SLIDING FAILURE OF A SOIL COVER ON A PVC LAGOON LINER CAUSED BY HYDRAULIC LIFTING

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ABSTRACT

On July 18, 1986 at 16:30 hours a general inspection of the sewage lagoon facilities in Red Deer, Alberta did not reveal anything out of the ordinary. At 19:30 hours, 3 hours later, a subsequent inspection revealed that about 1/4 of the entire soil cover on the inside slope of the PVC-lined lagoon, Cell No. 15 had failed by sliding into the lagoon. The failure was sudden, massive and complete. Failure occurred within less than 3 hours and no further sliding of the soil cover occurred afterwards. An investigation was undertaken to determine the cause of the failure.

The failure of the soil cover was remarkable for several reasons:

- The sliding failure of the soil cover at various locations along the perimeter of the lagoon was sudden and occurred within less than 3 hours.
- Once failure had occurred, no further failures or even further movement of the soil cover was observed.
- The boundaries between the sections of the failed soil cover and the intact soil cover were very abrupt and well defined.
- The soil cover failed along the contact with the PVC liner and the PVC liner surface was extremely clean with virtually no soil debris remaining.

The soil cover failed following a prolonged rainfall. There is evidence to suggest that hydraulic lifting of the soil cover occurred prior to failure and eventually led to failure. This paper summarizes the results of the failure investigation. The summary includes the background circumstances, photographs of the failed soil cover, hypothesis to explain the cause of failure, lessons learned and remedial measures that were undertaken.

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INTRODUCTION

The City of Red Deer expanded their sewage treatment facilities in 1983 and the expansion included the construction of three sewage sludge lagoon ponds, Cell Nos. 13, 14 and 15. The location of Cell No. 15 relative to the other lagoons is illustrated on Figure No. 1. The sizes of the lagoons vary and Cell No. 15 covers an area of about 27 000 m^2. Cell No. 15 is an irregular L-shape and the perimeter around the cell is about 830-m long.

The lagoon dykes of Cell No. 15 were constructed of compacted earthfill consisting primarily of silty clay soil. The dykes are 4.6-m high with 3 horizontal to 1 vertical side slopes. The crest of the dykes is at El. 848.0 m and the bottom of lagoon cell is at El. 843.4 m. A 40 mil PVC liner was installed over the entire inside area of the lagoon to minimize seepage and a 300-mm thick soil cover was placed over the liner for protection. The soil cover primarily consisted of sandy silt soil covered with 50 mm to 100 mm of topsoil which was seeded with grass to minimize surface erosion due to wave action. The crest width of the dykes is 6 m, and since the dyke crest is also used for vehicle access, the crest is covered with about 150 mm of road-crush gravel. A typical cross-section of the lagoon cell dyke is illustrated on Figure 2.

The sewage lagoons are operated by filling with supernatant from the anaerobic digesters on a year round basis. The level of the supernatant in the sewage lagoon is allowed to increase during the winter months and is then drawndown in the summer by returning the supernatant to the treatment plant. After treatment of the supernatant, the effluent is discharged into the Red Deer River. The lagoons were designed for a maximum supernatant depth of 4.2 m, which is 0.4 m below the crest. The supernatant level in the lagoons normally commences increasing about September and continues during the winter, reaching the maximum level about April. The lagoons are drawndown during May to September, and typically the drawdown rate ranges from 15 mm to 30 mm per day.

The drawdown of Cell No. 15 commenced in early May, 1986 when the lagoon level was 0.95 m below the dyke crest (3.7-m deep). The rate of drawdown in 1986 was more rapid than normal and much of the drawdown had already occurred by mid-July. The rate of drawdown ranged typically from 25 mm to 40 mm per day. On July 18, 1986, at 16:30 hours a general inspection of the sewage lagoon facilities, including Cell No. 15, did not reveal anything out of the ordinary. At 19:30 hours, 3 hours later, a subsequent inspection revealed that about 1/4 of the entire soil cover on the inside slope of the PVC-lined lagoon, Cell No. 15, had failed by sliding down into the lagoon. The combined length of the failed portions of the soil cover was about 200 m. The failure was sudden, massive and complete. Failure occurred within less than 3 hours and no further sliding of the soil cover occurred afterwards. The PVC liner was not damaged except for one small tear which may have occurred during the original construction. The supernatant depth in Cell No. 15 was 1.4 m when the soil cover failed.

The rainfall during the summer of 1986 was heavier than normal for Central Alberta. Five weeks of prolonged rainfall occurred with a particularly heavy rainfall of 81 mm during the last two days of the five-week period immediately preceding the soil cover sliding failure. As will be shown later, the prolonged rainfall was one of the major factors responsible for the failure.

SITE EXAMINATION OF SOIL COVER FAILURE

The soil cover on the lagoon slopes of Cell No. 15 after failure is illustrated on Photographs 1, 2 and 3. Observations of the failures at the site, and as shown on the photographs, revealed that there were various degrees of soil cover movement during the failure. In some cases, the entire soil cover, from crest to toe, slid down the 10-m-long exposed slope and displaced the sludge at the toe of the slope. The displaced sludge surface was raised above the lagoon level as shown on Photograph 2. In other areas the soil cover slid several metres and stopped, while elsewhere, the amount of sliding was less, in the range of 0.3 m to 1.0 m. Some areas illustrated a general hummocky appearance with tension cracks 5 mm to 20 mm in width. Finally, for a large portion of the soil cover no evidence of sliding was visible.

A detailed examination of the sliding failure revealed a few specific features. In several of the larger areas of sliding, there was a general impression that the lower portion of the soil cover initiated the failure and due to the tensile strength of the grass root mat within the soil cover, the upper portions of the soil cover were dragged down by the lower portions. This impression was supported further by the general observation that where only a relatively small amount of sliding movement had occurred, the soil cover was stretched and contained tension cracks but with the larger movement detected on the lower portion of the slope. In some locations the soil cover separated, leaving isolated portions of the soil cover as little islands stranded on the PVC liner (Photograph 1). While no major sliding was detected on the east lagoon slope, some tension cracks were evident along the top of the dyke slope similar to those shown on Photograph 4.

The boundary between the portions of the soil cover that had failed and the remaining soil cover was abrupt and very distinct. Furthermore, the PVC liner surface that was exposed was usually very clean with very little soil debris remaining. Both of these features can be observed in Photographs 1 to 3 inclusive, and in a close-up in Photograph 5. Photograph 5 is a view looking up the slope at the soil cover remaining on the slope.

The entire soil cover failure was sudden and no further movement was observed after failure had occurred. To provide specific information on possible continuing creep movement, several stakes were driven into the soil cover two days after failure had occurred but no measurable further movement of the soil cover could be detected. This is most unusual since many natural slides continue to slide and creep for extended periods.

Two types of vegetation were evident on the soil cover on the inside slopes of the lagoon. A thick grass cover extended from the crest to about 2 m below the crest and a thick growth of weeds covered the rest of the slope. The fluctuating lagoon level killed most of the grass on the lower slope because of extensive submergence, but was replaced by weeds. Both the grass and weeds no doubt owed their luxuriant growth to the nutrients in the supernatant. The grass and weed roots extend to the bottom of the soil cover in contact with the PVC liner. Because of the physical PVC boundary, the roots in contact with the PVC liner have become densely matted, similar to that found on the inside of a root-bound pot of a plant that has overgrown the size of pot. An example of the densely matted roots in contact with the PVC liner is shown on Photograph 6.

Tension cracks at the crest of the slope are shown on the Photograph 4. The upper limit for the tension cracks approximately coincides with the edge of the grass cover, and the corresponding root mat. The root mat binds the soil cover and when the soil cover was under tension during sliding of the soil cover, the upper limit at which the soil cover failed was the limit of the significant soil root mat. In fact, as can be seen in the centre of Photograph 4, the tension crack extended into the gravel where the grass and root mat invaded the gravelled road surface adjacent to the dyke crest. Some of the PVC liner can just be seen exposed following sliding of the gravel and root matted cover.

