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Expected Cost Effect of Increasing the Size of a Frozen-Ground Waste Containment Project at Ft. Detrick, Maryland

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Expected power-consumption effect of increasing the size of a frozen-ground waste containment project at Ft. Detrick, Maryland

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Introduction

The Baltimore District of the Army Corps of Engineers was considering installing an artificial ground freezing system for waste isolation at a site in Ft. Detrick, Maryland. The size of the proposed water-isolation system had increased. This report presents the cost effect of this change in system size.

Site information

The site had a clay soil. A perched water table was located at 10-15 feet. For purposes of this report, a depth to the perched water table of 4 m (13.21 feet) was assumed. The depth to groundwater was not available but was assumed to be greater than 45 feet. Scenarios in which the perched water table was 2, 4, and 6 m thick were considered. As was conventional, the soil temperature was assumed to be equal to the mean annual temperature, which in Frederick, Maryland, was 12 °C. It was assumed that the soil had a porosity of $0.4 \text{ m}^3 \cdot \text{m}^{-3}$ and that unsaturated soils had a volumetric water content of $0.2 \text{ m}^3 \cdot \text{m}^{-3}$. The pertinent thermal properties used in calculations are presented in Table 1. The coolant temperature was assumed to be $-25 \text{ }^\circ\text{C}$. At this temperature, both saturated and unsaturated soils should contain about $0.015 \text{ m}^3 \cdot \text{m}^{-3}$ liquid water [Grant *et al.*, 1999]. Water's enthalpy of fusion was $337.7 \text{ kJ} \cdot \text{kg}^{-1}$.

Original design

The original design for the frozen-ground waste isolation project was 30 feet (9.144 m) long, 20 feet

(6.096 m) wide, and 10 feet (3.048 m) deep. The two frozen-ground walls along the length of the isolated volume were to be installed at 45° . The two sides would meet at the lengthwise centerline of the project. The end frozen-ground walls would be installed vertically.

Revised design

The revised design would be 50 feet (15.240 m) long, 45 feet (13.716 m) wide, and 45 feet (13.716 m) deep. The installation angle of the freeze pipes along the length of the isolated volume would have to be 63.4° to achieve this geometry.

Length of freeze pipe needed

The length of pipe needed was based on a 0.1-m-diameter pipe, placed at 1-m increments around the perimeter of the system. These increments were smaller than was conventional design practice but were chosen to reduce the time needed to form the barrier [Sanger and Sayles, 1979; Andersland and Ladanyi, 1994].

Original design

The original design would require 18 4.30-m-long, 4 3.048-m-long, 4 3.05-m-long and 4 1.52-m-long pipes. The total length of pipe would be 107.87 m.

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Table 1. Selected thermal properties of system components.

Material	Heat capacity	Thermal conductivity	Density
	$\text{kJ}\cdot^\circ\text{C}^{-1}\cdot\text{kg}^{-1}$	$\text{W}\cdot^\circ\text{C}^{-1}\cdot\text{m}^{-1}$	$\text{Mg}\cdot\text{m}^{-3}$
Clay	0.92	0.9	1.59 ^a
Water	4.2177	0.56	1.0
Ice	2.09	2.21	0.9

^aBulk densitySource: *Alter* [1969].

All of the pipe would be installed in unsaturated soil.

Revised design

The revised design would require 30 15.32-m-long, 4 13.72-m-long, 4 11.76-m-long, 4 9.80-m-long, 4 7.84-m-long, 4 5.88-m-long, 4 3.92-m-long and 4 1.96-m-long pipes. The total length of pipe would be 679.72 m, slightly more than six times the length required in the original design. All except the shortest freeze pipes would be installed in both water-saturated and unsaturated soil. The various total lengths of pipe that would be installed in unsaturated or unsaturated soil are presented in Table 2.

Calculation of thermal properties

Heat capacity

The heat capacities of unfrozen soils were calculated via:

$$c_{vu} = \frac{\rho_d}{\rho_w} (0.17 + 1.0f_w) c_{vw}. \quad (1)$$

The heat capacities of frozen soils were calculated via:

$$c_{vf} = \frac{\rho_d}{\rho_w} [0.17 + 1.0f_u + 0.5(f_w - f_u)] c_{vw} \quad (2)$$

[*Andersland and Ladanyi*, 1994, p. 57]. The calculated heat capacities are presented in Table 3.

