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SEABED DISPOSAL PROJECT TWO-DIMENSIONAL
AXISYMMETRIC PENETROMETER SIMULATIONS

P. F. Chavez, P. R. Dawson, K. W. Schuier

Sandia National Laboratories

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SEABED DISPOSAL PROJECT
TWO-DIMENSIONAL AXISYMMETRIC PENETROMETER SIMULATIONS

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ABSTRACT

Preliminary two-dimensional, one-constituent hole closure analyses of an experimental apparatus and the flow of in situ ocean sediments following a penetrometer emplacement have been performed. Boundary conditions associated with the experimental apparatus were found to greatly affect cavity response. Difficulties were encountered in modeling penetrometer-sediment interfaces and in obtaining smooth stress histories. The use of a different computer code in later analyses led to more realistic penetrometer-sediment interface models and to improved success in obtaining stress histories. These results along with some recommendations for future work are presented.

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I. INTRODUCTION

The isolation of nuclear waste in ocean sediments depends upon the containment of such wastes by not only waste containers, but also by the surrounding sediments. Thus independent of the manner considered for burying the wastes, it is required that the hole produced in the sediment during emplacement close.

One proposed method for emplacing wastes in the sediment is to use free-falling or fired penetrometers. The integral canister and penetrometer would be designed to penetrate the sediments to a predetermined depth. Following penetration, the cavity formed must close to reform the sediment barrier. Analyses of projectile penetration and subsequent short time sediment mechanical response have been performed. Initially the analyses sought to describe sediment response under conditions similar to laboratory tests being performed at the University of Rhode Island. The purpose of these simulations was to provide assistance in determining the effect of the inherent boundaries of the sediment tank, used in the experiments, on hole closure. Additional calculations simulating projectile penetrations under "in situ" conditions were conducted to assess the sensitivity of predicted behavior to assumed material properties, spacial and temporal discretizations, and numerical algorithms used to model the sediment-penetrometer interface.

II. URI HOLE CLOSURE EXPERIMENTS

To investigate two potential methods for emplacing radioactive wastes in deep sea sediments, a series of small scale laboratory experiments is being performed [1]. In these experiments dynamic emplacement is simulated by firing projectiles into closed containers filled with remolded consolidated sediments. Quasi-static emplacement is simulated by attaching a projectile similar to those used in the dynamic tests to a rod and slowly pushing it into the sediment-filled container. In both the quasi-static and dynamic tests, vertical loads were applied to the movable cover plate of the container to simulate different amounts of overburden stress. The primary objective of these experiments is to observe the closure behavior of the hole produced by the projectile.

In tests performed to date, two distinct patterns of hole closure have been observed. In dynamic tests where a confining plate was used to approximate overburden pressure on the upper surface of the sediments, the hole appeared to close immediately with the exception of a small cavity formed in the sediment in the center of the hole in the confining plate through which the projectile was fired. In some preliminary trial dynamic tests without the confining plate present, the cavity remained open following projectile penetration. In the quasi-static penetrations a slowly closing hole the full length of the projectile path was observed.

One-dimensional (radially symmetric) numerical calculations of the projectile penetration have been performed and reported [2]. Corresponding two-dimensional numerical calculations in support of the one-dimensional calculations have also been performed. The purposes of the calculations were to evaluate the importance of shear stresses on sediment deformations and cavity closure rate and to examine the feasibility of measuring additional quantities.

The hole closure experiments were modeled using the dynamic finite element code, HONTO [3]. The two-dimensional axisymmetric calculations used an elastic-plastic material model and a sliding interface routine.

Two 0.82 m diameter tank cylinders with axial lengths of 0.16 and 0.96 m were considered in order to evaluate the effect of tank volume on predicted stress magnitudes.

The 0.96 m tank length is more representative of the actual experimental apparatus. A rigid projectile with an overall length of 0.15 m and a body radius of 0.0127 m was modeled with three piecewise linear segments that attain the full body radius 0.046 m from the nose tip. The shape of this projectile closely approximates that of the projectile used in the experiments. An impact velocity of 20 m/sec was prescribed for the projectile which approximates that obtained in the experiments. At zero time the projectile begins moving into the sediment and opens the cavity.

