Landfill Instability and Its Implications for Operation, Construction, and Design

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INTRODUCTION

An inordinate number of Ohio waste containment facilities experienced collapse between 1996 and 2003. Failures included a massive 1.4 million cubic yard landfill waste slide, a 300,000 cubic yard landfill failure involving a geosynthetic clay liner, and a 100,000 cubic yard landfill failure involving leachate recirculation. Other failures of lesser magnitude also occurred involving liner systems during construction and waste containment closures. Recently an older closed landfill in an urban setting was being reshaped as part of a large commercial development and also began to slide, halting the project and impacting adjacent properties. Construction and operational activities triggered the majority of the above noted failures. These activities are often planned or carried out independent of the design process and subsequently bring about circumstances that are unforeseen during the design of the facility. Some examples of these activities include excavations for repair of gas and leachate systems, relocation of access roads, temporary routing of storm water, and phase changes. The failures led Ohio EPA to form the Geotechnical Resource Group (GeoRG) a work group dedicated to the geotechnical concerns of waste containment structures. GeoRG has completed a significant policy manual on geotechnical and stability analyses for the design of landfills and remedial closures. It is the most definitive treatise on the specific geotechnical issues facing waste containment structures available. The presentation will summarize pertinent failures, lessons learned, and the geotechnical analysis manual.

OPERATIONAL IMPLICATIONS

In the event of a landfill instability such as a slope failure the first concern is always safety, safety of site personnel, safety of site entrants, and safety of the general public. The situation will need to be assessed concisely and the necessary emergency procedures or precautions implemented as quickly as possible. The notification of internal and regulatory authorities will obviously also need to begin in a timely fashion as well.

Attention will then need to be directed towards operational logistics. If the site has limited available airspace impacted by the faillure the diversion of all or a portion of the incoming waste will need to be contemplated. If maximum daily waste receipts are regulated, neighboring landfills receiving diverted waste may need to take steps to increase their allowable incoming tonnage. Hauling companies and independents may have to scramble to find the most economical alternative. Rural sites where the majority of waste is hauled in by small independents may want to consider transferring waste.

Slope failures and other instabilities involving waste will usually require the relocation of wastes for corrective actions. The volume of waste to be relocated can increase significantly from the volume of unstable waste because of the need to lay back the slopes around the impacted area. One of the most common scenarios involves the failure of an existing waste mass during tie-in of an adjacent cell. A relatively small slip involving a 100 by 40 foot area can require the relocation of more than 15,000 cubic yards.

Slope failures exposing the waste mass will at a minimum increase odor, increase exposure risk to personnel and the public, and increase the risk of fire. The relocating and covering of waste should be preformed quickly and safely. If the site accepts asbestos, an air monitoring program may need to be developed. Spray-on daily cover can provide short term relief while the waste is being relocated and should be considered.

Slope failures often temporarily shut down gas extraction systems or permanently destroy them, so solid waste landfills that are involved in contractual waste to energy projects may be faced with legal action by the purchaser for damages. If landfill gas is used for a facility purpose such as in the case of a leachate evaporator, the site may incur unforeseen leachate disposal costs.

Unbudgeted engineering costs will also likely be incurred as regulatory authorities may stipulate forensic investigations and approval of remedial plans will likely be required. Regulatory programs are also beginning to discuss the idea of cost recovery for the intensive oversight that slope failures can generate from the federal, state, and local levels. This includes engineering, legal, health department, inspection, and possibly outside expertise.

CONSTRUCTION IMPLICATIONS

Statistically most landfill instabilities occur during construction. This is simply that point in time when stress conditions and stress concentrations in the foundation and stabilizing materials are in the greatest flux. This can be exacerbated by filling areas beyond a safe level. Operators should always know and understand the maximum slope and height, with an applicable safety margin, for the current fill area.

Landfill operators suddenly thrown into an emergency or reactionary mode by a slope failure will most likely rely on the existing contractor and consultants to plan and perform mitigating activities to limit further contamination or damages. Be aware that in rare instances this may be analogous to having the fox in the henhouse. Striking the balance between due diligence and cost effectiveness will be a difficult task. Contractors and engineers regardless of being incumbents or experts brought in on the fly will be in unfamiliar territory and possibly working around the clock on a time and expenses basis. Incumbents will be trying to get their hands around the matter at hand and experts will be coming up to speed on the site.

