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SEDIMENT MECHANICAL RESPONSE DUE TO EMPLACEMENT OF A WASTE CANISTER*

MASTER

C. H. Karnes, P. R. Dawson,** A. J. Silva[†] and W. T. Brown

Sandia National Laboratories[‡]
 P. O. Box 5800
 Albuquerque, New Mexico 87185

ABSTRACT

Preliminary studies have been conducted to determine the interaction between a waste canister and seabed sediment during and after emplacement. Empirical and approximate methods for determining the depth reached by a freefall penetrator indicate that a boosted penetrator emplacement method may be necessary. Hole closure is necessary, but has not been verified because calculations and laboratory experiments show sensitivity to boundary conditions which control the degree of dynamic hole closure. Laboratory studies show that closure will take place by creep deformation but closure times in seabed environments are uncertain. For assumed thermomechanical properties of sediments, it is shown that a heat generating waste canister will probably not move a significant distance during the heat generation period.

I. INTRODUCTION

The concept of subseabed disposal of radioactive wastes requires that waste-containing canisters be buried within certain sediments of the deep ocean. The objective of long-term waste isolation might be met if canisters can be emplaced with the assurance that sediment having properties essentially the same as the undisturbed materials fills a substantial portion of the emplacement-affected zone. It is not sufficient to simply bury canisters in sediment which allows ion migration paths having significantly shorter retention times than the natural sediment barrier.

The principal methods being proposed to emplace a canister in the sediment include using freefall or boosted penetrators with integral canisters, punching canisters into the sediment with a ram, or drilling holes into which canisters are placed. The freefall penetrator is the simplest method but it relies on terminal speeds being adequate to penetrate the sediment to sufficient depths and on holes closing behind penetrators without mechanical aids. If sufficient depths cannot be achieved with a freefall penetrator, a boosted penetrator is the next least complex emplacement system. The boosting system might be a launch tube held just above the sediment surface from which the penetrator is fired downward using a propellant.¹

If hole closure cannot be assured for the penetrator emplacement method, there are two more complex methods which will have to be evaluated. In one method, a ram or punch could be used to emplace a canister. Withdrawal of the ram would create sediment flow-in due to suction forces which will probably close the hole effectively. Engineering such a system could be difficult, however. The other method is drilling, which is very complex and expensive and would necessitate emplacing multiple canisters in each drilled hole to be economically feasible.²

There are three modes of sediment mechanical response which are pertinent to the emplacement and subsequent retention of a canister. The first is the manner in which the sediment interacts with the canister to resist penetration. Models must be developed and verified to predict the maximum depth reached by a penetrator and the forces required to emplace a canister quasi-statically by a ram or by other means. Such models must also address the effect of these processes on the structure of surrounding sediments. The second is the sediment mechanical behavior which controls the degree of hole closure after canister emplacement by a penetrator or after pull-out of a ram following quasi-static emplacement. The third is the long term behavior of the sediment due to the presence of heat generating canisters that

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**Sibley School of Mechanical and Aerospace Engineering, Cornell University.

[†]Department of Ocean Engineering, University of Rhode Island.

[‡]A U. S. DOE facility.

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produce spatial density gradients or mechanical property changes causing motion of the canister.

The purpose of this paper is to present the current research activities on the computer and physical modeling of the sediment mechanical response during and following a penetrator emplacement, as well as the long term sediment response due to the presence of a canister containing a heat source. The penetrator emplacement method is being investigated because it is the simplest. Additional research needs are also discussed.

II. PREDICTION OF PENETRATION DEPTH

In order to determine the feasibility of the freefall penetrator emplacement method or to design a boosted penetrator system, a reliable method must be available to predict the maximum penetration depth as a function of system parameters, sediment properties and entry velocity. True³ has formulated a model for the total force acting on a penetrator which includes the effects of buoyancy, sediment bearing failure, lateral surface adhesion and soil hydrodynamic drag. Beard⁴ has used True's model to analyze experiments using Doppler acoustic instrumentation to monitor penetrometer* acceleration during penetration of the ocean floor. The range of terminal speeds of Beard's lead filled penetrometers was from 26 to 29 m/s and maximum penetration depths ranged from 6 to 10 m depending on the sediment type. True's model includes the undrained shear strength as a parameter and, by matching the computed and measured maximum depths, Beard was able to obtain reasonable agreement ($\pm 30\%$) between computed undrained shear strength and either *in situ* vane shear data or data from core samples. It is equally valid to use True's model to predict acceleration, velocity and final depth of a penetrator if the sediment properties are known.