The sliding interface routine available in HONDO is used to model the penetration process. As one body with a sliding interface (the surface of the projectile) comes in contact with the second body (the surface of the sediment bed), overlapping of the bodies occurs. To keep these overlaps to a minimum, a surface force is applied to each body in proportion to the product of the amount of overlap and a restoring force modulus previously defined for each body. Thus, as the projectile moves into the sediment bed, the sediment is pushed out of the path of the projectile, slides around the projectile and forms a cavity. Once the projectile has passed, the closure of the stress free surface of the cavity wall is monitored to determine hole closure behavior.

Evaluation of the effects of the container and confining plate on the closure behavior was approximated using different boundary conditions at the outside radius of the sediment layer. The two cases studied are:

$$\text{Case 1. } U_z (z = 0 \text{ m \& } z = 0.16 \text{ m or } 0.96 \text{ m}) = 0 \text{ and } U_r (r = 0.41 \text{ m}) = 0$$

$$\text{Case 2. } U_z (z = 0 \text{ m \& } z = 0.16 \text{ m or } 0.96 \text{ m}) = 0 \text{ and } \sigma_r (r = 0.41 \text{ m}) = 0$$

where U_z and U_r represent the axial and radial displacement components and σ_r is the radial stress. Case 1 models the presence of both the rigid tank wall and the fixed confining plate which is used to apply a simulated overburden stress to the sediment. Case 2 replaces the rigid tank wall with a free surface.

An isotropic, elastoplastic material model was used to represent the mechanical behavior of the saturated sediments. The elastic properties, yield strength, and hardening modulus are given in Table 1. A von Mises yield surface with an associated bilinear strain hardening flow law was assumed.

TABLE 1

Tank Simulation Elastoplastic Material Model Parameters

$E = 1.35 \text{ GPa}$	(Young's Modulus)
$\nu = 0.45$	(Poisson's Ratio)
$\sigma_0 = 20 \text{ KPa}$	(Yield Strength)
$E_H = 10 \text{ KPa}$	(Hardening Modulus)

Although rate-dependent material models are available in HONDO, they have not been applied here due to lack of experimental data on the rate dependent behavior of sediments.

The second purpose of the simulations was to examine the magnitude of the pressure pulse in the sediment and the strains in the tank wall to determine if experimental measurements of these quantities are feasible. Boundary conditions corresponding to Case 1 were used as they are expected to yield higher stress levels than would be present in the experiment because stresses in the experiment would be reduced by motions of the cover plate and tank walls and by compaction of small amounts of sediment that are not fully saturated. In conjunction with the second purpose Young's modulus was varied to study its effect on the magnitude of the stress in the sediment and the strain in the tank walls. Two values of Young's modulus were used:

$$E_s = 1.35 \text{ GPa} \quad \text{and} \quad E_s = 3.0 \text{ GPa}$$

which bound the range of values reported in the literature for reconstituted sediments [4].

Numerical analyses of the hole closure experiments were continued until either mesh distortion due to cavity closure behind the projectile halted the calculation or until the projectile completely passed through the region of analysis. Figure 1 shows the projectile as it penetrates the sediment and opens the cavity for either case. The cavity closure response for the two cases studied in either tank is clearly evident from Figures 2 and 3. Without radial constraint at the outside radius (Case 2), the cavity remains open after the projectile has passed. Later plots of mesh deformations also show that even though the projectile has completely passed through the region of analysis (which takes about 15.5 ms in the 0.16 m tank and 55.5 ms in the 0.96 m tank)

no closure is evident. In the case with the radial displacement constraint (Case 1), almost immediate closure of the cavity occurs in either tank after the projectile has passed. Also interesting to note in Figures 1, 2 and 3, are the shear deformations which are present in the sediment near the cavity surface. These shear deformations, although not transmitted very deep into sediment may be important in the in situ hole closure phenomenon. The two-dimensional computations show the same closure dependence on assumed boundary conditions as was predicted in the one-dimensional calculations [3].

Figures 4 and 5 show the radial displacement plots for Case 2 for two nodal points located in the 0.16 m deep tank about 0.05 m below the surface of the sediment at the centerline and at radius 0.07 m. It is apparent from these figures that the radial displacements at roughly five times the radius of the projectile are an order of magnitude smaller than at the centerline. Similar results are obtained for the 0.06 m deep tank.

