Exploratory of Desiccation Crack in Liner Soils Propagation in Clay Liners

Manoj Kumar[1]* Vishal Arora[2]

[1]Lecturer in Civil Engineering, Department G.B.N. Govt. Polytechnic, Nilokheri, Karnal, Haryana

[2]Lecturer in Civil Engineering, Department G.B.N. Govt. Polytechnic, Nilokheri, Karnal, Haryana

***Abstract* – A laboratory investigation on a scaled model of a landfill liner was conducted to provide data regarding the occurrence fill liner was conducted to provide data regarding the occurrence and extent of desiccation cracking of prototype liners. The crack and extent of desiccation cracking of prototype liners. The crack intensity factor, CIF, was introduced as a descriptor of the extent of intensity factor, CIF, was introduced as a descriptor of the extent of surficial cracking. CIF is defined as the ratio of the surface crack surficial cracking.**

CIF is defined as the ratio of the surface crack area A, to the total surface area of the clay liner, At. A computer area Ac, to the total surface area of the clay liner, At. A computer aided image analysis program was used to determine CII' values aided image analysis program was used to determine CIF values from scanned photographs of the desiccation process. The variation from scanned photographs of the desiccation process. The variation of the CII' was related to duration of drying and measured soil the CIF was related to duration of drying and measured soil moisture suctions. moisture suctions.

The soil of this investigation experienced significant cracking, soil of this investigation experienced significant cracking, with crack widths approaching 10 mm in the first drying cycle and with crack widths approaching 10 rom in the first drying cycle and penetration through the entire 16 cm thickness.

Crack propagation penetration through the entire 16 cm thickness. Crack propagation was limited to a very intense period of the desiccation process. was limited to a very intense period of the desiccation process. Nearly 90 percent of the crack development occurred during a 19¬ Nearly 90 percent of the crack development occurred during a 19¬ hour time period, although the total duration of the desiccation hour time period, although the total duration of the desiccation cycle was approximately 170 hours. The soil moisture suction cycle was approximately 170 hours. The soil moisture suction changed by only 2 bars during the period of rapid crack growth, changed by only 2 bars during the period of rapid crack growth, although it changed by more than 40 bars during the period of although it changed by more than 40 bars during the period of reduced growth. reduced growth.

Keywords: Soil liners; Clays; Desiccation Cracks; Geo-Environmental Engineering

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INTRODUCTION

Historically, land disposal has been the most commonly used method of waste disposal. Even now, land mainly used method of waste disposal. Even now, landfills continue to accept nearly 75 percent of the fills continue to accept nearly 75 percent of the municipal waste generated in the India.

Landfills accept a variety of wastes that could contain Landfills accept a variety of wastes that could contain a mixture of organic and inorganic hazardous con- a mixture of organic and inorganic hazardous constituents. Therefore, poorly designed landfills and migration of leachate from the landfills.

Federal and local regulations govern the design Federal and local regulations govern the design and permitting of containment facilities for the land and permitting of containment facilities for the land disposal of solid and hazardous waste. In these regulations, primary reliance is placed on the landfill liner lations, primary reliance is placed on the landfill liner system as the ultimate barrier against leakage of the system as the ultimate barrier against leakage of the waste to the surrounding environment.

The value of the hydraulic conductivity of the barrier liner is used the hydraulic conductivity of the barrier liner is used as the principal indicator of its containment poten as the principal indicator of its containment potential. However, numerous observations of leachate plumes downgradient of landfills have illustrated that plumes downgradient of landfills have illustrated that leakage occurs in spite of the existing design regula leakage occurs in spite of the existing design regulations (Assmuth, 2012; Goodall and Quigley, 2007; tions (Assmuth, 2012; Goodall and Quigley, 2007; Lesage et al., 2013).

Clay soils are commonly used in the construction of landfill liners. Clay soils are also the primary compo landfill liners. Clay soils are also the primary component of other environmental barriers, including slurry of other environmental barriers, including slurry walls for containment of contaminated groundwater walls for containment of contaminated groundwater and pond liners for the storage of liquid wastes.

Previous investigations have shown that the performance ous investigations have shown that the performance of these barriers is affected by desiccation and subse of these barriers is affected by desiccation and subsequent cracking of the clay soil (Miller, 2008)

Other failure mechanisms involving clay liners include syneresis cracking (Mundell, 2006) and include syneresis cracking (Mundell, 2006) and freeze/thaw cracking (Erickson et al., 2004).

