. Figure 6-7 contains pictures of shear bands in specimen BCL 10 and BCL 10 Layered. Shear bands in specimen BCL 10, which appear as light colored linear features, show no indication of movement because there are no distinct colored layers within the specimen. However, the layered sand specimen (BCL 10 Layered) shows that movement takes place along the shear bands.

Three categories of shear bands have been identified:

- primary shear bands,
- secondary shear bands, and
- tertiary shear bands.

Primary shear bands form in the direction of shearing, in this case, vertically. Some of the shear bands which are formed are classified as second order shears (McKinstry, 1953) or secondary shear bands. The primary deformation is vertical however, the shear bands are orientated at an acute angle to the primary deformation. Secondary shear bands can be either continuous or terminating. Continuous shear bands form a visible feature which is continuous across the passive side of the specimen. Terminating shear bands end when they encounter clay layers. Tertiary shear bands form off of primary or secondary shear bands, in
Figure 6-7. Examples of Shear Bands

Specimen BCL 10mm

Specimen BCL 10mm Layered

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the direction of primary shear. Figure 6-8 contains photographs of the three categories of shear bands.

When shear bands encounter a clay layer, they appear to be terminated and not passed through the clay layer. This is shown in Figure 6-8 (Specimen ESLT 15). Shear bands are seen in the second and third sand layers. However, the shear band from the second sand layer is not passed through the second clay layer into the third sand layer. A new shear band forms in the third sand layer. The two shear bands have the same orientation and location within their respective sand layers. Shear bands mark the edge of the shear zone in layered specimens.

Slip Lines

Slip lines are the clay equivalent to shear bands (Vermeer, 1990). The lines can not be seen with the unaided eye but are visible once movement has taken place along the slip lines. Slip lines are also displacement discontinuities. Figure 6-9 contains a photograph showing movement along the slip lines in specimen ESLT 4.

Unlike the shear bands present in sand layers, slip lines are formed in a vertical orientation. This categorizes slip lines as primary shear. Slip lines are formed at or near the active/passive interface.

Step Structures

Step structures or segmented clay layers are formed when movement takes place on one or more than one slip line within a clay layer. Step structures are found only on the active side of the layered specimens. Figure 6-10 contains
Figure 6-8. The Three Categories of Shear Bands

Specimen BCL 10mm

Secondary Shear Band
Tertiary Shear Band
Primary Shear Band

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Figure 6-8. Continued.
Specimen ESLT 4

Figure 6-9. Slip Lines
Figure 6-10. Formation of a Step Structure in Specimen ESLT 23
photographs showing the progressive formation of a step structure in Specimen ESLT 23. At a displacement of 25 mm, a slip line at the active/passive interface has begun to form in clay layer 2. Also, a second slip line is starting to form away from the active/passive interface. At a displacement of 30 mm, two fully formed slip lines are present in clay layer 2. At a displacement of 35 mm, the step structure is fully formed. Further displacement causes the photograph to be elongated, as shown in the photograph of the specimen at a displacement of 45 mm.

Sand Pockets

Sand pockets are small portions of sand layers which have been cut off from their parent sand layer by clay. This type of structure forms in layered specimens with thin sand layers. Displacement along multiple slip lines in clay layers causes portions of sand layers to be cut off. In this study, sand pockets formed in specimens with sand layer thicknesses of 7 mm and less. Figure 6-11 contains photographs of deformed specimens ESLT 4 and ESLT 1, both of which contain sand pockets.

Clay Smear

A clay smear is a thin layer of clay which separates sand layers juxtaposed across a fault (Lindsay et. al., 1993). This study has identified two types of clay smear structures. Figure 6-12 contains photographs of deformed specimen ESLT 4. The photograph of specimen ESLT 4 showing the passive/active interface contains a clay smear which fits the above definition. In this specimen, there appears to be only a single clay layer separating the active and passive sides of the
Figure 6-11. Sand Pockets In Specimens ESLT 4 and ESLT 1
Figure 6-12. Clay Smears
specimen. However, this single clay layer is actually made up of multiple clay layers. There are thin stringers of sand at the bottom portion of the specimen within the clay layer which separates the two halves of the specimen.

