13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2782

IMPACT OF LARGE VOIDS ON SEISMIC PERFORMANCE OF LANDFILL LINER SYSTEMS

Upul ATUKORALA[1], Humberto PUEBLA[2], Frank SHURI[3], and Victor OKEREKE[4]

SUMMARY

This paper describes ground response analyses carried out for a major landfill in Washington State, USA, to assess the behavior of "refrigerator size" voids, their potential for propagation within the landfill, and the resulting forces that could develop in the geomembrane liner. The analyses considered the interaction of the liner with its bedding materials and the surrounding landfill materials. Although the problem is three-dimensional in nature, the analyses presented here were carried out assuming two-dimensional conditions. Parametric studies were undertaken to assess the liner forces as a function of (a) the depth between the top of the void and the landfill liner and (b) the type of material surrounding the cavity (i.e., cohesionless or cohesive). The 2,475-year seismic loading (10% probability in 250 years) was used for the design of the landfill liner system.

The results of the numerical simulations indicate that the risk of propagation of the voids under seismic loading conditions is low, and that static loading conditions control the forces that develop in the liner. The forces in the liner were very sensitive to the assumed properties of the material surrounding the cavity, increasing by a factor of almost 10 if the waste material had no cohesion.

INTRODUCTION

Although modern landfill practice effectively excludes large open metal objects such as drums and appliances, these types of objects are sometimes present in older waste fills. Because of space constraints and complex permitting requirements for new sites, particularly in developed areas, vertical landfill expansions over existing waste areas have become an attractive alternative. In such expansions, it is common practice to install a geosynthetic and/or soil liner system that meets current regulatory requirements over existing waste areas. However, large open voids or cavities could form in the old waste due to disintegration of the large, hollow metallic objects. In response to loads from the overlying waste, these cavities could collapse and result in settlement

[1] Principal, Golder Associates Ltd., Burnaby, British Columbia, Canada
[2] Senior Engineer, Golder Associates Ltd., Burnaby, British Columbia, Canada
[3] Associate, Golder Associates Inc., Redmond, WA, USA
[4] Supervising Engineer, King County Solid Waste Division, Seattle, WA, USA

under the liner system that could damage the liner; such failure is obviously a concern to landfill operators and regulators.

In evaluating the effects of void collapse, it has generally been assumed that the largest opening in the waste would result from a household appliance that is 3 feet high by 3 feet wide by 6 feet long. The resulting void is often referred to as a "refrigerator size" void or cavity. It is imperative that the liner be designed to withstand the tensile forces that occur when the cavity collapses. In general terms, the forces developed in the liner will depend on the size of the cavity, the strength and type of landfill materials surrounding the void, and the location of the cavity relative to the liner. At present, well-established guidelines do not exist for the design of a liner over large cavities.

In seismically active regions such as the western parts of Canada and the U.S., understanding the behavior of a "refrigerator size" cavity during strong seismic shaking, especially the possibility for upward propagation of the cavity, is an additional factor that should be considered in order to maintain the integrity of the liner system.

This paper presents the results of numerical analyses undertaken to examine the forces that could develop in the liner due to on-going disintegration of waste and the dynamic forces that develop in the liner due to propagation of seismic ground motions. The analyses were performed as part of the design effort required for a synthetic liner that will be placed over existing waste dating from 1960 for vertical expansion at the Cedar Hill Landfill, a major landfill in Washington State, USA.

MECHANISMS OF FORCE DEVELOPMENT IN THE LINER

There are three main processes that can induce forces in a liner separating the old waste from new waste:

- Areal total and differential settlements that occur in the old waste materials with time following placement of new waste materials;
- Localized settlements resulting from the collapse of cavities in the old waste under static loads; and
- Inertia loads and deformations that occur due to wave propagation effects during a seismic event.

Estimating the total and differential areal settlements that occur in a given landfill is a difficult task due to material variability with respect to both location and the time-dependent properties of waste materials. Settlements also depend on a number of other factors including, but not necessarily limited to, the applied vertical loads, types of waste materials that constitute the landfill, and the methodology followed by the landfill operator to raise the landfill. In practice, the long-term areal settlements are most accurately estimated using landfill-specific data compiled over a period of time, if possible.

The cavity-induced settlements and the resulting forces on the liner due to static loads are primarily dependent on the size and location of the cavity relative to the liner, the material properties of the old landfill waste, the load applied by the new waste, and the liner-waste interaction behavior.

The seismic behavior of a cavity and the resulting effect on the liner are largely dependent on the level of shaking, the degree of collapse of the cavity, the material behavior of the liner itself, and the liner-waste interaction behavior. The existing forces in the liner at the time of the seismic event, resulting from areal settlements as well as localized settlements occurring due to the formation of a cavity, are also critical in the assessment of the performance of the liner under seismic loading conditions.

NUMERICAL SIMULATION OF WASTE PLACEMENT

The forces that develop in the liner due to placement of waste were assessed by developing a numerical model that simulated the existing waste, the liner system, and the new waste placement process. Analyses were carried out for the conditions that would exist at closure, some 5 years after the start of new waste placement. The numerical simulations were carried out using the finite difference computer code FLAC (1).

