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SYMPOSIUM ON RECENT ADVANCES IN GEOTECHNICAL CENTRIFUGE MODELING

A symposium on Recent Advances in Geotechnical Centrifuge Modeling was held on July 18-20, 1984 at the University of California at Davis. The symposium was sponsored by the National Science Foundation's Geotechnical Engineering Program and the Center for Geotechnical Modeling at the University of California at Davis.

The symposium offered an opportunity for a meeting of the International Committee on Centrifuges of the International Society for Soil Mechanics and Foundation Engineering. The U.S. participants also met to discuss the advancement of the centrifuge modeling technique in the U.S. A request is being transmitted to the American Society of Civil Engineers to establish a subcommittee on centrifuges within the Geotechnical Engineering Division.

RECENT ADVANCES IN GEOTECHNICAL CENTRIFUGE MODELING

Center for Geotechnical Modeling

University of California, Davis

July 18-20, 1984

A Centrifuge Modeling Procedure for Landfill Cover Subsidence

by

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ABSTRACT

Trench cover subsidence has been a common and damaging form of landfill cover failure. It results from void filling and volume reduction of buried waste materials and takes the form of depressions, tension cracks, and potholes in landfill covers. Following subsidence, water flow through the affected cover may rise dramatically due to tension crack seepage, ponding over depressed areas, and direct flow through potholes. Water that reaches the waste material will become contaminated and may threaten ground and surface water supplies if leakage occurs through the surface cover or the bottom liner system.

This paper describes a geotechnical centrifuge and an experimental procedure, that were developed at the University of Kentucky, for testing scale model landfill cover systems under subsidence conditions. The study was part of an EPA sponsored investigation of the hydrologic response of multi-layered landfill covers. Two field scale cover systems, consisting of 2 ft layers of compacted clay, sand, and topsoil, were constructed, and modeled in the laboratory at 1/24 scale. A 1.14 m (3.75 ft) radius, swinging bucket centrifuge, capable of accelerating 27 kg (60 lb) samples to 100 G's, was designed and built for the study. The effects of subsidence were reproduced by forming cavities beneath model covers during centrifugation.

Initial model tests have been conducted with the silty clay soil that was used to construct the prototype clay layer. The sand and topsoil layers were assumed to provide no resistance to subsidence and were modeled by a lead shot surcharge. Preliminary data has been collected for: (1) the largest (critical) cavity diameter that can be spanned by model clay layers compacted at moisture contents below, equal to and above optimum; (2) the time to cover failure (cracking or collapse) when the critical cavity diameter is exceeded; (3) qualitative estimates of the degree to which cracking vs. plastic flow of the clay layer occurs when the critical cavity diameter is exceeded; and (4) predicted behavior of the test plots under subsidence conditions.

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INTRODUCTION

Subsidence

Proper design, construction and performance of a surface infiltration barrier (trench cover system) is integral to a properly functioning waste landfill. However, buried waste materials do not typically provide a stable support structure for the overlying cover. Many trench cover failures have been attributed to subsidence of the waste materials. Three cover subsidence responses have been observed:

- area subsidence - settlement of the entire trench cover
- slumps - local cover depressions
- sinkholes - vertical erosion channels

After subsidence, water flow through the cover may rise dramatically, due to tension crack piping, ponding, and direct flow through potholes. Water that reaches the waste material will become contaminated and can threaten local ground and surface water supplies if leakage occurs through the surface cover or the bottom liner system.

This paper describes an apparatus and test procedure that were developed for modeling trench cover slump subsidence in a multi-layer system with a compacted clay infiltration barrier. The goals of the study were to predict the behavior of two, full-scale trench covers under subsidence conditions and to gain a better understanding of the slumping phenomenon for application to the design of subsidence resistant trench covers.

The functions of solid and hazardous waste trench covers as determined by the Office of Solid Waste, U.S. EPA, are outlined in Table 1.