The investigation of the soil cover failure included hand excavation of several shallow test pits into the failed soil cover. Soil samples were taken at four of the test pits at the locations illustrated on Figure 1. The soil cover was nominally 300-mm thick and the upper 50 mm to 100 mm consisted of topsoil with the remainder being inorganic sandy silt with some clay. The results of the grain size analyses on the inorganic soil are shown in Figure 4. As can be seen, the grain size of the soil samples were very similar, and the combined silt and clay content (passing No. 200 sieve) ranged from about 57% to 75%. The soil samples were selected at locations where the soil cover had slid various amounts, ranging from very little movement to movement up to 6 m. There was no correlation between the magnitude of movement and the soil type.

RAINFALL

ASSESSMENT OF RECORDED RAINFALL

The rainfall that occurs at the Sewage Treatment Plant is monitored daily and the records for June and up to July 18 in 1986 are summarized on Table 1. As can be seen from Table 1, 24.5 mm of rain was recorded for July 16, 53 mm on July 17, and 3.5 mm on July 18 for a total of 81 mm over the 2.5-day period prior to the July 18 soil cover failure. Furthermore, the rainfall records in Table 1 reveal that a considerable amount of rain had occurred in June and July. The early part of June was dry but from June 11 to July 18 (a total of 38 days), some rain had occurred on 28 days. On 22 days of those days, the rainfall was more than 1 mm, and during nine days of the 28 days, the rainfall was more than 5 mm. The total amount of rain between June 11 to July 18 was 237 mm.

An examination of rainfall records (Environment Canada, 1982) for the 30-year period 1951-1980 revealed that for the Red Deer Airport weather station, the mean monthly rainfall was 84.1 mm and 77.7 mm for June and July, respectively, with the total rainfall for the year of 334.8 mm. The rainfall of 90.2 mm recorded at the Sewage Treatment Plant in June, 1986 is similar to the mean, but the 154.2 mm recorded for the first 18 days of July is twice mean rainfall of 77.7 mm normally recorded for the entire month of July. Furthermore, the maximum rainfall in a 24-hour period in 43 years of record was 85.3 mm and this is approximately similar to the total rainfall of 77.5 mm recorded over a two-day period, July 16 and 17. Also the total rainfall in June and the first 18 days of July was 244 mm which is about 73% of the total 30-year mean annual rainfall of 334.8 m.

Most of the rainfall occurs in five summer months, May to September inclusive. Annual precipitation includes both rain and snow, but only rain is being considered here. It is apparent that both the total amount of rainfall in 1986, especially in July, and the maximum intensity of rainfall prior to the soil cover failure considerably exceeded the normal conditions experienced in the Red Deer area.

Table 1 - Rainfall at the Red Deer Sewage Treatment Plant (1986)

Date	Rainfall (mm)	Date	Rainfall (mm)	Date	Rainfall (mm)
June 1	-	19	12.2	July 1	-
2	-	20	-	2	2.0
3	-	21	-	3	0.6
4	-	22	-	4	8.0
5	-	23	-	5	12.4
6	4.7	24	1.6	6	6.6
7	2.4	25	11.6	7	0.6
8	-	26	0.6	8	2.4
9	-	27	0.6	9	27.4
10	-	28		10	9.5
11	1.0	29	2.6	11	-
12	0.3	30	1.0	12	2.2
13	-			13	-
14	43.0	Total for June	90.2	14	-
15	0.2			15	1.5
16	1.2			16	24.5
17	3.5			17	53.0*
18	3.8			18	3.5**
				Total for July 1-18	154.2

* The rainfall was 44 mm in 8 hours on July 17.

** Failure of soil cover occurred between 16:30 and 19:30 hours, July 18.

INFLUENCE OF RAIN ON SOIL COVER

The soil cover should be essentially saturated prior to commencing drawdown but since the rate of drawdown is not particularly rapid, some drainage could occur, particularly near the top of the slope. After a prolonged rainfall it would appear reasonable to assume that the soil cover became saturated again. This assumption should be examined critically and there are basically two considerations: firstly, was there a sufficient volume of rain to saturate the soil cover; and secondly, did the rainfall extend over a long enough period of time to allow the rain to seep into the soil cover leading to saturation?

The porosity of the compacted sandy silt soil cover is expected to be about 35% and, for a 300-mm-thick layer, about 25 mm of rain would be required to fill the soil pore space if the initial degree of saturation is about 75%. Since the total amount of rain in June and up to July 18 is 244 mm, sufficient rainfall appears to have occurred, even allowing for runoff and evaporation-transpiration.

The second question is related to the time required for rain to seep through the soil cover to saturate the soil, and this matter is related to the permeability of the soil. The sandy silt soil cover is comprised of primarily coarse silt, with some fine sand and a minor amount of clay. The silty soil will have a relatively low permeability and while no laboratory tests are available, it is estimated that the permeability would probably be in the range of 1×10^{-4} cm/s to 1×10^{-5} cm/s.

The time required for rain to seep through the 300-mm-thick soil cover and to saturate the soil will depend on the permeability of the soil and various other factors. To provide some guidance, a simple seepage model was considered to estimate the time required for a drop of rain to seep through the 300-mm soil layer under a gradient of unity. On this basis it would take 3.7 or 37 days to saturate the soil cover for soil permeability values of 1×10^{-4} cm/s and 1×10^{-5} cm/s, respectively. Rainfall occurred almost continuously for 38 days from June 11 until the soil cover failed in July 18. On the basis of the preceding simple analysis, the soil cover probably became saturated during the prolonged rainfall. The actual analysis is considerably more complicated and would need to take into account the degree of initial saturation, and evaporation-transpiration of the vegetated soil cover. Such an attempt may not be very rewarding and possibly only real success will be obtained with actual measurements.

In summary, on the basis of simplifying analyses and parametric evaluation, it is expected that there was enough rain, and that the rain extended over a sufficiently prolonged period to saturate, or nearly saturate the soil cover, with the excess rainfall flowing over the top of the soil surface as runoff.

STABILITY OF SOIL COVER AND POSTULATED FAILURE HYPOTHESIS

On the basis of the examination of the failed soil cover, the duration of the rainy weather preceding the failure and other conditions, the failure of the soil cover is believed to be caused by the hypothesis postulated in the following paragraphs. The general analysis and equations governing the stability of the soil cover is considered first. Then the stability of the soil cover under four different conditions is considered next; namely, a) stability with no pore-water pressure; b) stability under saturated conditions with pore-water pressure, c) stability under the conditions of hydraulic lifting of the soil cover, and d) stability under rapid drawdown conditions. The failure hypothesis is presented next with some earlier reference made during the assessment of the stability of the soil cover. Finally, the results of a limited informal survey of the experience of other similar lagoons with soil covers in Western Canada and Ontario is presented.