Thermal conductivity

The thermal conductivities of the unfrozen and frozen soils were estimated with the protocols presented in *Andersland and Ladanyi* [1994, p. 53-54] The thermal conductivities of the soils were calculated via:

$$k = (k_{\text{sat}} - k_{\text{dry}})K_e + k_{\text{dry}}. \quad (3)$$

For the unfrozen soils the Kersten number was calculated via:

$$K_e = \log S_r + 1.0. \quad (4)$$

This yielded values of 0.7 for the unsaturated soil and 1.0 for the saturated soil. The Kersten number was also 1.0 for the saturated and unsaturated frozen soil. The thermal conductivity of the dry soil was calculated via:

$$k_{\text{dry}} = \frac{0.137\rho_d + 0.0647}{2.7 - 0.947\rho_d} \quad (5)$$

which yielded a value 0.2366 $\text{W}\cdot^\circ\text{C}^{-1}\cdot\text{m}^{-1}$. The thermal conductivity of saturated unfrozen soils was calculated via:

$$k_{\text{sat}} = k_s^{1-n} k_w^n \quad (6)$$

yielding a value of 0.7444 $\text{W}\cdot^\circ\text{C}^{-1}\cdot\text{m}^{-1}$. The thermal conductivity of saturated unfrozen soils was calculated via:

$$k_{\text{sat}} = k_s^{1-n} k_w^{f_u} k_i^{n-f_u} \quad (7)$$

yielding a value of 1.2629 $\text{W}\cdot^\circ\text{C}^{-1}\cdot\text{m}^{-1}$. The calculated thermal conductivities are presented in Table 3.

Table 2. Total lengths of pipe and the lengths in unsaturated and saturated soil under the revised design for three thicknesses of the perched water table

Perched water table thickness (m)	Total pipe length (m)	
	Unsaturated soil	Saturated soil
2	580.20	99.52
4	493.40	186.32
6	405.64	274.08

Table 3. Calculated thermal properties of the saturated and unsaturated soils and the attendant times to freeze and total energy demand.

Soil	$\frac{c_{vu}}{\text{MJ}\cdot\text{C}^{-1}\cdot\text{m}^{-3}}$	$\frac{c_{vf}}{\text{MJ}\cdot\text{C}^{-1}\cdot\text{m}^{-3}}$	$\frac{k_u}{\text{W}\cdot\text{C}^{-1}\cdot\text{m}^{-1}}$	$\frac{k_f}{\text{W}\cdot\text{C}^{-1}\cdot\text{m}^{-1}}$	$\frac{t}{\text{days}}$	$\frac{Q}{\text{MJ}\cdot\text{m}^{-1}}$
Unsat.	2.4813	1.8610	0.9233	1.7361	17.519	202.58
Sat.	3.8225	2.5316	1.7361	1.7361	17.121	252.70

Calculation of time and energy requirements

The time required to form a frozen ground wall was calculated via:

$$t = \frac{R^2 L + \left(\frac{a_r^2 - 1}{2 \ln a_r}\right) c_{uf} \nu_s}{4 k_f \nu_s} \times \left\{ 2 \ln\left(\frac{R}{r_0}\right) - \left[\frac{c_{vf} \nu_s}{L + \left(\frac{a_r^2 - 1}{2 \ln a_r}\right) c_{uf} \nu_s} \right] \right\}. \quad (8)$$

The energy required to form a frozen ground wall was calculated via:

$$Q = \pi R^2 \left(L + \left(\frac{a_r^2 - 1}{2 \ln a_r}\right) c_{uf} \nu_s + \frac{c_{vf} \nu_s}{2 \log\left(\frac{R}{r_0}\right)} \right) \quad (9)$$

[Sanger and Sayles, 1979]. The calculated times and energy requirements are presented in Table 3.