The other type of clay smear is shown in the photograph showing the active/passive interface of specimen ESLT 4 (Figure 6-12). In this photograph, there are actually two clay smears. The first clay smear is at the active/passive interface and the second clay smear is away from the active/passive interface in the active side of the specimen. Between the two clay smears are sand pockets. This clay smear structure formed by movement along two slip lines.

Deformation Structures Summary

Six deformation structures have been identified in this study: drag structures, shear bands, slip lines, step structures, sand pockets and clay smears. Each of the deformation structures may be classified as either strain or displacement discontinuities and are formed by one or more of the shear deformation processes. Figure 6-13 shows the classification of the deformation structures and which shear deformation process is responsible for their formation. Interparticle movement and slip have been classified as Class 1 deformation and drag has been classified as Class 2 deformation. Class 1 deformation structures, shear bands, slip lines and step structures, are formed by interparticle movement. They have been termed displacement discontinuities. A combination of interparticle movement and slip is required to form sand pockets and clay smears. These structures have also been termed displacement discontinuities. Class 2 deformation, drag, is required to form drag structures, which are classified as strain discontinuities.
Figure 6-13. Relationship Between Deformation Processes, Structures and Classification of Structures
Constancy of Passive Side Geometry and Deformation Repeatability

Constancy of passive side geometry and deformation repeatability are two of the criteria by which the results are deemed acceptable. Constancy of passive side geometry refers to how the specimen deforms. For this investigation, the goal is to shear the specimen perpendicular to the layering with one side, the passive side, having little or no deformation vertically, horizontally or radially and the other side, the active side, sliding past the passive side, deforming vertically and horizontally but not deforming radially. This stress condition is referred to as a $K_0$ stress condition, which is the predominant state of stress of sediments undergoing burial in the presence of uniform gravitational loading (Maltman, 1994).

Deformation repeatability refers to obtaining similar results from testing identical specimens. The repeatability concept may apply to forces measured during shearing or the deformation seen in the specimens.

The Special Design Layering scheme specimens were used to show that constancy of passive side geometry and repeatability of deformation was achieved using the Cycle 5 deformation apparatus. Seven specimens were deformed: three Design 2 (D2) specimens, two Design 3 (D3) specimen and two Design 4 (D4) specimens. The specimen layering geometries are shown in Figure 5-6.

Figure 6-14 contains photographs of two deformed Design 3 specimens and two deformed Design 4 specimens. The deformation in the Design 3 specimens is very similar. Each of the specimens contain a dragged top clay layer, a step structure in the second clay layer, a sand pocket and sand pockets beginning to form and a clay smear.
Figure 6-14. Special Design Specimens Used to Show Deformation Repeatability
Likewise, the deformation in the two Design 4 specimens is also very similar. Each of the specimens contain a dragged top clay layer, step structures, sand pockets beginning to form and clay smears. These photographs show the deformation in specimens with similar layering geometries is repeatable.

Constancy of passive side geometry is best determined from photographs of undeformed specimens and photographs of the passive side of deformed specimens. Photographs of the passive side of the deformed specimens will show if any horizontal movement has occurred in the passive side of the specimen. Figure 6-15 contains photographs of specimens D2 and D4 showing both the undeformed specimen and the passive side of the deformed specimen. The photographs show that minimal horizontal movement has occurred in the passive side of the deformed specimen. This is demonstrated by little or no change in layer positions and little or no compression of the bottom clay layer in the specimens.

