United States
Environmental Protection
Agency
Research and Development

Risk Reduction
Engineering Laboratory
Cincinnati, OH 45268
EPA/600/S2-89/057 Sept. 1990

EPA

Project Summary

Stability of Lined Slopes at Landfills and Surface Impoundments

D. H. Mitchell, M. A. McLean, and T. E. Gates

This report describes research conducted at the Pacific Northwest Laboratory to provide the technology for determining the stability of soils in contact with flexible membrane liners (FMLs) on covers and interior side slopes of hazardous waste landfills and surface impoundments. Included in the research were analyses of slope stability, laboratory tests to measure the frictional properties of various types of interfaces in landfill and surface impoundment containment structures, and larger-scale tests to verify the data from the laboratory tests.

Instability (sloughing) of soils covering FMLs has not been documented at hazardous waste landfills and surface impoundments. However, sloughing has occurred in canals and tailings ponds. The sloughing at tailings ponds occurred during heavy rainfalls, leading to the conclusion that sloughing was caused by a buildup of pore-water pressure in the soil, thereby reducing stability. The same effect has been demonstrated in tests on a 100-ft², "engineering-scale" test stand constructed for the research described in this report. Stability analyses, incorporating the effect of pore water, were developed.

Friction angles determined by direct-shear tests, the typical method used to measure interfacial and matrix soil properties, were compared with friction angles measured on the larger test stand. In general, the direct-shear method produced friction angles less than those measured with the larger engineering-scale system. Therefore, friction angles determined by the direct-shear method are probably conservative for use in stability analyses.

This Project Summary was developed by EPA's Risk Reduction Engineering Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The U.S. Environmental Protection Agency (EPA) has issued guidance describing technologies that will meet RCRA minimum technology requirements for hazardous waste landfills and surface impoundments. The guidance recommends that these facilities be lined and covered with combinations of soils and flexible membrane liners (FMLs). Thus, interfaces will be created between synthetic and soil materials.

Instability along the interfaces between synthetic and soil materials could lead to slippage and loss of integrity of the containment system. Before issuing a permit, the EPA should assess, among other things, this potential for instability. The full report describes the technology needed to make this assessment.

Background

Double-liner systems for a landfill and for a surface impoundment are illustrated schematically in Figures 1 and 2. Slopes of the landfills and impoundments may have several layers of geosynthetic materials and soils. The geosynthetic materials may

