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**BUOYANT MOVEMENT OF NUCLEAR WASTE CANISTERS
IN MARINE SEDIMENTS**

Paul R. Dawson

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BUOYANT MOVEMENT OF NUCLEAR WASTE CANISTERS
IN MARINE SEDIMENTS

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ABSTRACT

Coupled creep and heat transfer calculations have been performed to assess the potential for large movements of waste canisters buried in marine sediments. Results using a creep constitutive model established from data reported in published literature indicate that, although upward movement is predicted, the effective deviatoric stress levels are sufficiently low that creep rates would eventually diminish to zero.

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I. INTRODUCTION

The movement of nuclear waste canisters emplaced in ocean sediments due to long term sediment creep deformations has been postulated as a possible mechanism for breaching the isolation of the wastes if stored in the seabed. Density differences, that result from heating of the sediment as the wastes decay, produce buoyant forces within the heated sediment and suggest that convective cells capable of transporting canisters upward could be formed. Thermomechanical analyses that include both creep deformations of the sediment and heat transfer within the canister-sediment system have been performed to evaluate the possible magnitude of this movement and to assess the stress levels the buoyant forces produce.

II. SUMMARY

The thermomechanical response of the canister-sediment system has been analyzed using a temperature dependent secondary creep law for the sediment based on reported creep data for saturated clays. The thermal response indicated that a peak temperature rise of 300 K was reached at the canister-sediment interface after approximately 4 years. Points in the sediment at distances farther from the canister experienced a lower peak temperature at a later time. The increased temperatures of the sediment in the vicinity of the canister produced buoyant forces on the sediment that pushed the sediments and canister upward. The peak canister velocity occurred after approximately 15 years. Effective stresses in the sediment of less than 1 kPa indicated that, if marine sediments behave in a similar manner to other saturated clays, the creep rates would diminish to zero and canister movement would cease.

III. ANALYTICAL MODELING

The response on the sediment-canister system has been analyzed using the finite element computer code COUPLEFLO [1]. COUPLEFLO is based on formulations for creeping viscoplastic flow and conductive-convective heat transfer. The viscoplastic flow and heat transfer formulations are coupled to provide the thermomechanical history of the system. Coupling between the viscoplastic flow and heat transfer exists in terms of temperature dependent material properties and body forces, changing geometry, and viscous dissipation.

The viscoplastic flow formulation is based on Lamb's variational principle. The Euler equations resulting from this variational principle, including an added incompressibility constraint, are summarized as follows:

$$\text{Equilibrium:} \quad \frac{\partial \sigma_{ij}}{\partial x_j} + X_i = 0 \quad (1)$$

Strain-rate velocity:

$$\dot{\epsilon}_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (2)$$

$$\text{Incompressibility:} \quad \dot{\epsilon}_{ii} = 0 \quad (3)$$

Boundary conditions:

$$u_i = \bar{u}_i \text{ on } S_u \quad (4)$$

$$\sigma_{ij} n_j = \bar{T}_i \text{ on } S_T \quad (5)$$

where

σ_{ij} = the stress tensor

X_i = the body force vector

$\dot{\epsilon}_{ij}$ = the strain rate tensor

u_i = the velocity

$\bar{u}_i$ = an imposed velocity on S_u

$\bar{T}_i$ = an imposed traction vector on surface S_T

v_i = the unit normal vector to S_T

the body forces, X_i , are dependent on the temperature and can be represented as

$$X_i = \rho g_i (1 - \alpha(\theta - \theta_{\text{ref}})) \quad (6)$$

where

ρ = the density

g_i = the gravitational vector

α = the expansivity

θ = the temperature

θ_{ref} = the reference temperature.

The constitutive model used to characterize the creep behavior of the sediments is a relationship between the deviatoric stresses and strain-rates. To incorporate thermally activated behavior, [2], temperature dependent material properties have been included in the model. This model can be written as

$$\sigma'_{II} = C_1 e^{C_2/\theta} \dot{\epsilon}_{II} \quad (7)$$

where

σ'_{II} = the effective deviatoric stress

$\dot{\epsilon}_{II}$ = the effective strain-rate

C_1 and C_2 = constants determined from creep data (discussed in the next section).