Comparison of Specimen Deformation Within Layering Schemes

The Comparison of Specimen Deformation Within Layering Schemes section fulfills Objective 3 which was described in Chapter 3. This section will compare the deformation of specimens within the five layering schemes developed for Cycle 5. Layering schemes are groups of specimens with similar layering geometries. The five layering schemes which were used are BCL specimens, CSR 50-50 specimen, ESLT specimens, TSL specimens and SLT specimens. Descriptions of the specimens and figures containing graphical representations of the specimens can be found in Chapter 5.
Figure 6-15. Photographs of Passive Side of Specimens Before and After Deformation Showing No Change in Passive Side Geometry

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Bottom Clay Layer Specimens

The purpose of testing the Bottom Clay Layer (BCL) Specimens was to determine the influence of different thicknesses of bottom clay layers on the deformation of sand specimens. The specimens which were tested had bottom clay layer thicknesses of 75, 50, 25, 10 and 5 mm. Figure 6-16 contains tracings of deformed specimens BCL 75mm, BCL 50mm, BCL 25mm and BCL 10mm. The dashed lines represent shear bands, the dashed zones represent clay layers and the cross-hatched zones represent the plunger displacement into the specimen.

The tracings show the differences in the shear bands between the four specimens. The shear bands are labeled in the order they are formed and also indicate their classification. For example, SB1-S is the first shear band which was formed and is classified as a secondary shear band.

As the sand layer thickness increases, the type and number of shear bands present in the specimen increases. Specimen BCL 75mm contains three shear bands, each of which are categorized as secondary terminating shear bands. The shear bands are orientated at a low acute angle to the primary shearing direction and terminate at the bottom clay layer.

Specimen BCL 50mm contains four shear bands. The uppermost shear band, SB1-S, is a secondary continuous shear band. Shear bands SB2-S and SB3-S are terminating secondary shear bands which have similar orientations as the shear bands in specimen BCL 75mm. Specimen BCL 50mm also contains a primary shear band, which is labeled SB4-P.

Specimen BCL 25mm contains seven shear bands. There are four secondary shear bands, SB1-S, SB2-S, SB3-S and SB4-S, one primary shear band
Figure 6-16. Tracings of BCL Specimens Showing Shear Bands
Figure 6-16. Continued
SB5-P and two tertiary shear bands, SB6-T and SB7-T, which formed off of the primary shear band.

Specimen BCL 10mm has three secondary shear bands SB1-S, SB2-S, SB3-S, one primary shear band, SB5-P, and four tertiary shear bands SB4-T, SB6-T, SB7-T and SB8-T which formed off of both secondary and primary shear bands.

It should be noted that these shear band maps were not formed by using only photographs of deformed specimens. The deformation photographs were used to determine which shear bands were first to form.

These specimens provide some insights into the deformation of sand specimens which contain bottom clay layers of varying thicknesses. As the top sand layer increases in thickness, a greater number and more types of shear bands form. In specimens with thin sand layers, secondary terminating shear bands form. As the top sand layer increases in thickness, secondary continuous and primary shear bands begin to form. In specimens with thick sand layers, tertiary shear bands form.

As the number and type of shear bands which form increase, the length and width of the shear zone also increases. It stands to reason that if the number of shear bands increase, the deformed area of the specimen will also increase. However as the top sand layer increases in thickness, the intensity of disturbance along the active/passive interface increases, that is, as the number and type of shear bands increase, the complexity of deformation also increases.
Clay Sand Ratio 50-50 Specimens

The purpose of testing the Clay Sand Ratio 50-50 (CSR 50-50) Specimens was to determine the influence of layer thickness on the deformation of specimens while keeping a constant clay-sand ratio. Four specimen layering geometries were used: layers 50 mm thick, layers 25 mm thick, layers 10 m thick and layers 5 mm thick.