Material Model and Liner System

A key factor controlling the tensile strains and forces that develop in the liner is the magnitude of the total and differential areal settlements of the existing waste under both self-weight and the weight of the new waste material. For this study, the areal settlements were numerically simulated using "equivalent" waste stiffness parameters computed from the settlements predicted at the time of closure. These predicted settlements were based on field measurements of landfill-specific settlement data collected over a period of about 12 years. The analysis of this data indicated a relatively consistent settlement-time-waste thickness relationship that can be expressed in the form:

[1] $$S = 0.000942\ T\ t^{0.5678}$$

where, S is the settlement in feet, T is the waste thickness at the time of final waste placement in feet, and t is the cumulative time since final placement of waste in days.

The existing waste was modeled as a Mohr-Coulomb material, and the time-dependent long-term areal settlements at closure were simulated instantaneously using "equivalent" stiffness parameters. The placement of new waste was simulated in 10-ft-thick layers. Since the settlement-time relationship established for the existing waste, given by Equation [1] above, indicates a close resemblance to the behavior of normally consolidated clays, the new waste was modeled using the Cam Clay stress-strain model.

The shear strength parameters of waste materials was established from data presented by Eid et al. (2) for municipal solid waste (MSW) landfill materials, reproduced as Figure 1. The lower-bound strength curve was selected for this analysis, disregarding any cohesion that may be present in the waste materials. It is considered reasonable to assume that any apparent cohesion in new waste will not be significant over long time periods, due to on-going waste decomposition and creep.

The total in-place unit weight of MSW typically ranges from 50 to 90 lb/ft^3; Fassett et al. (3). Based on available data on unit weight of waste for the subject landfill and published data on MSW materials, unit weights of 50 lb/ft^3 (moist) and 65 lb/ft^3 (saturated) were assigned to new waste, while unit weights of 65 lb/ft^3 (moist) and 75 lb/ft^3 (saturated) were assigned to existing waste, reflecting the greater degree of consolidation of the latter material.

The liner system was modeled using beam elements with zero bending stiffness, interacting with both existing and new waste material through interfaces on either side. In this manner, and by using FLAC's large strain mode for analysis, sliding and relative displacements between the liner and the existing and/or new waste material were simulated. In addition, a tensile limit equivalent to the liner tensile yield strength was assigned to the beam elements to capture the potential stress redistribution that would take place if yielding of the liner occurred.

The material parameters used for landfill waste and the liner are summarized in Tables 1a and 1b.

Table 1a: Summary of Material Parameters for Landfill Waste

Existing Waste (Mohr-Coulomb Material):		
• Shear Modulus	3.20E+5 to 5.60E+5	lbf/ft^2
• Bulk Modulus	8.50E+5 to 1.49E+5	lbf/ft^2
• Friction Angle	35	degrees
• Cohesion	0	lbf/ft^2
New Waste (Cam Clay Material):		
• Shear Modulus	1.07E+6	lbf/ft^2
• Bulk Modulus	3.20E+6	lbf/ft^2
• M	1.42	
• λ	0.13	
• κ	0.03	
• (mpc)o	1500	lbf/ft^2
• (mp)1	1500	lbf/ft^2
• (mv)1	1.75	

Table 1b: Summary of Material Parameters for the Liner

Geomembrane (HDPE 60 mil)		
• Modulus of Elasticity	1.94E+7	lbf/ft^2
• Yield Strength	1.58E+3	lbf/ft
• Cross Sectional Area	5.00E-2	ft^2
• Unit Weight	59	lbf/ft^3
Liner-Waste Interface		
• Shear Stiffness	1.07E+6	lbf/ft
• Normal Stiffness	4.72E+6	lbf/ft
• Interface Friction Angle	24	degrees

Liner Forces At Closure

The landfill surface settlement profile predicted using the "equivalent" stiffness parameters established for the subject landfill is shown on Figure 2. The settlement profile projected using field measurements is also shown for purposes of comparison. This figure shows that the agreement between the projected and computed settlements is very close. This agreement was considered key in predicting the liner system response to placement of new waste, in effect calibrating the model parameters to the behavior of waste at this site.

A profile of the predicted tensile forces along the liner is shown on Figure 3. The maximum tensile force is 875 lb/ft near the top of the backslope where the liner is anchored; in the model, it was not allowed to slip. The pattern of forces in the liner is not uniform and shows a tendency to decrease towards the middle of the backslope, where the tensile forces vary between 0 and about 350 lb/ft, and then to increase towards the toe of the backslope, reaching a second peak of about 800 lb/ft. This trend is the result of the varying thickness of both the existing and new waste. Both waste fills decrease in thickness down-slope to a point about halfway along the total backslope length, but thereafter, the thickness of the new waste material increases, applying a heavier load on the underlying existing waste and liner system. Beyond the toe of old waste, the forces in the liner are small since the liner system is in direct contact with firm native ground, where the settlements induced by the overlying waste material are relatively insignificant.

DEVELOPMENT OF AN IDEALIZED MODEL FOR CAVITY ANALYSIS UNDER STATIC LOADING CONDITIONS

Theoretically, "refrigerator size" cavities could occur anywhere in an old landfill due to on-going disintegration of waste materials. However, the occurrence of cavities in areas where there will be a significant thickness of overlying waste is more critical, since the loads in these areas are higher and therefore the potential for damage is greater.