GENERAL STABILITY EVALUATION OF SOIL COVER

Initially, the soil cover is stable on the PVC liner due to the frictional sliding resistance between the soil and the PVC liner. The stability of the liner is analyzed in terms of the soil-PVC liner model illustrated on Figure 3. The factor of safety of the imaginary block of soil of unit width on the PVC liner is given by the following familiar equation for an infinite slope.

$$\textit{Factor of Safety} = \frac{\textit{Summation of forces resisting sliding}}{\textit{Summation of forces causing sliding}} \quad \ldots\ldots \quad (1)$$

For a soil cover with no pore-water pressure, but with a cohesion/adhesion value of C,

$$\textit{Factor of Safety} = \frac{N \tan \phi_m + C}{W \sin \alpha} \quad \ldots\ldots\ldots\ldots \quad (2)$$

but N = W cosα, and W = γh, so N = γhcosα, and substituting in Equation (2), we get

$$\textit{Factor of Safety} = \frac{\gamma h \cos\alpha \tan \phi_m' + C}{\gamma h \sin\alpha} \quad \ldots\ldots\ldots\ldots \quad (3)$$

where	γ	=	bulk unit weight of soil
	h	=	height of soil
	α	=	angle of inclination of slope
	ϕ_m'	=	effective angle of shearing resistance between soil and PVC liner
	C	=	cohesion/adhesion of soil to PVC liner

For a soil cover with pore-water pressure at the base of soil, the effective stress at the base of the soil cover provides the frictional sliding resistance, then the effective stress N' is applicable instead of N, and N' = W'cosα, and W' = (γh - $\gamma_w h_w$) so N' = (γh - $\gamma_w h_w$) cosα, and substituting in Equation (2) we get

$$\textit{Factor of Safety} = \frac{(\gamma h - \gamma_w h_w) \cos\alpha \tan \phi_m' + C}{\gamma h \sin \alpha} \quad \ldots\ldots \quad (4)$$

The friction value, ϕ_m' , between the soil cover and the PVC liner has not been determined for this site. Friction values between 25° and 21° have been suggested by Koerner (1990) for a mica schist sand and for a PVC liner with a rough or smooth surface, respectively. The mica schist sand may be closest to the sandy silt soil cover that was in place at the lagoon. An average frictional value of ϕ_m' = 23 degrees was adopted for this study.

STABILITY OF SOIL COVER WITH NO PORE-WATER PRESSURE

The factor of safety against sliding downslope of a moist but unsaturated soil cover with no pore-water pressure and cohesion is considered first. For this condition the term C in

Equation (3) is zero, and for $\phi'_m = 23°$ and $\gamma = 19.6$ kN/m^3, the corresponding factor of safety is about 1.3. The real factor of safety against sliding of the soil cover was probably greater than 1.3 because of two factors.

Firstly, the analysis is based solely on frictional resistance and assumes that no cohesion or adhesion is present between the soil and the PVC liner. However, since the load applied by the 300-mm-thick soil liner is quite small even an extremely small value of adhesion can increase the factor of safety substantially. An adhesion value of 2 kPa increases the factor of safety from about 1.3 to about 2.3. Secondly, there is an extensive grass root system throughout the soil cover. As indicated by the example of a small adhesion, even a little additional strength contributed by the grass root mat structure will increase the factor of safety significantly. Consequently, the soil cover could become very wet, but as long as the soil cover did not become saturated, the factor of safety against sliding was adequate and probably considerably larger than 1.3.

STABILITY OF SATURATED SOIL COVER WITH PORE-WATER PRESSURE

The failure of the soil cover occurred on July 18 following more than five weeks of prolonged rainfall, including a heavy rainfall of 81 mm during the 2.5 days prior to failure. The sandy silt soil cover on the PVC liner has relatively low permeability and saturation probably took considerable time. As soon as the soil became saturated, the groundwater surface in the soil cover coincided with the soil surface. Since the saturated bulk unit weight of the soil is typically twice the unit weight of water, the effective stress of the soil on the PVC liner was reduced to about one half. The corresponding frictional sliding resistance was also reduced about one half with the factor of safety based on the frictional resistance alone being reduced from 1.3 to about 0.65.

Again, the real factor of safety was probably greater than 0.65 because of the beneficial effects of even a small amount of cohesion/adhesion and the strength of the grass root mat structure. Even a small adhesion value of 2 kPa will increase the factor of safety from about 0.65 to about 1.6 so, it is doubtful that failure of the soil cover occurred at the moment of saturation of the soil. However, once saturation has developed, several events occurred, probably quite rapidly, and these events which are described in the following paragraphs, led to the eventual failure.

STABILITY OF SOIL COVER DURING HYDRAULIC LIFTING

Once the soil cover became saturated or nearly saturated, the excess rainfall would runoff along the top surface of the soil cover. Some of the water which penetrated the soil cover would begin to seep downward along the contact between the soil cover and the PVC liner, initially forming a very thin film. Since the volume of water in the film is extremely small, the film probably developed quickly, starting at the bottom of the slope and progressing up the slope quite rapidly. The permeability of the grass root mat at the soil-PVC liner contact was probably larger than the soil alone and this feature aided the development of water film. The pressure in the water film is equal to the hydrostatic pressure corresponding to the top level of the film at any one time. Once the hydrostatic pressure exceeded the weight of the soil cover and adhesion, the soil cover was lifted hydraulically, breaking any cohesion/adhesion bonds to the PVC liner.

After the adhesion bonds were broken and the soil cover was lifted a fraction of a millimetre, the frictional sliding resistance over the lifted portion was reduced to zero. The soil cover was then essentially floating on a very thin film of water and only the fibrous grass root mat structure prevented the soil from sliding downward. As more of the soil cover was lifted hydraulically due to further rainfall seepage, the tensile load on the root mat became substantial and cracks began to appear as the soil cover was stretched.

In terms of the soil model given in Figure 3 and Equation (4), the hydraulic lifting described in the preceding paragraphs occurred when the water pressure beneath the soil cover in any given area equals or exceeds the corresponding saturated bulk unit weight of the soil cover. When this occurs, the effective stress becomes zero and the term $(\gamma h - \gamma_w h_w) = 0$ in Equation (4), and the corresponding factor of safety would become zero if $C = 0$. Failure will not occur, however if the C term includes the strength of the fibrous grass root mat and this strength is sufficient.

As stated above, when the water pressure increases sufficiently so that the effective stress at the bottom of the soil cover is zero, and hydraulic lifting commences, we get

$$(\gamma h - \gamma_w h_w) = 0 \quad \ldots\ldots\ldots\ldots \quad (5)$$

or re-arranging

$$\gamma h = \gamma_w h_w \ldots\ldots\ldots\ldots \quad (6)$$

Since typically γ is about twice the value of γ_w, then Equation (6) can be rewritten as

$$h_w \approx 2h \quad \ldots\ldots\ldots\ldots \quad (7)$$

Equation (7) is applicable for the condition at which effective stress at the contact of soil cover-PVC liner is zero and hydraulic lifting is commencing. As can be seen from Equation (7) hydraulic lifting commences when the head of water is typically about twice the height of soil at any particular location. The head of water to cause hydraulic lifting, however, can be larger than twice the height of soil and will depend on the value of the adhesion bond between the soil and PVC liner.

STABILITY OF SOIL COVER DURING RAPID DRAWDOWN

Often the rapid drawdown case is the most severe stability condition for the upstream slope of a fluid retaining dyke or dam. In this case, it is believed that the prolonged rainfall condition is more severe as will be explained. The sewage lagoons are filled during the winter months and the soil cover in the lagoons will be saturated after months of submergence. The lagoons are drawndown in the spring but since the rate of drawdown at this site is not particularly rapid, some drainage will occur so the limiting case of rapid drawdown may not be fully applicable. Consequently, following drawdown, the factor of safety against sliding will be reduced, and if the soil cover is saturated or nearly saturated, the factor of safety will be less than unity. Even with a reduction in the frictional sliding resistance, failure may be prevented by the presence of a small amount of adhesion or soil tensile strength from the grass root mat. There will probably be a tendency to form a thin film of water at soil cover-PVC contact. In fact a little hydraulic lifting of the lower portion of the soil cover may occur. However, once such heaving occurs, the water film drains into the heaved portion and the hydrostatic pressure decreases considerably.

After drawdown has occurred, drainage of the soil cover commences immediately and conditions improve with time so that the tendency for the water film and hydraulic lifting to develop tend to decrease with time. The prolonged rainfall case is a more severe condition because additional rainfall and seepage tend to increase the hydrostatic pressure and hydraulic lifting, and conditions become worse with time. The only more severe condition would be a prolonged rainfall immediately following rapid drawdown.