Photographs of three deformed specimens, 25mm S/C, 10mm S/C and 5mm S/C, are presented in Figure 6-17. It is evident that as the layering within the specimen gets thinner, more complicated deformation structures are formed. In specimen 25mm S/C, shear bands, step structures are the only deformation structures which are seen. The specimen 10mm S/C contains shear bands, step structures and drag structures. The specimen with the thinnest layers, 5mm S/C, contains drag structures, step structures, sand pockets and clay smears. As the layering thins, the deformation becomes more complicated and the shear zone decreases in thickness.

The deformation of the CSR 50-50 specimens differs according to the layer thickness. The differences in deformation will be illustrated using photographs from different stages of deformation. Specimens 25mm S/C, 10mm S/C and 5mm S/C will be used for comparison purposes. Figure 6-18 contains pictures of the three specimens after 15 mm of deformation.

Specimen 25mm S/C has three secondary terminating shear bands already formed and the top of the first clay layer in beginning to deform. Specimen 10mm S/C has undergone a much more complicated deformation. The top clay layer has already formed a drag structure but the lower clay layers are deformed but no
Figure 6-17. Photographs of 25mm S/C, 10mm S/C and 5mm S/C After 50 mm of Deformation
Figure 6-18. Photographs of Specimens 25mm S/C, 10mm S/C and 5mm S/C After 15 mm of Deformation.
movement has taken place across the clay layers (strain discontinuities). Specimen 5mm S/C contains a drag structure (top clay layer), the bottom 5 clay layers contain slip lines which are beginning to be sheared and the three intermediate clay layers are deformed, but have not yet been dragged or sheared.

Figure 6-19 contains photographs of the three specimens after 30 mm of deformation. Specimen 25mm S/C has a slip line formed in the top clay layer, a primary shear band forming in the second sand layer and the bottom clay layer is beginning to deform. Specimen 10mm S/C shows the drag structure on the first clay layer is fully formed, two shear bands are visible in sand layer 3 and a slip line is beginning to form in clay layer 4. In specimen 5mm S/C, drag structures have formed in the top two clay layers, step structures have formed in the remaining clay layers, a clay smear has formed at the bottom of the specimen and sand pockets are beginning to form.

These specimens show that as the layering gets thinner, the deformation gets more complicated. Specimens with thinner layers have deformation structures such as slip lines and drag structures forming much earlier in their deformation history than do specimens with thicker layers.

Equal Sand Layer Thickness Specimens

The Equal Sand Layer Thickness (ESLT) Specimens were used to investigate the effect of systematically increasing the Clay-Sand Ratio (CSR) on the deformation of the specimens. Seven different specimens having equal sand layer thicknesses of 40, 23, 15, 10, 7, 4 and 1 mm were tested.
Figure 6-19. Photographs of Specimens 25mm S/C, 10mm S/C and 5mm S/C After 30 mm of Deformation.
Photographs of six of the deformed specimens are contained in Figure 6-20. Specimen ESLT 40 contains three secondary terminating shear bands. The top clay layer was only beginning to deform when the capacity of the proving ring was exceeded. Specimen ESLT 23 contains both secondary terminating shear bands and primary shear bands. The top clay layer is dragged and the second clay layer contains a step structure. Specimen ESLT 15 also contains both secondary terminating shear bands and primary shear bands. The top clay layer is dragged and the second and third clay layers contain step structures. It also appears that with further deformation the sand layers would be separated across the active/passive interface and a clay smear would have been formed.

Specimen ESLT 7 contains drag structures, sand pockets, clay smears, step structures and slip lines. Interestingly, there are no shear bands present in this specimen. Specimens ESLT 4 and ESLT 1 have the same structures as specimen ESLT 7. The only difference is that the width of the shear zone is narrower.

As the clay content increases, the number of sand deformation structures decrease in number and the number of clay deformation structures increases. Also, as the clay content increases, the width of the shear zone decreases.