Cover designs vary considerably, but the following methods of infiltration control are common to all designs: 1) reduction of surface soil permeability, and 2) grading and other methods of runoff diversion. Under ideal conditions, isolation of the waste from surface water infiltration should continue indefinitely. However, cover performance in the field may be much different than predicted, due to the inherent variability, instability, and behavioral uncertainties of the materials involved. In addition, cover failure can result from attack by weather, erosion, waste materials, water and gas movements, construction and maintenance vehicles, plants, animals, and subsidence of the waste layer. (Skryness, 1982)

The most common and often the most damaging of the failure mechanisms mentioned above is the inability of cover systems to adjust to short- and long-term subsidence of the underlying waste and backfill materials. Volume change of the trench fill and the resultant slumping, cracking, or collapse of the trench cover is shown in Figure 1. Subsidence may breach cover integrity and jeopardize cover performance in each of the areas enumerated in Table 1. The most damaging effects of subsidence are significantly increased infiltration rates due to ponding and crack formation, direct exposure of the waste cell to precipitation and surface runoff, release of contaminants, and accelerated degradation of the disposal site. (Skryness, 1982)

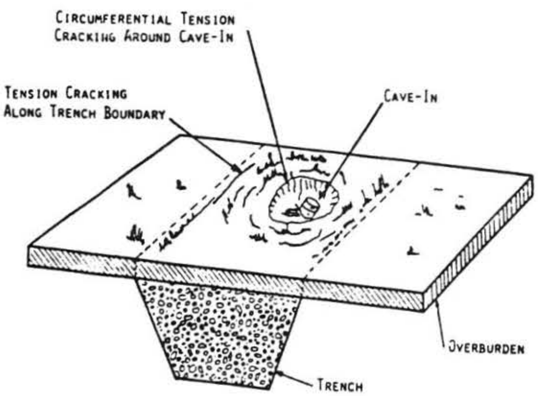

Figure 1. Trench cover slump failure

Effective trench covers are difficult to construct and maintain. Constructing a trench cover to withstand subsidence while still functioning effectively as an infiltration barrier is an even more difficult task. Several approaches to this problem have been suggested. However, problems exist with each of the proposed schemes, and there are many uncertainties about the short and long-term ability of any cover system to

Table 1. Functions of solid and hazardous waste trench covers (Lutton, 1979)

- Control moisture infiltration and final cover erosion
- Preserve slope stability and resist cracking
- Control potentially harmful gas movement and noxious odors
- Minimize settlement and maximize compaction
- Minimize fire hazard potential
- Minimize vector breeding areas and animal attraction
- Resist cold climate deterioration and operational difficulties
- Minimize wind erosion and dust generation and blowing material
- Provide sightly appearance to the landfill operation.
- Provide for vegetative growth.
- Dewater solid waste

withstand subsidence. Few of the concepts have been tested, either in the laboratory or in the hostile environment of a waste disposal facility. Considering the fact that subsidence has been the most common mechanism of trench cover failure to date, a definite need exists for continued research in this area.

Prototype Study

The U. S. Environmental Protection Agency, through its Municipal Environmental Research Laboratory's Solid and Hazardous Waste Research Division, has addressed this need by sponsoring several projects which seek to define, measure, and develop solutions to the problems associated with landfill subsidence. In August 1982, EPA allocated funds to the University of Kentucky for a project entitled, "Demonstration and Evaluation of the Hydrologic Effectiveness of a Three Layer Landfill Cover Under Stable and Subsidence Conditions". The objective of this project was to design, construct, and monitor a series of full-scale, multi-layer cover cells under stable and subsidence field conditions, in order to evaluate their performance as infiltration barriers. To duplicate the effects of slumping subsidence on the cover cells, a system for creating sub-surface cavities beneath the covers was included in the design. Since little quantitative documentation of cover behavior under subsidence conditions was available, the project also included a laboratory investigation of this phenomenon.