A series of penetration experiments into ancient seabed sediment near Wendover, Utah, was conducted by Young.⁵ Penetrometers containing accelerometers hard-wired to the surface were impacted into these nearly saturated seabed clay sediments with entry velocities ranging from 13 to 93 m/s. Incorporating data from these experiments, Young developed an empirical equation relating the maximum penetration depth to the penetrator mass, diameter, entry velocity and a non-dimensional soil constant. Figure 1 shows the correlation between measured maximum depths and the values computed from Young's equation for the

Wendover experiments. Also shown in Fig. 1 are predictions using True's model for the corresponding experiments. True's model tends to overpredict the penetration depth, particularly for the greater depths.

Since the clay sediments at Wendover have shear strengths⁶ very similar to deep ocean sediments of interest to the Subseabed Disposal Program, one can assume the same soil constant used by Young for Wendover sediments to estimate the penetration depth of a postulated waste canister penetrator having a mass of 1500 kg, a diameter of 0.3 m and an assumed terminal speed of 35 m/s. The resulting depth is calculated to be 43 m, which is within the range of interest⁷ but has a large uncertainty. The use of Young's model for this calculation represents an extrapolation to considerably more massive penetrators than for which it was intended, but the length-to-diameter ratio and velocity are well within the range of applicability. It should be pointed out, however, that the Wendover experiments are not simulations of ocean penetrator emplacement processes because the presence of water above the sediment in the deep ocean canister emplacement situation will tend to decrease the penetration depth by an unknown amount by creating a reduced base pressure which increases the effective drag.

In order to apply True's model to a postulated deep seabed emplacement of a waste canister penetrator, one can assume the same penetrator parameters as above and a shear strength-depth relationship⁸ which matches that of a particular part of the Central North Pacific and integrate True's predicted acceleration to obtain a predicted maximum penetration depth of 27.4 m. This simple analysis accounts for the effects of water and sediment flowing in behind the penetrator, but neglects the effects of partial resistance to penetration before the penetrator is fully engulfed by the sediment.

Of course, True's and Young's models indicate nothing about the behavior of the sediment after penetration is complete. In particular, the question of hole closure is not a part of either model and there is no information in either set of experiments addressing the phenomena.

III. HOLE CLOSURE MECHANISMS IN THE DEEP SEABED

There are several possible mechanisms which could cause a hole left by a penetrator in the deep seabed to close. Closure could result immediately after passage of the penetrator if the suction or reduced pressure induced by the hydrodynamic flow past the penetrator is sufficient. (Cavitation will not occur under conditions of emplacement in the deep seabed.) It is proposed

*A penetrometer is an instrumented penetrator.

that, if the hole were to remain open during penetration, then water must flow into the hole to account for the volume swept out by the penetrator. However, for water to follow the penetrator, a pressure gradient down the hole must exist that would also act laterally tending to force the sediment into the hole radially. Figure 2 shows this process schematically. At the present time there is no solution to this flow problem available to predict the extent to which this mechanism is applicable or the distance the water follows the penetrator before being stopped by sediment flow-in. If this process does occur, producing immediate and total closure of the hole with remolded sediment with nearly the original water content, then the water migration rate and hence, the barrier will be essentially the same as that of the undisturbed sediment.

Acting simultaneously with the suction or reduced pressure sediment flow-in mechanism is the elastic recovery or unloading of the sediment. The penetration process causes volumetric compression as well as shearing of the sediment. Passage of the penetrator relieves the radial (lateral) component of the stress allowing the inner surface of the sediment to move inward.

If immediate closure of the hole does not occur as a result of the combined effects of suction and elastic unloading, a remaining long term mechanism may be applicable but the result may not be acceptable for the Subseabed Disposal Program requirements. In the unlikely situation where the penetrator has reached its maximum depth and has left an emplacement hole fully open and filled with water, the hole would be expected to close gradually by sediment creep due to the overburden stresses. Dawson, et al.⁹ have shown, using a porous media creep model for the sediment, that hole closure will take place in times ranging from one day to several weeks depending on the lateral boundary conditions assumed. However, uncertainties in the creep closure mechanism may make reliance on this mode unacceptable because of unpredictable mixing of seawater with the sediment and unknown times for the mixture to reconsolidate to in situ conditions.