**Top Sand Layer Thickness Specimens**

The Top Sand Layer (TSL) Specimens were tested to investigate the effect of systematically increasing the thickness of the top sand layer while keeping a constant Clay-Sand Ratio. Each of the specimens contained 2 clay layers which were 10 mm thick. One clay layer was at the bottom of the specimen and the other was below the top sand layer. The thickness of the top sand layer was 40, 30, 20 and 10 mm. Photographs of the deformed specimens are contained in Figure 6-21.
Figure 6.20. Photographs of Specimens ESLT 40, ESLT 23, ESLT 15, ESLT 7, ESLT 4 and ESLT 1 after 50 mm of deformation
Figure 6-21. Photographs of Deformed TSL Specimens

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Specimen TSL 10 has a drag structure in the top clay layer and primary shear bands in the bottom sand layer. There are no shear bands in the top sand layer. Specimen TSL 20 has secondary terminating shear bands in the top sand layer and primary shear bands in the bottom sand layer. The top clay layer has a drag structure.

Specimen TSL 30 has secondary terminating shear bands in the top sand layer and primary shear bands in the bottom sand layer. The top clay layer has both a step structure and a drag structure. Specimen TSL 40 shows only terminating secondary shear bands. However, this specimen was not deformed to a deformation of 50 mm like the other specimens.

These specimens show that as the clay layer was moved further into the specimen, different deformation mechanisms took place. The step structure, which was present in TSL 30, forms from movement along slip lines in clay layers.

Sand Layer Thickness Specimens

Sand Layer Thickness (SLT) Specimens are composed of clay layers which are 10 mm thick and sand layers which are 10 mm thick or greater. These specimens were tested to investigate the influence of systematically increasing the clay percentage by adding clay layers to the upper portion of the specimen. Four SLT specimens were deformed. Photographs of the deformed specimens are shown in Figure 6-22.

Specimen SLT 10-70 has a drag structure in the top clay layer and primary shear bands in the bottom sand layer. There are no shear bands in the top sand layer. Specimen SLT 10-10-50 has a drag structure in the upper clay layer and the
Figure 6-22. Photographs of Deformed SLT Specimens

Specimen SLT 10-70

Specimen SLT 10-10-50

Specimen SLT 10-10-10-30

Specimen SLT 10-10-10-10-10
second clay layer is beginning to deform. There are also terminating secondary shear bands in the second clay layer. Specimen 10-10-10-30 contains drag and step structures in the clay layers and primary shear bands in the bottom sand layer. It appears that with further deformation, sand pockets and clay smears would have been formed within the specimen. Specimen 10-10-10-10-10 contains drag structures and step structures. It appears that with further deformation, sand pockets and clay smears would have been formed within the specimen.

These specimens also show that as clay layers are added closer to the middle of the specimen, different deformation mechanisms act to deform the specimen.

Comparison of Specimen Deformation Between Layering Schemes

Several relationships between specimen layering schemes, layering geometries and specimen deformation have been observed during the course of this study. The relationships have been separated into two categories: sand deformation structures formed during shearing and clay deformation structures formed during shearing.