Given that the thickness of new waste material in the upper portions of the backslope is not large, a cavity under the liner at this location would translate into relatively low loads acting on the liner. Therefore, the cavity analysis was carried out for a waste profile that corresponds to the conditions near the toe of the existing landfill, the location with the highest vertical loads.

Simplified Numerical Model

Given the relatively small size of the cavity with respect to the dimensions of the landfill and the thickness of waste material overlying the liner, a numerical model with elements small enough to accurately evaluate cavity behavior would have required a tremendous amount of computational power. Therefore, a smaller scale detailed model that would accurately capture the response of the local zone around the cavity was developed for the analysis of cavity behavior. This idealized model consisted of two waste material layers separated by a liner system. Based on a critical section in the vertical expansion area, the upper waste layer was assumed to have a thickness of 100 ft and to rest on the liner. This layer represents the new waste materials that would be placed after construction of the liner system. The bottom waste layer was assumed to be 150 ft thick and to rest on a rigid base. This waste layer represents the old waste where the cavities could develop. The idealized profile considered for cavity analysis thus extended 250 ft vertically, and the lateral distance was set at 100 ft on either side of the cavity centerline. The ground surface of the model was assumed to be horizontal, i.e., there were no initial shear stresses in the system.

The cavity analysis was simplified by assuming 2-D plane strain conditions, rather than modeling a 3-D cavity geometry. In effect, it was assumed that the cavity would be 6 ft wide and 3 ft deep in cross sectional area and very long in the third dimension. It is believed that this simplification resulted in conservative estimates of liner forces and cavity-induced deformations, since the support provided by the ends of the cavity perpendicular to the 2-D section was ignored.

The effects of arching were examined by carrying out analyses in which the cavity was considered to be located at 0 ft, 6 ft, 12 ft, and 18 ft (i.e., 0, 1, 2, and 3 void lengths) below the liner.

Material Models

The nature of a cavity occurrence problem is highly non-linear in terms of both material response and geometry, due to the potential for cavity collapse, stress and strain concentrations, arching, and stress re-distribution around the cavity. The results reported in this paper were obtained by carrying out stress-deformation analyses in which the stress-strain behaviour and strength of the waste materials were modeled with the Mohr-Coulomb criterion. Furthermore, the analyses were performed using the large strain option in FLAC. As for the areal settlement analysis, the geomembrane liner was modeled using beam elements with zero flexural stiffness, interacting with waste material through interfaces on either side. In order to evaluate the maximum stresses that might be experienced by a geosynthetic liner, the HDPE geomembrane was allowed to deform indefinitely, rather than breaking at typical failure stress levels.

The two waste layers were assigned stress-dependent moduli derived from the Kavazanjian et al. (4) suggested profile of shear wave velocity for MSW materials. With respect to waste material strength, two scenarios were considered:

- The material had a stress dependent strength represented by a friction angle of 35° and a cohesion value of 500 psf, based on the average values for municipal waste reported by Eid et al. (2).
- The material strength was only frictional (ϕ = 35°), based on the lower-bound values for municipal waste reported by Eid et al. (2). However, a 0.3 m thick "ring" of soil with cohesion of 100 psf was assumed around the cavity to prevent the material in the cavity perimeter from flowing immediately into the void.

The material parameters used in the analyses are summarized in Table 2.

Table 2: Summary of Material Properties for Cavity Analysis

Shear Modulus, G (lb/ft^2)	**Bulk Modulus, B (lb/ft^2)**	**Friction Angle, ϕ (deg)**	**Cohesion, c (lb/ft^2)**
106,500 to 1,255,500	284,000 to 3,348,000	35	0 to 500

Results of Analyses for Static Loading Conditions

The idealized cavity model was first brought to equilibrium under the gravitational field. Subsequently, a 6-ft-wide and 3-ft-high cavity was created under the liner system by numerically removing the appropriate elements in the finite difference model. The response of the system and effect of the cavity on the liner were evaluated for each of the four cavity locations described above.

For the cases when the waste material was assumed to have both frictional and cohesive strengths, the cavity did not collapse, the predicted deformations were relatively small, and the resulting tensile forces were correspondingly low. The maximum tensile forces in the liner occurred for the case when the cavity was located immediately below the liner. In this case, the maximum tensile force was about 150 lb/ft just outside the cavity wall, and decreased rapidly to insignificant values at a distance of about two cavity widths from the centerline. As the depth of the cavity below the liner was increased, the effect on the liner became smaller, although the distance to which the presence of the cavity was felt by the liner increased to a maximum of about five cavity widths.

In contrast, for the case when the waste material was assumed to only have frictional strength properties, the waste material collapsed into the cavity, the predicted deformations were quite large, and the tensile forces induced in the liner were significantly higher. The maximum tensile force in the liner was computed for the case when the cavity was located one cavity width (6 ft) below the liner. In this case, the maximum tensile force was about 1,500 lb/ft at a distance of approximately two cavity widths from the centerline. The force in the liner decreased to insignificant values at a distance of approximately six to seven cavity widths from the center of the cavity. As the depth of the cavity below the liner increased beyond 6 ft, the effect of the cavity on the liner decreased. However, the predicted maximum tensile forces induced by the presence of the cavity remained above 800 lb/ft even for the maximum depth (18 ft) considered in this study. The maximum liner forces as a function of cavity depth is shown on Figure 4. The computed liner force distribution for the case when the cavity is located one cavity width below the liner is shown on Figure 5.