Specialty equipment and skills may be required to carry out mitigating efforts and or remedial activities. Long reach excavators, heat resistant slope inclinometers, and roto-sonic drill rigs are specialty equipment the authors have seen used for waste slope failure investigations and remediations. Remote controlled equipment, intrinsically safe equipment, and self contained breathing apparatus are some examples of specialty items that may be needed. Example technologies that may be required for mitigation and remedial efforts include directional drilling, microtunneling, and downhole surveying.

Also note that whatever construction was occurring will likely grind to a halt, or even be destroyed by the slope failure. Sites that build "just-in-time" may face a space crunch that will keep the landfill in an emergency (i.e. expensive) mode long after mitigation and remedial activities are in hand.

DESIGN IMPLICATIONS

The first matters that a consultant will likely have to contend with after a slope failure have little to do with design. A significant amount of time will likely be spent with regulatory authorities discussing known events leading up to the failure, anticipated mitigation efforts, possible impact assessment measures, likely remedial plans, etc. In addition, media or public interest may require the consultant's time to address technical questions. It should be noted that this interest can be intense and persist for months.

For failures involving airspace the remaining waste volume will need to be determined. If air space is limited, and it always seems to be, engineering efforts should be directed towards developing schemes to utilize airspace impacted by the instability and or formulating abbreviated methods for developing new airspace as quickly as possible.

The mitigation/remediation engineer must hastily and accurately assess client need and regulatory climate for achieving design approval. In the permitting world there are often months for this dialogue to play out. With a failure involved there may only be days.

Some level of forensics will need to be conducted. The regulatory authority may require a full blown investigation or the forensic investigation may simply be a matter of understanding the failure for planning the remedial design.

Primary questions that arise and will need answers are:

- How much moved?
- Has it stopped moving completely?
- Is the landfill or at least the rest of landfill stable?

Remediation of typical slope failures in soil often involves removal of excess driving weight from the upper slope, buttressing of the toe with additional weight, and dissipation of pore pressure. While these techniques will also work with waste, keep in mind that if a liner system is involved the remedial course will often necessitate removal of all waste associated with the failure in order to repair the containment and leachate collection systems.

If exhumation of waste is required try to establish clear conditions for terminating removal. For example removal of waste can result in the rebound of underlying materials accompanied by subsequent (perhaps a day or two later) wrinkling of geosynthetics. It looks uncannily similar to the wrinkles one would expect from a slope that continues to creep. Additional issues that can be anticipated when removal of waste is required are: condition of geosynthetics, condition of compacted clay, maintaining the integrity of the compacted clay liner during the extended period for removal and reconstruction, reuse of undamaged geosynthetics or other engineered components.

PREVENTION

Facilities that haven't determined their risk of slope failure are exposing themselves to a great deal of liability. Owners and operators need to consider having their facilities completely evaluated for stability. Most facilities have had the stability of the cap or final configuration of the landfill analyzed. Interim waste slopes and as constructed liner slopes should also be analyzed as failures of these slopes seem to be the majority of the cases in the literature. This is especially if their facility has slopes greater than 4H:1V.

In September, 2004, the Geotechnical Resource Group (GeoRG) in the Division of Solid and Infectious Waste Management of the Ohio Environmental Agency (Ohio EPA) issued a policy for conducting geotechnical and stability evaluations for waste containment facilities. This policy was issued to assist landfill owners in demonstrating that geotechnical and stability requirements had been met. The policy document is available at, http://www.epa.state.oh.us/dsiwm/document/guidance/gd_660.pdf.

The policy was developed to highlight and avoid the many risks associated with slope failures at waste containment facilities. These risks include risks to human health, the environment, communities, governments, and responsible parties such as risks of ground water and surface water contamination, air contamination, fire, and interruption of waste collection services. Stability failures are usually caused by landfill activities that increase the applied shear stress to the weakest material in the landfill cell area or decrease the shear resistance of this weakest material. Some of the planned or unplanned activities that can lead to a slope failure include: placement of soil or waste from the top to the bottom of a slope, lengthy or unplanned toe excavations, regrading of waste for operational or closure purposes, leachate recirculation, overfilling, blasting, stockpiling of materials, waste relocations, relocation of access roads, and inadequate base liner length on the facility bottom to resist driving forces caused by the waste on the associated interim or final slope. The large number of slope failures that have occurred in Ohio prompted development the policy to ensure proper and thorough geotechnical and stability evaluations would be conducted and facilitate Ohio EPA review by encouraging uniformity of submittals.