An experimental program¹⁰ was undertaken to investigate the response of sediments during and subsequent to penetration by dynamically or quasi-statically emplaced projectiles. The study was intended to identify, in a controlled laboratory situation, the mode and rate of hole closure for these two emplacement concepts. Boundary conditions are appreciably different in the laboratory compared to an in situ environment, especially for dynamic penetration, so that the experiments should

not be viewed as an attempt to exactly simulate deep seabed emplacement phenomena. Rather, considerable information on basic behavior of these sediments was obtained which is especially useful for development and verification of computational techniques.

Prior to the experiments, sediment was completely remolded into a thick slurry and reconsolidated with predetermined stresses using a pressurized balloon at the top boundary. Reconsolidation took place in a smooth-walled fiberglass tank, 0.46 m diameter and 1.20 m height. After consolidation had essentially ceased, the tank was transferred to a test frame for the penetrator experiments. For the dynamic penetrations, instrumentation included an accelerometer on each 25 mm diameter projectile fired from an air gun, transducers embedded in the sediment to monitor total stress and pore water pressure and accelerometers to monitor sediment response. For the quasi-static penetration, a rack and pinion system with a load cell was used for emplacement and an acoustic probe device was developed to monitor post-penetration cavity closure history. Schematics of the dynamic and quasi-static penetration experiments are shown in Fig. 3. In all tests, the sediment was extensively sampled and tested to observe the distortion resulting from penetration and to determine geotechnical properties.

Eight samples of three types of remolded marine sediments (Pacific illite, Pacific smectite and Atlantic carbonate) were prepared and consolidated to various stress levels to simulate sediment conditions at different depths below the seafloor. All tests were conducted with water at atmospheric pressure above the sediment and the majority of dynamic penetrations were conducted using a rigid top boundary to simulate the presence of overlying material. These tests revealed complete and immediate cavity closure following dynamic emplacement. Modifications to this procedure involved using a semi-rigid top boundary (water-filled balloon) to model the overlying sediments while reducing the degree of constraint placed on the sediment by a rigid boundary. This test also caused complete and immediate cavity closure. In the first two series of tests, four penetrometers were fired into each of the tanks of sediment at the centers of each quadrant. A final modification to the testing procedure involved penetrating the sample at the centerline of the tank and with no top confining surface. This free surface test produced an open cavity nearly the entire length of the penetration path with only the bottom 10% of the cavity closing behind the projectile.

The laboratory cavity closure experiments have been partially analyzed by solving

numerically the equations of motion for the penetrator and the surrounding sediments. The computations were performed using the two-dimensional, finite difference code, TOODY.¹¹ TOODY explicitly integrates the equations of motion for arbitrary bodies in either a planar or axisymmetric Lagrangian reference frame. This code has the capability to automatically rezone the region of analysis as the calculations proceed, allowing problems with large deformations to be analyzed with relative ease. Sliding interfaces within the region can be simulated using a kinematic algorithm.

The sediments into which the penetrators were fired were modeled as elastic-plastic materials. Interactions between the sediment skeleton and pore fluid in terms of relative motion or difference in hydrostatic stress were neglected. The deep ocean sediments of interest are highly impermeable, making significant motion of the pore water through the skeleton unlikely in the short time span of the penetration event. The possibility of significantly different hydrostatic stresses in the pore fluid and skeleton is quite plausible, however, and is being addressed by incorporating an effective stress model into TOODY.¹² The elastic-plastic material model used incorporates a Von Mises yield criterion and an associated flow law. The dependence of the yield stress on the pressure (i.e., Mohr-Coulomb type yield criterion) was not included in the computations. Elastic moduli and yield stress values of 3.15 GPa and 20 kPa, respectively, were taken from the literature for saturated marine sediments.¹³

In the computations, the region of analysis simulated the tank axisymmetric geometry used in the experiments. The tank wall and bottom were assumed to be rigid boundaries while the upper surface of the sediment and the cavity wall above the penetrator were modeled as being stress free to simulate the last dynamic test described above. No attempt was made to include the effect of water on these surfaces and therefore any influence of pressure reduction in the wake is not taken into account. The interface between the penetrator and sediment was treated as frictionless, which is a poor assumption.

