SOIL INSULATION FOR BARRIER LAYER PROTECTION IN LANDFILL COVERS

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ABSTRACT

Landfill covers are designed to isolate waste from the environment by incorporating low-permeability barrier layers. The barrier layer minimizes and controls gas escaping from the waste and the amount of infiltrating moisture available for leachate generation. Barrier layers are typically designed and constructed of a thick layer of compacted fine-grain native soil material or a manufactured geosynthetic clay liner. The barrier layer must be protected from frost damage. Freezing of a compacted soil layer has been shown to cause quick and irreversible degradation. Large increases in permeability have been demonstrated in compacted clay barriers subjected to a minimum number of freezing and thawing cycles. Design methods to protect the barrier layer from frost damage have not been addressed in the research literature. A design procedure is addressed in this paper that determines the thickness of soil required to protect a barrier layer. The procedure is based on site-specific temperature data and properties of available cover soil.

INTRODUCTION

Barrier layers in cover systems are an integral component of landfill design to prevent exposure of toxic constituents to the environment. Protection of the barrier layer from burrowing animals, wind and water erosion, wet-dry cycles, and freeze-thaw cycles is crucial to the success of the landfill closure (Koerner and Daniel, 1997).

Barrier layers in landfill covers must have low hydraulic conductivities to minimize fluid flow (Daniel, 1987). Compacted soil layers (CSLs), or manufactured geosynthetic clay liners (GCLs), are used to achieve the low saturated hydraulic conductivity (permeability). CSLs attain a low permeability by compacting fine-grain soils wet of their optimum moisture content (Mitchell et al., 1965; Daniel and Benson, 1990). These efforts produce a dispersed soil fabric that is a barrier to fluid movements (Mitchell et al., 1965). Irreversible damage to the barrier layer is caused as compaction moisture freezes by increasing the hydraulic conductivity through formation of cracks, microcracks, and interconnected macropores (Kim and Daniel, 1992; Othman and Benson, 1993; Benson and Othman, 1993; Benson et al., 1995). A CSL barrier must be protected from freezing temperatures at all times because orders of magnitude increases in permeability have been observed during the first three to five freezing cycles (Chamberlain, 1989; Chamberlain and Gow, 1979; Kim and Daniel, 1992; Othman and Benson, 1993).

In contrast, laboratory and field testing of a barrier layer constructed with a GCL did not show an increase in saturated hydraulic conductivity when subjected to freeze-thaw cycles (Hewitt and Daniel, 1998; Kraus et al., 1997). Although GCLs are apparently not susceptible to frost damage, recent case histories and research into the clay chemistry of GCLs indicate that natural processes do cause increases in permeability. An ion-exchange transformation of sodium bentonite to calcium bentonite occurs (Egloffstein, 1997). This transformation can increase the saturated hydraulic conductivity by tenfold within a matter of months (James et al., 1997). GCL exposure to freeze-thaw and wet-dry cycles and to the general environment should be avoided through the addition of a protective layer because these processes compound the ion-exchange transformation (Egloffstein, 1997).

FROST PROTECTION

A layer of insulating soil overlying the barrier layer is suggested for protection. The minimum thickness of the soil should be determined by the depth of frost penetration into the protective layer. Kim and Daniel (1992) have reported that the cost to bury a barrier layer beneath more than 0.6 m (2 ft) of soil may be significant. However, replacement or repair of a frost-damaged cover is expected to have a more significant cost.

Although frost depth penetration can be estimated from large-scale regional maps available in local building codes, design manuals, and guidance publications (e.g., NAVFAC DM–7.1, 1982; Koerner and Daniel, 1997), this method is not recommended. Variations in the physical properties of a soil, such as soil mineralogy, soil bulk density, and water content, may cause frost penetration to vary by a factor of two or more (Brown, 1964). Soil data (e.g., type, density, and moisture condition) are absent in regional predictions. Regional sources typically provide contours of average frost depth that are usually based on historical records of frost effects, such as frozen pipes, and do not necessarily represent site-specific temperature and soil data (Aldrich, 1956).