FAILURE HYPOTHESIS

The various stages of the stability of the soil cover have been described in the preceding paragraphs. The soil cover with no pore-water pressure was shown to have adequate stability based solely on frictional resistance. The stability based solely on frictional resistance is not adequate under saturated conditions, but even a small adhesion between at the soil cover-PVC liner contact or small tensile strength from the grass root mat is adequate to prevent failure. It has also been shown that under further rainfall, hydraulic lifting of the soil cover could commence, and under these circumstances only the strength of the grass root mat prevents sliding failure of the soil cover. However, at this stage the soil cover is under tensile stress and cracks in the soil cover probably developed.

Rainfall runoff flowing into the cracks suddenly increases the rate and quantity of water penetrating the soil cover in comparison to the considerably smaller amount of water that can penetrate the soil cover by seepage. Lifting of the soil cover can now proceed rapidly, progressing up the slope and spreading laterally. In a relatively short period of time, very large areas of the soil cover along the lower portion of the slope are lifted hydraulically and essentially floating, only held in place by the tensile strength of the soil root mat.

As can be expected, seepage, saturation and hydraulic lifting of the soil cover will proceed at significantly different rates around the sewage lagoon. However, once heaving of some areas of the soil cover begins to occur, the hydrostatic pressure will lift the adjacent areas of the soil cover, even if these areas have not been saturated. Consequently, heaving of the soil cover will proceed rapidly around the lagoon because the volume of water required to lift the soil cover can be quite small and hydrostatic pressure is essentially transmitted instantaneously.

Eventually, the heaving of the soil cover develops sufficiently so when the stress on the soil cover exceeds the tensile strength of the root mat, the soil cover fails in tension and slides down the slope extremely rapidly on a thin film of water. In most cases, the failure extended to the crest of the slope as illustrated on Photographs 1, 2 and 3. This probably occurred because the weakest tensile strength of the soil root mat is at the contact with the gravel road on the crest of the dykes.

One of the most remarkable features of the failure of the soil cover is the rapid speed at which failure occurred. The failure occurred within a 3-hour period and no movement of the soil cover was detected afterwards. The abrupt commencement and stopping of a soil slope failure is considered extremely unusual. The sensitive or "quick" clays in Eastern Canada and in Scandinavian countries fail rapidly, but continuing failure may occur for some time afterwards.

In this case sliding of the soil cover stopped abruptly, and in fact a few large chunks of soil slid part way down the slope and stopped.

The reason for the rapid commencement and stopping of the failure can be explained by the failure mechanism that has been described. Once the hydrostatic lifting of the soil cover commences, it spreads rapidly, both up the slope and also laterally. As mentioned earlier, the lateral spreading occurs even though the entire soil cover is not saturated. Since hydrostatic pressure will probably become essentially uniform around the perimeter of the lagoon, at least for very large areas of the slope, this action brings essentially the entire slope to approximately the same level of tensile stress at the same time.

The tensile strength of the soil cover root mat is probably quite similar along much of the lagoon so when the tensile strength was exceeded at one location, it was exceeded at many other locations at essentially the same time. When a large slab of soil cover began to slide down the slope, the tensile strength of the soil cover assisted in pulling down large areas of the adjacent soil cover on both sides of the initial failure.

As soon as failure commences, the hydrostatic pressure beneath the adjacent areas of the soil cover which had been lifted (but not failed) was relieved immediately and the frictional sliding resistance was mobilized again. In areas where the soil cover was saturated, the factor of safety was about 0.65, but if the tensile strength of the soil root mat was not exceeded, the combined factor of safety was larger than 1.0 and the sliding stopped. In areas where the soil cover was not saturated to the soil surface, the factor of safety due to frictional sliding resistance ranged from about 0.65 to about 1.3. This type of behaviour was exhibited by several large isolated areas of soil cover which stopped sliding partway down the slope. These areas were probably not completely saturated, and once the hydrostatic pressure was released, the factor of safety must have been greater than 1.0 since the sliding stopped.

In summary, the soil cover failed after hydraulic lifting caused by prolonged rainfall. For a while, even with lifting, the soil cover remained in place due to the tensile strength of the soil cover root mat. Eventually, the hydrostatic pressure increased sufficiently and when the tensile strength of the soil root mat was exceeded, sliding failure occurred in a rapid and dramatic manner. The influence and contribution of the various factors associated with the postulated failure hypothesis are examined in the following section as a test of the failure mechanism.

OTHER EXPERIENCE

The rather unusual sliding failure of the soil cover at the sludge lagoon prompted an informal survey in 1986 to assess whether there has been other similar experience. The survey consisted of contacting government agencies in the provinces of Alberta, Saskatchewan, Manitoba and Ontario. These agencies were usually involved in the municipal field in the position of granting licenses for the construction and operation of lagoons.

None of the agencies contacted were aware of a similar type of failure problem occurring in the past. Failures due to wave erosion have occurred but they were not aware of a sliding types of failure of soil covers constructed on geosynthetic membranes. The lagoon depths were similar, ranging from about the same depth to about one-half of the depth of the Red Deer lagoon. The slide slopes were similar and a wide range of soil types had been used as cover material.

It should be noted that the survey was of limited scope, was not formal, and the responses were general, based on memory. It is also possible that similar sliding failures may have occurred in the past, but repairs may have been undertaken and not reported. Nevertheless, it is significant that with a number of ponds with soil-covered geosynthetic membranes in operation, no sliding failures have been reported. Consequently, it is concluded that the sliding failure of the soil cover in Red Deer was possibly an unusual event, probably due to a unique combination of several factors.

ASSESSMENT OF POSTULATED FAILURE HYPOTHESIS

The postulated failure hypothesis that hydraulic lifting of the soil cover led to failure is evaluated to demonstrate that the hypothesis agrees with the known observations and facts as follows:

- The hypothesis requires that the soil cover be saturated or nearly saturated for much of the soil cover. The available information suggests that this would have been the case since the slope was saturated prior to drawdown, and there was sufficient rainfall and time to resaturate the soil cover subsequent to drawdown.

- Failure did not occur upon saturation as would have been the case if the stability of the soil cover on the PVC liner was dependent on frictional sliding resistance only. Consequently, additional resistance was provided by either adhesion or tensile strength of the soil root mat, or both.

- Hydraulic lifting of the soil cover would have destroyed the adhesion over any particular location and failure would have occurred unless the soil cover was held in place by the tensile strength of the soil root mat. If adhesion was the predominant component, then failure would have occurred progressively as the adhesion bonds were broken at various locations. This did not occur.

- The tensile strength of the soil root mat was the predominant factor in maintaining the soil cover on the slope as hydraulic lifting developed. This is the only explanation for the very sudden and dramatic failure that occurred when the tensile strength of the root mat was exceeded.

- The concept of hydraulic lifting of the soil cover and rapid spreading of this condition both up the slope and laterally appears to explain the condition that much of the soil cover on the slope was brought to the same level of stress at about the same time, and that the entire soil cover failure occurred within a short period of time.

- The soil cover must have slid on a film of water to explain the rapid sliding failure.

- The development of the root mat at the soil cover-PVC contact combined with hydraulic lifting appear to satisfactorily explain the extremely clean PVC liner surface that was observed immediately after failure.

- The abrupt and well-defined boundaries of the failed soil cover suggest tensile failure which is consistent with the concept of hydraulic lifting.

- A large portion of the soil cover failure extended to the edge of the gravel road on the crest of the slope. This is consistent with the concept that the tensile strength was a major stabilizing factor since failure occurred where the tensile strength was the weakest.

- The soil cover failure commenced and stopped suddenly and there was no continuing creep movement. In fact, portions of the soil cover became stranded part way down the slope. This behaviour is consistent with the concept of hydraulic lifting since immediately after the hydrostatic pressure is relieved no further movement of the soil cover would occur.