The prototype structures for the laboratory study were three multi-layer cover test plots that were constructed at Tyrone, Kentucky on property leased from Kentucky Utilities Company by the Department of Agricultural Engineering. Each plot was subdivided into three cover cells. Figure 2 shows the plan view of the field cover plots. A cross section through a typical cover cell is illustrated in Figure 3. The plots were constructed in three layers: a bottom 2 ft layer of compacted clay that served as the primary infiltration barrier, a 2 ft sand drain layer, and a 2 ft topsoil, vegetative surface layer. Both cover systems were constructed over a 3 ft sand bed. Soil auger pipes were incorporated in the sand beds. After a 2 to 3 year monitoring period under stable conditions, cover subsidence will be induced by augering material from the underlying sand beds. The initial goal of the laboratory study was to investigate the effects of augered cavity size, and initial soil moisture content of the clay barrier layer, on the nature and effects of subsidence.

Selection of Centrifugal Modeling

The main force which results in slumping is the soil cover self-weight. Centrifugal model testing was selected for this study because it is the only laboratory procedure which can reproduce the effects of gravity in a reduced-scale model (Al-Hussaini,1976). The use of centrifugal soil modeling is becoming an accepted method for verifying laboratory soil parameters, geotechnical design assumptions and safety factors (Townsend and Bloomquist, 1983). It has also been applied to complex problems of soil response, for which acceptable solutions have yet to be developed. (Al-Hussaini, 1976)

The basic concept of centrifuge modeling is to create a scale model that is similar in geometry, material properties, and boundary conditions, to the full-scale prototype, and to subject the scale model to a radial acceleration via centrifugation such that the increase in self-weight stresses in the model matches those at corresponding points in the prototype. If the model dimensions are scaled by a factor 1/n as compared to the prototype dimensions, then an acceleration field of n times the acceleration of gravity is required for stress similarity between model and prototype. (Cheney, 1982)

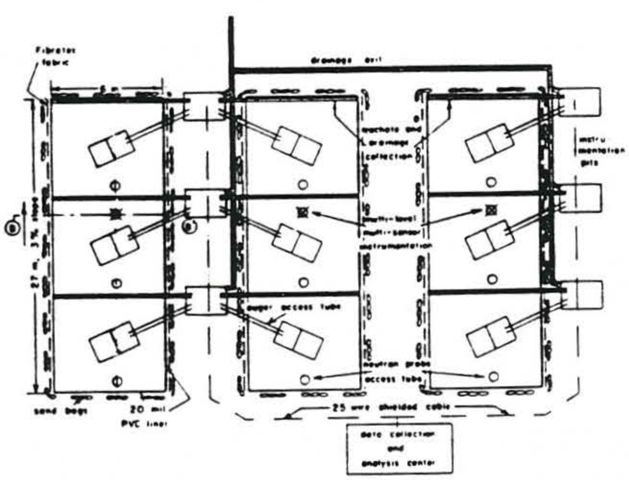

Figure 2. Plan view of prototype cover plots

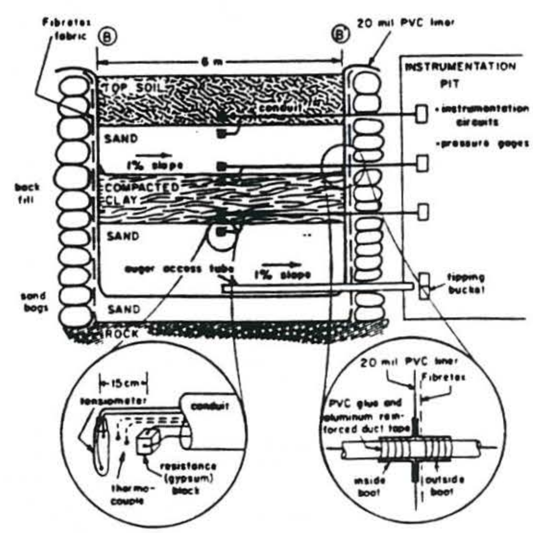

Figure 3. Cross sectional view of a prototype cover cell

the slab. Design of the centrifuge support frame was based on compatibility with this system. Available lab area limited the maximum diameter for the complete centrifuge assembly to 12'. Both 110 V and 220 V electric power is available, as are high pressure air and water lines. The lab has a complete workshop which is useful for constructing, maintaining and modifying the centrifuge.