Several assumptions are incorporated in this formulation. One is that inertia terms have been neglected in the equilibrium equations. A second assumption is that strain increments resulting from the creep of sediment are much larger than elastic strain increments. The third assumption is that changes in density resulting from thermal expansion affect only the body forces in the equilibrium equations. The density changes are assumed to have negligible effect on the continuity and energy equations. The fourth assumption made is that pore water within the sediment skeleton has adequate time to drain so that excess pore-pressures do not occur.

The energy of the system is modeled using a formulation for conductive-convective heat transfer. The governing equations for heat transfer are as follows:

$$\text{Energy:} \quad \frac{\partial}{\partial x_1} \left(k \frac{\partial \theta}{\partial x_1} \right) - \rho C_p u_1 \frac{\partial \theta}{\partial x_1} + Q = \rho C_p \dot{\epsilon} \quad (8)$$

Boundary conditions:

$$\theta = \bar{\theta} \text{ on } S_\theta \quad (9)$$

$$\bar{q} = \left(k \frac{\partial \theta}{\partial x_1} - \rho C_p u_1 \theta \right) u_1 \text{ on } S_q \quad (10)$$

$$\text{Initial conditions:} \quad \theta(x_1, 0) = \bar{\theta}(x_1) \quad (11)$$

where

k = the conductivity

C_p = the specific heat

Q = the heat generation rate

$\bar{q}$ = the surface heat flux on S_q

$\bar{T}$ = the imposed temperature on S_0

u_1 = the unit normal vector to S_q

An incremental solution procedure has been used to follow the histories of the coupled heat transfer and creep deformations. The analyses begin by determining the velocity distribution using the equations governing viscoplastic flow with the material properties and body forces based on sediment at ambient conditions (i.e., ambient temperature and hydrostatic stress state determined by overburden load). The temperature distribution corresponding to the end of the first time step is then determined by solving the energy equation using a Crank-Nicholson finite difference algorithm in the time domain. The system geometry is then advanced to its new position corresponding to the end of the time step through Euler integration of the velocity field. Subsequent movement of the sediment-canister system is evaluated by continuing to incrementally step the solution ahead in time and using the velocities and temperatures at the end of one time step as initial conditions for the next step.

Details of the finite element formulations for viscoplastic flow and heat transfer are available in Ref. [1]. The transient coupling procedure is also discussed.

IV. CREEP BEHAVIOR OF SEDIMENTS

Experiments to evaluate the creep behavior of ocean sediments typical of study site sediments for the Seabed Disposal Project have not yet been performed as part of the project. In order to proceed with the preliminary assessment of thermally induced buoyant motion of sediments near a waste canister, data reported in the literature for the creep behavior of saturated clays has been used to model the sediments. The clays are not the same as ocean sediments and will not have creep properties identical to the sediments. However, examination of reported data enables a range of creep rates to be established that are representative of relatively high creep rates to relatively low creep rates. From this range of values a creep law representing intermediate creep rates was selected and used in the analyses.

Bishop [2] has reported creep measurements of London clay and Pisa clay. Tests were performed at 20°C and extended to over 600 days in duration. Bishop observed that, although there were no stress levels below which creep did not occur, at stress levels below approximately 30% of the initial yield strength creep rates continually diminished as tests proceeded. Using the lowest applied stresses reported by Bishop and the creep rates existing at the end of the experiments for these stress levels, equivalent viscosities were computed as

$$\dot{\epsilon}_{II} = \frac{\sigma'_{II}}{\eta_{II}} = C_1 e^{C_2/\dot{\epsilon}_{II}} \quad (12)$$

where

μ = the viscosity (see Appendix A)

Akai et al. [3] have published creep data on Fukuskusa Clay. The stress levels reported are higher than the shear strengths reported for marine sediments. Tests were conducted for periods generally less than 1000 minutes. The equivalent viscosity computed using their data was lower than the viscosity computed from Bishop's data. Since the stress levels reported by Bishop are more appropriate to the buoyancy calculations, the viscosities computed from Bishop's data were judged to be more applicable.