The stress histories, shown in Figures 6 through 9 for Case 1, indicate that the radial stresses at $r = 0.09$ m and $r = 0.41$ m and $z = 0.055$ m for both tanks increase almost linearly in time as penetration occurs. When the projectile passes, the stress begins to diminish as the relief wave propagates into the sediment. At later times, the stress might be expected to increase again as a result of the initial stress pulse being reflected off the container walls, as was observed in the one-dimensional calculations [3]. Significantly, the two-dimensional calculations show that at times soon after penetration, a state of essentially uniform hydrostatic compression is achieved throughout the tank.

This observation suggests that the average quasi-static behavior of a fixed volume cylindrical tank subjected to projectile penetration can be approximated by assuming that the change in sediment volume is equal to the projectile's volume. Then the bulk strain in the sediment is the ratio of the volume of the projectile embedded in the sediment to the original volume of the sediment. A projectile consisting of a right circular cone 0.032 m long on top of a 0.118 m long right circular cylinder of radius 0.0127 m closely approximates that used in the numerical calculations.

The mean stress can be calculated from the bulk strain as $\sigma_m = -k\epsilon_b$ where k is the bulk modulus of the sediment and is given by $k = E_s/3(1 - 2\nu)$. Here E_s and ν are Young's modulus and Poisson's ratio for the sediment, respectively. The mean stress calculated at various times for the different tank lengths and Young's moduli is shown in Figures 6 through 9 as single squares in the plots. The agreement between the numerical solution and this simple bulk behavior model is quite good, and generally is within 10%. The close comparison between the elastoplastic numerical solution and the simple bulk behavior solution indicates that with constrained boundaries the penetration is essentially a hydrodynamic event.

To investigate the possibility of measuring the strains in the tank wall a simple bulk behavior model will be used to estimate the strains. Assuming the tank behaves in a linear elastic manner and in plane strain, the circumferential strain, ϵ_θ , is

$$\epsilon_\theta = \frac{\sigma_\theta}{E} (1 - \nu^2)$$

The circumferential stress in the tank can be calculated from equilibrium as:

$$\sigma_\theta = \frac{Pr}{t}$$

giving

$$\epsilon_\theta = \frac{Pr}{tE} (1 - \nu^2)$$

where p = mean pressure in the sediment

r = tank radius ($\approx .23$ m corresponding to the latest simulation tank)

t = tank wall thickness ($\approx .006$ m)

E = Young's modulus for the fiberglass tank (~ 4.7 GPa)

ν = Poisson's ratio for the tank (.25 $\leq \nu \leq .45$)

Bulk strain in the sediment is computed as the change in sediment volume divided by the original volume. Allowing for expansion of the tank due to the pressure, the bulk strain is then the volume of the expanded tank less the volume of the original tank and the projectile divided by the original tank volume. Or in mathematical terms after minor simplification

$$-\epsilon_B = \frac{\pi r^2 \left(1 + \frac{Pr}{Et} (1 - \nu^2) \right)^2 - \pi r^2 - \pi_p^2 \left(\frac{h_p}{h_t} \right)}{\pi r^2}$$

where ϵ_p is the bulk strain (compression negative)

r_p is the radius of the projectile

h_p is the length of the projectile

h_t is the length of the tank

Using the relationship between bulk strain and mean pressure ($p = K\epsilon_p$), an equation for the pressure is obtained:

$$\left[\frac{pr}{Et} (1 - \nu^2) \right]^2 + p \left[\frac{2r(1 - \nu^2)}{Et} + \frac{1}{K} \right] - \frac{r_p^2}{r^2} \frac{h_p}{h_t} p = 0$$

Solving for the pressure using the 0.96 m tank gives:

$$P = \begin{cases} 33.3 \text{ kPa} \\ -0.28 \text{ GPa} \end{cases} \quad \text{for } \nu = .25$$

$$\text{and } P = \begin{cases} 39.2 \text{ kPa} \\ -0.33 \text{ GPa} \end{cases} \quad \text{for } \nu = .45$$

Substituting the positive values back into the equation for circumferential strain of the tank walls yields:

$$\epsilon_\theta \approx .00024$$

This value is quite low and would be difficult to measure in the time frame of a dynamic projectile emplacement. Further, due to the assumptions of rigid constraints and no volume compaction, the strains computed here are higher than would be expected in actual tests.