The centrifuge was conceived as a horizontal rotating arm mounted on a vertical drive shaft powered by an electric motor. The design and construction of the centrifuge was broken down into six basic sub-units:

- sample container and counterweight
- rotating arm
- power supply, transfer, control system
- structural frame
- sand bag wall and protective housing
- data collection and slip-ring assembly

Project funding was limited. Therefore, a major design goal was to build a simple device, using stock parts and materials. Figure 4 shows a cross sectional view of the complete apparatus.

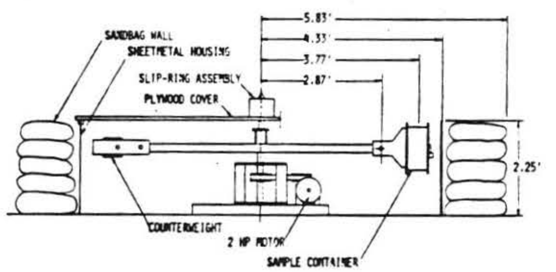

Figure 4. Cross section of centrifuge

Sample Container and Counterweight

The main features of the centrifuge sample container are illustrated in Figure 5. Container design was based on the model size limitations imposed by centrifugation as well as on the following conditions:

- The minimum clay layer thickness was 0.5", based on workability.
- Field cover cells were composed of 2' of compacted clay, 2' of sand and 2' of topsoil.
- Field cover cells were 20' wide.
- Augering was expected to create inverted, cone shaped cavities beneath the field cover cells.
- Kahle and Rowlands (1981) reported that most subsidence features at the Sheffield, Illinois low-level radioactive waste landfill were 12' in diameter or less.

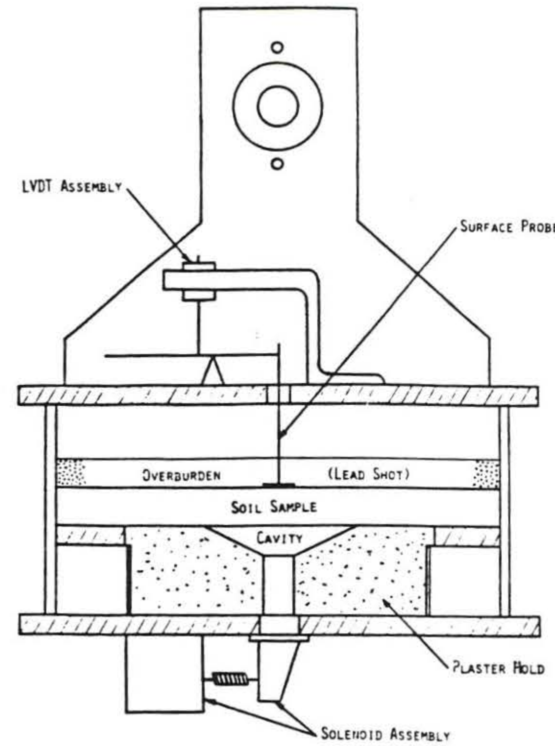

Figure 5. Centrifuge sample container

Consideration of these factors led to the selection of a 1/24 model scale and a maximum prototype cavity diameter of 12' for model construction. Circular models were used, to preserve the radial symmetry of the prototype sand cavities. The sand and topsoil layers of the prototype cover system were assumed to provide no resistance to collapse, acting only as a surcharge to the clay layer, and were modeled as a layer of lead shot having the same weight as the equivalent depths of the two soil layers. Model covers were supported over cavities that were initially filled with lead shot. Subsidence was reproduced by emptying the cavities in flight. At 1/24 scale, the prototype cover was modeled as a 1" thick clay layer, surcharged by 0.5" of lead shot. The maximum cavity diameter was 6".