PREDICTING FROST PENETRATION

Accurate prediction of frost penetration is a complex problem dominated by the intensity and duration of freezing (Mitchell, 1976). A theoretical solution to the problem was presented by Berggren (1943) to calculate freezing depths based on thermal properties and fundamental heat transfer relationships of soils. Another solution independently derived by Aldrich and Paynter (1953) related common soil properties to thermal and heat transfer relationships. This formulation is called the modified Berggren formula (MBF) and is expressed in equation (1):

$$X = \lambda\sqrt{\frac{48kF}{L}} \qquad (1)$$

where

X = depth of frost penetration in meters (feet);

λ = dimensionless coefficient relating volumetric heat capacity, thermal diffusivity, and latent heat of the soil;

k = thermal conductivity of soil, kg $cal^{-1} \cdot m^{-1} \cdot h^{-1} \cdot {}^{\circ}C^{-1}$ ($Btu^{-1} \cdot h^{-1} \cdot ft^{-1} \cdot {}^{\circ}F^{-1}$);

F = surface freeze index, degree-day Celsius (degree-day Fahrenheit); and

L = latent heat of fusion, kg $cal \cdot m^{-3}$ ($Btu \cdot ft^{-3}$).

Aitken and Berg (1968) wrote a digital computer solution solving the MBF to compute frost penetration in a multilayered soil system. This digital solution was converted to a microcomputer format in 1987 by the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (USACE CRREL). A personnel computer (PC) version of this code is available on request from

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PROCEDURE

Five steps based on projected frost depth penetration are used to determine the minimum soil thickness necessary to insulate a barrier layer. A PC-based spreadsheet program is required to manipulate daily meteorological data used in this procedure.

Step 1: Determine Freeze-Index Parameters

The magnitude and duration of freezing periods that govern frost penetration into soil are represented in freeze-index parameters (Mitchell, 1976). A minimum of 20 years of daily temperature data are used to compute freeze-index parameters for a 200-year frost depths recurrence interval. Daily site-specific temperature data are available in electronic format from the National Climatic Data Center in Asheville, North Carolina, and from State climatologists.

The procedure to determine annual freeze-index parameters is obtained from Straub and Wegmann (1965). Freeze-index parameters reflecting the magnitude and duration of annual freezing periods are

- Air freeze index (degree-day Fahrenheit).
- Mean annual temperature (ºF).
- Duration of freeze (number of days).

A degree day is defined as the freezing temperature of water subtracted from the daily mean temperature. The air-freeze index is the number of degree days between the highest and lowest points on the cumulative degree-days time curve for one freezing season. The duration of freeze is the length of time in days that the degree-day is below freezing, as indicated on the cumulative degree-days time curve by a negative slope. The mean annual temperature is obtained from the mean of average daily temperatures.

Step 2: Determine Surface Temperature Correction Factor

Daily temperature data measured 1.5 m above the ground surface are used to determine the air-freeze index (Aldrich, 1956). Ground surface temperatures are greater than the measured air temperatures because they are affected by net solar radiation, conduction, and convective heat transfer (Aldrich, 1956). This condition is accounted for by using a conversion factor N that is defined as the ratio of surface-freeze index to air-freeze index. Based on recommendations from CRREL (U.S. DOE, 1989), a conservative N value of 1.0 should be used for landfill cover designs.

Step 3: Determine Thermal Properties of Soil

Thermal properties needed for the analysis of thermal problems in soils are thermal conductivity, k ,volumetric heat capacity, C, and latent heat of fusion, L (Mitchell, 1976). Thermal conductivity is a function of water content and dry density of the soil; values have been determined for both frozen and unfrozen cohesive and noncohesive soils (Kersten, 1949). Volumetric heat capacity expresses changes in thermal energy per soil volume per change in temperature. This property is derived from the specific heat of ice, water, and soil minerals at temperatures around the freezing point (Mitchell, 1976). Latent heat of fusion expresses changes in thermal energy per unit volume when soil moisture freezes and thaws and depends only on the amount of water in a unit volume of soil (Aldrich, 1956). All required thermal properties of the soil are accounted for in the MBF program by knowing three parameters:

- Soil type, either fine-grain silts and clays or coarse-grain sand and gravels.
- Dry unit weight (pounds per cubic foot).
- Expected gravimetric moisture content during operation (percent).