A geotechnical and stability evaluation should be considered whenever a responsible party is applying for authorization to permit, establish, modify, alter, revise, or close any type of waste containment facility. These evaluations should also be considered whenever circumstances indicate that doing so is prudent. These circumstances include when an earthquake occurs, a phreatic or piezometric surface exceeds the maximum level used in prior stability analyses, new data on the foundation soils becomes available, operation does not correspond to the design, and/or a slope failure occurs.

The policy suggests that the engineering report should contain seven sections to ensure coverage of the important geotechnical and stability evaluations. These sections are discussed in detail below and are: (1) subsurface investigation, (2) materials testing, (3) liquefaction potential evaluation and analysis, (4) settlement analysis and bearing capacity, (5) hydrostatic uplift analysis, (6) deep-seated failure analysis, and (7) shallow failure analysis.

Subsurface Investigation

The policy recommends that the results of the subsurface investigation be included in a separate section of the geotechnical and stability report instead of co-mingling it with the various analyses. This section provides the information used to characterize the unconsolidated (soil) stratagraphic units underlying the proposed or existing waste containment facility. The purpose of characterizing the subsurface conditions is to determine if the soils beneath a facility will remain stable under static and dynamic conditions during construction and operation of the facility, and after the facility is closed. A comprehensive soil stratigraphy should be developed and the critical layer(s) identified. A critical layer is defined as a soil of any thickness that has a drained or undrained shear strength suspected of being capable of allowing a failure of all or part of the facility constructed on it. In addition, the subsurface investigation must identify and characterize all compressible layers. Compressible layers are soil or fill materials that may settle after establishing a facility and that may continue settle after closure of the facility. The compressible layer must be identified and characterized to conduct the settlement and bearing capacity analyses described subsequently. At a minimum the subsurface investigation information should include:

- A summary describing the objectives of the subsurface investigation, assumptions used, methodologies used, and identification of the critical layers, and temporal high phreatic or piezometric surface(s).
- Tables summarizing all field and laboratory test data.
- Topographic maps showing the location of each boring, cross-section, and the extent of the critical design layers.
- Cross-sections that show the soil stratigraphy, temporal high phreatic surfaces, and temporal high piezometric surfaces, and the characteristics of each soil unit.

- A description of the investigation into the critical layers in terms of stability and compressibility.
- Any other figures, drawings, or references relied upon during the investigation and marked to show this information relates to the particular facility.

Materials Testing

The results of all materials testing completed during the design of the waste containment facility should be included in the Subsurface Investigation section. However, the following information should be included in the Materials Testing section so the test data can be evaluated on accuracy and relevance. Testing of the in situ soils must occur during the subsurface investigation when preparing to design a waste containment facility. Testing of soil materials that will be used for structural fill, recompacted soil layers, and other engineering components, e.g., geosynthetics can be conducted and is recommended during the subsurface investigation or as conformance testing before construction. Geosynthetic testing is likely to occur during the conformance testing because of frequent changes in the geosynthetic materials. The testing should be conducted using ASTM test methods or other applicable standards. The information that should be reported in this section includes:

- A narrative and tabular summary of the scope, extent, and findings of the materials testing.

- A description of collection and transport procedures for the soils samples to assess sample quality.
- Test setup parameters for both soil and geosynthetic testing and protocols for each test, e.g., normal stresses used, hydration, and displacement/shear rate.
- Description and characterization of specimen tested to asses how representative the specimen is to critical field conditions.
- The intermediate data created during each test.
- The final results of each test and the corresponding engineering properties.
- Any figures, drawings, or reference relied upon during the testing and data reduction that are marked to show how they relate to the facility.

Liquefaction Potential Evaluation & Analysis

Several states' rules require that the soil units at a waste containment facility be able to withstand the effects of a plausible earthquake and rule out the possibility of liquefaction. This is required because it is generally accepted that the engineered components of a waste containment facility will lose their integrity and no longer be able to function if a foundation soil layer liquefies. Soil liquefaction occurs in loose, saturated cohesionless soil units, i.e., sands and silts, and sensitive clays, and results in a sudden loss of strength and stiffness. Liquefaction can adversely impact a waste containment facility because of foundation settlement, lateral spreading, and even flow failure.

The purpose of this section is to describe the geotechnical evaluation performed to assess the liquefaction potential of the foundation materials. The liquefaction analysis procedure is outlined in the policy. The evaluation includes an assessment of the design earthquake and peak bedrock acceleration, and a liquefaction potential analysis based on available geotechnical and geologic data for the site.