A 12" diameter plexiglas cylinder housed the model and allowed for photography and visual observation of the sample. The cylinder was 6" in height, to accommodate a base plate, clay layer, and lead shot surcharge, and to allow for other model configurations. The base plate assembly supported the clay sample and was sized to fit snugly within the plexiglas tube. The unit was designed to simplify the process of creating different diameter cavities beneath the model clay layer. The assembly consisted of an aluminum ring, a plexiglas ring, and a plaster disk. The aluminum and plexiglas rings were bolted to the lower aluminum base plate with the plaster disk resting inside the rings. A conical subsidence cavity and shot removal hole were milled in the plaster disk. Two, 1/2" x 14" diameter aluminum plates enclosed the container. A groove, of the same diameter and width as the plexiglas cylinder, was machined into each plate and served to lock the cylinder into position. An o-ring in each groove served to cushion the plexiglas/aluminum contact. A mounting bracket, which allowed the cylinder assembly to swing freely from the centrifuge arm, was bolted to the top plate. A linear voltage displacement transducer (LVDT) was mounted to the top plate for data collection purposes. A 7/8", lead shot release hole, was drilled through the bottom plate. Activation of a spring-loaded solenoid gate opened the hole and allowed the lead shot to fly out of the subsidence cavity in the plaster disk.

The sample container mounted to one arm of the centrifuge; a counterweight mounted to the other arm. Rotational balance required that the sample container and the counterweight to be of equal mass and that the centers of mass of both, be equidistant from the center of rotation. To meet these requirements, the counterweight's mass could be easily changed. Two, steel plates form the basic structure of the counterweight. Fourteen steel plates, weighing approximately 5 pounds each, were used for gross balancing. As many plates as necessary could be bolted together to counterbalance the sample container. Fine balance was achieved by adding extra washers and nuts to the counterweight.

Rotating Arm

A 2" square, cold-rolled, 1018 steel bar was used as the rotating arm of the centrifuge. The length of the arm was determined by the spacial limitations of the Structural Engineering Laboratory. The largest possible length was desired, in order to minimize the deviation of the radial centrifuge force field from the essentially parallel gravitational force field of the Earth. Allowing for the permanent fixtures in the laboratory (counters and cabinets), walkways, a protective sandbag wall around the centrifuge, and the grid locations of the tie-down system, a 6.0' arm length was selected.

A 1.0" diameter hole was drilled through each end of the bar. The sample container and the counterweight were connected to opposite ends of the arm with 1.0" diameter x 9.0" long steel bars that were passed through the two flange bearings in each mounting bracket and the hole in the rotating arm. Each bar was bolted to the arm to prevent the sample container and the counterweight from moving laterally due to drag forces.

A slot was milled into the bottom center of the arm to receive the drive shaft. Thus, a mechanical connection was created between the two components. A 5/8" bolt, passed through a hole in the arm and screwed into a threaded center hole in the drive shaft. The self-weight of centrifuge arm, the sample container, and the counterweight assembly (approximately 250 pounds) also acted to hold the two pieces together.

Power Supply, Transfer and Control System

Calculations based on a radius of 3.75' indicated that 2 HP was required to balance the aerodynamic drag forces at a maximum speed of 280 rpm. Accordingly, a 2 HP, 1750 rpm, DC electric motor coupled to a 5:1 worm gear speed reducer was used to power the apparatus.

A gearbelt system transferred power from the gear reducer to the centrifuge drive shaft. This drive system has several safety and performance advantages over a direct, belt, chain, or gear drive. Slippage does not occur at normal loads with this system, since power is transmitted by positive engagement of belt teeth with pulley grooves instead of by friction. As a result, little heat was generated during operation, and drive-shaft bearing loads are reduced due to the low belt tension that is required. In the event of a motor or bearing failure, the gearbelt will slip and lessen the risk of personal injury and/or destruction of the apparatus.

The drive shaft was fabricated from a 1.5" diameter, 14" long, solid bar of cold-rolled 1018 steel. A keyseat was milled into the shaft to provide a positive connection with the gearbelt pulley. Parallel flats were cut into the upper sides of the shaft and hole was drilled into the top end of the shaft and tapped to receive the 5/8" bolt. These two features allowed the top end of the drive shaft to be inserted into the rectangular slot in the bottom of the rotating centrifuge arm, and the two units to be securely bolted together. The drive shaft was supported in the structural frame by two, 1.5" bore, self-aligning, relubricatible, wide inner ring ball bearings.