The test acceleration records were integrated to give the velocity and displacement histories of the projectile. The velocity history (Fig. 4) shows the increase in velocity as the projectile is accelerated to its penetration speed. The numerical simulation begins when the penetrometer has reached its peak speed (approximately 32 m/s) and enters the sediment in the test tank. Comparison of the predicted velocity of the penetrator with that obtained by integrating the

measured acceleration indicates that the predicted acceleration is of greater magnitude than the measured values. Because the inclusion of friction along the sediment/penetrator interface could only create greater accelerations, the overprediction is most likely due to higher assumed shear strength parameters than existed for sediments in the tank. Bamford¹⁴ determined after the calculations had been completed that the sediment shear strength was 13.5 MPa compared to 20 MPa for the calculations.

An accelerometer placed at a depth of 320 mm and radius of 50 mm (from the expected projectile path) provided data from which sediment velocity and displacement histories were computed as shown in Fig. 5. Again, although the histories obtained from measurements and from the TOODY calculations are qualitatively similar, the resistance to penetration was overpredicted, with lower lateral velocities and displacements being calculated. (Time in Fig. 5 starts when the penetrator first enters the sediment, approximately 22 ms after initiation of the penetrator response in Fig. 4.) At approximately 7 ms, the sediment velocity at the accelerometer location has reached its peak value. The tail of the penetrometer has just passed this position after 7 ms and the cavity is free to rebound inward. Elastic recovery causes the velocity to reverse which results in a final inward displacement of the accelerometer relative to its original position. The cavity wall itself, however, does not fully close due to shear deformations along the penetrator-sediment interface that produce vertical movement of the sediment.¹⁵

Other computations have been performed to assess the effects of the assumed boundary conditions and material model parameters on the predicted hole closure behavior. The boundary conditions imposed within the laboratory have been shown to have a pronounced effect on cavity closure.¹⁶ Placement of a heavy plate on the upper surface to simulate the overlying sediments causes the cavity to close almost immediately. This is due to the combined effect of the tank walls and cover plate that produces a state of bulk compression that unloads elastically following penetration.

Thus, the boundary conditions in the laboratory simulations result in significant differences in the closure behavior of cavities formed by a penetrator. Because of the inherent effects of boundary conditions that must be imposed in the laboratory, but differ from the actual field application, extrapolation of the laboratory results to the field environment is not immediately possible. However, close correlation between computations and measurements within the laboratory setting are

the necessary first steps in gaining confidence to make accurate predictions in sub-seabed environments.

The results of the quasi-static tests reveal open cavity behavior following projectile penetration. The measured closure rate of the cavity decreases steadily for the first several hundred minutes after penetration as shown in Fig. 6. The initial closure phase was found to be dependent on the consolidation stress and sediment type although the penetration resistance was not found to be dependent on sediment type.¹⁷

IV. LONG TERM CANISTER MIGRATION

Following emplacement of wastes in sub-seabed sediments, temperatures in the vicinity of a canister begin to rise from the heat produced as isotopes within the wastes decay. The production of heat can possibly have serious effects on the long term isolation of wastes within the sediment. Unless the canister is neutrally buoyant with respect to the sediment-pore water system, there can be differences in gravitational forces acting on the sediment and canister that would tend to displace the canister from its original emplaced position. As the nearby sediment becomes warmer from heating, its effective stiffness diminishes allowing motion of the canister relative to the sediment. For canisters of higher overall density than the sediment/pore water system, the canisters could sink slowly downward through the sediment column.

However, the heating of sediments also causes thermal gradients within the sediment that produce differential body forces. This system of forces leads to convective motion of the sediment in which warmer sediments tend to rise and, by surface adhesion, transport with them the canister that produces heat. The net motion of a waste canister, then, is the combination of the upward drag from rising sediments and the downward sinking of a canister of greater density than the sediments.

The creep behavior of waste canister/saturated sediment systems has been analyzed using a finite element code that includes coupling between the mechanical and thermal response. The mechanical response of the sediment is assumed to be creeping flow of a fluid-like medium having a temperature dependent viscosity; while the canister itself was modeled as nearly rigid. Parameters for the model for the sediment creep behavior were taken from the literature for fine-grained clays.¹⁴ The creeping motion was assumed to be sufficiently slow that pore pressures generated as a result of sediment skeleton deformations dissipated quickly

relative to the deformations themselves. This assumption permitted the skeleton deformations to be computed independently from the pore water motion. The skeleton deformations were considered to be incompressible, so that volume changes of the skeleton during deformation were neglected and only shear deformations were modeled. The temperature rise of the sediment was assumed to produce only changes in the density and, hence, the gravitational body forces, while having negligible effect on the conservation of mass and energy equations.

