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Project Summary

Settlement and Cover Subsidence of Hazardous Waste Landfills

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Numerical models using equations for linearly elastic deformation were developed to predict the maximum expected amount of settlement and cover subsidence, and potential cracking of the cover by differential settlement in uniformly, horizontally layered hazardous waste landfills. The hazardous waste landfill models represented landfills in which unsaturated wastes were contained in standard steel drums that were assumed to deteriorate ultimately in the landfill. The models were analyzed using methods of linear elasticity to estimate the maximum amount of subsidence of the final cover to be expected before and after landfill closure and after deterioration of the waste containers. The model landfill consisted of alternating layers of intermediate inert cover soils and steel drums filled with simulated waste materials. Waste drums, waste materials, and intermediate cover soils were assigned values of density, Young's modulus, and Poisson's ratio for the analysis. Landfill geometry, layer thicknesses, waste drum placement, steel drum stiffnesses, and laboratory consolidation tests on the soils and simulated wastes were also considered. To simulate postclosure waste layer deterioration, compression of the fill was calculated for decreasing values of the Young's modulus of the waste layers. The analyses indicate that as much as 92 percent of the expected subsidence of the cover is caused by closure of cavities (void space) inherent in landfilling. The maximum expected subsidence was calculated to be approximately 12 percent of the total landfill thickness. If all of the waste drums are assumed to contain 10 percent void space (a "worst case" condition) the maximum subsidence could be as high as approximately 20 percent of the fill thickness.

Finite element method (FEM) analysis of differential settlement across the landfill indicates that tensile stresses do not develop, and therefore that cracking by settlement does not occur in the final cover of the landfill as modeled. Numerical and FEM models were based on data gathered for several active commercially operated hazardous waste landfill facilities in the United States. Other settlement and subsidence mechanisms, including karst and subsurface mining experiences, sanitary and low-level nuclear waste landfill experiences, and classic soil consolidation theory were addressed in addition to linear elastic deformation.

This Project Summary was developed by EPA's Hazardous Waste Engineering Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Background

Settlement of sanitary and low-level nuclear waste landfills with subsequent damage to or compromise of the integrity of the covers is a recognized and documented occurrence. The U.S. Environmental Protection Agency (EPA) is concerned that settlement within hazardous waste landfills may produce similar subsidence problems with cover systems.

The failure or distortion of the cover system may cause consequences that are totally unacceptable to managers of hazardous waste. Little documentation exists of the extent, potential for, or mechanics of settlement/subsidence in hazardous waste landfills.

Purpose

This study was conducted to determine the potential for settlement of the fill and subsequent subsidence-related damage to cover systems of hazardous waste landfills and to provide information necessary for developing and improving interim and future regulatory guidance. A goal was to develop predictive numerical models to estimate the amount of subsidence and strain that would be expected to occur in the landfill and cover as a result of settlement. It was first necessary to characterize the hazardous waste landfill with respect to design, operation, and physical properties. This study examined the characteristics of several hazardous waste landfills with special attention to those features expected to influence the potential for settlement of the fill and subsidence of the final cover. Numerical models were developed from assessment of landfill characteristics and suspected settlement/subsidence mechanisms. The potential for degradation or compromise of the final cover is examined through models developed in the full report.

Scope

The study addresses hazardous waste landfills operating under the interim standards imposed by EPA under authority of the Resource Conservation and Recovery Act (RCRA) of 1976. The predictive models developed for the investigation are based on facilities operated by the commercial hazardous waste disposal industry. Other landfill types and subsidence mechanisms operating in geotechnical circumstances other than hazardous waste landfill situations were reviewed in developing hazardous waste landfill models, but the mechanisms and characteristics used to construct the models are those derived from an assessment of several hazardous waste landfills operating with interim status permits under RCRA.