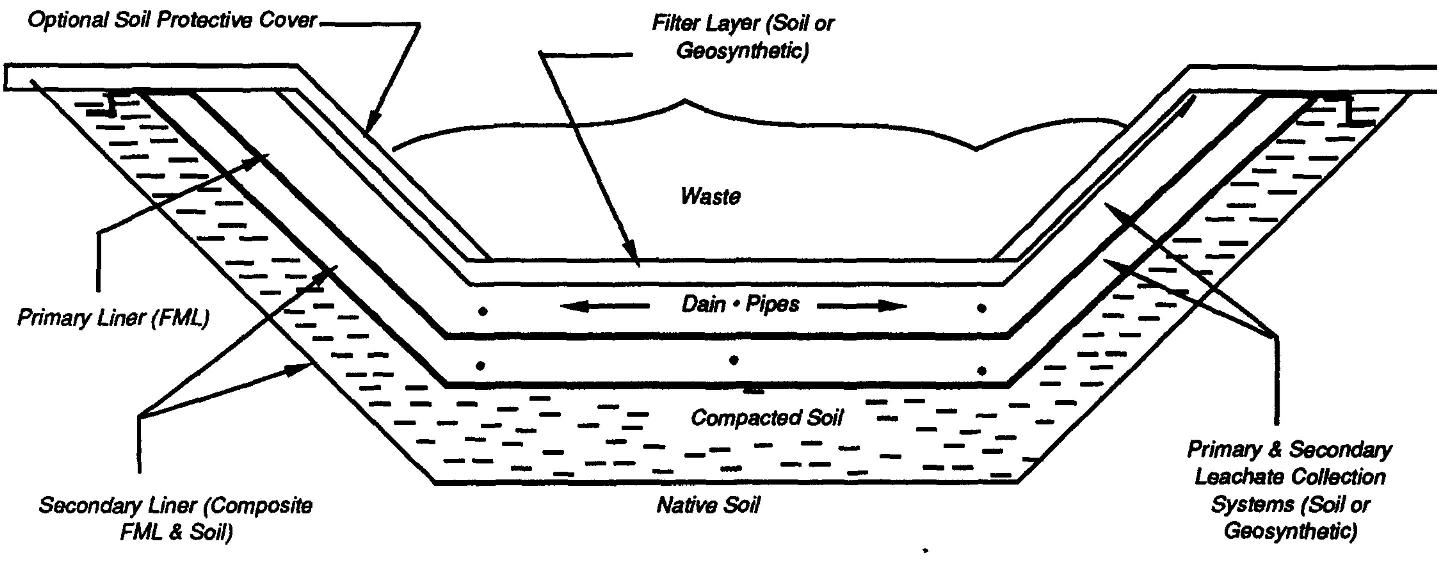

Figure 1. Cross section of landfill double liner system.

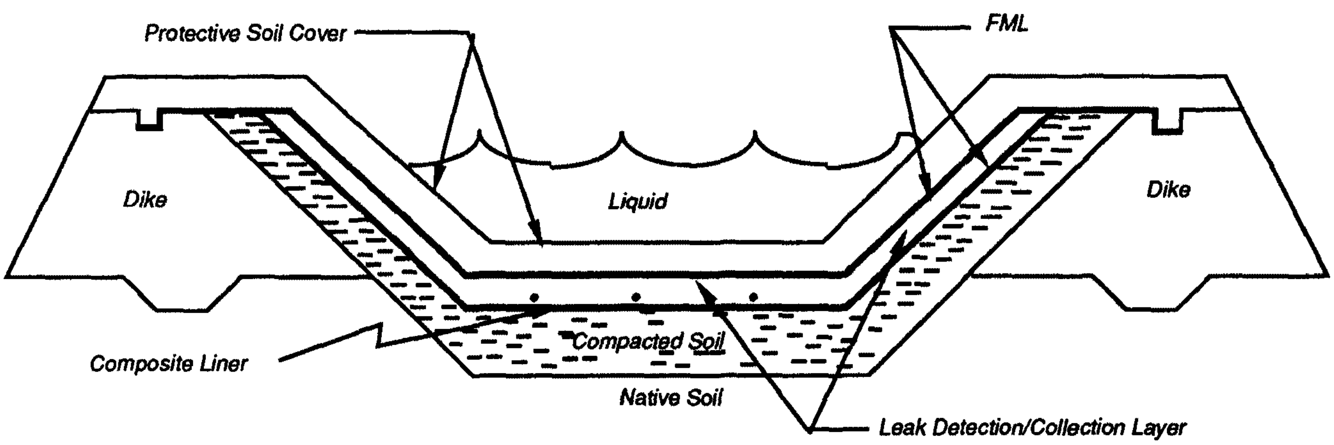

Figure 2. Cross section of surface impoundment double liner system.

include FMLs, geotextiles (those permeable synthetic materials that provide filtration or separation), and drainage nets (those synthetic materials that provide paths for leachate or other liquid flow).

As indicated in Figures 1 and 2, geosynthetic materials are in direct contact with soil lining materials or with an overlying layer of soil placed as protection for the geosynthetic material. This can lead to instability at the interface, particularly if the geosynthetic material is a FML and the interface is sloped. The side slopes of the landfill or impoundment structure are especially susceptible. Soil may slide down the FML surface, or it may drag the FML with it. Sliding of the soil is termed *sloughing* (Figure 3).

Operators of landfills and surface impoundments want steep side slopes to maximize the containment capacity of their facilities. EPA has stated that field experience indicates a maximum side-slope ratio that will hold an earth cover on a smooth liner (FML) is 3 horizontal to 1 vertical, or 18.3°. This project has found that instability can occur even on this relatively low slope.

Cases of interfacial instability have not been documented for hazardous waste landfills and surface impoundments. However, the potential exists, as evidenced by several cases of sloughing in similar structures used for other purposes such as wa storage and containment of mine tailing: is this potential, and the further potential loss of containment capability, that ha inspired the research described in this port.