PREVENTION OF HYDRAULIC LIFTING OF SOIL COVER

Prevention of hydraulic lifting of the soil cover can be achieved by constructing a sand blanket between the soil cover and the PVC liner as illustrated in Figure 5. To allow dissipation of seepage water pressure, outlets from the sand blanket are required at the bottom of the lagoon and at one or two more levels. More than one outlet is good design in the event that some outlets are sealed or restricted by clogging with sludge or freezing.

The sand blanket must be sufficiently previous to accommodate the maximum seepage that will penetrate the soil cover, allowing for additional seepage associated with possible development of cracks in the soil cover. The sand blanket must also be pervious enough to drain sufficiently during drawdown of the lagoon. Filling of the lagoon will ensure full submergence of the soil cover and the underlying sand blanket.

One of the disadvantages of using a sand blanket is that there will be no adhesion to the PVC liner. The tensile strength of the grass root mat will still be able to develop. Even without adhesion, it is expected that the soil cover should have adequate stability since the sand blanket will ensure that the contact stress between the sand blanket and the PVC liner will be effective stress allowing the full development of frictional sliding resistance. Also, the tensile strength of the grass root mat will increase the overall soil cover stability.

One alternative to a soil cover is to use a gravelly material with the coarse size large enough to resist wave action. The gravel must also be pervious enough to drain adequately during drawdown, and during intense rainfall. Another alternative is to construct a tapered wedge-shaped soil cover with the thickness increasing from the crest towards the bottom of the lagoon. However, to resist full hydrostatic uplift, the thickness of the soil at any location will need to be about 1/2 the possible hydrostatic head. This would require a thickness of 4.6/2 = 2.3 m of soil at the bottom of the slope for the Cell No. 15 conditions. Actually the thickness can be less, depending on the tensile strength of the grass root mat. However, the strength of the grass root mat is difficult to estimate and may not be constant with time. The use of one or two horizontal sand layers judiciously located will decrease the maximum hydrostatic pressure that can develop, and reduce the maximum soil cover thickness required.

Any of the solutions proposed above will require detailed design for successful implementation and the specific site conditions and operational conditions should also be taken into consideration.

REMEDIAL MEASURES CONSIDERED

Several remedial measures were considered for repairing the failed soil cover for Cell No. 15. The possible remedial measures were limited by the requirement of economic consideration, and the ability to apply the same solution either to the failed sections, or to the entire slope. The remedial measure shown on Figure 6 was one of the solutions considered. The solution consisted of constructing a berm about 2.4-m wide at 2.5 m above the base of the lagoon at a slope of about 4.7H:1V. A fine gravel layer is placed just above the berm level as a separation between the edge of the soil cover and the top of the berm. The gravel layer will allow dissipation of any hydrostatic pressure that could develop beneath the upper soil cover. The berm below the gravel layer is thick enough to withstand any hydrostatic pressure that could develop.

The proposed solution could be constructed relatively easily for the areas where there was complete failure of the soil cover. However, in the areas of intact soil cover, or where there was only minor damage, the field construction forces were concerned about the difficulty of excavating a small wedge of existing soil cover to construct the fine gravel drain without damaging the PVC liner. This consideration coupled with the fact that the actual reconstruction could not commence until late fall, meant that construction of a 300-mm-thick soil cover on the failed portions during possible freezing conditions was not practical and led to another solution. The final solution adopted by the construction staff consisted of constructing a wedge of soil similar to that shown on Figure 6 except that the tapered wedge extended to the crest, and no gravel drain was installed. The reconstruction commenced in October 1986 and was essentially completed at the end of November 1986, with final trimming and grass seeding of the slope in May, 1987. The reconstructed lagoon slopes have performed adequately since completion.

Cell No. 14 located south of Cell No. 15 was initially constructed at the same time and in the same manner. On June 8, 1988, after 47 mm of rainfall, cracks appeared near the crest of the dyke at several locations following drawdown. The amount of drawdown was less than for Cell No. 15 in 1986 and extensive slope failure did not occur. However, it was considered prudent to undertake the same remedial measures as adopted for Cell No. 15. The reconstructed slopes for Cell No. 15 have performed adequately since completion.

SUMMARY AND CONCLUSIONS

The failure of the soil cover on the slopes of the sewage lagoon, Cell No. 15 was sudden, massive and complete. All the available evidence indicates the hydraulic lifting of the soil cover was the reason for the failure. Hydraulic lifting developed after a prolonged 5-week-long rainfall during the summer of 1986 which considerably exceeded the normal rainfall expected in the Red Deer area, both in terms of the amount of rainfall and the intensity over a 2-day period immediately prior to failure.

For the conditions at Cell No. 15, it is believed that the hydraulic lifting condition is more severe than rapid drawdown. It is also possible that failures of other soil covers which have been attributed to drawdown failure, or sloughing in the past may actually be hydraulic lifting.

The grass root mat in the soil cover for Cell No. 15 was believed to have substantial tensile strength. In fact, it was the tensile strength which allowed the development of considerable hydraulic lifting and hydrostatic pressure, and led to the dramatic failure. The tensile strength of root mats may contribute considerably to the stability of shallow zones on other slopes, perhaps more than has been given credit in the past.

ACKNOWLEDGEMENTS

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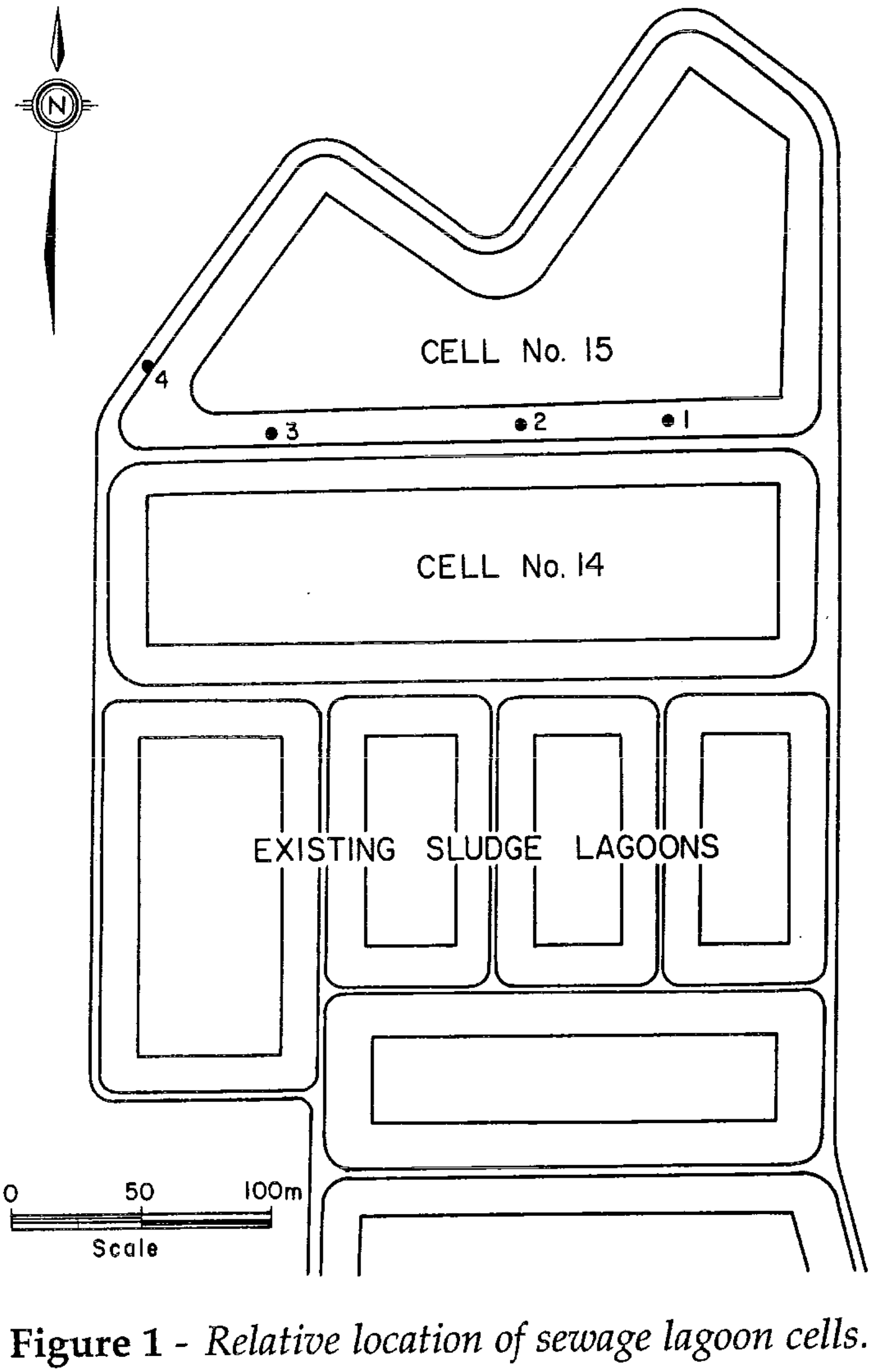