CAVITY ANALYSIS UNDER SEISMIC LOADING CONDITIONS

The impact of seismic loading on the liner forces was analyzed in the time domain by applying an acceleration time history at the base of the model described above. For consistency with RCRA Subtitle D requirements for sitting landfills, ground motion parameters that correspond to a return period of 2,475 years (or having a 10 percent chance of being exceeded in 250 years) were used. The corresponding site-specific input firm-ground spectrum was obtained from the USGS website and was used as the basis for the development of an input target uniform hazard response spectrum. The peak ground acceleration (PGA) that corresponds to this level of shaking is nearly 0.6 g.

The bedrock acceleration time-history recorded from the M7.3 Landers earthquake of June 28, 1992 was selected as earthquake ground motions applicable to the 2475-year event. This earthquake motion has previously been used in ground response analysis carried out for important projects in the Seattle area, because it has roughly the same capability and motion (strike-slip) as postulated for the Seattle Fault, which controls potential ground motions in this area. The details of the Landers earthquake are presented in Table 3.

Table 3: Earthquake Details

Event	Date	Magnitude	Epicentral Distance	Peak Horizontal Ground Motions		Station
				a(g)	v(m/s)	
1992 Landers (345 degrees)	June 28, 1992	M7.3	42 km	0.71	N/A.	SCE Lucerne Valley Station

The earthquake motion was modified to fit the Target Response Spectrum using the computer program SYNTH. The modified acceleration time-history is shown on Figure 6.

Modified Numeric Model

Because of the additional computational demands associated with applying dynamic loading, the model used for the static analysis had to be further simplified. Based on the results obtained from the static analyses, it was determined that at a distance of approximately six to seven cavity widths from the center of the cavity, the effects of the cavity were negligible. Hence, the lateral width of the model was reduced to 50 ft on either side of the cavity centerline. In addition, the thickness of the underlying waste layer was reduced to 25 ft (Figure 7) to more closely represent the conditions at the specific location considered as most critical for cavity occurrence.

These simplifications were implemented to speed up the computational process, without unduly compromising the accuracy of the results. Nevertheless, some minor differences with respect to the results obtained in the static analyses were expected, since the boundaries of the seismic model are closer to the cavity. To account for this effect, the liner forces for the modified model was first evaluated under static loading conditions, so that the *incremental* effect of dynamic loading could be accurately determined. The maximum geomembrane stress using the modified model was 1,985 lb/ft (Figure 8), or about 30% higher than the more accurate result described above.

Damping in Waste Materials

Modeling hysteretic damping of landfill material is a very difficult task. Hence, the dynamic analyses in this study were carried out using Rayleigh damping. Estimating the appropriate level of damping to be used in the FLAC model was not straightforward since there was yielding or failure of waste materials in certain areas of the landfill due to strong shaking associated with the design earthquake.

Recognizing that it would be impossible to capture all aspects of damping in waste, a parametric study was undertaken to assess the impact of damping on the shear stresses induced in the waste materials. The first step in this study was to assess the mobilized damping ratios in the different waste layers by carrying out 1-D analyses with the computer code SHAKE. In the SHAKE analyses, stress-dependent stiffness properties were used for landfill waste. The dynamic shear moduli for the waste materials were computed from the shear wave velocity data presented by Kavazanjian et al. (4) for MSW landfills, and assuming a k_o condition of 0.5. The shear modulus reduction and damping variation curves utilized in the 1-D analysis were those recommended by Matasovic and Kazavanjian (5) for landfill materials. The SHAKE analyses did not include the effects of shear strength of waste materials, the presence of a liner, or the occurrence of a cavity. The results indicated that, on average, about 12% to 14% damping may be characteristic in the waste materials due to wave propagation effects associated with the 2,475 year ground motions.

Using the SHAKE results as a base, parallel 1-D FLAC analyses were carried out utilizing the mobilized shear moduli of the different waste layers and considering the same input base motion. In FLAC, the waste material was modeled as a Mohr-Coulomb material with shear strength properties that correspond to a friction angle of 35°. No cohesion was included in estimating the shear strength.

Two 1-D FLAC analyses were performed, using two different damping scenarios that are considered to bound the reasonably-expected field conditions:

- Damping Case-1: The model was run using the degree of damping obtained from the SHAKE analyses where the material response was modeled as equivalent linear elastic (i.e., 13.5% Rayleigh damping). Due to the additional damping induced by transient material yielding, the response of the system is likely to be excessively damped. Therefore, it was considered that the corresponding 2-D FLAC analysis will result in a lower-bound estimate of liner forces.

- Damping Case-2: The model was run using a small amount of Rayleigh damping (i.e., 1%) and letting the model damp out the strong motions through material yielding and simple hysteretic loops. Damping in this model is considered to be slightly higher than that from the unload-reload loops of actual landfill materials since the hysteretic loops produced by the Mohr-Coulomb model are larger. Consequently, the corresponding 2-D FLAC analysis will result in a realistic upper-bound estimate of liner forces.

The results of the 1-D FLAC analyses confirmed that within the region of the cavity and the liner, Damping Case-2 generally predicted conservative results. The differences in the computed dynamic shear stresses varied by as much as 10 to 15%. The results of this phase of the analysis suggested that uncertainty in the damping response had a relatively minor effect on the calculated shear stresses in the vicinity of the cavity at the selected location.