Stability Analysis

Sloughing of soil on FMLs is simila shallow failure of the surface stratum slopes, as found in natural soils. The dif ence in permeability between the surf and the underlying stratum allows an crease in pore pressure in the surface s tum when rainwater percolates into it. surface stratum may collapse as a res

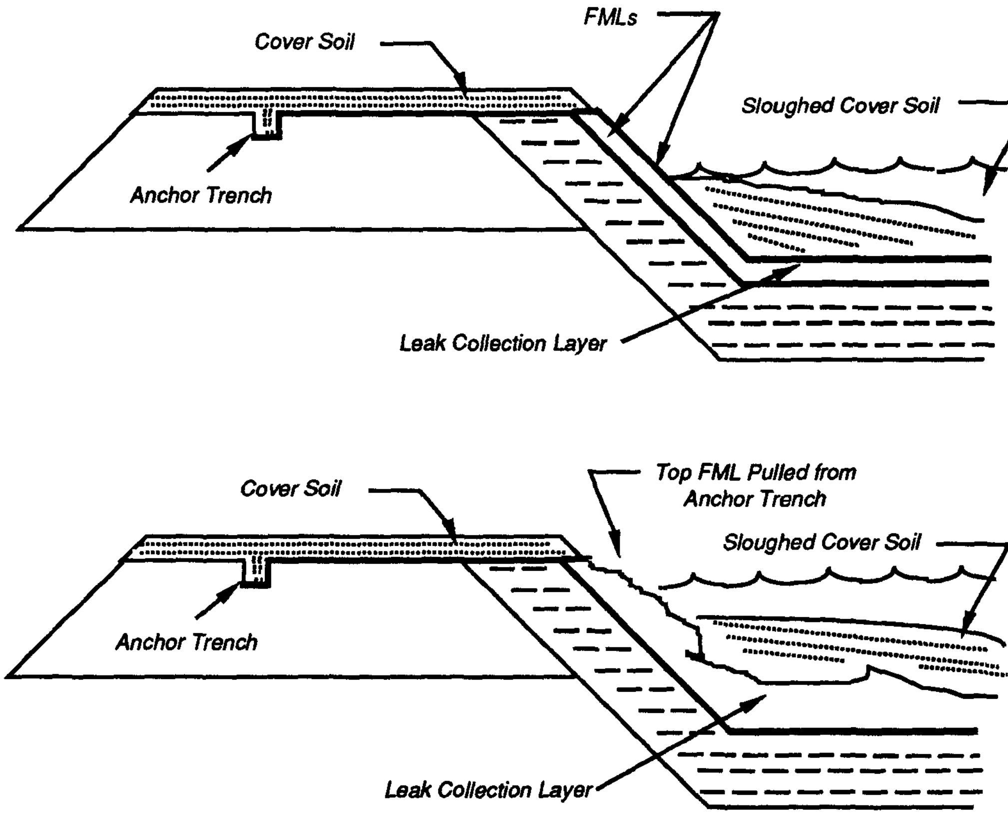

Figure 3. Examples of cover instability (sloughing).

The effect of pore-water pressure on the stability of soils placed over FMLs can be significant and should be incorporated into the stability analysis.

The frictional force resisting sloughing at the interface (see Figure 4) is:

$$f = (\gamma z \cos\beta - \mu)(\tan\phi)L \quad (1)$$

where

γ = soil density

z = soil depth (perpendicular to the slope

β = slope angle

L = length of slope

μ = pore-water pressure

ϕ = friction angle of the failure plane

Another force resisting sloughing is adhesion (c) of the surfaces on each side of the interface plane.

The force promoting sloughing (see Figure 4) is gravity, represented by:

$$g = (\gamma z \sin\beta) \quad (2)$$

Thus, the factor of safety (FS), the ratio of resisting forces to promoting forces, can be determined by:

$$FS = \frac{(\gamma z \cos\beta - \mu)(\tan\phi) + c}{\gamma z \sin\beta} \quad (3)$$

By examining the equation, one can see that, as pore pressure increases, the effective stress on the liner lessens and, therefore, the frictional force lessens. Decreasing the resisting forces (numerator) decreases the factor of safety (FS).

The value for pore-water pressure is not something that typically would be measured at an actual disposal site. Instead, one would expect that maximum pore-water pressure would be determined by modeling or by worst-case assumptions.