Approach

The approach was to determine from the literature the known mechanisms and analytical techniques of settlement and subsidence in all geotechnical areas including mining, landfill, engineering fills, karst (geologic), tunneling and foundation investigations; to determine the mechanisms most likely to be active in a hazardous waste landfill; and to select the proper methods of analysis. A review was made of literature pertinent to settlement and subsidence in landfills. The initial computer data search used the information retrieval systems DIALOG, National Technical Information Service (NTIS), GEOREF, and COMPENDEX to compile listings and abstracts of pertinent reports and documents. Review and updating of literature continued throughout the study. Site characterization, necessary for model development and problem assessment, was accomplished by contacting the hazardous waste disposal industry and through site visits to selected facilities to obtain real data on site geometry, liner and cover design and properties, waste and fill placement procedures, waste and fill physical properties, compaction efforts, leachate collection and control, subsidence experiences, and other relevant information. Sites were selected for their location, representing several areas of the nation and several climate and soil conditions; for their size, representing for the most part large facilities; and for their current activity, i.e., their status as viable commercial landfill facilities operating under RCRA guidance.

In addition, selected state agencies familiar with hazardous waste disposal in their states were contacted for further information including information about potential or existing subsidence problems, and to obtain an indication of the amount and kinds of variation in operational procedures to be expected nationwide. The authority for implementing RCRA interim standards on the state level is vested in the state Departments of Health, Water Resources Boards, special environmental regulatory commissions or departments, Natural Resources Departments, Pollution Control or Solid Waste Management Boards, or state EPAs. Some states have multiple jurisdiction for implementing the standards. The National Directory of State Agencies was used to establish an initial list of contacts. Other regional or site-specific data were obtained from consulting engineering firms and scientists and engineers of state agencies.

Numerical FEM models were developed for selected hazardous waste disposal situations using the data compiled in site characterization and by modifying existing FEM analytical models. The approach in the modeling analysis was to simulate worst-case conditions that would be expected in RCRA landfills, i.e., those situations producing the greatest amount of settlement. Accordingly, the larger facilities where wastes are buried in drums were used to develop the model landfill. The subsidence problem was analyzed by modeling pre- and postclosure maximum settlement in the middle of the landfill and differential settlement across the landfill.

Landfill Modeling

Several commercially operated landfills observed during this study were large pits excavated in natural earth to depths of 50 to 100 ft. The natural earth was typically a soil or rock of low permeability. Landfill structures observed were generally lined with clay and/or synthetic polymeric membranes and equipped with a leachate collection and withdrawal system. The structures were typically filled with alternating waste layers 2 to 3 ft thick and intermediate cover layers about 1-1/2 ft thick. After filling, the landfills are capped with a permanent clay cover layer which is continuous with the sides and bottom liner system. A polymeric membrane may or may not be used in the cover. A representative model landfill section chosen for the purpose of mathematical analysis and demonstration for this investigation is 50 ft deep and 200 ft wide across the cell bottom. Sides slope up to the original ground level at 3 horizontal on 1 vertical and the cover layer slopes up to the crown at 5 percent to give a total depth of 62.0 ft at the center of the landfill. The model landfill is assumed to be constructed and filled exactly as several observed representative landfills.

Solidified material buried in steel drums is expected to make up the most significant portion of the waste in the cells under consideration. A mathematical equation based on the theory of elasticity was developed to allow calculation of maximum subsidence. Use of the equation requires input of waste properties such as density, depth of burial, and stiffness (Young's modulus). Subsidence occurs as a result of postclosure cavity collapse and waste-drum deterioration and softening. The mathematical equation predicts subsidence as a result of waste layer softening which is simulated by lowering the Young's modulus of the layers.

The equations developed in this report and their related subsidence prediction curves apply as well to horizontally layered landfills of varying depths, physical properties,and geometries and are not restricted to landfills with the specific dimensions presented in this report. The analyses are for homogeneous and isotropic materials in layered, unsaturated waste cells. Subgrade materials are presumed to be rigid (noncompressible). The site-specific amount of maximum subsidence depends on the fill depth and the physical properties of the waste, fill, cover and liner materials. Waste properties are presumed to show the most site-specific variability of all the contributing materials and are critical to the accurate prediction of subsidence. Strengths and stress-strain data of actual or simulated waste materials would permit more effective predictions of expected subsidence with the models developed for the full report.