Sand Deformation Structures Formed During Shearing

The only sand deformation structures observed in this study are shear bands. However, three different types of shear bands were identified: primary shear bands, secondary shear bands and tertiary shear bands. The names primary and secondary shear bands do not reflect the order in which the shear bands are formed, but their orientation with respect to the direction of primary shearing.
Two relationships between sand deformation structures and specimen layering geometries have been identified. The first relates the percentage of sand in the specimen and the number of sand layers in the specimen to the types of shear bands which were formed during shearing. This relationship is shown in Figure 6-23. This figure shows only specimens which were deformed to the full plunger displacement of 50 mm. Specimens which contained numerous thin sand layers (specimens ESLT 1 and ESLT 4) did not form visible shear bands in the specimen during shearing. These specimens are located in the lower right hand corner of Figure 6-23. As the number of sand layers in the specimen decrease (the thickness of the sand layers increase), the complexity of the shear banding formed within the sand layers increases. Progressing vertically and to the left in Figure 6-23, a zone has been identified in which only secondary shear bands formed. Secondary shear bands are formed at an oblique angle of approximately 40 degrees to the direction of primary shearing. The specimens which formed only secondary shear bands are BCL 75, ESLT 7, 5mm S/C and 10mm S/C. The next zone shows which specimens contained both secondary and primary shear bands. Primary shear bands are formed in the direction of primary shearing. Specimens which contain both secondary and primary shear bands are 25mm S/C, 50mm S/C, ESLT 15 and ESLT 23. At the upper left hand corner of the figure is a zone which contains specimens which formed secondary, primary and tertiary shear bands. Tertiary shear bands are formed from secondary or primary shear bands and their orientation is approximately parallel to the primary shear direction. The only specimen which forms all three types of shear bands was specimen BCL 25.
Figure 6-23. Relationship Between Sand Percentage and Number of Sand Layers to Type of Shear Bands
This trend is also shown in Figure 6-24. Figure 6-24 contains a plot which relates specimen sand percentage and sand layer thickness to the types of shear bands formed within each specimen. As the sand layer thickness increases (sand percentage increases) the complexity of the sand deformation structures also increases. Once again, the only specimens shown in Figure 6-24 are those which have been sheared to 50 mm plunger displacement.

Clay Structures Formed During Shearing

Six clay structures have been identified in this study. They are slip lines, drag structures, step structures, sand pockets, clay smears and double clay smears. Figure 6-25 relates the specimen sand percentage to the strain required to form the clay structures in ESLT layering scheme specimens. In this figure, strain is not defined by the plunger displacement divided by the initial length of the specimen rather, the strain is a local strain measured from photographs taken of the specimens during deformation. Figure 6-26 shows how the local strains were measured. To measure local strain, the initial thickness of the clay layer of interest and the initial thickness of the sand layer right below the clay layer were measured. This combined thickness is known as the initial length. When the clay layer formed the structure of interest, the actual displacement of the clay layer on the active side of the specimen was measured. This is known as the displaced length. The local strain was then computed by dividing the displaced length by the initial length. Local strains are independent of the plunger displacement into the specimen.

Figure 6-25 shows the amount of local strain it took to form various clay deformation structures in ESLT specimens. This figure shows the progression of
Sand Deformation Structures
Formed After 50 mm Displacement

Sand Percentage (%) vs. Sand Layer Thickness (mm)

- Primary Shear Bands
- Secondary Shear Bands
- Tertiary Shear Bands
- No Shear Bands

Figure 6-24. Relationship Between Sand Percentage and Sand Layer Thickness to Type of Shear Bands
Figure 6-25. Local Strain to Form Structures in ESLT Specimens.
LOCAL STRAIN = \frac{\text{Displaced Length}}{\text{Initial Length}} \times 100

Figure 6-26. Technique Used to Measure Local Strains in Deformed Specimens
each specimen during deformation. For example, specimen ESLT 23 formed only a slip line and a step structure through 50 mm of plunger displacement whereas specimen ESLT 1 formed slip lines, step structures, clay smears and double clay smears through 50 mm of plunger displacement. Two important conclusions can be drawn from this figure. Firstly, the thinner the sand layers present in the specimen, the more complex the deformation structures formed after 50 mm of deformation. However, if it were possible to further deform the thick sand layered specimens, it is assumed that deformation structures which formed in the thin sand layered specimens would also form in the thick sand layered specimens.

Another important conclusion which can be drawn from this figure is that as the sand layer thickness increases, less local strains are required to form the clay deformation structures.