Cracking leads to a decrease in the containment function of the leads to a decrease in the containment function of the liner, which can result in an increase in infiltration of liner, which can result in an increase in infiltration of surface water into the containment system or surface water into the containment system or migration of the contained liquids into surrounding soils of the contained liquids into surrounding soils and groundwater. Both effects jeopardize the integrity and groundwater.

Both effects jeopardize the integrity of the containment system and, thus, the environment of the containment system and, thus, the environmental quality of the surrounding subsurface. The presence of cracks may alter predicted contaminant concentrations due to bypass flow, resulting in inant concentrations due to bypass flow, resulting in increased transport rates and modifications to adsorp increased transport rates and modifications to adsorption and other non-conservative processes.

Desiccation cracks are also important in agricultural applications. The movement of pesticides and fertilizers to the root zone, as well as the efficiency of irrigation operations are impacted on by efficiency of irrigation operations are impacted on by the presence of desiccation cracks and other forms of macropores (Prendergast, 2005). The determination of the crack geometry is The determination of the crack geometry is required for characterizing various phenomena also required for characterizing various phenomena associated with desiccated soils.

Bosscher and Douglas (2008) emphasized the need for accurate description of the spatial characteristics of joint systems include of the spatial characteristics of joint systems including desiccation cracks. These characteristics were required for groundwater models to determine flow in required for groundwater models to determine flow in fractured soils and for geotechnical models to deter fractured soils and for geotechnical models to determine the strength parameters of fractured soils.

CRACK THEORY

Although the mechanisms controlling cracking are very complicated, there has been some progress in very complicated, there has been some progress in developing theoretical models of the process. It is theoretical models of the process. It is known that surface tension effects at air-water-solid known that surface tension effects at air-water-solid contacts inside the soil generate negative pore water inside the soil generate negative pore water pressures (positive suctions) in the unsaturated soil.

The matrix suction may result in soil contraction, and ultimately soil shrinkage and cracking. This shrinkage produces vertical cracks below exposed horizontal age produces vertical cracks below exposed horizontal drying surfaces. The depth of the cracks increases drying surfaces. The depth of the cracks increases gradually, as desiccation of the soil deposit progresses. The volume change is directly related to the shrink volume change is directly related to the shrinkage limit. For plasticity index (P1) values greater than 35, excessive shrinkage can be expected (Daniel, Morris et al. (2012; 2004) offered analytical solutions to predict the depth of cracks for the case of a steady state suction distribution from ground surface steady state suction distribution from ground surface to water table.

QUANTIFICATION OF CRACK DIMENSIONS

Most data available regarding the geometry of des- data available regarding the geometry of desiccation cracks are related to landfill applications. Basnett and Brungard (2012) observed cracks resulting from desiccation on the side slopes of a clay liner ing from desiccation on the side slopes of a clay liner during landfill construction. The cracks were 13 mm landfill construction. The cracks were 13 mm to 25 mm in width and extended to 0.30 m depth. to 25 mm in width and extended to 0.30 m depth. Miller and Mishra (2009) observed uniformly desiccation cracks during their field investigation of landfill clay liners.

Montgomery and Parsons (2009) observed desiccation cracking at test plots simulating covers constructed at a landfill in plots simulating covers constructed at a landfill in Wisconsin. Subsequent to three years of exposure, the upper 0.20 to 0.25 m of the compacted clay plots had upper 0.20 to 0.25 m of the compacted clay plots had become become desiccated, with crack widths exceeding 13 desiccated, with crack widths exceeding 13 mm. mm. They reported maximum crack depths of 1.0 m at at a number of locations in the test plots.

Corser and Cranston Cranston (2011) reported observations of cracks down to to 0.10 m deep within compacted cover sections from a 0.10 m deep within compacted cover sections from a test test fill in an arid part of California.

EXPERIMENTAL SET-UP

Three blowers were m (length) and 0.5 m (depth). Three blowers were fixed on the wall of the tank to simulate wind action fixed on the wall of the tank to simulate wind action on the soil surface and increase the rate of soil desiccation. A rainfall simulation system consisting of pipe, regulator, flow meter, pressure gauge, and water pipe, regulator, flow meter, pressure gauge, and water spraying nozzle was positioned over the tank. The spraying nozzle was positioned over the tank. The oscillation of the nozzle was controlled electronically of the nozzle was controlled electronically to provide complete and regular coverage of the entire to provide complete and regular coverage of the entire tank. Variable rainfall intensities were simulated by changing the flow nozzle.