Response of Cover to Maximum Subsidence

Analyses of the numerical settlement models developed for this study indicate that the maximum landfill cover subsidence that would be expected under worst-case conditions (deep fill, deteriorated drums, and low-stiffness waste layers) would be approximately 11½ percent which for the representative landfill would result in a final cover slope of about 2 percent from the crown to the landfill boundary. Most of the subsidence (around 10 percent) occurs by closing of cavities incorporated during filling. The 11½ percent subsidence would not create ponding (negative slope) for the representative landfill assuming a 5 percent cover slope (12.5-ft crown) was established at closure. The resulting 2 percent slope is, however, less than the minimum suggested by EPA (3 percent) to promote drainage. Drainage off the cover is desired to prevent infiltration of standing or slow-draining precipitation with the danger of filling and overflowing the landfill (the bathtub effect) and of creating excessive leachate. An additional subsidence of 8 to 9 percent must be considered if drums are assumed to contain the maximum allowable 10 percent void space when placed in the fill. However, an assumption that all the drums would contain 10 percent void is considered realistic by the authors.

This study has shown that consolidation of the unsaturated intermediate cover (fill) layers occurs relatively soon and prior to closure. Landfills whose waste layers consist predominantly of waste-filled steel 55-gallon drums will experience additional settlement after probably several years during which time the drums and waste deteriorate to progressively lower elastic moduli and strengths. Estimations of waste layer and fill moduli for intact and deteriorated waste container conditions were made and applied to the prediction curves to derive the 11½ percent maximum expected subsidence.

Response of Cover to Subsidence Cracking (Differential Settlement)

The analysis of the assumed hazardous waste disposal cell described shows that tensile cracking does not occur within the body of the landfill configuration modeled for this analysis. For the soil and filling techniques assumed, the stresses which would cause tensile cracking do not develop. The stress and displacement fields observed in the landfill body are well behaved and smooth with no unexpected singularities. There are several reasons for this, including the fact that the landfill material behaves plastically, yielding rather than rupturing. The foundation completely supports the waste material and is very stiff relative to the waste cell contents. An analysis of the vertical surface displacement shows that vertical movement is maximum in the center of the cell and subsidence is almost uniform over the flat-bottomed portion of the cell. This confirms that a central column analysis of subsidence is justified, and allows the subsidence at any point across a typical cell to be estimated if the center subsidence is known. Tensile stresses from differential settlement occurring in other landfills (nonuniform waste layers, for example) were not analyzed.

Other Considerations

The settlement models for this study were developed under the assumption that drained, unsaturated conditions prevailed within the landfill and that containers of free liquids were not included in the fill. It is prudent to consider the effects on settlement of including substantial volumes of free liquids, or stabilized liquids that become unstable with time, in the landfill. A liquids-filled waste drum that had deteriorated sufficiently would release its contents into the surrounding soil or soil-like intermediate cover or into bulk wastes surrounding the drum. Assuming the surrounding fill and bulk wastes were less than 100 percent saturated, the freed liquids would be absorbed into the pore spaces and would increase the saturation of the fill materials. Stabilized or "solidified" liquids that might be released after deterioration of drum contents would be expected to act similarly, but with a smaller volume of liquid. The intermediate cover layers placed will be compacted with construction equipment as discussed earlier. Regardless of the compactive effort applied, two conditions of compaction are possible; compaction wet of optimum water content and compaction dry of optimum water content. If the layers are compacted wet of optimum, allowed to consolidate to 100 percent consolidation under the applied load, and then exposed to free liquid (water), volume change of the clay layer will usually be insignificant. However, if the layers are compacted dry of the optimum water content, two effects might conceivably be expected as a result of post-closure release of liquid; the cover layer could tend to absorb liquid and swell (increase in volume) or collapse (decrease in volume) upon exposure to the liquid. Laboratory investigation has shown that collapse of soil usually occurs at low water contents and at high stress levels, which would mean that the layers at greater depths in the landfill would tend to collapse. Volume change due to collapse is irreversible, that is, the settlement or subsidence due to this phenomenon is not recoverable. Swell usually occurs in soils at low water contents and low stress levels, which would mean for this study that layers at shallow depths in the landfill would tend to swell when exposed to water. Swell, however, may be reversible in that, as surplus water which was absorbed into the soil diffuses with time into dryer regions of the layers, shrinkage may occur and the soil may tend to return to its original volume.