Figure 6-27 shows the relationship between specimen sand percentage and deformation complexity by plotting sand percentage versus the average number of sand pockets formed within the specimen after 50 mm of plunger displacement. The two specimen layering schemes shown in the figure, ESLT specimens and CSR 50-50 specimens, show a similar trend in deformation complexity with decreasing layer thickness. The three CSR 50-50 specimens shown in Figure 6-27, (25mm S/C, 10mm S/C and 5mm S/C), show that as the specimen layering decreases, more sand pockets are formed within the specimen. The specimen names represent the thicknesses of both the sand and clay layers within the specimens.

The six ESLT specimens shown in Figure 6-27 show a similar trend in deformation complexity with decreasing sand percentage (decreasing sand layer
Figure 6-27. Relationship Between Sand Percentage and Average Number of Sand Pockets Formed
thickness). The ESLT specimens have clay layers which are 10 mm thick and sand layers, which are of equal thickness, whose thicknesses are indicated in the specimen name. From Figure 6-27, as the sand layer thickness decreases, the number of sand pockets formed within the specimen increases.

Figure 6-28 also shows how the clay layer deformation complexity increases with decreasing sand percentage. This figure contains a plot of specimen sand percentage versus the average width of the shear zones within the CSR 50-50 specimens and the ESLT specimens. The average width of the shear zones was measured by placing a sheet of clear plastic around the specimen tube and tracing the outline of the sand layers after a deformation of 50 mm. The width of the two shear zones (active/passive and passive/active) were then measured and the widths were then averaged. Figure 6-29 contains a tracing of specimen 10mm S/C. The width of the shear zone was taken as the distance between two vertical lines which cut across undeformed layers of clay and sand material. All shear zone widths were measured in this manner.

As shown in Figure 6-28, as the thickness of the sand and clay layers in the CSR 50-50 specimens decrease, the width of the shear zone also decreases. A similar trend is shown by the ESLT specimens. As the thickness of the sand layers decrease (or, as the clay content of the specimen increases) the average width of the shear zone decreases. It is interesting to note that for the ESLT 1 specimen, which contains approximately 10 percent sand, the average width of the shear zone is 12.5 mm. This indicates that a classic slip surface is not formed within the high clay content specimens rather, a zone of deformed material, or a shear zone, is formed between the active and passive sides of the specimen.
Clay Deformation Complexity:
Average Width of Shear Zones

Figure 6-28. Relationship Between Sand Percentage and Average Width of Shear Zone
Figure 6-29. Tracing of Specimen 10mm S/C
Figure 6-30 contains a plot which shows the relationship between sand percentage and sand layer thickness to the clay deformation structures which form in various specimens after 50 mm of plunger displacement. This figure shows that as the sand layer thickness decreases (clay percentage increases) the clay deformation structures which form after 50 mm of plunger displacement become more complicated. Specimens containing thick sand layers, 25mm S/C, ESLT 23 and ESLT 15, only form a step structure after 50 mm of plunger displacement. Specimens with intermediate sand layer thicknesses, 10mm S/C and ESLT 7, formed clay smears after 50 mm of plunger displacement. Specimens with the thinnest sand layers, 5mm S/C, ESLT 4 and ESLT 1, formed the most complicated clay deformation structure, double clay smears, after 50 mm of plunger displacement.

Summary of Comparison of Specimen Deformation Between Layering Schemes

The comparison of specimen deformation between layering schemes is summarized graphically in Figure 6-31. Figure 6-31 is based on specimens which are 101.6 mm in length and undergo a plunger displacement of 50 mm. In general, as the sand percentage of a specimen increases, the sand layer thickness increases, more complex sand deformation structures are formed in the specimen. This means that at a low sand percentage (thin sand layers), no visible shear bands would be formed and at a high sand percentage (thick sand layers), tertiary shear bands would be formed. This was illustrated in Figures 6-23 and 6-24.
Figure 6-30. Relationship Between Sand Percentage and Sand Layer Thickness to Type of Clay Deformation Structures
Figure 6-31. Relationship Between Sand/Clay Percentages and Deformation Structure Complexity
In general, as the clay percentage of a specimen increases, more complex clay deformation structures are formed in the specimen. A specimen with a high clay percentage has a thin sandwich thickness and a specimen with a low clay percentage has a thick sandwich thickness. Sandwich thickness is defined as the thickness of a sand layer and the clay layer directly below it. This mean that at a low clay percentage, a step structure would be formed and at a high clay percentage, a double clay smear would be formed. This was illustrated in Figures 6-25, 6-27, 6-28 and 6-30.