Figure 5 illustrates the importance of pore-water pressure in determining the factor of safety in the stability analysis. The soil depth is two feet in this case. The factor of safety is also very sensitive to the slope angle and to the interfacial friction angle. It is less sensitive to soil depth over the FML, except when the pore-pressure head approaches the depth of the cover.

Interface adhesion (c) does not appear to be an important factor in the analysis and apparently can normally be neglected.

If the analysis results in a factor of safety of less than 1.0, it is possible that the toe of the slope may provide the required stability. The full report includes the methodology for calculating the resisting force of the toe. The report also includes consideration of anchor-trench resistance for those cases where the geosynthetic component may be providing sliding resistance.

Direct Shear Tests

Direct shear tests were performed to measure interfacial properties of soils and geosynthetic materials, to demonstrate the effects of compaction and moisture on friction angle and adhesion, and to provide direct-shear results for comparison with engineering-scale tests.

The direct-shear test procedures are detailed in the full report. The test apparatus was a Soiltest model D-124A direct-shear

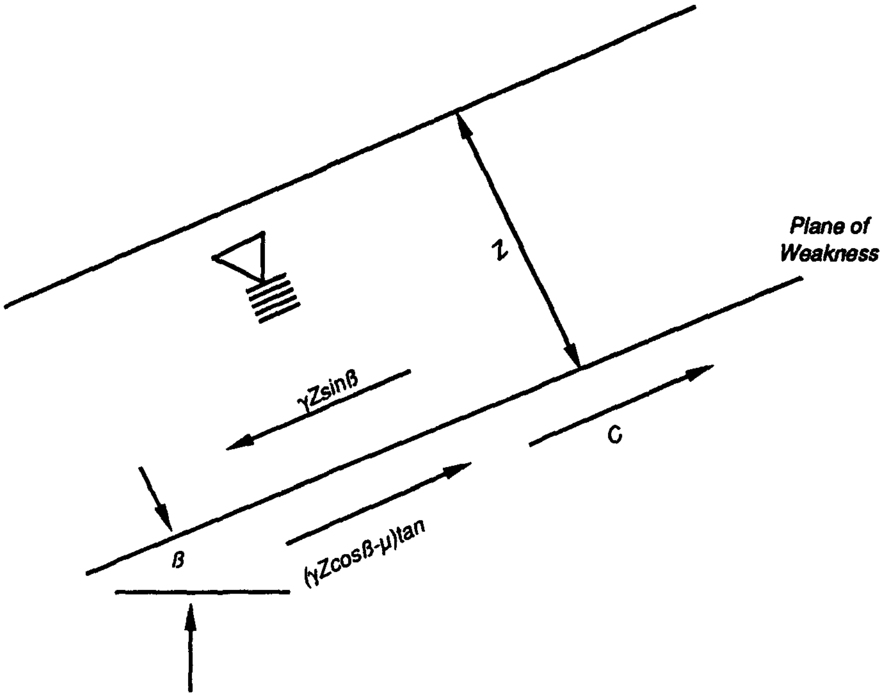

Figure 4. *Forces acting on soil mass on infinite planar sloped surface.*

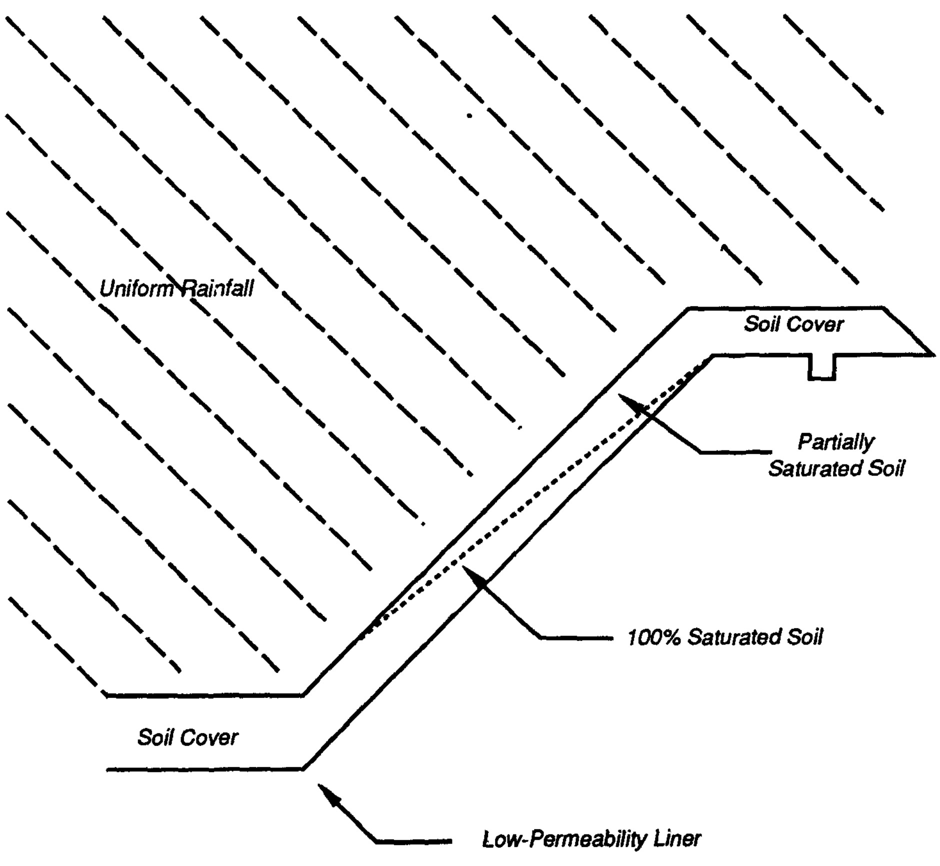

Figure 5. *Pore-water pressure in soil on sloped system.*

device, designed specifically fo shear-testing in soil samples. The shea box could accommodate 2 x 2-inch (5.1 : 5.1-cm) soil and geosynthetic specimens.