Singh and Mitchell [4] have reported the creep behavior of several types of clay, including San Francisco Bay mud, illite, and Osaka alluvial clay. Mitchell et al. report that a state of secondary creep is never reached in the tests performed. Further, they indicate that a secondary creep approximation yields good results only for long times after loading. However, even after long times following initial loading, the creep rates are not constant, but rather are increasing for high stress levels and are decreasing for low stress levels. Data taken from Mitchell's (et al.) work is also shown in Appendix A with the computed viscosities.

Mitchell and others [5] have investigated the effect of temperature on creep rates. Investigations were performed to determine if creep deformations are thermally activated processes. Their work shows a linear dependence between $\ln \left(\frac{k}{\theta} \right)$ and $\frac{1}{\theta}$. The proportionality constants for different saturated clays were taken from the paper and used to evaluate the functional relationship between creep rate and temperature for a fixed stress level (i.e., the coefficients C_1 and C_2 in Equation (7) were evaluated). (See Appendix A.)

The equivalent viscosities computed from published data ranged from 2×10^8 Pa.s for short duration tests at high stress levels to 1×10^{13} Pa.s for longer duration tests at low stress levels. The lower stress values are more appropriate to the buoyancy analyses reported here. A value of 1×10^{12} Pa.s was selected the viscosity at 300 K. Using the relationship reported by Bishop between $\ln \left(\frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right)$ and $\frac{1}{\theta}$ a constitutive model was constructed. The viscosity as a function of temperature is shown in Figure 1.

V. CANISTER-SEDIMENT MODEL

An axisymmetric region extending from the sediment surface to 100 meters below the surface and from the canister centerline radially outward 100 meters has been analyzed (Figure 2). The canister has an 0.5 m radius and 3 m length and was initially buried at an average depth of 30 m. The use of triangular elements in the axisymmetric model gives the canister a double cone shape with a volume of 0.785 m^3 . A three meter long cylindrical canister with an equivalent volume has a radius of 0.288 m. The finite element mesh consisting of 192 isoparametric elements is shown in Figure 3.

The region is assumed to consist of sediment that is isotropic, homogeneous, and fully saturated. Further, the initial stress state corresponds to the hydrostatic stress resulting from the weight of the overburden material. Disturbances in the sediment from canister emplacement are neglected.

The sediment is assumed to be initially at 280 K. The sediment-water interface remains at this temperature throughout the analyses. The lower boundary and the boundary at a radius of 100 m are assumed to be adiabatic. The power of the canister is initially 3.5 kW and decays with a thirty year half-life.

The sediment is assumed to remain in contact with the canister surface and not to slip relative to the canister surface. The sediment upper surface is assumed to be free of traction vectors while no motion normal to the boundary is imposed on the remaining boundaries.

Sediment thermal properties, such as conductivity and heat capacity, are listed in Table 1. Approximate values of these properties are also

given for the canister. The sediment properties were obtained from W. Schimmel (1262).

The effect of imposing outside radius boundary conditions (i.e., zero radial flow and zero radial heat flux) on the flow field and temperature distribution were not investigated. During the 25 years of the analyses, temperature rises near the boundary were insignificant. Further, with the ratio of canister radius to region radius of 1/200, the sediment velocity at the region outside radius was approximately 1/100 of the canister velocity.

VI. BUOYANT MOVEMENT PREDICTIONS

The thermomechanical response of the canister-sediment system has been analyzed for a period of approximately twenty-five years following emplacement. The velocity and displacement histories of the canister are shown in Figures 4 and 5. Initially the canister begins to sink. As heating of the sediment around the canister proceeds (Figure 6), the sediment expands and becomes buoyant relative to surrounding sediments. The heated sediments then begin to rise and drag the canister upward. The velocity history shown in Figure 4 for the canister indicates that the velocity increases at an increasing rate for times less than 5 years. Between approximately 5 and 15 years after emplacement the canister velocity increases at a decreasing rate. After 15 years the canister velocity decreases. The peak velocity of the canister occurs at approximately 15 years after emplacement. The peak temperature at the canister-sediment interface, however, peaks at the much earlier time of between 3 and 4 years. This apparent lag in the mechanical response relative to the thermal response results from the buoyant motion of the sediment depending on the spatial distribution of energy rather than solely peak temperatures. That is, movement of sediment due to buoyancy depends both on the amount of sediment that has experienced a temperature rise as well as the thermal gradients within the sediment.