For specimens containing 50 percent sand and 50 percent clay, the layer thicknesses determine the complexity of the specimen deformation. When a specimen has thick layers, complex sand structures are formed and simple clay structures are formed. When a specimen has thin layers, complex clay structures are formed and simple sand structures are formed.
CHAPTER 7

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS
FOR FUTURE WORK

The final chapter reports the conclusions which have been drawn from this study and presents ideas for future work. A brief summary of the study is presented before the conclusions and recommendations are made.

Summary

The purpose of this study was to identify and describe the deformation mechanisms and deformation structures of artificially layered soil specimens. Soil specimens made of alternating layers of sand and clay were produced in the laboratory with different layering schemes and layering geometries. Layering schemes are groups of specimens with similar layering geometries and layering geometries refers to the number of layers of sand and clay, thicknesses of the layers and the layer positions within the specimen. The specimens were sheared perpendicular to layering using a specially designed deformation apparatus.

The study was divided into three tasks. Each Task contained sub-tasks which had to be accomplished before each Task was met. The three Tasks were:
• develop a test procedure,
• observe and describe deformation mechanisms and deformation structures, and
• compare specimen deformation within and between layering schemes.

The first task contained three sub-tasks: Specimens, Apparatus Design and Data Collection. The sub-tasks were completed after four rounds of modification (Developmental Design Cycles) and the sub-tasks produced three accomplishments.

• A new deformation apparatus was designed, developed and manufactured.
• A technique to produce artificially layered soil specimens in the laboratory was developed.
• A visual data acquisition system was developed.

These developments were used to study the deformation of artificially layered soil specimens.

The second Task was to observe and describe the deformation mechanisms and deformation structures in the deformed specimens. Three deformation mechanisms were identified and six deformation structures were identified and described.

The third Task was to compare specimen deformation within and between the five layering schemes developed for the last developmental design cycle of this study. The specimen deformations were compared and it was shown that there was consistency in the passive side geometry of the undeformed and deformed specimens and the deformation of identical specimens was repeatable. These were
the two quantifiable criteria used to determine if the test results were satisfactory for each developmental design cycle.

Conclusions

This study has shown that as the sand layer thickness of the specimens increased, the sand deformation structures become more complex. The sand deformation structures, shear bands, do not appear to form in specimens with very thin sand layers but as the sand layer thickness increases, secondary shear bands, primary shear bands and tertiary shear bands form.

As the clay percentage of the specimen increases, the clay deformation structures become more complex. In specimens with a low clay percentage, slip lines and step structures are formed. As the clay content increases, clay smears and double clay smears are formed. Specimens with higher clay content generally require more local strain to form clay deformation structures and have narrower shear zones than specimens with a lower clay content.

Recommendations For Future Work

There are several areas and extensions of this study which would greatly improve any future studies. The first recommendation for future work would be to change the focus of the study from a qualitative study to a quantitative study. This could be accomplished by:

- developing a system to measure force required to shear soil specimens.
- changing the specimen shape from cylindrical to rectangular so measurements can be easily made on photographs or using image analysis programs.

In addition to changing the study from a qualitative study to a quantitative study, finite element modeling could be incorporated to see whether computer models could predict the deformation mechanisms and deformation structures seen in the deformed specimens. Another direction for future study would be to investigate the effects of specimen size and deformation rates. Finally, a more focused study on a limited number of layering schemes could provide additional information on the deformation mechanisms and deformation structures seen in the deformed specimens.
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