A parameter study was performed on a system consisting of a canister buried at approximately 30 m in a 60-meter deep sediment column. The transient response of the temperature distribution and velocity field were computed for a range of the effective shear viscosity values of 10^{11} to 10^{16} Pa·s (at 280 K) and a range in heat loads from 0.75 kW to 3.5 kW (initial power). These calculations indicate that, for low heat output and high viscosity, the sinking of the canister in the sediments dominates and the net motion is downward. For higher heat loads, the convective circulation of sediments produces overall upward motion of the canister. However, heat loads of these magnitudes are not currently considered viable for sub-seabed isolation because of metallurgical and geochemical constraints.¹⁹ A summary of peak canister temperatures and canister motion is presented in Table I.²⁰

The relative motion of the sediment skeleton and pore water and the distribution of stresses between the skeleton and water can be assessed properly by developing a model for the mechanical and thermal behavior of saturated marine sediments that incorporates these phenomena. The two-dimensional computer code, NEPTUNE,²¹ is under development for this purpose. NEPTUNE currently has the capability to solve the nonlinear equations for creeping flow of sediments coupled with the migration of pore water resulting from pressure gradients, i.e., Darcy flow. The thermal response is determined by solving the energy equation, which includes terms for conduction, convection by fluid movement through the skeleton, heat generation, and temporal changes in the energy. NEPTUNE presently is limited to an incompressible fluid phase, with expansion of the skeleton and pore fluid handled using the Boussinesq approximation.²² Analysis of sub-seabed disposal applications has been initiated using NEPTUNE with constitutive model parameters being determined from laboratory material property tests on typical deep sea clays.

V. RESEARCH NEEDS

The computations performed to date have relied principally on sediment properties for saturated clays as reported in the literature. The Subseabed Disposal Program is sponsoring additional laboratory testing to evaluate saturated sediment behavior for stress states, strain rates and temperatures corresponding to conditions possible during isolation of wastes. Dynamic properties of saturated sediments are necessary for models being developed to analyze emplacement and related operations. Tests of both drained and undrained specimens subjected to uniaxial and triaxial stress states are being conducted on both illite-rich and smectite-rich clays. Stress states are such that the resulting strain-rates range from $10^{-3}/s$ to $10^3/s$. The sediment deformation response will be used in conjunction with an elastic-plastic effective stress model that includes a pressure dependent yield condition and void-ratio dependent elastic moduli.

Quasi-static and creep tests are continuing to characterize the sediment behavior for longer duration loading associated with creep closure of emplacement cavities and thermally induced creep. Tests performed to date indicate that the sediments are similar to other smectite and illite clays, both in terms of the failure envelope parameters and the sensitivity to remolding.²³ The creep terms are being performed at stress levels 10 to 70 percent of the short term peak strength identified in the quasi-static tests. Creep testing simulates both drained and undrained conditions under constant stress and constant load conditions. The longer duration creep tests also involve elevated temperature environments since the heating of sediments results in the need to know properties at higher than ambient temperatures. The effects, if any, of radiation on the mechanical properties of deep ocean sediments is not known. Changes in the clay platelet bonding mechanisms from exposure to radiation could modify the macroscopic mechanical properties of the skeleton structure. Further complexities may arise from synergistic effects of radiation and elevated temperatures that would not be observed from tests involving these conditions that are performed separately. Planning for the Subseabed Disposal Program includes activities that will address these effects.

The laboratory testing of sediments is yielding data from which the mathematical representations of sediment thermomechanical behavior will be formulated. The constitutive models resulting from this process are required for computations to

be performed using methods under development.

In order to treat the calculational problems associated with the dynamic hole closure process, it is important to consider the conditions in which water could flow into the hole initially and then be stopped by the radial flow-in of sediment. This type of calculation presents some difficulty for a Lagrangian code such as TOODY, since the water undergoes very large displacements and distortions. In a Lagrangian code, such distortions must be handled by frequently rezoning the mesh. The problem is further complicated by the creation of new water-sediment interfaces as the penetrator opens a cavity. Although the sliding interface algorithm can address interfacial boundaries, modeling of the multiple interfaces that are present (penetrator/sediment, sediment/water and penetrator/water) is extremely complex and is not currently within the capability of TOODY or most other codes. Accurate prediction of the emplacement process must include the combined effects of these changing interfaces. A possible alternative approach to this problem is to treat the flow process with an Eulerian calculation. Preserving material interfaces, which is important in the penetration process, is more difficult using Eulerian representations, however, and mixing of the sediment and water might be predicted that is entirely due to characteristics of the numerical procedure.