Figure 1 - *Relative location of sewage lagoon cells.*

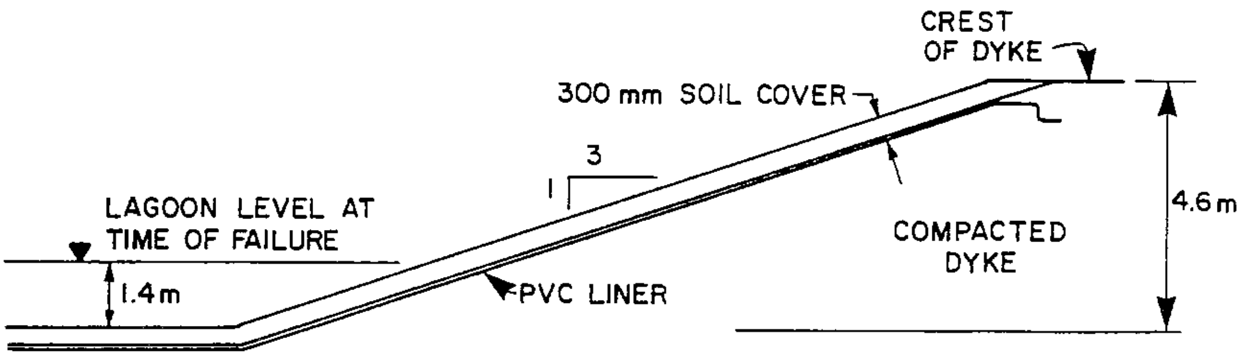


Figure 2 - *Typical section of Cell No. 15 lagoon dyke.*

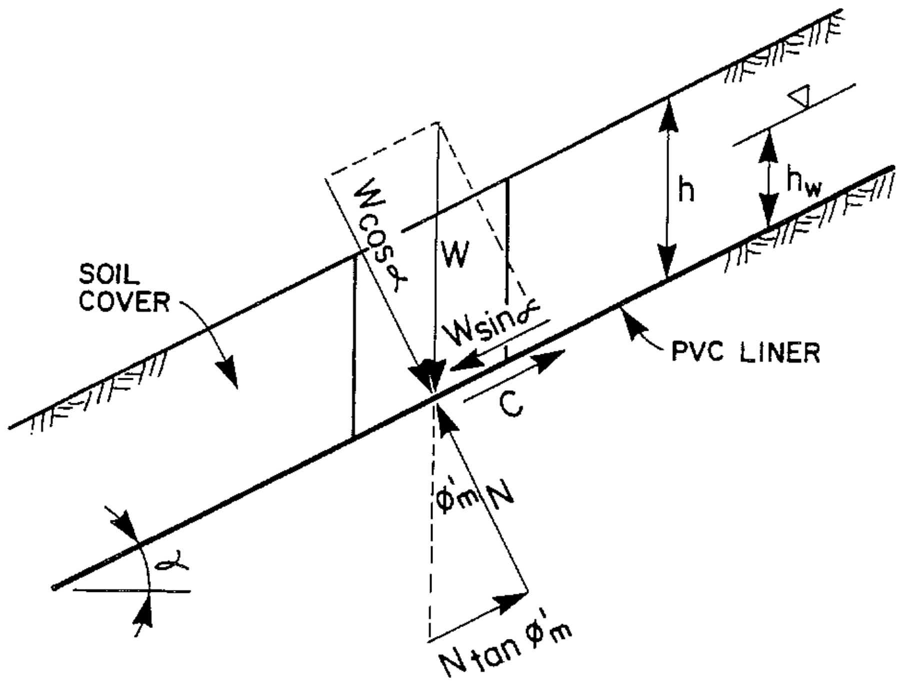


Figure 3 - *Schematic diagram of forces involved in evaluating soil cover stability.*