The centrifuge payload velocity (acceleration) was regulated by a solid state speed control unit, which could operate both manually and automatically. In the manual mode, the operator used a potentiometer to directly vary the motor speed. In the automatic mode, the required angular speed was input to the control unit, which then accelerated the centrifuge to this speed at a preselected linear rate. A light emitting diode panel, which displayed the centrifuge speed in rpm, and a feedback circuit which limited speed fluctuations, were available in both modes. The controller also allowed for direct input and output via a microcomputer system.

Support Structure

The supporting structure for the centrifuge consisted of a square base frame which tied the other system components together and a box frame that supported the drive shaft.

The drive shaft support frame was constructed of two, 0.5" steel plates, and four pieces of 3x3 structural tubing. The two plates were drilled to receive the 1.5" bore drive shaft bearings, which were bolted down at the center of each plate. Four pieces 0.625" diameter threaded rod, which passed through the top plate, the steel tubes, and the bottom plate, served to tie the drive shaft support frame together and to secure it to the base frame.

The base frame was 40.0" square and was constructed of structural tubing in a nine-square grid pattern. The center square had 15" long sides that corresponded to the dimensions of the drive shaft support frame. Holes were drilled through the four outside corners, and the frame was secured to the floor using the existing structural tie-down system and connectors. Rubber strips were cemented to the bottom of the frame to dampen vibrations generated by the centrifuge.

The electric motor and gear reducer were bolted to a 0.5" steel plate, which was also bolted to the base frame. The motor, reducer, and plate moved as a single unit. In this way, the gearbelt could be removed or installed without changing the motor/reducer shaft alignment.

Slip Ring Assembly

Thirteen circuits (including the centrifuge frame) were available for signal transfer to and from the centrifuge payload. A two circuit slip ring assembly, unsuitable for precise data collection, was used to activate the solenoid. A ten circuit assembly was available for more sensitive applications. Four circuits were used to power and receive data from the LVDT in this study.

Protective Housing

For safety reasons, a 12 ft. diameter sand bag barrier wall was constructed around the centrifuge. A 9 ft. diameter x 27 in. high, sheet metal housing and a plywood cover were constructed inside the sand bag wall to reduce the wall drag coefficient and to reduce the centrifuge "fan" action. The plywood cover was hinged to allow access for model testing and centrifuge maintenance. The ten circuit slip ring assembly mounted to the cover.

EXPERIMENTAL PROCEDURE

Data Collection

The data recorded for each test is listed below.

- model scale factor
- centrifuge speed
- radius to the sample container's centroid
- cavity geometry
- number of blows for clay layer compaction
- clay layer weight
- clay layer moisture content values
- lead surcharge weight
- initial and subsided elevations of points on the surface of the clay layer
- time allowed for pore pressure dissipation
- midpoint subsidence of the clay layer
- photographs of the subsided clay layer
- qualitative description of the test

Surface elevation measurements were made with a dial-gauge. A template was temporarily attached to the test capsule, and used to locate the points to be measured. It was made from a 15" square sheet of plexiglas, with dial-gauge guide holes drilled on 0.5" centers in a 23 x 23 grid pattern. Each hole was identified by a set of reference coordinates.

During each test, subsidence was recorded by monitoring the mid-point deflection of the soil layer. The LVDT mounted on the top plate of the sample container was used to convert the movement of a surface displacement probe into a voltage that was linked to a strip chart recorder via the slip ring assembly. Physical connection between the LVDT and the probe was made with a balanced lever, which minimized the additional load applied to the soil surface. The elapsed time and the LVDT output as read from a voltmeter, were written down on the chart record at regular time intervals during the test and when rapid changes in deformation were observed.

Preparation of the Soil

Representative samples of the soil used to construct the prototype clay barrier layers were obtained from the field site and transported to the laboratory, where they were air dried and broken into fragments. Pieces of rock larger than 0.5" in diameter were picked out by hand during this process. The soil was further broken up by passing it through a crushing machine. It was then passed through a No. 4 U. S. standard sieve and stored in 5 gal. plastic buckets.