Original design

The original design had a total of 107.87 m of pipe installed in unsaturated soil. Each meter of pipe would withdraw 202.58 MJ for a total of energy requirement of 4,977.5 kilowatt hours. The actual energy consumption would be higher due to, among

other factors, inefficiencies in the refrigeration and brine-distribution systems and pumps needed to circulate the brine.

Revised design

By a similar calculation, the revised design with a 2-m-thick perched aquifer would require 32,501 kilowatt hours of energy. The 4-m-thick and 6-m-thick perched aquifers would require 33,491 and 34,493 kilowatt hours of energy. These are more than six times the energy requirement of the original design.

Concluding remarks

The estimated capital and operating costs of the revised design were roughly 6.4 times the original design. This dramatic increase in costs suggested that the expected benefits of the revised plan should be evaluated to determine if they were commensurate.

Notation

a_r	distance, relative to R , over which the soil was cooled by the freeze pipe, dimension 1
c_{vf}	volumetric heat capacity of a frozen soil, $\text{MJ}\cdot^\circ\text{C}^{-1}\cdot\text{m}^{-3}$
c_{vu}	volumetric heat capacity of an unfrozen soil, $\text{MJ}\cdot^\circ\text{C}^{-1}\cdot\text{m}^{-3}$
c_{vw}	volumetric heat capacity of liquid water, $\text{MJ}\cdot^\circ\text{C}^{-1}\cdot\text{m}^{-3}$
L	$f_u\Delta H_{vw}$, $\text{m}^3\cdot\text{m}^{-3}$
f_u	volumetric fraction of liquid water in the soil, $\text{m}^3\cdot\text{m}^{-3}$
f_w	volumetric fraction of liquid water and ice in the soil, $\text{m}^3\cdot\text{m}^{-3}$
k	thermal conductivity, $\text{W}\cdot^\circ\text{C}^{-1}\cdot\text{m}^{-1}$
k_{dry}	thermal conductivity of a dry soil, $\text{W}\cdot^\circ\text{C}^{-1}\cdot\text{m}^{-1}$
k_f	thermal conductivity of frozen soil, $\text{W}\cdot^\circ\text{C}^{-1}\cdot\text{m}^{-1}$
k_i	thermal conductivity of ice, $\text{W}\cdot^\circ\text{C}^{-1}\cdot\text{m}^{-1}$
k_s	thermal conductivity of clay, $\text{W}\cdot^\circ\text{C}^{-1}\cdot\text{m}^{-1}$
k_{sat}	thermal conductivity of a saturated soil, $\text{W}\cdot^\circ\text{C}^{-1}\cdot\text{m}^{-1}$
k_u	thermal conductivity of unfrozen soil, $\text{W}\cdot^\circ\text{C}^{-1}\cdot\text{m}^{-1}$
k_w	thermal conductivity of water, $\text{W}\cdot^\circ\text{C}^{-1}\cdot\text{m}^{-1}$
K_e	Kersten number, dimension 1
n	porosity, $\text{m}^3\cdot\text{m}^{-3}$
R	one-half the interval between freeze pipes, m
r_0	radius of the freeze pipe, m
n	porosity, $\text{m}^3\cdot\text{m}^{-3}$
Q	energy extracted by freeze pipes, $\text{MJ}\cdot\text{m}^{-1}$
S_r	degree of saturation, $\text{m}^3\cdot\text{m}^{-3}$
t	time required to freeze, s
T_{fp}	freeze pipe temperature, $^\circ\text{C}$
T_{mp}	melting point temperature, $^\circ\text{C}$
T_s	soil temperature, $^\circ\text{C}$
ΔH_{vw}	volumetric enthalpy of fusion for water, $\text{MJ}\cdot\text{m}^{-3}$
ρ_d	bulk density of the soil, $\text{Mg}\cdot\text{m}^{-3}$
ρ_w	density of liquid water, $\text{Mg}\cdot\text{m}^{-3}$
ν_0	$T_s - T_{\text{mp}}$, $^\circ\text{C}$
ν_w	$T_{\text{mp}} - T_{fp}$, $^\circ\text{C}$

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