The two-dimensional numerical simulations of the hole closure experiments have verified the effects of the boundary constraints on the closure response shown by the one-dimensional calculations [2]. Specifically, when the presence of the confining plate and tank wall were simulated, the cavity closed. Cavity closure was not predicted when the rigid tank wall was replaced with a free surface. Thus, although the shear stresses caused by the projectile penetration into the sediment were observable, they were not great enough to cause hole closure in this case.

In addition, the calculations show that the strains in the tank wall would be difficult to measure and would require sophisticated experimental techniques. Further, the good agreement between the bulk behavior calculated for a quasi-static penetration and the numerical dynamic penetration indicated that the process is basically a hydrodynamic event.

III. IN SITU SIMULATIONS USING HONDO

The penetration of a projectile with dimensions similar to the proposed waste canisters was simulated using HONDO. A rigid projectile .254 m in diameter and 1.5 m in length entered a sediment region 10 m deep and 12.5 m in radius at an initial velocity of 30 m/s. (A projectile shorter than a typical canister was used in the simulations in order to observe sediment response following penetration with the projectile at less computational cost.)

The sediment was characterized with an elastic-plastic model having a von Mises yield surface but no strain hardening. Values of the parameters for this model are listed in Table 2.

TABLE 2

In Situ Simulation Elastoplastic Material Model Parameters

$E = 3.0 \text{ GPa}$	(Young's Modulus)
$\nu = .487$	(Poisson's Ratio)
$Y_0 = 20 \text{ KPa}$	(Yield Strength)
$E_H = 0.0$	(Hardening Modulus)

The preliminary boundary conditions considered for the sediment region included stress free upper and lower surfaces and an imposed pressure of 48 KPa on the outside radius (used to approximate the overburden stress). The effect of the water above was assumed to add only a hydrostatic component to the stress and thus was assumed to have no influence on the deformations. For this reason presence of the water head was initially neglected.

The sliding interface capability of HONDO was again used to model the penetration of the projectile into the sediment. Although the projectile was rigid, it was found that increasing the number of elements within the projectile improved the sediment displacements in the vicinity of the interface. Figure 10 shows the projectile mesh.

Some difficulties were encountered in these calculations. First, excessive grid distortion occurred near the top free surface as a result of crater formation. It

was necessary to either constrain the top surface such that only radial displacements were permitted or to apply an overburden stress to limit axial displacements. The application of an overburden stress is more representative of the ocean floor, but it was found that no difference in qualitative closure behavior occurred for the two conditions. It was also necessary to use coarse meshing along the centerline of the sediment to avoid grid distortions that terminated the calculations. This compromised the accuracy in the stress field near the canister where stress gradients are high.

Secondly, difficulty was experienced in specifying the moduli for the sliding interfaces between the penetrometer and the sediment. Values that yielded good qualitative displacement history in one case (i.e., the sediment appeared to follow the projectile shape well) might not do so in another case having either different geometry, material properties, or projectile impact velocity. Specifying a modulus that is too low allows the sediment to penetrate the projectile while specifying a modulus too large causes unrealistic separation of the sediment and projectile early in the penetration event. Problems of modulus specification were also encountered in the URI simulations but were not extensively investigated until the "in situ" analyses were performed.

Extensive variations in the interface moduli were considered with values extending over several orders of magnitude. In general, the best values of moduli were selected by visual examination of mesh deformation plots.

The first set of simulations started with the projectile above the sediment region as indicated in Figure 11. Several trials were performed in which the restoring force moduli were varied in order to obtain a reasonable interface between the sediment and the projectile. Two such results are shown in Figures 12 and 13. In Figure 12 the sediment separates from the projectile in a manner typical of calculations performed with a high interface moduli. In Figure 13 lower values of interface moduli were used giving sediment deformations that closely follow the projectile surface. It was found that the mesh resolution in the sediment affected the selection of an interface moduli. When the resolution of the mesh near the centerline of the region was increased, different interface moduli were necessary to provide for reasonable sediment displacements near the projectile.