For soil alone, the shear plane wa: through the mass of the specimen. Fo soil-geosynthetic combinations and fo combinations of geosynthetics, the speci mens were carefully prepared and emplace in the shear box so that the shear plan coincided with the interface of the materials Tests were done with soils that were com pacted, where appropriate, to specifie densities, and at specified moisture cor tents. All tests were performed under satu rated conditions except for the FML geotextile tests that were dry. Table 1 show the direct-shear test matrix.

Table 2 summarizes the direct-she test results for soil and FML combination As expected the soils alone showed th highest friction angles, and the soil con bined with the harder FML (high-densi polyethylene [HDPE]) showed the lowes Table 3 shows the results of the direct-she tests for FMLs in combination wi geotextiles and drainage nets. Frictic angles are low, substantially lower th: soil-FML combinations. This suggests th interfaces between geosynthetics and FM (instead of FMLs and soils) may limit t angle of slopes unless the various comp nents are well-anchored.

Engineering-Scale Tests

The "engineering-scale" (large-sca tests were conducted to compare with t laboratory direct-shear tests in determini whether the latter can provide reliable d: for interfacial stability analyses. In additi the engineering-scale tests were design to verify the effect of pore-water pressure the stability of FML-soil combinations.

The test stand (Figure 6) was fabricat specifically for the purposes of this proje It could accommodate a mass 10 x 10 f (3.05 x 3.05 m) in horizontal dimensic and up to 50 inches (127 cm) thick. T bottom 14 inches (35.6 cm) was filled v soil, providing the base for the geosynth material. The geosynthetic material co then be loaded with up to 36 inches (9 cm) of soil. During the tests only 12 incl (30.5 cm) of soil was applied. One side the test stand could be raised to cre various slopes of the test materials. geosynthetic material being tested v mounted securely to the sides of the stand at the 14-inch (35.6-cm) level.