The velocity of the canister as indicated in Figure 4 has been integrated to give the displacement history in Figure 5. For times beyond 15 years the displacement curve has a monotonically decreasing slope, as is evident from the decrease in velocity shown in Figure 4. As seen from the discussion in the next paragraphs, these displacements cannot be extrapolated to longer periods of time.

In establishing a constitutive model for the sediment, the assumption was made that the effective deviatoric stress levels would be low relative to the initial yield strength. Creep data reported in the literature for low stress levels was weighted more heavily in evaluating an effective viscosity for the sediment. To verify that the use of a constitutive model based on low stress levels was appropriate in the canister motion analyses, the predicted strain-rates and effective deviatoric stresses have been examined. The strain-rates and deviatoric stresses for four points at various distances away from the canister centerline (on a line running horizontally through the canister midheight) have been plotted in Figures 8 and 9 with the corresponding temperatures for these points shown in Figure 7. The temperature of points nearer the canister climb fastest and begin to decay the earliest. At approximately 3 m from the canister the maximum temperature rises approximately 93 K after approximately 8 years. At greater distances from the source the maximum temperature rise is less and occurs at later times.

The strain-rates for the four points, as shown in Figure 8, increase with time as the region heats and the buoyant forces increase. The highest strain-rates occur in the vicinity of the canister. The effective deviatoric stresses, however, demonstrate a quite different behavior. At a radius of 3.094 m, the effective deviatoric stress diminishes quite rapidly as the temperature rises and the effective viscosity decreases. At large radii ($r = 10.719$ or 17.5 m) the temperature rise is much less ($\Delta\theta \leq 10$ K) and the effective deviatoric stresses roughly in proportion to the strain-rates (viscosity remaining relatively constant). However, at the radius of 7.031 m the effective deviatoric stresses increase proportionally to the strain-rates only until significant heating begins after 2 to 3 years.

The stresses then level off as the decrease in viscosity with increased temperature is offset by the increase in buoyancy of the heated region. Stresses begin to increase for radii of 3.094 m and 7.031 m as the temperature rise begins to decay and the viscosity increases.

The magnitude of the stresses indicated in Figure 9 for the four points in the sediment are less than 1 KPa. Thus, the assumption that low stress differences relative to the yield stress (20 KPa) is valid. From the previously discussed experimental observations, creep rates eventually diminish to zero for stress differences in this low regime. This implies that the effective viscosity would increase with time instead of the constant relationship used in these analyses and that motion of the canister would be expected to cease.

VII. CONCLUSIONS

Coupled secondary creep and heat transfer analyses have been performed to predict the possible motion of canisters containing nuclear wastes buried in the seabed. The analyses indicate upward movement of the canister could result from buoyancy induced by the heat producing wastes. However, the small magnitude of the resulting stress differences suggests that creep rates would diminish with time and movement would cease. The need for creep data for sediment specimens characteristic of disposal study sites over the range of possible temperatures is required to more accurately assess the magnitude of the movement.

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TABLE 1

Sediment Thermal Properties*

Conductivity: $k = .8 \frac{\text{Watt}}{\text{M K}}$

Heat Capacity: $C_p = 3400 = \frac{\text{Joule}}{\text{kg K}}$

Density: $\rho = 1880 \text{ kg/m}^3$

Expansivity: $\alpha = .255 \times 10^{-3} \text{ 1/K}$

Canister Thermal Properties

Conductivity: $k = 5.0 \frac{\text{Watt}}{\text{M K}}$

Heat Capacity: $C_p = 500 \frac{\text{Joule}}{\text{kg K}}$

Density: $\rho = 3500 \text{ kg/m}^3$

Expansivity: $\alpha = 0$

* Source: W. Schimmel - 1262

Figure 1. Sediment Effective Viscosity

Figure 2. Axisymmetric Sediment-Canister Model

Figure 3. Finite Element Mesh

Figure 4. Thermally Induced Canister Movement In Ocean Sediments--
Velocity History

Figure 5. Thermally Induced Canister Movement In Ocean Sediments--
Displacement History

Figure 6. Thermally Induced Canister Movement In Ocean Sediments--
Thermal History