Laboratory tests suggest that to minimize the problem of either swell or collapse of intermediate cover layers, compaction wet of the optimum water content is desirable. In practice, waste and intermediate cover layers of hazardous waste landfills are placed at the existing water content of the soils and no special compactive efforts are made.

At this time, no specific statement may be made regarding the effects of liquid released in a landfill. The ultimate effects of such releases would depend on site-specific factors such as the amount of liquid released, the water content of the layers at the time of compaction, the mineralogy of the intermediate cover layers, the compaction characteristics of the layers, and the stress levels within the layers exposed to liquids.

Conclusions

Conclusions reached as a result of the study are:

1. The dominant mechanisms of settlement of the fill and subsidence of the covers of horizontally layered hazardous waste landfills are expected to be closing of the inherent drum-placement void spaces and compression of cell contents including intermediate cover soils, waste, and waste containers. Cavity related piping and sinkhole phenomena are not expected to play a major role in predicted subsidence. This conclusion is based on review of representative active waste disposal practices in industry and government and analysis of documented and theoretical subsidence mechanisms reported in other, related activities.
2. The maximum postclosure subsidence of the cover (cap) of a simulated hazardous waste landfill operating under interim RCRA guidelines, from compressibility alone, is predicted to be about 11½ percent of the total height of the fill and cover at the center of the landfill. For a 62.5-ft-thick fill and cover the maximum expected subsidence, after deterioration of the waste containers, was 87 in. The final cover slope with that subsidence would be about 2 percent, which is undesirable under current RCRA guidelines. An additional 8 to 9 percent subsidence must be considered if waste drums are assumed to contain the maximum allowable 10 percent void space when placed in the fill.
3. Actual landfill settlement and cover subsidence may be less than the worst-case maximum predicted 11½ percent because more of the voids between containers will probably be filled as a result of less than optimum (tight) stacking of containers during placement. The 11½ percent figure is considered an effective value for design purposes.

Recommendations

Cover subsidence from settlement of compressible fill is expected to occur. Therefore, to minimize the severity of subsidence, managers of hazardous waste landfills should continue at least those operational methods that are being practiced at representative RCRA-guided secure landfills as determined from field observations of this study. Recommended operational methods include:

1. Landfill operators should make an effort to reduce voids when placing wastes and fill within the cell by insuring that intermediate cover soils are allowed to sift between waste containers and debris. Drums or other containers of wastes should be filled to minimize the volume of void within the containers. Much of the potential settlement from compressibility can be eliminated by preventing the inclusion of cavities in the waste placement process in the typical hazardous waste landfill.
2. Layering of waste and intermediate cover in thin lifts so that some compactive effort is achieved during filling.
3. Control of liquids by installation of efficient leachate collection systems and stabilization of liquid wastes to prevent saturation of the fill and to allow consolidation to occur as rapidly as possible.
4. Installation and monitoring of cover settlement plates so that the subsiding surface can be maintained at the proper slope. Hazardous waste landfills should be documented, instrumented, and monitored after closure. Subsidence of the cover as well as the settlement of internal waste layers should be monitored with time in an effort to gain understanding of postclosure internal changes, how they occur, and how they affect the overall behavior of the landfill. Many of the mechanisms at work within these landfill cells can be understood only by study and experience with representative landfill cells. The data obtained by field monitoring will permit evaluation and improvement of settlement/subsidence prediction models developed in this study. Landfill operators should remember that, while the cover surface can be maintained at a proper runoff slope by the addition of soil or other material, the internal cover liner, whether a clay layer or a flexible membrane liner or both, may have been deformed and stressed by subsidence. Internal cover liner damage or deformation cannot be remedied by simple cover surface cosmetic actions.
5. Placement of a buffer thickness of intermediate cover soils above the uppermost waste layer and beneath the final cover to lessen the potential for collapse of the cover directly above locally compressible zones such as deteriorating drums.

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The complete report, entitled "Settlement and Cover Subsidence of Hazardous Waste Landfills," (Order No. PB 85-188 829/AS; Cost: $13.00, subject to change) will be available only from:
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