Prior to testing, a quantity of soil was weighed out and a moisture content determination made for the material. The volume of water needed to increase the soil moisture content to a selected value was calculated. Tap water from the Kentucky River, the source of water applied to the field plots, was added to the soil. Blending of the soil and water was accomplished by hand mixing. The soil was then returned to the plastic buckets. To minimize subsequent moisture loss, a wet rag was also placed in each bucket. The soil was allowed to cure for at least 48 hours before testing to allow time for uniform water distribution among the soil particles.

Compaction of Soil Specimens

The compaction mold for the clay slab was made of a 0.5" thick x 11.5" diameter aluminum plate that was bolted to a 14" square x 1.5" thick steel base plate. Before preparing a new soil specimen, the plexiglas tube from the centrifuge testcapsule was slipped down over the aluminum plate to form the mold's side wall. The inside of the compaction mold was lightly coated with a commercial vegetable oil spray, to prevent soil from sticking to the sides and base of the mold. The quantity of soil needed for a particular test configuration (see Table 5) was then weighed out from storage and imme-

The motor speed was incremented at a constant, predetermined rate, to accelerate the payload from the initial 5 rpm rotational speed to that required for the test. The final centrifuge speeds and the corresponding start-up time intervals for each test configuration are listed in Table 5. The required speed was maintained for 5 minutes to assure that the soil layer and the other components were fully seated in the test capsule. Power to the motor was then cut off. After the centrifuge came to rest, the cover was reopened. The LVDT input and output voltages were readjusted. The chart recorder was checked for a zero reading. The housing cover was closed and the centrifuge was brought up to the required speed in the same manner as before.

The test capsule was accelerated for 60 to 120 minutes to allow for the dissipation of excess pore pressure. The chart recorder speed was increased. The solenoid was activated, releasing the lead shot and forming the cavity beneath the soil specimen. The chart recorder speed was reduced after a period of 5 minutes or after rapid changes in LVDT output were no longer observed. Acceleration was continued until collapse of the clay layer was indicated or until the operator decided to terminate the procedure. Power to the motor was then cut off. After the centrifuge came to rest, the cover was reopened and both payloads were removed.

Post-test Procedures

The test capsule was disassembled, the deflection probe removed, and the lead shot emptied from the cylinder. The template sheet was reattached and a final set of surface elevation measurements were taken. The soil specimen was removed from the cylinder and weighed. Photographs were taken of the upper and lower surfaces of the specimen as well as of any unusual features that were observed. A description of the sample's post-test condition was written down. Four samples were removed from the specimen for moisture content determination.

RESULTS AND DISCUSSION

Description of Soil

Model tests have been carried out using soil from the prototype clay barrier layers. The material was a silty, inorganic clay (CH). Table 6 lists some properties of this material.

Behavior of Model Clay Layers

To date, centrifuge model tests have been conducted in which the clay layer moisture content (w) and the subsidence cavity diameter were varied. Preliminary findings from these tests are summarized below.

Three responses were common to all tests.

- Small displacements were recorded for every test as the centrifuge was brought up to speed. These initial drops have been attributed to the re-seating of the movable components in the sample container with increased acceleration.
- During the pore pressure dissipation period, rapidly decreasing rates of displacement were observed during all tests. This behavior was probably caused by consolidation of the clay layer.
- Measurable subsidence of all clay layers was recorded at the instant of cavity formation. For dry soils and/or small cavities, the magnitude of subsidence was small. No apparent changes in the clay layers were visible. For wet soils and/or large cavities, immediate collapse resulted.

The design moisture content of the prototype clay barrier layers was 27% (2% above optimum). Test results for model layers compacted at 27% moisture and undermined by a range of cavity diameters are shown in Figure 6.