The policy suggests that seismic hazard used for the design of a proposed landfill should initiate with a peak horizontal bedrock acceleration obtained form the U.S. Geological Survey (USGS) website (www.usgs.gov) using the zip code of the landfill site.

The policy expands on federal guidance and presents five preliminary screening criteria, which are used to determine if a comprehensive liquefaction analysis should be conducted. If three or more of the criteria indicate that liquefaction is not likely, the potential for liquefaction can be dismissed and a more rigorous analysis is not required. The five prescreening criteria (1) geologic age and origin of the soil, (2) saturation of the cohesionless soil, (3) a depth below the ground surface greater than 50 feet, (4) high soil penetration or shear strength, and (5) high fines content and plasticity index. The information that should be reported in this section includes:

- A narrative and tabular summary of the scope, extent, and findings of the liquefaction evaluation and analysis including all soil units evaluated.
- A detailed discussion of the liquefaction evaluation including an evaluation of the five preliminary screening criteria, the relevant subsurface investigation results, a description of each layer that exhibit three or more of the preliminary screening criteria, and the detailed analysis used for these layers.
- Any figures, drawings, or reference relied upon during the testing and data reduction that are marked to show how they relate to the facility.

Settlement Analyses & Bearing Capacity

It is important to account for settlement in the design of the facility because (1) overall settlement can result in changes in liquid drainage flow paths for leachate and cause damage to piping in the leachate collection and removal system (LCRS) and (2) differential settlement can result in damage or failure of the bottom liner system, LCRS piping, containment berms and other engineered components. The main factors leading to settlement of a waste containment facility are changes in soil stratigraphy, landfill geometry, and unit weight of the waste materials. These factors are important where the facility is founded on a compressible foundation material, such as in situ clayey soils, poorly compacted materials, and/or waste materials. However, overall settlement and differential settlement should be analyzed for all of the soil materials involved including in situ soils, mine spoil, added geologic material, structural fill, recompacted soil liners, and waste materials. The differential settlement analyses should focus on areas where changes in foundation materials warrant evaluation, such as areas with high mining walls, separatory liners over waste, lateral or vertical changes in soil stratigraphy, and where significant changes in loading occurs.

Waste containment facilities should be designed to satisfy applicable minimum regulator design requirements at the time they are ready to receive waste and continue to satisfy applicable minimum design requirements after primary and secondary settlement is complete.

The bearing capacity analysis uses similar subsurface data, stress distribution calculations, and are similarly affected by the geometry of the facility. Design of a facility to account for induced settlement usually addresses the bearing capacity issue because if the consolidation settlements are tolerable, the soil has sufficient shear strength to resist a bearing capacity failure. However, there are cases that warrant a bearing capacity analysis such as construction of a landfill over soft clay, use of a vertical leachate sump riser, or fill placement over a stabilized waste. The information that should be reported in this section includes:

- A narrative and tabular summary of the scope, extent, and findings of the settlement and bearing capacity analyses including all soil units evaluated.

- A detailed discussion of the settlement and bearing capacity analyses including a description of the analyses, development of the settlement parameters, drawings showing the critical cross-section analyzed, and plan view maps showing the top of the liner system, the liquid containment and collection system, the location of the points where settlement is calculated, the expected settlement associated with each point, and the limits of waste the waste containment units.
- Any figures, drawings, or reference relied upon during the testing and data reduction that are marked to show how they relate to the facility.

Hydrostatic Uplift Analysis

Hydrostatic uplift may affect the subbase or engineered components of a landfill any time piezometric pressures groundwater exists at a facility. In addition, when an excavation or a portion of the facility will be constructed below the ground water surface, the potential for hydrostatic uplift of the landfill components can occur and should be considered in the design process. When the ground water head is sufficiently high, pressure may cause soil layers affected by the pressure to lose strength and fail much in the same manner as earthquake-induced liquefaction. The information that should be reported in this section includes:

- A narrative and tabular summary of the scope, extent, and findings of the hydrostatic uplift analysis including all soil units evaluated.
- A detailed discussion of the hydrostatic uplift analyses including a description of the analyses, the relevant subsurface investigation,

isogram maps comparing the excavation and construction grades, depicting the temporal high phreatic and piezometric surface, and showing the limits of the waste containment units.

- A summary of the worst-case scenario used to analyze the hydrostatic uplift potential of the facility should also be included.
- Any figures, drawings, or reference relied upon during the testing and data reduction that are marked to show how they relate to the facility.