The test stand was equipped with linear variable displacement transduc (LVDTs) arranged within the 12 inches (cm) of soil overlying the FML to measure downslope soil displacement. Press

Table 1. *Direct-Shear Test Matrix*

	Soil 1 SP	*Soil 2 SP*	*Soil 3 SM*	*Soil 4 SC*	*Soil 5 CL*
Soil only	X	X	X	X	X
HDPE	X*	X	X	X	X
HDPE/geotextile	X				
CSPE/geotextile	X				
HDPE/drain net	X				

** determined at 3 different densities.*

Table 2. *Direct-Shear Test Results for Soil and FMLs*

	Soil 1 SP		*Soil 2 SP*		*Soil 3 SM*		*Soil 4 SC*		*Soil 5 CL*	
	*ø**	*c***	*ø*	*c*	*ø*	*c*	*ø*	*c*	*ø*	*c*
Soil only	38	1.6	33	0.9	25	2.2	****	****	24	2.4
HDPE	31***	0.4***	21	0.4	22	0.7	25	0.1	18	0.1
CSPE	36	0.1	28	0.5	31	0.5	20	0.8	10	0.8

* *ø = interfacial friction angle.*
** *c = cohesion for soils and adhesion for soil/FML tests.*
*** *average values from tests at 3 different densities.*
**** *measured friction angle was well above values typically measured on this type of soil; errors in data or procedures are suspected.*

Table 3. *Direct-Shear Test Results for FMLs, Geotextile, and Drainage Net*

	HDPE		*CSPE*	
	ø	*c)psi*	*ø*	*c)psi)*
Mirafi 140N	9	0.3	18	0.8
PN 4000	12	0.2	*not performed*	*not performed*

transducers were also placed within the overlying soil to measure the pore-water pressure. Water was added to the system by an adjustable rainfall simulator.

In the tests of soil on a FML, 12 inches of soil was placed on the FML at the specified density. While applying "rainfall," the slope was increased periodically until soil slippage was noted by the LVDTs and by observation. Pore-water pressure was also monitored and recorded. For the tests of geotextile or geonet on a FML, the geosynthetic material was placed directly on the FML. Measurements of slippage were made with the LVDTs, but water was not applied. Each engineering-scale test was performed at least three times.

The following four tests were made at engineering scale:

- poorly graded sand on HDPE
- poorly graded sand on geotextile on HDPE
- poorly graded sand on geotextile on CSPE
- poorly graded sand on drainage net on geotextile on HDPE

The engineering-scale test results of poorly graded sand on HDPE are shown in Table 4. The friction angles were calculated from the equation:

$$\tan ø = \frac{\gamma z \sin \beta}{(\gamma z \cos\beta - \mu)}$$

derived from equation (3), with a factor of safety equal to 1.0 and adhesion equal to zero.

Note that two friction angles (27°) are significantly lower than the others and lower than the friction angle measured in the direct-shear test of the same materials. It is believed that the two low values are spurious and may have resulted from movement of the the test stand during the test.

The results of the tests of geotextile (Mirafi 140N) on HDPE and on CSPE are presented in Table 5, and the results of geotextile on drainage net on HDPE are shown in Table 6. In the latter tests, the geotextile was Mirafi 140N and the drainage net was PN4000. Table 5 shows that the direct-shear test produces a more conservative friction angle than the engineering-scale test for geotextiles on HDPE and CSPE (compare Tables 5 and 3). Table 6 compared with Table 3 shows a similar relationship.

Recommendations

The results of the study indicate that the designer can use direct-shear tests to provide data for interfacial stability analyses of landfill and surface impoundment structures. Direct-shear tests should be carried out using the same materials and simulating the conditions of the field application. That includes the orientation of the synthetic materials and direction of applied stress.

The effect of pore-water pressure in a protective cover soil should also be considered in the design. The designer should account for the uncertainty of key variables to assure that the desired factor of safety is maintained under worst-case conditions.

In order to maximize the slope of an FML-soil system, several options may be chosen. The pore-water pressure may be minimized by using coarser materials for the cover soil. Coarser material may be used over finer soil to gain the same effect while increasing the mass. The combination of soil and FML may also be selected to increase the friction angle.

Geosynthetic materials are evolving rapidly, and attention is being given to the effects of surface texture, combinations of materials, design configuration, and other factors on interfacial slope stability. The designer should be alert to these changes in his choice of materials for stability analysis, design, and use.

The full report was submitted in fulfillment of Interagency Agreement Number DW89930846-01-0 with the U.S. Department of Energy under the sponsorship of the U.S. Environmental Protection Agency.