A drainage system beneath the tank was equipped to collect and measure leakage the tank was equipped to collect and measure leakage via the compacted clay. These leakage measurements were used to calibrate a hydraulic model of flow were used to calibrate a hydraulic model of flow through desiccated liners (Mi, 2005). A 35mm automated camera was mounted 1.2m above the tank to mated camera was mounted 1.2m above the tank to record the entire process of crack initiation and prop record the entire process of crack initiation and propagation.

Psychrometers have successfully measured suction values as high as 30 atmospheres and situ suction values as high as 30 atmospheres and appear to be the best monitoring device for very dry appear to be the best monitoring device for very dry soil conditions, where other methods may be limited soil conditions, where other methods may be limited (Hoffman et al., 2012).

Psychrometers provide measurements of soil water potential using a relationship surements of soil water potential using a relationship between soil water potential and relative humidity. between soil water potential and relative humidity. Calibration is required for each psychrometer unit before it is used to measure soil water potential. before it is used to measure soil water potential.

Psychrometers are very sensitive to temperature fluctuations and require correction for even minor tem and require correction for even minor temperature changes. A layer of six evenly spaced perature changes. A layer of six evenly spaced psychrometers were placed during the liner com compaction process, at mid-depth of the clay liner.

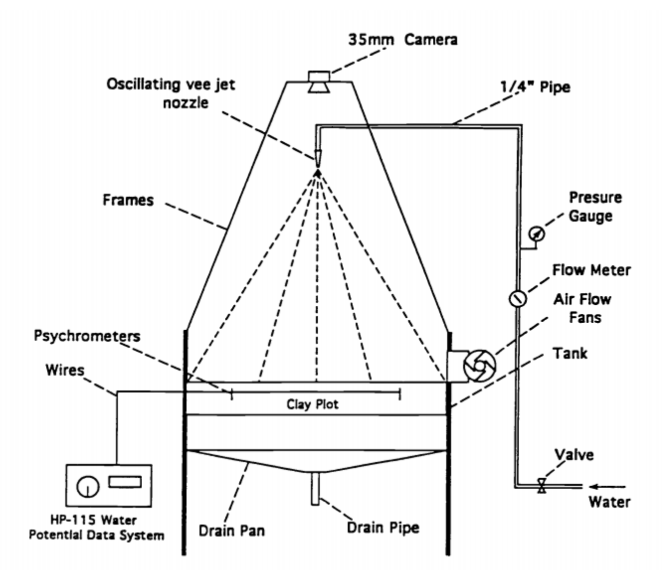


Figure 1. Components of the Experimental System for Desiccation Crack Development and Analysis.

MATERIALS

The clay soil used in this study was obtained from a borrow area used for construction of a liner for a a borrow area used for construction of a liner for a landfill in metropolitan Detroit, Michigan. The soil is landfill in metropolitan Detroit, Michigan. The soil is classified as a silty clay (CL-ML) using the Unified classified. The properties of the soil are presented in Table 1.

TABLE 1. Clay Liner Properties

Property	Standard*	Value
Specific Gravity	ASTM D 854-92	2.70
Hydraulic Conductivity, cm/sec	ASTM D 5084-90	1.07×10^{-8}
Particle Size Analysis	ASTM D 422-63(90)	
Percent Sand		20
Percent Silt		25
Percent Clay		55
Atterberg Limits	ASTM D 4318-93	
Liquid Limit (percent)		22.6
Plasticity Index (percent)		6.2
Optimum Moisture Content		13.5
(percent) (Standard Proctor)	ASTM D 698-91	
Maximum Dry Density, kN/m^3		19.3
(Standard Proctor)	ASTM D 698-91	

TABLE 2. Mineralogical Analysis of Soils

Soil Fractions	Minerals	Weight Percentage
Clay	Chlorite	8
	Illite	63
	Hornblende	3
	Kaolinite	11
	Microcline	6
	Quartz	5
	Plagloclase	4
Silt	Chlorite	3
	Illite	3
	Quartz	56
	Albite	6
	Calcite	21
	Dolomite	11
Sand	Quartz	90
	Calcite	7
	Dolomite	3

TESTING PROCEDURES

The experimental procedure consisted of two main steps: (1) soil preparation and compaction and (2) sim steps: (1) soil preparation and compaction and (2) simulation of wetting/drying cycles.