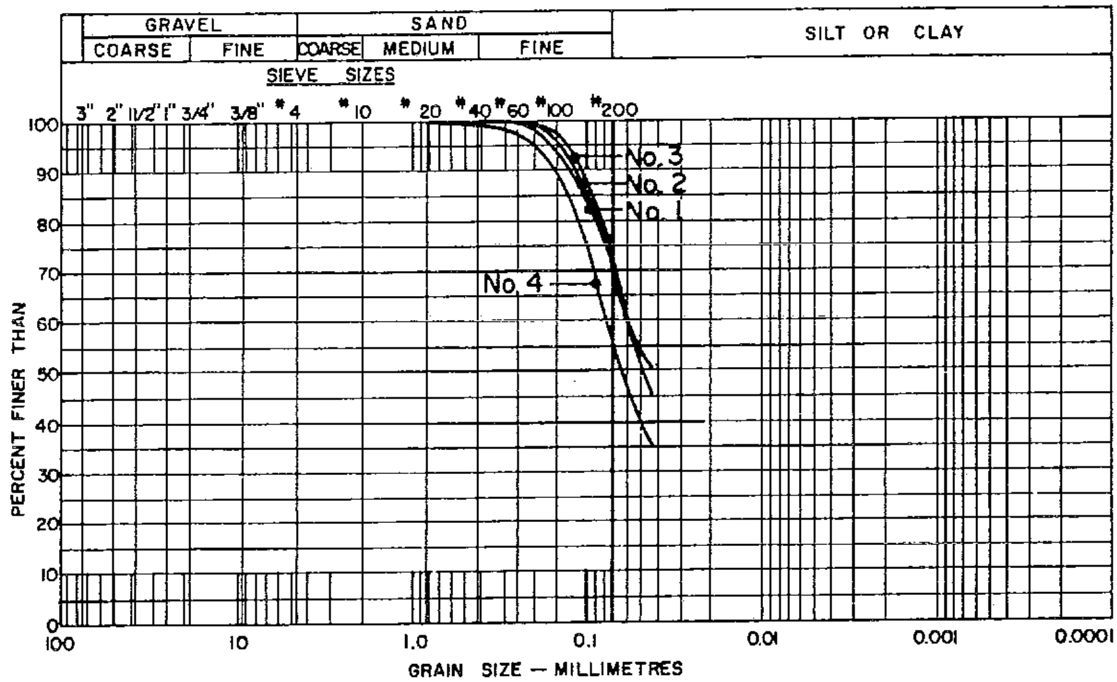


Figure 4 - *Typical grain size analysis of soil cover material.*

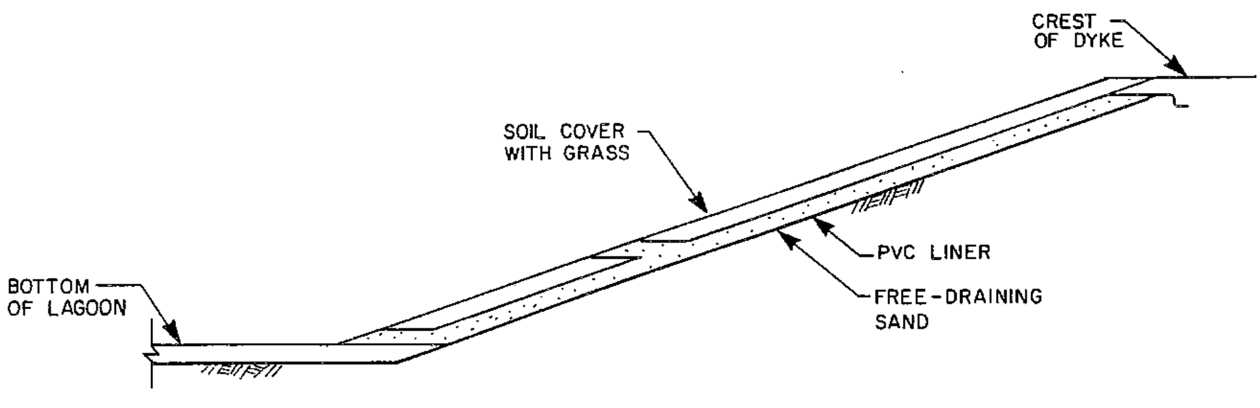


Figure 5 - *Use of sand blanket below soil cover to minimize sliding potential caused by hydraulic lifting.*

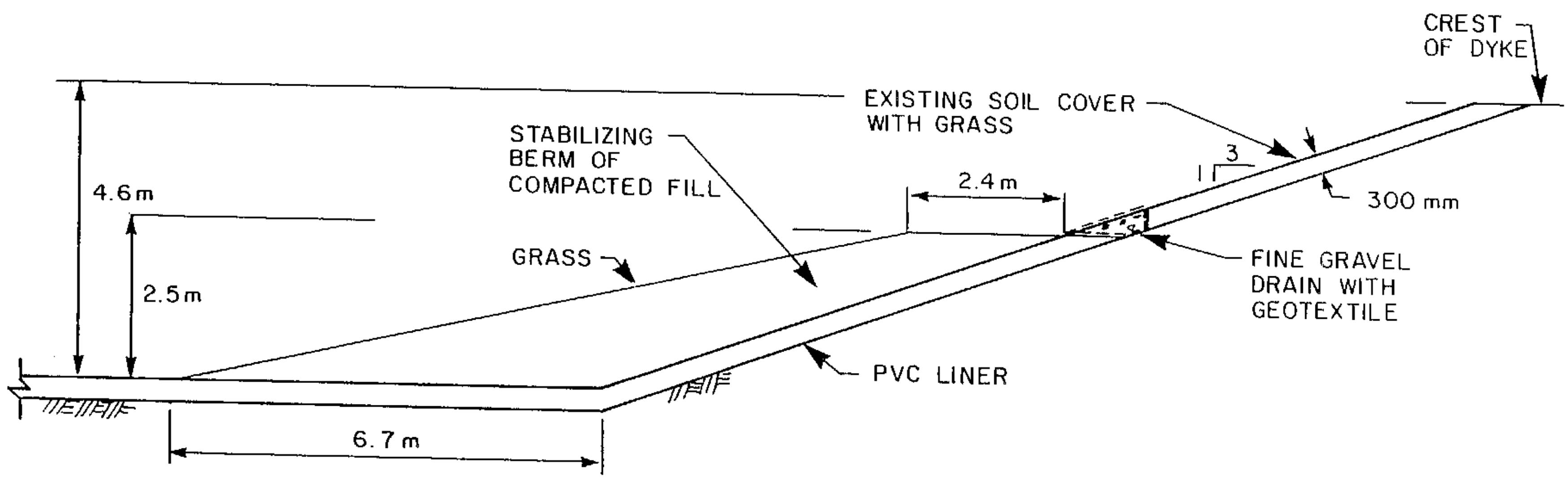
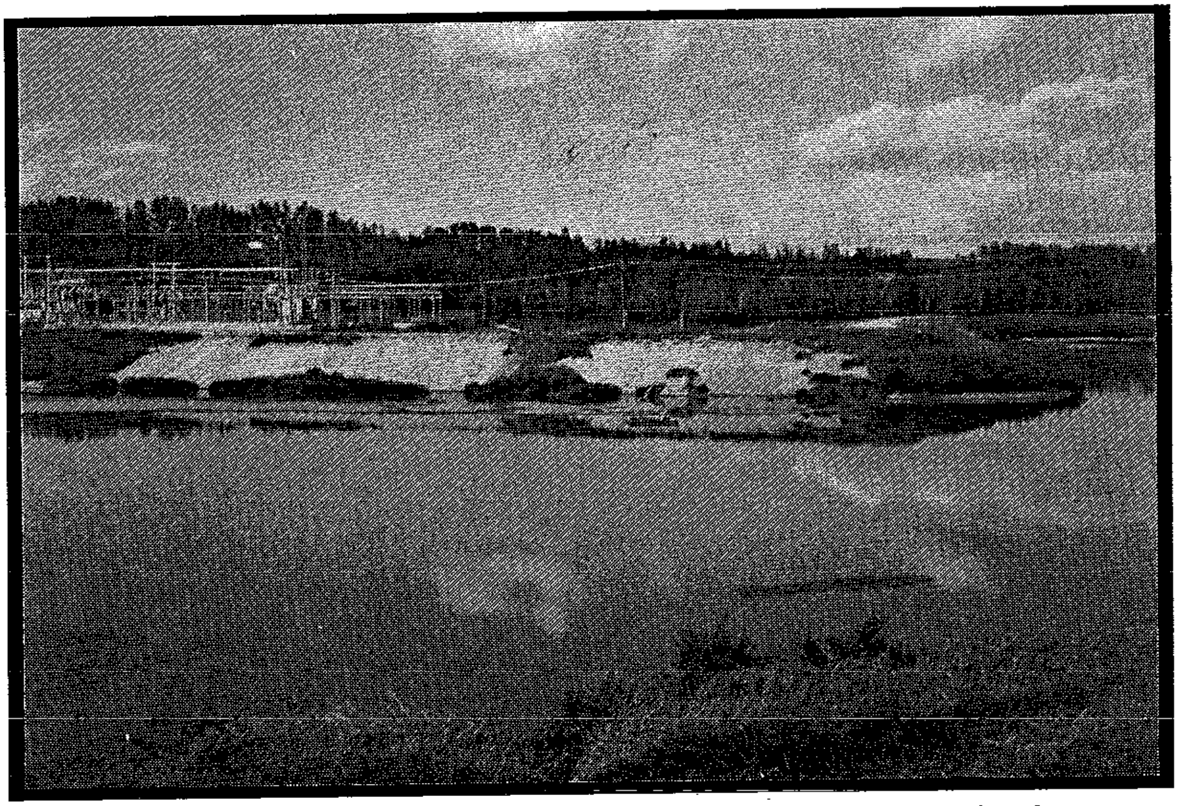
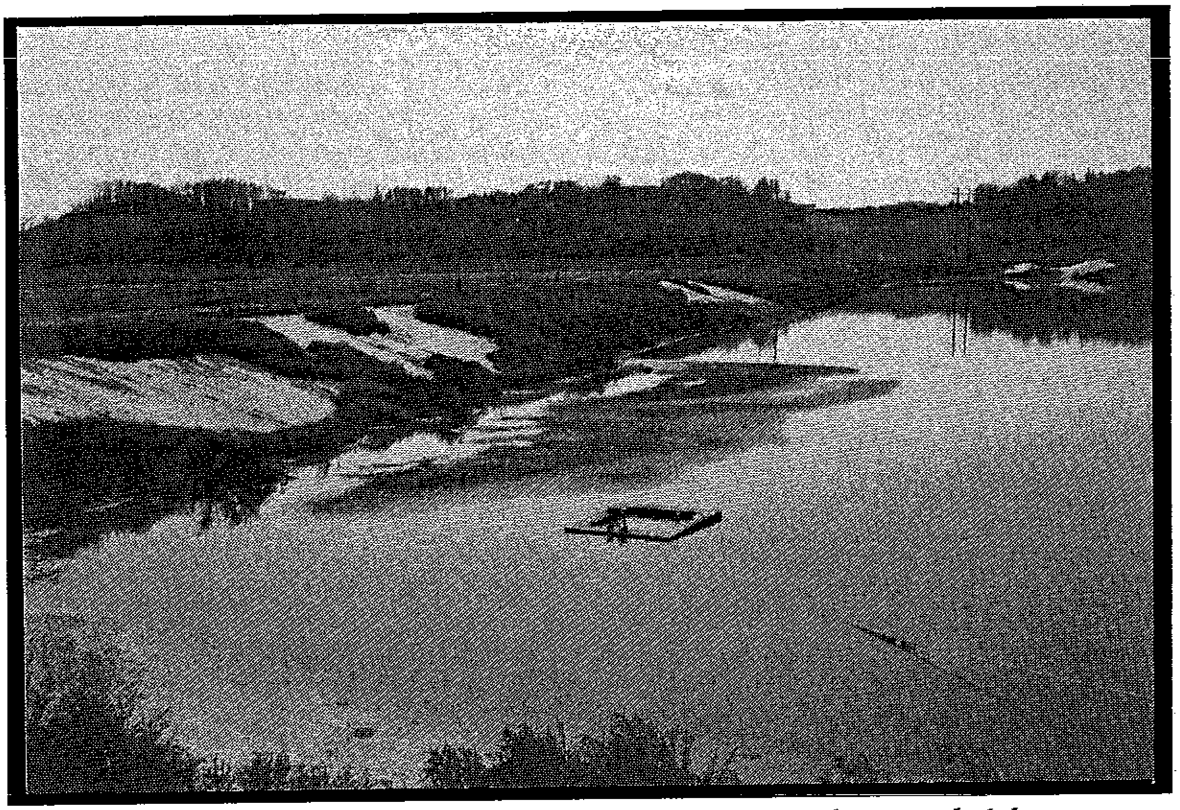