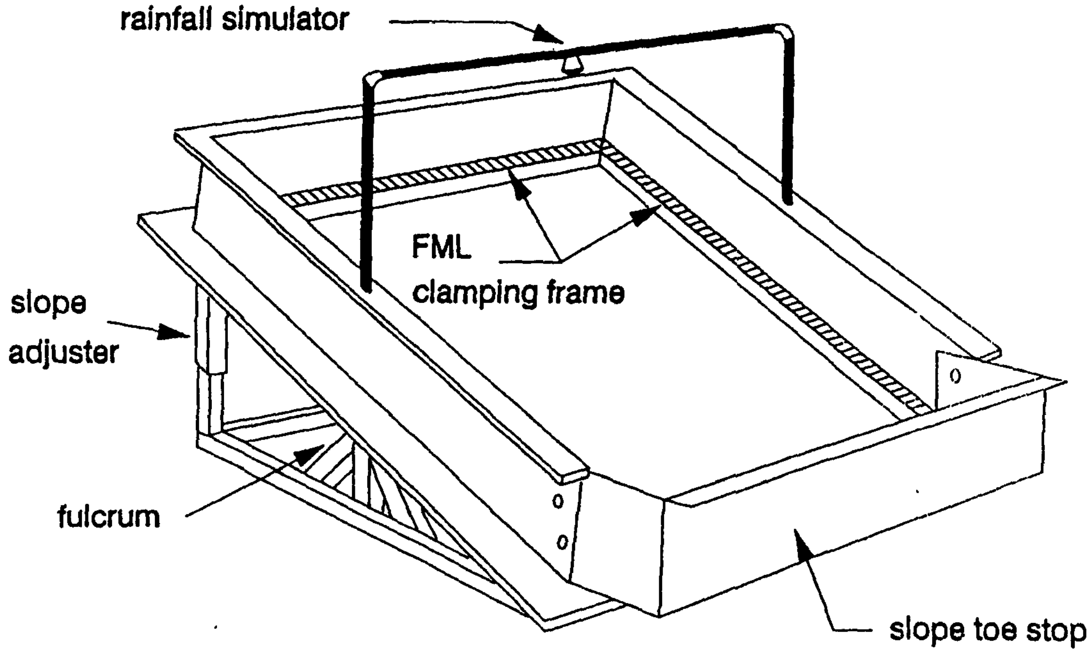

Figure 6. Engineering-scale test stand.

Table 4. *Engineering-Scale Test Results with HDPE and Poorly Graded Sand*

Test Date	Dry Soil Density lb/cf	Incipient Failure Angle (degrees)	Pore-Water Pressure in. H_2O	Calculated Friction Angle* (degrees)
9/16/86	104	18.9	6.3	38
9/21/86	101	17.2	6.5	35
9/25/86	102	22.5	5.0	37
10/27/86	99	14.8	6±**	27
11/06/86	106	>30	0	>30
11/13/86	106	13.9	6±**	27

* Calculated friction angle assumes no adhesion. The wet density of the soil was 123.5 lb/cf, from separate measurement of saturated soil at 104 lb/cf dry density.

** The pore-water pressure transducer output was erratic; the pressure was estimated from a backup manometer system.

Table 5. *Engineering-Scale Test Results with a Geotextile on HDPE and CSPE*

FML	Date of Test	Incipient Failure Angle (degrees)
HDPE	10/09/86	18.4
HDPE	10/09/86	21.1
HDPE	10/10/86	17.5
HDPE	10/15/86	23.8
HDPE	10/16/86	20.1
HDPE	10/23/86	<15.1
HDPE	10/24/86	12.9
HDPE	10/24/86	13.6
CSPE	4/11/87	28.5
CSPE	4/14/87	28.5
CSPE	6/04/87	25.8

Table 6. *Engineering-Scale Test Results with a Drainage Net on HDPE*

Date of Test	Failure Angle (degrees)
10/17/86	22.0
10/20/86	20.4
10/21/86	17.4

D.H. Mitchell, M.A. McLean, and T.E. Gates are with Battelle, Pacific Northwest Laboratories, Richland, WA 99352.
***Robert P. Hartley** is the EPA Project Officer (see below).*
The complete report, entitled "Stability of Lined Slopes at Landfills and Surface Impoundments," (Order No. PB 90-251 877/AS; Cost: $23.00 subject to change) will be available only from:
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