Figure 7. Thermally Induced Canister Movement In Ocean Sediments--
Sediment Thermal Response

Figure 8. Thermally Induced Canister Movement In Ocean Sediments--
Effective Strain-Rates

Figure 9. Thermally Induced Canister Movement In Ocean Sediments--
Effective Stress Levels

APPENDIX A. CREEP RATE DATA AND CONSTITUTIVE MODELS

Bishop [2]

London Clay

Temperature = 20°C

Applied Stress: $\sigma_1 - \sigma_3 = .334 \times 10^5 \text{ Pa}$

$$\sigma_{II} = .579 \times 10^5 \text{ Pa}$$

$$\epsilon_{II} = \sqrt{3} \epsilon_1$$

Creep Rates: $\dot{\epsilon}_1 = 10^{-3}/\text{day} = 1.16 \times 10^{-8} \text{ 1/sec after 100 days}$

$$\dot{\epsilon}_1 = 10^{-4}/\text{day} = 1.16 \times 10^{-9} \text{ 1/sec after 603 days}$$

Viscosity: $\mu = \frac{\sigma_{II}}{3\dot{\epsilon}_{II}} = 9.6 \times 10^{11} \text{ Pa-sec (100 days)}$

$$\mu = 9.6 \times 10^{12} \text{ Pa-sec (603 days)}$$

Pisa Clay

Temperature = 20°C

Applied Stress: $\sigma_1 - \sigma_3 = .966 \times 10^5 \text{ Pa}$

Creep Rate: $\dot{\epsilon}_1 = 10^{-3}/\text{day at 300 days}$

Viscosity: $\mu = 2.7 \times 10^{12} \text{ Pa-sec}$

Aka1, Adachi, and Ando [3]

Fukakusa Clay

Applied Stress: $\sigma_1 - \sigma_3 = 1.37 \times 10^5 \text{ Pa}$

Creep Rate: $\dot{\epsilon}_1 = 1.82 \times 10^{-4}/\text{sec}$

Viscosity: $\mu = 2.5 \times 10^8 \text{ Pa-sec}$

Mitchell [4]

San Francisco Bay Mud

Applied Stress: $\sigma_1 - \sigma_3 = .412 \times 10^5 \text{ Pa}$

Creep Rate: $\epsilon_1 = 1 \times 10^{-3} \text{ 1/min}$

Viscosity: $\mu = 2.4 \times 10^9 \text{ Pa-sec}$

Illite

Applied Stress: $\sigma_1 - \sigma_3 = 4.9 \times 10^5 \text{ Pa}$

Creep Rate: $\epsilon_1 = 1.67 \times 10^{-6} \text{ 1/sec}$

Viscosity: $\mu = 2.94 \times 10^{11} \text{ Pa-sec}$

Osaka Alluvial Clay

Applied Stress: $5.29 \times 10^4 \text{ Pa}$

Creep Rate: $1.67 \times 10^{-7} \text{ 1/sec}$

Viscosity: $3.17 \times 10^{10} \text{ Pa-sec}$

Mitchell [5]

From Figure 8: $\frac{\partial(\ln \frac{\epsilon}{\theta})}{\partial(\ln \frac{1}{\theta})} = -15.85 \times 10^3$

$$\ln\left(\frac{\epsilon}{\theta}\right) = -15.85 \times 10^3 \left(\frac{1}{\theta}\right) + K_1$$

$$\ln\left(\frac{\epsilon_1}{\theta_1}\right) - \ln\left(\frac{\epsilon_2}{\theta_2}\right) = -15.85 \times 10^3 \left(\frac{1}{\theta_1} - \frac{1}{\theta_2}\right)$$

Choose

$$\theta_2 = 373 \text{ K}$$

$$\theta_1 = 293 \text{ K and } \epsilon_1 = 6 \times 10^{-7} \text{ 1/min}$$

then

$$\epsilon_2 = 1.4 \times 10^{-3} \text{ 1/sec}$$

$$\mu = 2.14 \times 10^7 \text{ Pa-sec at 373 K}$$

$$\mu = c_1 e^{c_2/\theta} \text{ (Thermally Activated Model)}$$

$$\mu = 1.69 \times 10^{-10} e^{\frac{146886}{\theta}}$$

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