The 2-D dynamic analyses were carried out using stress-level dependent shear moduli for an assumed cavity occurrence at 6 ft (1 cavity width) below the liner. This cavity depth was selected for the dynamic analysis because the largest liner forces under static loading conditions were computed for this scenario. As for the static case, the waste was modeled as a frictional material with a friction angle of 35° with no cohesion. In order to prevent the material in the cavity perimeter from immediately flowing into the void, the 1-ft wide elements immediately around the cavity were assigned a cohesive strength of 100 psf (5 kPa); all other elements were modeled with zero cohesion.

A summary of the maximum tensile forces predicted in the liner system is presented in Table 4. For clarity, the forces due to static loading, cavity occurrence, and dynamic effects are shown separately. For seismic loading, the maximum tensile force was predicted to occur 10 to 12 ft away from the centerline of the cavity (i.e., 1.5 to 2 cavity widths).

Table 4. Maximum Tensile Forces Induced in the Liner

Liner Force Component	Case 1 Lower Bound	Case 2 Upper Bound
Maximum Incremental Force Due to Cavity Occurrence, lb/ft	1,985	1,985
Maximum Incremental Force Due to Seismic Loading, lb/ft	95	135
Maximum Liner Force, lb/ft	2,080	2,120

These results indicate that the incremental stresses produced by seismic loading are relatively low, reflecting the fact that large waste displacements into the cavity (and hence large liner tensions) have already occurred under the static loading condition. In addition, the analysis is relatively insensitive to variations in assumed damping behavior.

CONCLUSIONS

The results of the numerical simulations indicate that the potential for propagating the voids under seismic loading conditions is low, and that static loading conditions control the forces that develop in the landfill liner.

The forces in the liner were sensitive to whether or not the waste material has a cohesive component of shear strength, increasing by a factor of almost 10 if the waste does not have cohesion. Although the available published data indicate that MSW materials do exhibit both cohesive and frictional components of shear strengths, they may behave with diminished cohesive strength over the long term as a result of factors such as waste composition and creep. Hence, the results assuming no cohesion represent a reasonable upper-bound to potential liner stresses.

The computed dynamic loading increment in the liner was much smaller than the static component, primarily due to large deformations or complete collapse of the void in most of the cases under static loads. For design purposes, the maximum geomembrane stress may be estimated as the sum of the maximum static load under collapsed conditions and the dynamic increment.

This study also indicated that even under worst-case static loading conditions, stresses in the geomembrane decreased to less than 50% of the maximum value when the cavity was deeper than 3 times the void-width below the liner. Hence, if the liner is designed to withstand the stresses of shallow cavity collapse, voids below this depth will not have a significant effect on the liner system. For the "refrigerator size" void, this depth is on the order of 15 to 20 feet, which is often within the detection capabilities of geophysical methods.

REFERENCES

1. Itasca Consulting Group, Inc., 1998, *FLAC (Fast Lagrangian Analysis of Continua)*, Version 3.4, Minneapolis, Minnesota.

2. Eid, H.T., Stark, T.D., Evans, W.D., and Sherry, P.E., 2000, "Municipal Solid Waste Slope Failure. I: Waste and Foundation Soil Properties", *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 126, No. 5, ASCE, Reston, Virginia.

3. Fassett J.B., Leonards, G.A., and Repetto, P. C., 1994, "Geotechnical Properties of Municipal Solid Waste and Their Use in Landfill Design", in *Proceedings of WasteTech '94*, National Solid Waste Management Association, Washington, D.C.

4. Kavazanjian, E. Jr., Matasovic, N., Bonaparte, R., and Schmertmann, G. R., 1995, "Evaluation of MSW properties for Seismic Analysis," *Geoenvironment 2000*, ASCE Geotechnical Special Publication No. 46, 2, ASCE, Reston, Va., pp. 1126-1141.

5. Matasovic, N., and Kavazanjian, E. Jr., 1998, "Cyclic Characterization of OII Landfill Solid Waste," *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 124, No. 3, March, pp. 197-210.

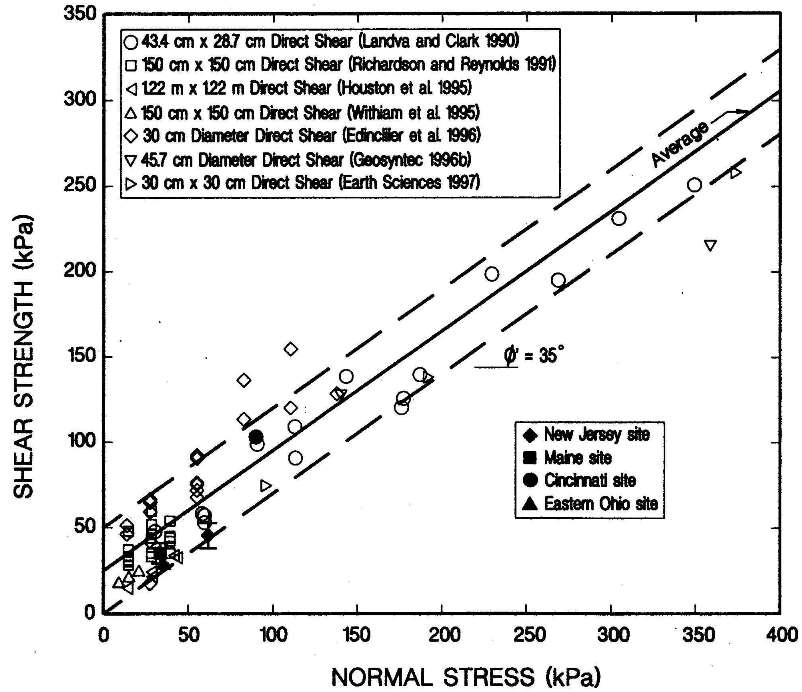

FIG. 5. Summary of Measured and Back-Calculated Data on Shear Strength of Municipal Solid Waste

Figure 1. MSW Strength from Eid et al. (2000).