COMPACTION

The soil compaction required special attention to ensure uniformity in density and moisture conditions ensure uniformity in density and moisture conditions throughout the test liner. Prior to compaction, the throughout the test liner. Prior to compaction, the large soil clods were broken down into smaller units large soil clods were broken down into smaller units (maximum equivalent diameter less than 1.0 cm). The soil was wetted approximately to the optimum soil was wetted approximately to the optimum moisture content (1 percent). The wetted soil was left in content (1 percent).

The wetted soil was left in sealed boxes for two days of soaking to achieve sealed boxes for two days of soaking to achieve uniform moisture absorption. The loose soil was then form moisture absorption. The loose soil was then placed in the experimental tank and manually com placed in the experimental tank and manually compacted using a square steel pad of area 25 cm2 and using a square steel pad of area 25 cm2 and weighing 96 N. The pad was lifted approximately 60 weighing 96 N.

The pad was lifted approximately 60 cm and dropped freely to the soil surface. The specific cm and dropped freely to the soil surface. The specific values for lift height and number of blows were determined by equating the compaction energy per unit area of this method to the standard proctor compaction test. The clay soil was standard proctor compaction test.

WETTING AND DRYING CYCLES

Rainfall was onset of a stable soil pore water suction). Rainfall was then applied to the dry soil. The period between the then applied to the dry soil. The period between the fully dry condition and infiltration of the ponded water from the simulated rainfall was termed the water from the simulated rainfall was termed the dry-wet period. The soil tank was sealed with a glass dry-wet period. The soil tank was sealed with a glass cover during the infiltration phase to prevent evaporation of moisture. The last period of a cycle was the ration of moisture. The last period of a cycle was the wet-dry period. The cover was removed at the begin- wet-dry period. The cover was removed at the beginning of the wet-dry period which began with the end of the second period and terminated with the develop of the second period and terminated with the development of fully dry conditions.

RESULTS AND DISCUSSION

The water potential of the soil1iner throughout the wetting and drying process is shown in Figure 2. The wetting and drying process is shown in Figure 2. The water potential decreased during the compaction-dry water potential decreased during the compaction-dry period from -22.1 bars to -58.3 bars. During the dry- period from -22.1 bars to -58.3 bars. During the dry wet period, the water potential values increased from wet period, the water potential values increased from -58.3 bars to -6.0 bars. Finally, during the wet-dry -58.3 bars to -6.0 bars. Finally, during the wet-dry period the water potentials decreased to -60.7 bars, period the water potentials decreased to -60.7 bars, which was the driest condition achieved.

The geometric features of cracks, such as width, depth, and surface area, are important parameters, depth, and surface area, are important parameters, because they influence both the soil hydraulics and because they influence both the soil hydraulics and mechanics. The crack intensity factor (CIF) was intro mechanics. The crack intensity factor (CIF) was introduced as a descriptor of the extent of surficial cracking.

Figure 3 illustrates key aspects of the CIF. Figure 3a shows the CIF variation with time for the wet-dry 3a shows the CIF variation with time for the wet-dry period (C-D of Figure 2), while Figure 3b shows the period (C-D of Figure 2), while Figure 3b shows the relation between the CIF and water potential for the relation between the CIF and water potential for the same period. From Figure 3a, the CIF remained close same period.

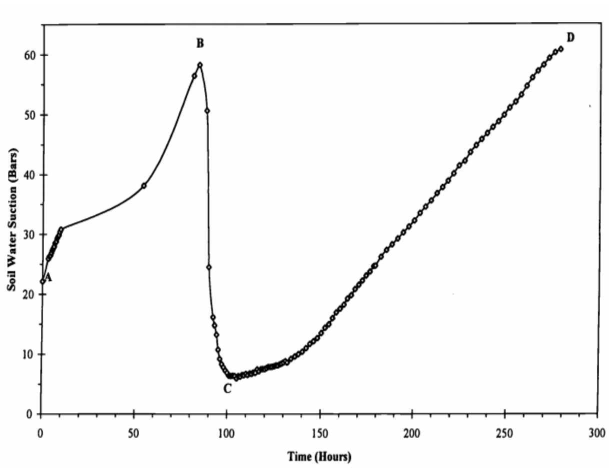
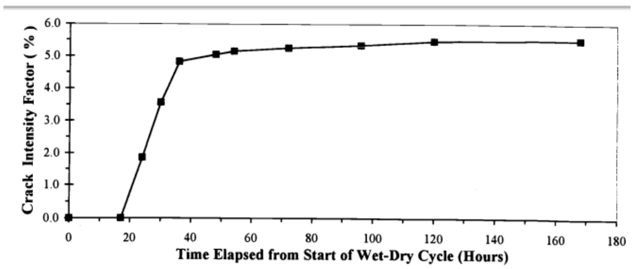
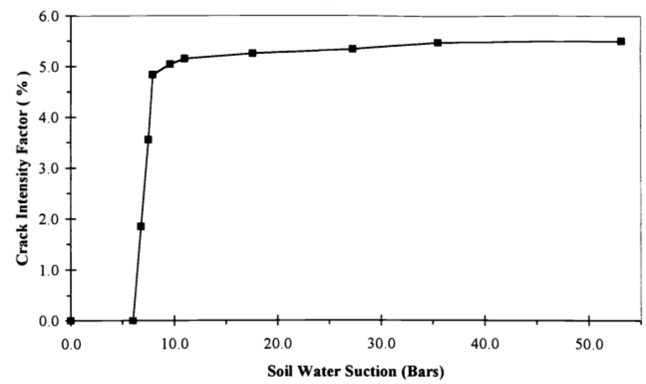