The magnitude of the interface moduli also affected the magnitude of the stresses. Shown in Figures 14 and 15 are the radial stress in an element which initially was located on the upper surface along the centerline. The stress reaches a greater peak magnitude (-1.8 MPa as compared to -1.3 MPa) for the larger interface modulus (9 MPa) than for the lower interface modulus (6 MPa). Spikes in the stress history result from the projectile reaching and displacing sediment nodal points along the interface discretely in time.

An analyses was also performed using a projectile partially embedded in the sediments as shown in Figure 16. This was done in order to reduce the cratering effect near the sediment surface thereby reducing the element distortion. In this case the sediment detached from the projectile as shown in Figure 17, giving unreasonable sediment deformations. However the peak radial stress magnitude, shown in Figure 18 for this case, was similar to the previous analyses performed using the same interface modulus (9 MPa).

IV. IN SITU SIMULATIONS USING TOODY

Dynamic penetrometer computations were performed using the two-dimensional, explicit, finite difference code, TOODY [5]. The version of the code employed for the calculations has the capability to automatically rezone the region so that problems involving large deformations can be analyzed. The code also includes a sliding interface algorithm that models the entry of a rigid projectile into the sediment.

A projectile penetration was simulated using TOODY in which the projectile (1.25 m radius and 1.5 m length) entered a sediment region (3.2 m radius and 5.0 m depth) with an initial 30 m/s velocity. The upper and lower surfaces of the sediment were assumed to be stress free. The outside radius of the sediment boundary was also assumed to be stress free. These conditions do not account for either the water head or the essentially infinite radial extent of the medium. It was felt that from trial runs that transients introduced by pressure boundary conditions could affect the low sediment stress histories produced by the penetration event alone. For this reason pressure boundary conditions were omitted. An elastoplastic model with perfectly plastic response was used to describe the mechanical behavior of the sediment. Coefficients for this constitutive equation are listed in Table 3.

TABLE 3

In Situ Simulation Elastoplastic Material Model Parameters

$E = 3.15 \text{ GPa}$	(Young's Modulus)
$\nu = .45$	(Poisson's Ratio)
$Y_0 = 20 \text{ KPa}$	(Yield Strength)
$C_0 = 1.48 \text{ Km/sec}$	(Bulk Sound Speed)

The deformed grid is shown for several times during the penetration of the projectile in Figures 19 through 21. Several rezonings of the grid were performed during the calculation. Curvature of the grid pattern upward and toward the surface near the centerline is a result of these rezoning operations.

Stress histories resulting from the penetration event have been examined at several locations throughout the sediment region. In general, these histories were found to exhibit large amounts of noise due to impulses introduced as the projectile

encountered and began to displace grid points along the centerline of the projectile path. Several analyses were performed in an attempt to reduce the noise. In these calculations the artificial viscosity coefficients used to smooth the numerical solution and to prevent mathematical discontinuities, grid resolution and time step were varied.

The combinations of parameters used in the simulations are summarized in Table 4. Examination of the results indicated that the most effective manner of reducing the noise was to increase the resolution of the grid. This reduced the change in strain within a zone resulting from the initial displacement of a grid point from the region centerline. This also had the effect of increasing the net cost of each analysis since allowable time step dropped. Either raising or lowering the artificial viscosity (variations in the linear and quadratic terms were considered both separately and in combination) did not reduce the noise appreciably. Stress histories for a few of the cases analyzed are provided in Figures 22 through 25 for a point located on the surface of the sediment .5 m from the centerline. The stress histories at other points throughout the region exhibited considerably more noise. As can be seen from the stress histories either raising or lowering the artificial viscosity caused larger variations in the stress history.

It is important to note that the radial stress leveled off between 2.0 to 2.5×10^4 Pa in each of the histories even though the magnitude of the deviation from the mean varied. The other stress components showed similar behavior. Pulses in the stress histories have been correlated with the arrival of discontinuities in velocity caused by the projectile encountering mesh points along the centerline.