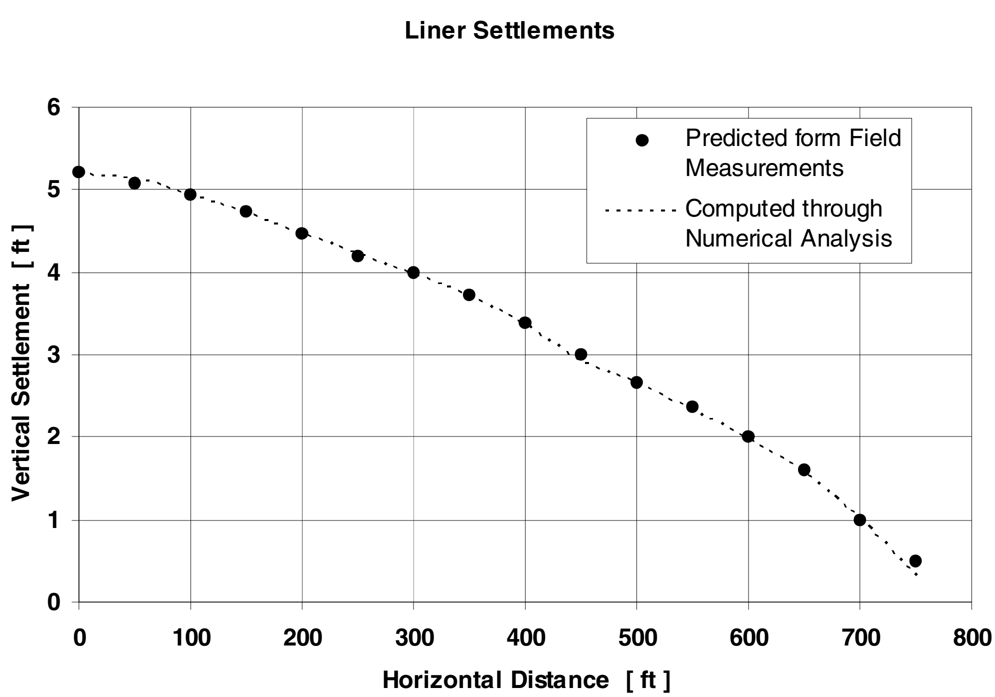

Figure 2. Predicted Landfill Settlement Profile at Closure.

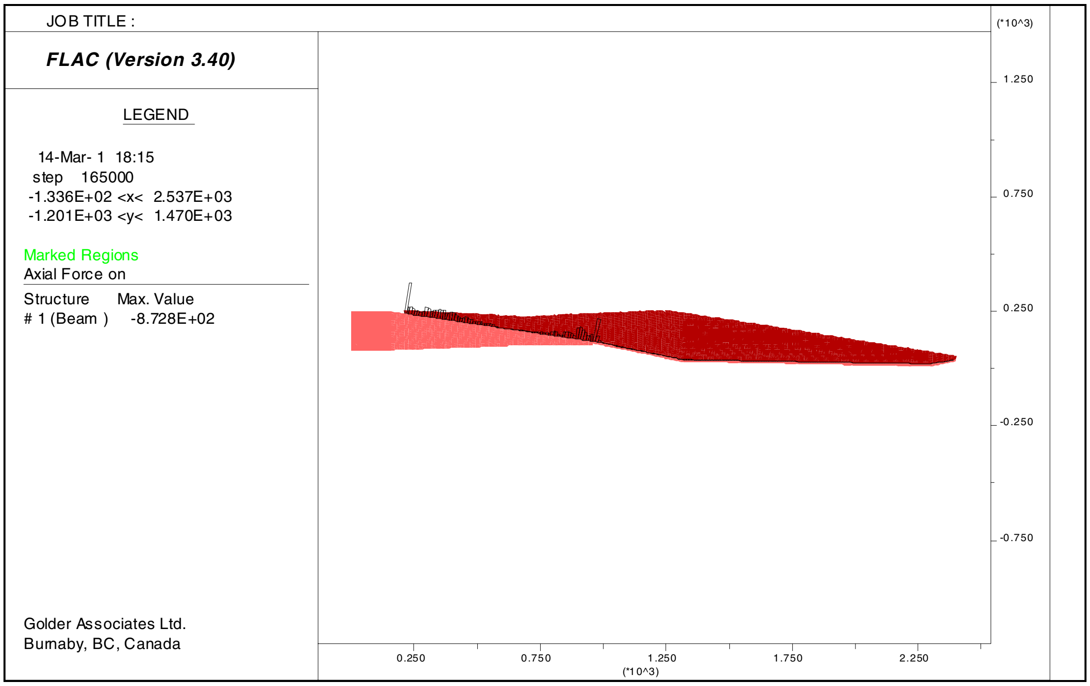

Figure 3. Profile of Predicted Tensile Forces Along Liner.