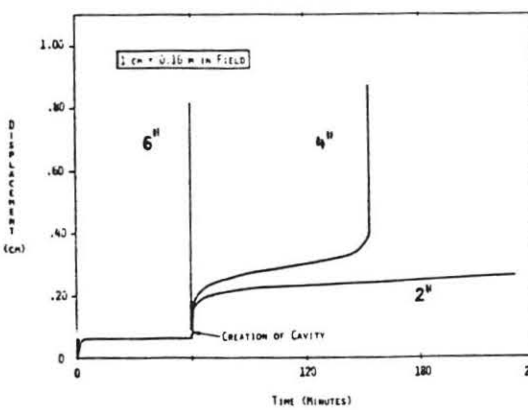

Figure 6. Model subsidence response at optimum moisture content

Table 6. Properties of Soil Used in Centrifuge Studies

Optimum moisture content (standard Proctor)	25 %
Maximum dry density (standard Proctor)	98 pcf
Percent sand	25 %
Percent silt	37 %
Percent clay	38 %
Specific gravity	2.82
Liquid limit	57 %
Plastic limit	26 %
Plasticity index	31 %

All 6 inch cavity tests (12 ft field equivalent) at 27% moisture content resulted in immediate failure of the clay layer (total collapse with severe cracking). All 2 inch cavity tests (4 ft field equivalent) were stable, showing no evidence of cracking or collapse during the periods of acceleration. Tests with 4 inch cavities (8 ft field equivalent) exhibited the full range of subsidence behavior. As a result, 4 in. cavities were used in most tests.

Results from 4 inch cavity tests, for moisture contents ranging from 26.7% to 28.7%, are illustrated in Figure 7. The curves in Figure 7 indicate that clay layer subsidence behavior is highly sensitive to the moisture content at compaction.

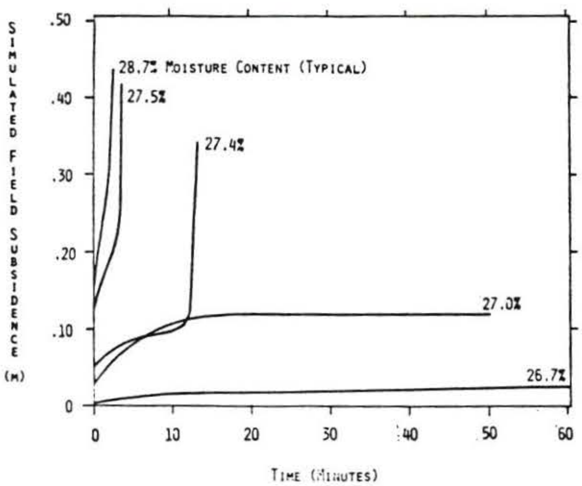

Figure 7. Model subsidence response with 4 inch diameter cavities

The observed subsidence behavior of model covers undermined by 4 in. diameter cavities is summarized below:

- Initial subsidence was recorded at the sample midpoint in all cases. Values ranged from 0.02 in (.04 ft field equivalent) at 4.5% below optimum to 0.125 in (0.25 ft) at 4.5% above optimum.

- For moisture contents below optimum, subsidence tended to occur without cracking and without visible slumping.

- For moisture contents greater that optimum but less than 2% above optimum, clay layers tended to remain stable following cavity formation. However, radial cracking of the lower surfaces, circumferential cracking of the upper surfaces, and slumping was observed.

- For moisture contents greater that 2% above optimum but less that 2.4% above optimum, collapse tended to occur after a period of slow deformation.

- For moisture contents greater than 2.4% above optimum, rapid collapse tended to occur immediately after cavity formation.

CONCLUSION

The severe problems which hazardous waste landfill sites have experienced due to trench cover subsidence dictate that methodologies be developed to better understand this phenomenon. This study was initiated to develop a laboratory procedure for examining these processes. Centrifugal model testing was determined to be the best experimental technique for small-scale studies, primarily because of its ability to duplicate the forces and resultant stresses which lead to failure in the field. The scope of this work was limited to clay layers subjected to "slump", a type of subsidence characterized by localized void spaces beneath the cover.

Pending verification of test results, this experimental methodology will be used to:

- estimate the largest cavity that can be spanned by a given trench cover
- estimate the time to cover failure when this cavity diameter is exceeded
- estimate the degree of subsidence cracking and slumping for application to infiltration studies
- develop recommendations for subsidence resistant landfill cover designs
- investigate the influence of other parameters on subsidence
- investigate the physical mechanisms of subsidence

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