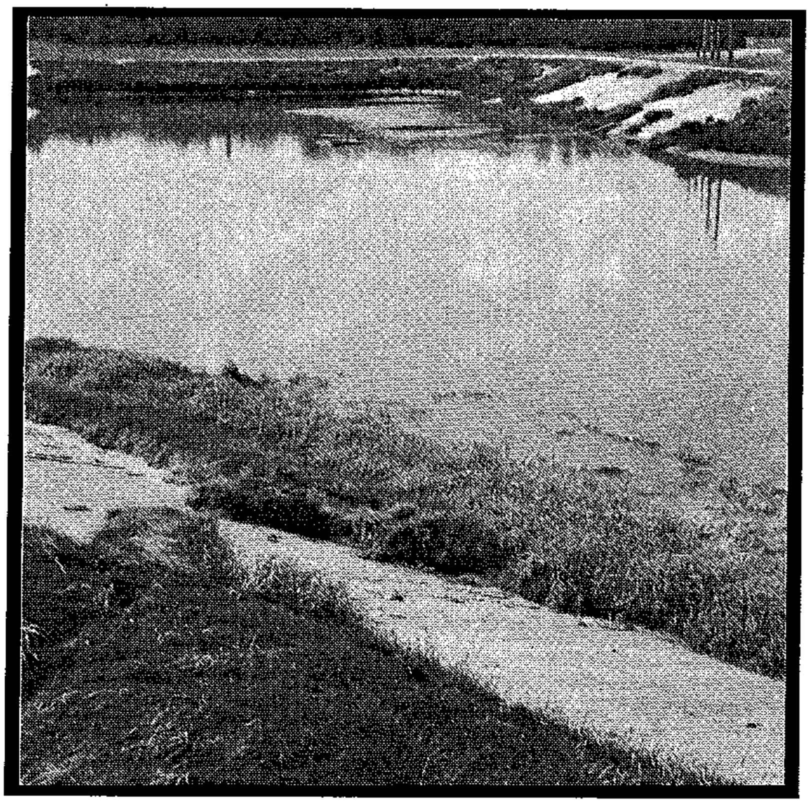
Figure 6 - *Proposed remedial measure for Cell No. 15.*



Photograph 1 - *Failed soil cover. View looking north-east at north dyke.*



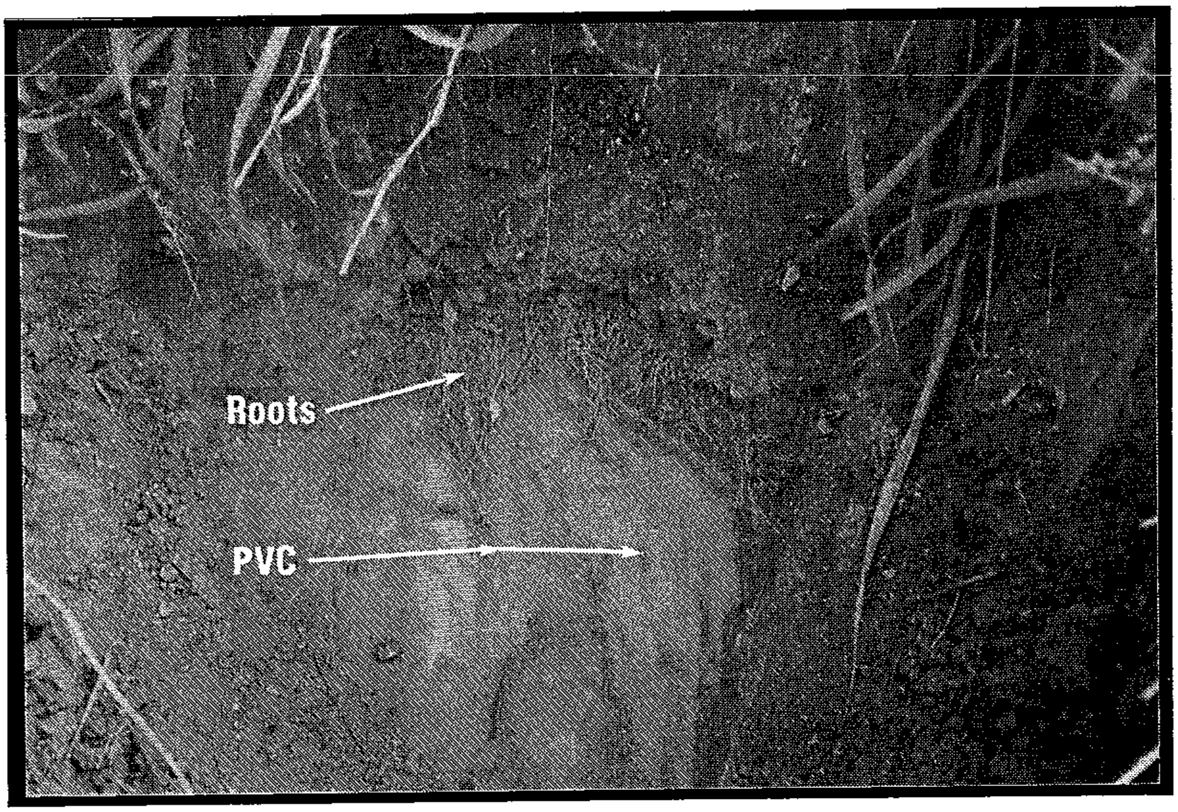
Photograph 2 - *Failed soil cover. View looking west along south dyke.*



Photograph 3 - *Failed soil cover. View looking west.*

Photograph 4 - *Tension cracks in soil cover at dyke crest.*

Photograph 5 - *Close-up view of edge of intact soil cover and exposed PVC liner.*



Photograph 6 - *Close-up view showing matted root structure at soil - PVC contact.*