TABLE 4

Variation of Parameters Used to Obtain Smooth Stress History

 Δr = discretization in r direction Δz = discretization in z direction

KT = fraction of maximum time step

B1 = quadratic bulk artificial viscosity coefficient

B2 = linear bulk artificial viscosity coefficient

Δr	Δz	KT	B1	B2
.0325 m	.05 m	.45	1.2	.06
.0325 m	.05 m	.2	1.2	.06
.0325 m	.05 m	.45	12.	.06
.0325 m	.05 m	.45	1.2	.006
.0325 m	.05 m	.45	1.2	.6
.0325 m	.05 m	.45	12.	.6
.0325 m	.05 m	.45	.12	.06
.0325 m	.05 m	.45	.12	.006
.025 m	.025 m	.45	1.2	.06

V. CONCLUSIONS

We believe that both the numerical and analytical models of the URI hole closure experiments show that the tank and cover plate strongly influence hole closure behavior. In general, these results indicate that without the constraints provided by the tank and plate, dynamic closure would not occur in the laboratory.

Both HONDO and TOODY calculations have demonstrated the difficulty of performing in situ dynamic hole closure calculations in a very soft material such as seabed sediments. Work recommended for HONDO includes the improvement of interface stresses and deformations as well as finer mesh discretization near the projectile. Recent work by J. W. Swegle [6] has shown that it is possible to reduce the noise in the stress histories associated with TOODY. This is accomplished by modifying the shape of the nose cone so that a smooth velocity transition is made for grid points as they are initially displaced by the projectile. Clearly, improvements in the codes must be made before one can confidently use the results to predict hole closure in the field.

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Figure 1. Simulates Penetrometer Emplacement - Penetrometer Entering Sediment.

Figure 2. Cavity Closure Response for Rigid Tank Walls (Case 1).

Figure 3. Cavity Closure Response for Stress Free Outside Wall (Case 2).

Figure 4. Radial Displacement History at $r = 0.0$ m and $z = .05$ m.

Figure 5. Radial Displacement History at $r = .07$ m and $z = .05$ m.

Figure 10. Radial Stress History in a 10m Deep Tank with $P_g = 1.35 \text{ MPa}$.

Figure 7. Radial Stress History in a .96 m Deep Tank with $E_s = 1.35 \text{ GPa}$.

Figure 6. Radial Stress History in a .10 m Deep Tank with $E_f = 3.0$ GPa.

Figure 1. Radial Stress History in a $1/4$ in. Deep Tank with $R_0 = 3.0 \text{ cm}$.

Figure 10. Mesh Plot of the Simulated Penetrometer.

Figure 11. Mesh Plot of the Simulated Penetrometer Poised Above the Sediment Region.

Figure 12. Mesh Deformation Plot Typical of a High Interface Modulus.

Figure 13. Mesh Deformation Plot Displaying a Well Matched Interface.

Figure 14. Radial Stress History for High Interface Modulus (9 MPa).

Figure 15. Radial Stress History for Low Interface Modulus (6 MPa).

Figure 16. Mesh Plot at Time = 0.0 for Partially Embedded Projectile.

Figure 17. Mesh Deformation Plot at Time = 14.7 ms for Partially Embedded Projectile.

Figure 15. Radial Stress History for Partially Embedded Projectile.

1. 1000 STAGES - 1000 COLUMNS SIMULATION
TIME 1.000000E-05 SEC. CASE 100

Figure 19. TOODY Mesh Deformation Plot at Time = 2.83 ms.

TOUGH PLASTIC WIRE CLOUTURE SIMULATIONS
TIME = 9.000000 SEC. (0.000000 SEC.)

Figure 20. TOUGHBY Mesh Deformation Plot at Time = 9. ms.

TIME: SEATED WIRE CLOSURE SIMULATION
TIME 1.0761E-01 SEC. CYCLE 100

Figure 21. TOODY Mesh Deformation Plot at Time = 16.8 ms.

Figure 22. Radial Stress History for Default Values of Viscosity and Coarse Meshing.

Figure 25. Radial Stress History with Viscosity Coefficient = 0.01.

Figure 24. Radial Stress History with Viscosity Coefficient* Lowered.

Figure 25. Radial Stress History with Finer Spacing Discretization.