To prove the engineering feasibility of any canister emplacement concept, experiments must be planned and conducted in the deep ocean seabed in addition to experiments in the laboratory. The experiments must demonstrate both that the candidate procedure can emplace a canister to the proper depth and that the emplacement path does not represent a breach of the sediment barrier to the migration of radionuclides.

If either a freefall or boosted penetrator is a reasonable emplacement method, the depth to which seawater intrudes into the sediment along the emplacement path must be determined as a function of penetrator geometry and entry velocity and compared with computational models when they become available. Simulation experiments in the laboratory to determine the effects of water intrusion behind the penetrator must be conducted in a pressurized environment to prevent cavitation. Even if the hole in the sediment below the water intrusion is closed, it is expected that "closure" will be a matter of degree and a method must be devised to characterize fully the extent to which the physical properties of the sediment

in the path are different from those of the undisturbed sediment. If the affected sediments are simply remolded without being mixed with additional seawater, then it is expected that the permeability, an important consideration in determining ion migration rates, will be about the same as for undisturbed sediment. The methods which must be developed to characterize the path must include *in situ* techniques such as, for example, acoustic imaging to determine seawater intrusion depths. In addition, techniques must be developed to retrieve core samples of sediments in the disturbed region along the emplacement path. This will allow laboratory experiments to be conducted to determine other important physical properties.

VI. CONCLUSIONS

Preliminary results indicate that the maximum penetration depths expected from freefall penetrators may be only marginally sufficient and boosted penetrators may be necessary to achieve adequate burial depths.

Although one might argue intuitively that the hole created by the penetrator of a canister should close, this conclusion is not a certainty. Results have shown that the behavior of the hole, particularly for dynamic penetration, is strongly dependent on the boundary conditions employed in calculations as well as in laboratory experiments. It is necessary to conduct laboratory and field experiments which are closer simulations of deep ocean emplacement processes and to develop more elaborate calculational techniques which can account for the effects of water and sediment flow behind the canister during penetration.

Finally, canister motion during the heat generation period appears not to be a problem, however, these results must be confirmed after significantly more information has been obtained on the thermomechanical behavior of candidate deep ocean sediments.

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TABLE I
Long Term Movement Predicted Behavior

Case	C_1^*	C_2^*	Thermal Load (kW)	Density of Canister (kg/m^3)	Temp. Peak (K)	Peak Velocity of Canister (mm/yr)	Displacement After 60 yrs (mm)
Ref.	$.17 \times 10^{-7}$	14700.	1.50	2275.	498.	-5.99	-130.
A	$.17 \times 10^{-7}$	14700.	0.75	2275.	387.	-0.41	-12.
B	$.17 \times 10^{-7}$	14700.	1.50	1500.	498.	-0.25	-3.2
C	$.17 \times 10^{-7}$	14700.	1.50	4000.	498.	-18.3	-370.
D	$.17 \times 10^{-6}$	14700.	1.50	2275.	498.	-1.89	-38.
E	$.188 \times 10^{-6}$	5000.	1.50	2275.	498.	-0.095	-2.4
F	$.17 \times 10^{-8}$	14700.	1.50	2275.	498.	-53.6	-1140.
G	$.17 \times 10^{-9}$	14700.	3.50	3500.	597.	+94.6	+1700.**

*Viscosity = $C_1 e^{C_2/\theta}$ (Pa·s) θ = temperature, K

**After 25 yrs

FIG. 1. COMPARISON OF TWO MODELS WITH WENDOOVER EXPERIMENTS

FIG. 2. SCHEMATIC OF POSTULATED HOLE CLOSURE MECHANISM

FIG. 3. DYNAMIC PENETRATION EQUIPMENT

FIG. 4. PENETRATOR RESPONSE

FIG. 5. RESPONSE OF SEDIMENT AT 0.32 m DEPTH AND 0.05 m RADIUS

FIG. 6. CAVITY CLOSURE RATE VS. TIME FOLLOWING QUASI-STATIC PENETRATION