Deep-Seated Failure Analysis

Deep-seated translational failures can occur along a weak geosynthetic interface or through a weak foundation material. The Ohio EPA considers any failure that occurs through a material or along an interface that is loaded with more than 1,440 psf to be a deep-seated failure. The potential for a slope to experience a deep-seated translational or rotation failure is dependent upon many factors including, the angle and height of the slope, the angle and extent of the foundation materials, the geometry of the slope toe, the foundation soil pore-water pressures, seismic or blasting effects, and low shear strength of any material. Translational failures are more prevalent at facilities containing geosynthetics. Rotational failure are more prevalent at facilities that are made of or filled with weak materials or are supported by relatively weak foundation soils. Rotational failures tend to occur through a relatively uniform material, where translational failures tend to occur when dissimilar materials are involved.

Deep-seated failures can be catastrophic, detrimental to human health and the environment, and very costly to repair. Thus, extensive slope stability analyses should be conducted for the evaluation of deep-seated failure surfaces for a proposed waste containment facility. The analyses should consider slopes during construction, slopes during filling, and final slopes.

The information that should be reported in this section includes:

- A narrative and tabular summary of the scope, extent, and findings of the deep-seated failure analysis including all soil units evaluated and the input and output files from the slope stability software.
- One or more tables summarizing the internal and interface shear strength of the various components of the internal, interim, and final slopes of the facility.
- Graphical depictions of any individual and compound stress-dependent shear strength envelopes being utilized for each geosynthetic interface, material, or composite system.
- One or more tables summarizing the factors of safety of the deep-seated failure analysis on all of the cross-sections analyzed.
- Identification of the critical cross-section and failure surface.
- A detailed discussion of the deep-seated stability analyses including a description of the analyses, development of the shear strength and other parameters, drawings showing the critical cross-section analyzed, and plan view maps showing the location of the cross-sections analyzed.

- Any figures, drawings, or reference relied upon during the testing and data reduction that are marked to show how they relate to the facility.

Shallow Failure Analysis

The potential for shallow translational failures or shallow rotational failures of internal and final slopes should also be evaluated. Internal slopes are slopes that will eventually be buttressed with waste or fill. The Ohio EPA considers any failure that occurs through a material or along an interface that is loaded with 1,440 psf or less to be a shallow failure. In a typical waste containment facility the internal slopes considered include the leachate collection and removal drainage layer placed on a sideslope and the final cover system. The veneer of drainage material on a sideslope must remain stable until it is buttressed by solid waste. The final cover system over the waste also must remain stable for at least the 30 year post-closure period.

The information that should be reported in this section includes:

- A narrative and tabular summary of the scope, extent, and findings of the shallow failure analysis including all soil units evaluated and the input and output files from the slope stability software.
- One or more table summarizing the internal and interface shear strength of the various components of the shallow slopes in the facility.

- Graphical depictions of any individual and compound stress-dependent shear strength envelopes being utilized for each geosynthetic interface, material, or composite system.
- One or more tables summarizing the factors of safety of the shallow failure analysis on all of the cross-sections analyzed.
- Identification of the critical cross-section and failure surface.
- A detailed discussion of the shallow failure stability analyses including a description of the analyses, development of the shear strength and other parameters, drawings showing the critical cross-section analyzed, and plan view maps showing the location of the cross-sections analyzed.
- Any figures, drawings, or reference relied upon during the testing and data reduction that are marked to show how they relate to the facility.

CONCLUSIONS

An inordinate number of Ohio waste containment facilities experienced collapse between 1996 and 2003. Failures include a massive 1.4 million cubic yard landfill waste slide, a 300,000 cubic yard landfill failure involving a geosynthetic clay liner, and a 100,000 cubic yard landfill failure involving leachate recirculation. The failures led Ohio EPA to form the Geotechnical Resource Group (GeoRG) a work group dedicated to the geotechnical concerns of waste containment structures. GeoRG has completed a significant policy manual on geotechnical and stability analyses for the design of landfills and remedial closures. It is the most definitive treatise on the specific geotechnical issues facing waste containment structures available. It is anticipated that the policy manual will clarify the geotechnical concerns for landfill design, result in better submittals, and hopefully reduce the number of slope failures in waste containment facilities.

Considering the substantial liability involved with landfills, ensuring the stability of landfill construction and operation should be of paramount importance. Ohio's policy "Geotechnical and Stability Analyses for Ohio Waste Containment Facilities" is a great tool and landfill owners, consultants, and regulators should consider adding it to their book shelves for ready reference.