Figure 2. Soil Water Potential Measurements for the Clay Liner:
A-B: Compaction-Dry Period; B-C: Dry-Wet Period; and C-D: Wet-Dry Period.



(a)

(a)



(b)

Figure 3. Crack Intensity Factor (CIF) Analysis for the Wet-Dry Period –
(a) CIF Variation With Time; (b) CIF Variation With Soil Water Suction.

TABLE 3. Characteristic Features During the Three Stages of Cracking.

Stage	Time (hours)	Water Potential (negative bars)	CIF (percent)
Initial Cracking	17 ~ 36	6.0 ~ 7.9	0.0 ~ 4.8
Enhanced Cracking	36 ~ 72	7.9 ~ 17.6	4.8 ~ 5.3
Stable Cracking	72 ~ 168	17.6 ~ 53.2	5.3 ~ 5.5

The crack pattern was primarily linear, with a few extensions of smaller primarily linear, with a few extensions of smaller cracks. During the compaction-dry period, cracks did cracks. During the compaction-dry period, cracks did not penetrate the entire depth of the soil layer. During the dry-wet period, rainfall was simulated.

There was significant growth in the crack dimensions during significant growth in the crack dimensions during this period. The observed maximum crack widths for the compaction-dry and wet-dry periods were 5.0 mm the compaction-dry and wet-dry periods were 5.0 mm and 9.5 mm, respectively.

CONCLUSIONS

A laboratory investigation of desiccation cracking A laboratory investigation of desiccation cracking of a clay landfill liner was completed to provide of a clay landfill liner was completed to provide qualitative and quantitative data regarding crack qualitative and quantitative data regarding crack geometry and to relate cracking to measurable soil geometry and to relate cracking to measurable soil properties. Previous studies have suggested that des properties.

Previous studies have suggested that desiccation cracking is not expected to be significant for low plasticity soils and that desiccation cracking is low plasticity soils and that desiccation cracking is less likely for soils compacted dry of the optimum less likely for soils compacted dry of the optimum moisture content (Daniel, 2011).

The soil investigated in this study had a low P1 and was compacted dry of in this study had a low PI and was compacted dry of optimum. However, it experienced significant crack optimum. However, it experienced significant cracking, with crack widths approaching 10 mm in the first ing, with crack widths approaching 10 mm in the first drying cycle, and crack penetration through the entire drying cycle, and crack penetration through the entire 16 16cm thickness of the clay.

The desiccation crack features were highly dependent on the cycle of desiccation being observed. The initial crack pattern was primarily linear with many initial crack pattern was primarily linear with many small branches. Cracks initiated during this cycle did not penetrate the entire depth of the soil layer. Following moisture addition, desiccation was allowed to lowing moisture addition, desiccation was allowed to continue.

The cracks which formed after moisture addition developed a polygonal pattern of crack net- addition developed a polygonal pattern of crack networks and some penetrated the entire liner thickness. The CIF was introduced to describe the extent of CIF was introduced to describe the extent of cracking in soils. The visual observation of the cracking process was quantified using the CIF.

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Corresponding Author

Manoj Kumar*

Lecturer in Civil Engineering, Department G.B.N. Govt. Polytechnic, Nilokheri, Karnal, Haryana

E-Mail – vikas.pandey94@gmail.com