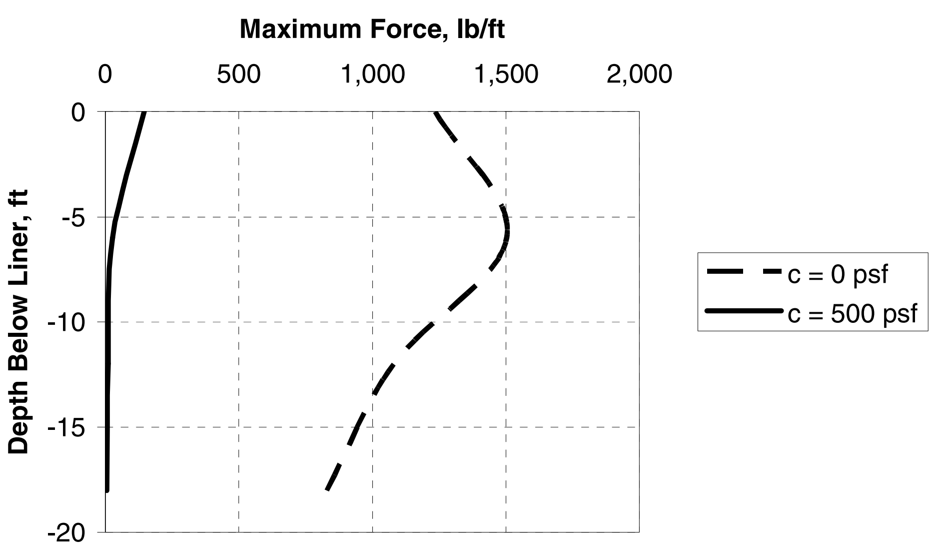

Figure 4. Maximum Geomembrane Tension vs. Void Depth Below Liner
Static Loading Condition.

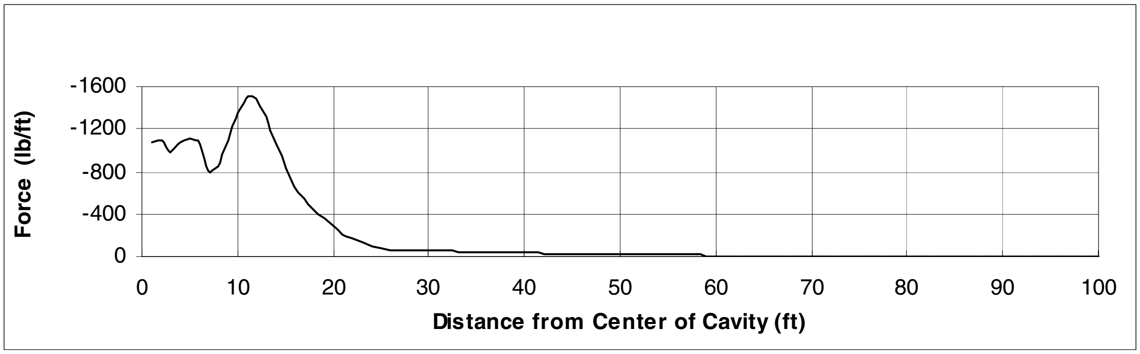

Figure 5. Tensile Force in Geomembrane – Cavity 1 W Below Liner.

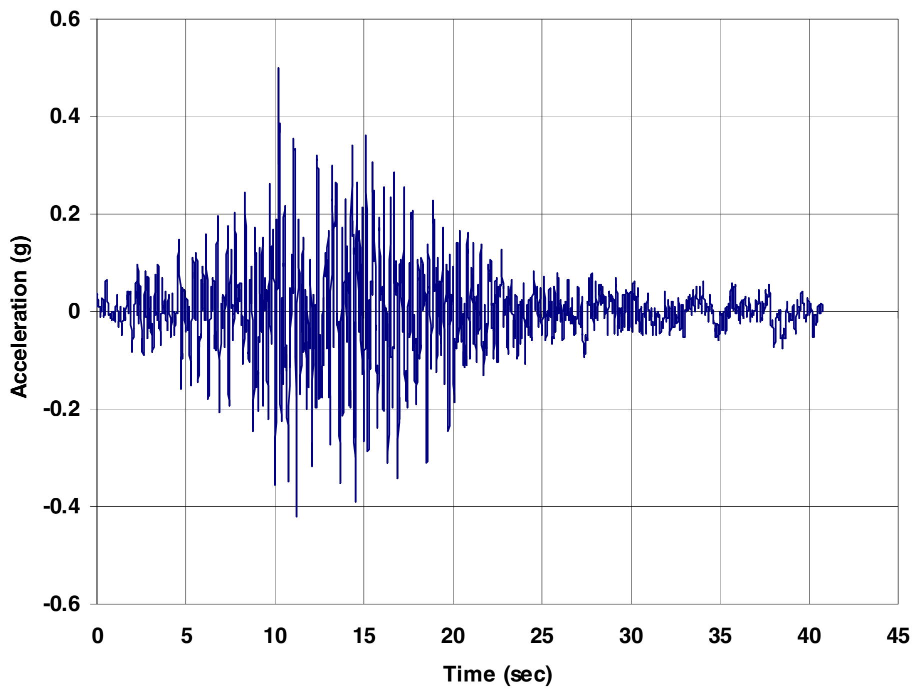

Figure 6. Modified Earthquake Motion to Fit Target Response Spectrum.