Step 4: Predict Frost Depths

At the core of the procedure is the MBF program. Soil properties—soil type, dry unit weight, gravimetric moisture content, and the surface-temperature correction factor —remain as constant input throughout the procedure. The 20 freeze-index parameter inputs are varied to predict 20 different frost depths. Knowing these 20 frost depths provides a 20-year record for prediction of future frost penetration. However, extreme value statistics outlined in Step 5 should be used if it is desired to project frost penetration into the protective layer beyond the period of record.

Step 5: Determine Frost Depth at Desired Recurrence Intervals

Resulting frost depth predictions are ranked and Gumbel extreme value statistics are used to project freeze-depth recurrence intervals within a 200-year time frame. Six steps are necessary to make Gumbel extreme value predictions:

1. Rank the compiled list of predicted frost depths in ascending order and compute the plotting position (Ang and Tang, 1975) for each frost depth as

$$P_x = \left(\frac{m}{n + 1} \right) \tag{2}$$

   where
   P_x = plotting position,
   m = ordered sequence of frost depth values, and
   n = number of observations.

2. Compute the recurrence interval T_r for each predicted frost depth as the inverse of the plotting position (Schultz, 1976) with the equation

$$T_r = 1/P_x = \frac{n+1}{m}. \tag{3}$$

3. Plot the frost depth in relation to recurrence interval on Gumbel extreme value probability paper. A best-fit line can be drawn through all data points and the freezing depths to determine a desired recurrence interval. If Gumbel extreme value probability paper is unavailable, data can be plotted on arithmetic graph paper by computing the linearized recurrence intervals, defined as the recurrence interval standard variate. Linearization is performed by equating the Gumbel extreme value distribution formula to the probability of exceedance (Yevjevich, 1982). The Gumbel extreme value distribution is written as

$$P(X \le x) = e^{-e^{-y}} \tag{4}$$

where
$P(X \le x)$ = probability of exceedance,
e = exponent, and
y = standard variate.

The probability of exceedance is also equal to the inverse of the recurrence interval (Schultz, 1976) in the equation

$$P(X \le x) = \frac{1}{1 - T_r}. \tag{5}$$

4. Equations (4) and (5) are equated, rearranged, and the logarithm taken twice to yield a formulation for the standard variate:

$$y = -\ln\left[-\ln\left(1 - \frac{1}{T_r}\right)\right]. \tag{6}$$

5. Compute the standard variate for each data pair using equation (6).

6. Plot the frost depths in relation to the standard variate on arithmetic graph paper. A best-fit line can be drawn through these data or a linear regression can be used to extrapolate or interpolate freezing depths. If a linear regression is performed with these data, it is necessary to plot the data to ensure that extreme data lie on the regressed line, otherwise unrealistic predictions can be made.

DISCUSSION

The 200-year recurrence interval should be used with this procedure to determine the minimum thickness of the protective layer in a landfill cover under long-term closure conditions when active maintenance is not planned. When a landfill is regulated under the Resource Conservation and Recovery Act (RCRA) Subtitle C and Subtitle D, I also recommend that the minimum thickness of a protective layer should be determined by the 200-year frost depth. Conservatism is warranted here because of the high cost to repair a frost-damaged barrier layer. For temporary winter shutdowns where a lesser degree of protection is required, the thickness of the insulating soil layer predicted by the 10- or 20-year recurrence interval should be selected, depending on the degree of risk the designer will accept.

CONCLUSION

This procedure can be used to determine the minimum thickness of soil required to insulate a barrier layer in a site-specific landfill cover from the damaging effects of freeze-thaw cycles. The procedure uses site-specific meteorological data with a codified modified Berggren formula developed by CRREL. Frost penetrations into a soil mass are based on 20 freeze-index parameters and common soil data. Frost depth penetrations are then ranked and used in a Gumbel extreme-value statistical projection to evaluate the probability of exceeding the predicted frost depth for any recurrence interval up to a 200-year recurrence interval.

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