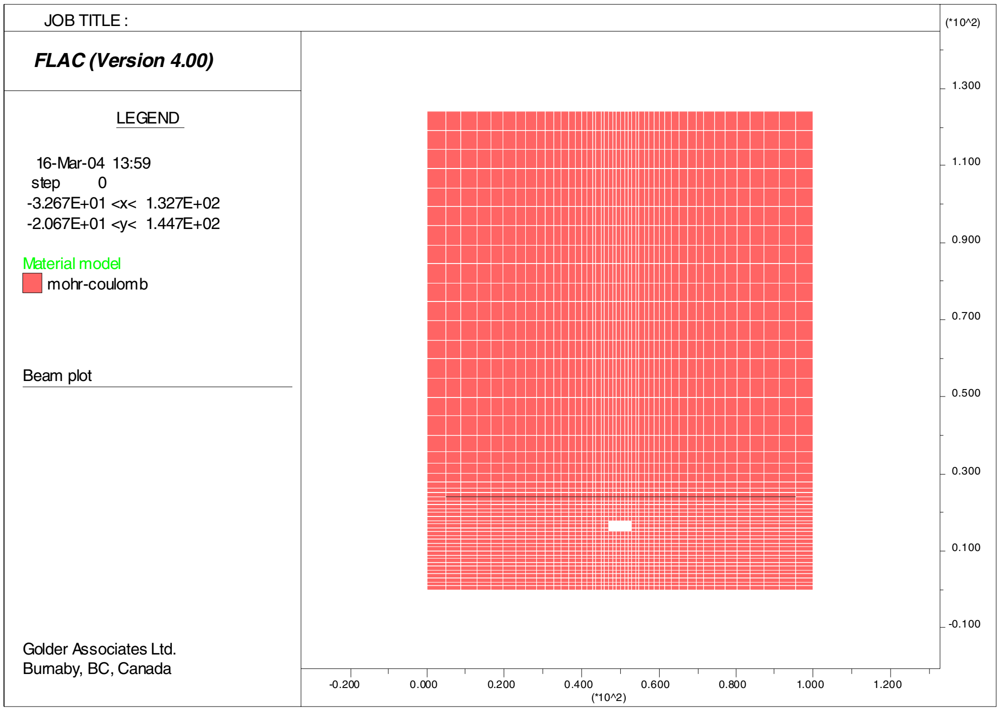

Figure 7. Cavity Finite Difference Model for Seismic Analysis.

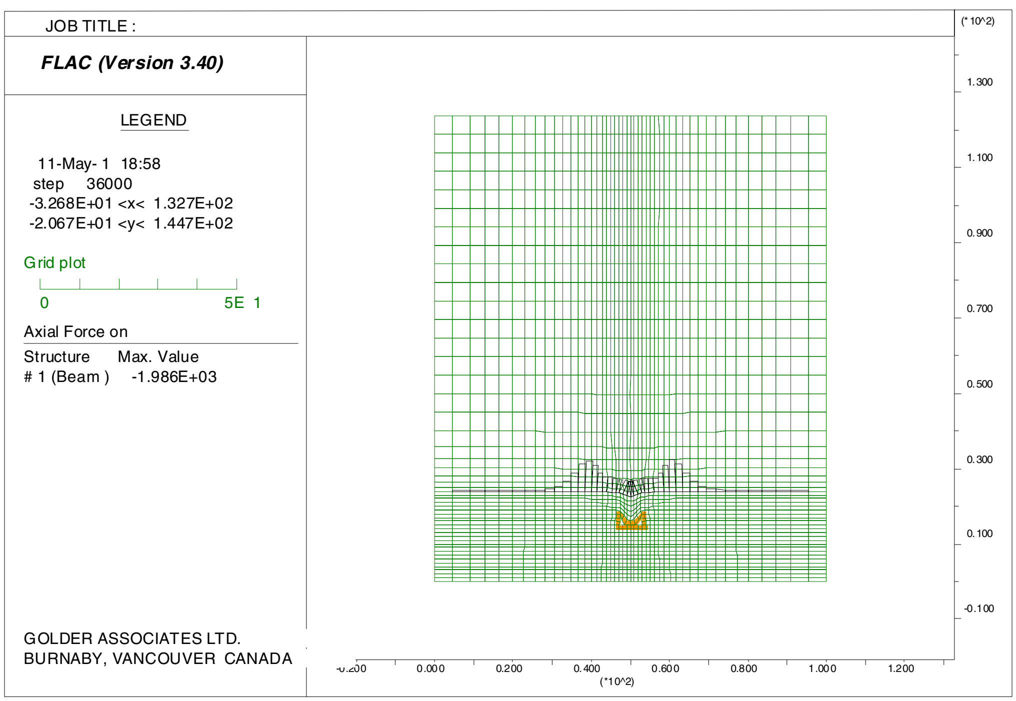

Figure 8. Liner Forces Induced by Cavity Occurrence in Model for Seismic Analysis.