Stability Assessment of Ten Large Landfill Failures

Robert M. Koerner[1]-Hon. Member ASCE and Te-Yang Soong[2]

Abstract

This paper presents and analyzes ten large solid waste landfill. Five are unlined or soil lined, and five are lined with one or more geosynthetic materials. The case histories are analyzed by a 3-D computer code adjusting variables (mainly interface shear strength) to arrive at a FS = 1.0. A triggering mechanism, unique to each site, is then applied resulting in a FS < 1.0. The same variables and triggering mechanisms are then used in a 2-D computer code with FS-values further decreasing by different amounts. The ratio of 3-D to 2-D factors-of-safety is called a wedge factor.

Conclusions reached are as follows:

(i) Interface shear strengths are the overriding considerations in varying FS-values. Accurate determination cannot be overemphasized.
(ii) The triggering mechanisms were all liquid related, i.e., leachate buildup within the waste mass, wet clay beneath the geomembrane, or excessively wet foundation soil.
(iii) The average wedge factor of all case histories without, then with, the triggering mechanisms is 1.24.

1. Introduction

Worldwide waste generation represents a dilemma of major proportions. The situation is particularly serious in industrialized countries where industrial waste generation rates are extremely high. Domestic, or household, waste rates are even higher and now all countries are involved, whether industrialized or not. In the

[1]H. L. Bowman Professor of Civil Engineering and GRI Director , Drexel University, CAE Dept., Philadelphia, PA 19104
[2]Senior Consultant, Earth Tech Consultants, Inc., 36133 Schoolcraft Road, Livonia, MI 48150

United States, there were approximately 3000 active domestic landfills in 1996 disposing of 250×10^6 tonnes per year, U.S. EPA (1998). While data is not directly available, the combined industrial and domestic generation of waste on a worldwide basis is probably in the range of 500 to 800 kg/person/year.

This total waste mass must somehow be accommodated for treatment and/or disposal. The major methods are recycling, incineration, ocean dumping or landfilling. All have disadvantages (e.g., high cost, air pollution, soil pollution and/or water pollution) and are clearly site-specific insofar as the optimum disposal method is concerned. However, landfilling is the one method that appears to be widespread throughout the world and happens to be the disposal method that pertains to this paper.

The number of engineered landfills containing domestic and industrial waste materials is estimated to exceed 10,000 on a worldwide basis. When added to the number of waste piles and abandoned landfills, the total becomes staggering. Furthermore, with the ongoing difficulties of siting new landfills, the current tendency is to make existing landfills both larger in area and higher in height than with previous practice. The term "megafill" is often heard with respect to the large overall mass that a current landfill represents.

Irrespective of the type of waste or size of landfill, the key to an environmentally safe and secure landfill is its containment system. At the minimum, this consists of a synthetic liner system with leachate collection beneath the waste mass, and eventually a final cover placed above it after waste placement has terminated. Such landfills will be designated as being "lined" in this paper which deals with waste stability. Unfortunately, many landfills (most of those that were developed before 1990, and essentially all that were developed before 1980) have neither a liner (synthetic or compacted clay) nor a leachate collection system beneath the waste. This is obviously of great environmental concern, however pollution, per se, is not within the scope of this paper. This class of landfills, however, will be considered from a stability perspective and will be designated as being "unlined" in this paper. The stability of both unlined and lined landfills, from the perspective of case history failures, will be analyzed and assessed accordingly.

It should also be noted that for the purposes of landfill stability, the situation can be challenging either during the active filling of the landfill or after the landfill has been completed to its intended areal extent and final height. In fact, most of the landfills to be addressed in this paper had the associated failure occur during the active filling process, i.e., during the waste placement operations.

This paper will present and analyze ten landfill failures in a case history format. Five cases are unlined and five cases are lined. Most are massive failures and one was accompanied by the loss of 27 lives, see Table 1.

Table 1 - Summary of Waste Failures Presented in this Paper

Case History	Year	Location	Type	Quantity Involved
Unlined				
U-1	1984	N. America	single rotational	110,000 m^3
U-2	1989	N. America	multiple rotational	500,000 m^3
U-3	1993	Europe	translational	470,000 m^3
U-4	1996	N. America	translational	1,100,000 m^3
U-5	1997	N. America	single rotational	100,000 m^3
Lined				
L-1	1988	N. America	translational	490,000 m^3
L-2	1994	Europe	translational	60,000 m^3
L-3	1997	N. America	translational	100,000 m^3
L-4	1997	Africa	translational	300,000 m^3
L-5	1997	S. America	translational	1,200,000 m^3

Wherever prior publication of a particular failure is in the open literature, it will be referenced accordingly. Some of the failures, however, are not in the open literature and proprietary information cannot be disclosed. Thus, all of the case histories will be presented in a sanitized format.

Before beginning with the individual case history descriptions however, some background on the stability analysis methods to be used will be presented. Both two dimensional (2-D) and three dimensional (3-D) procedures will be addressed using the simplified Bishop method for rotational failures, and the simplified Janbu method for translational failures. This information will be brief since, (i) these techniques, particularly the 2-D procedures, are well known in the geotechnical engineering literature, (ii) the information on the 3-D method used has been presented elsewhere in greater detail, Soong, et al. (1998), and (iii) the focus of this paper is on the underlying causes of the failures, i.e., the so-called *triggering mechanisms*. An assessment of the commonality of these mechanisms (and avoidance thereof from occurring in the future) is a major focal point in the paper.

A second major focal point of the paper is a direct comparison of 3-D versus 2-D analysis results. This issue has not seen a great amount of discussion since the commonly held belief is that 2-D analyses result in slightly lower FS-values (commonly felt to be 5 to 10% lower). This slight amount of conservatism is usually justified in light of the complications and greater amount of detail required in performing 3-D analyses.

2. *Stability Analysis Procedures and Methods*

Designers regularly perform calculations to verify the safety of natural slopes, excavated slopes, and constructed embankments. Such calculations serve as a basis for choosing either slope angles and slope lengths with specified factor-of-safety (FS) values before construction, or for the re-design of slopes after a failure. The procedure involves determining the shear stresses developed along the most critical failure surface and comparing them to the shearing resistance of the material through which the surface passes. The entire procedure is called a slope stability analysis and it is well developed in the geotechnical engineering literature, e.g., see Sherard, et al. (1963), or Hirschfield and Poulos (1973).

2.1 Two-Dimensional Procedures

By far, the majority of slope stability procedures that are performed are based on 2-D cross sections and analysis. Using a 2-D procedure, there are many analysis methods but all assume that the critical cross section resulting in the lowest FS-value can be identified. Since numerous iterations are invariably required, computer codes are commonplace in order to identify the critical cross section. A 2-D cross section of a circular arc failure is shown in Figure 1(a). In the conventional manner it is subdivided into n-slices where the i-th slice is shown in Figure 1(b). From this point a number of different calculation methods can be followed.

For the analysis of the case histories to follow which failed along a circular arc, the simplified Bishop method will be used. The derivation is available in Hirschfield and Poulos (1973) and McCarthy (1982), and leads to the following equation for the FS-value.

$$FS = \frac{\sum_{i=1}^{n}\left[c\Delta b_i + \left(W_i - u_i\Delta b_i\right)\tan\phi\right]\frac{1}{m_i}}{\sum_{i=1}^{n} W_i \sin\theta_i} \tag{1a}$$

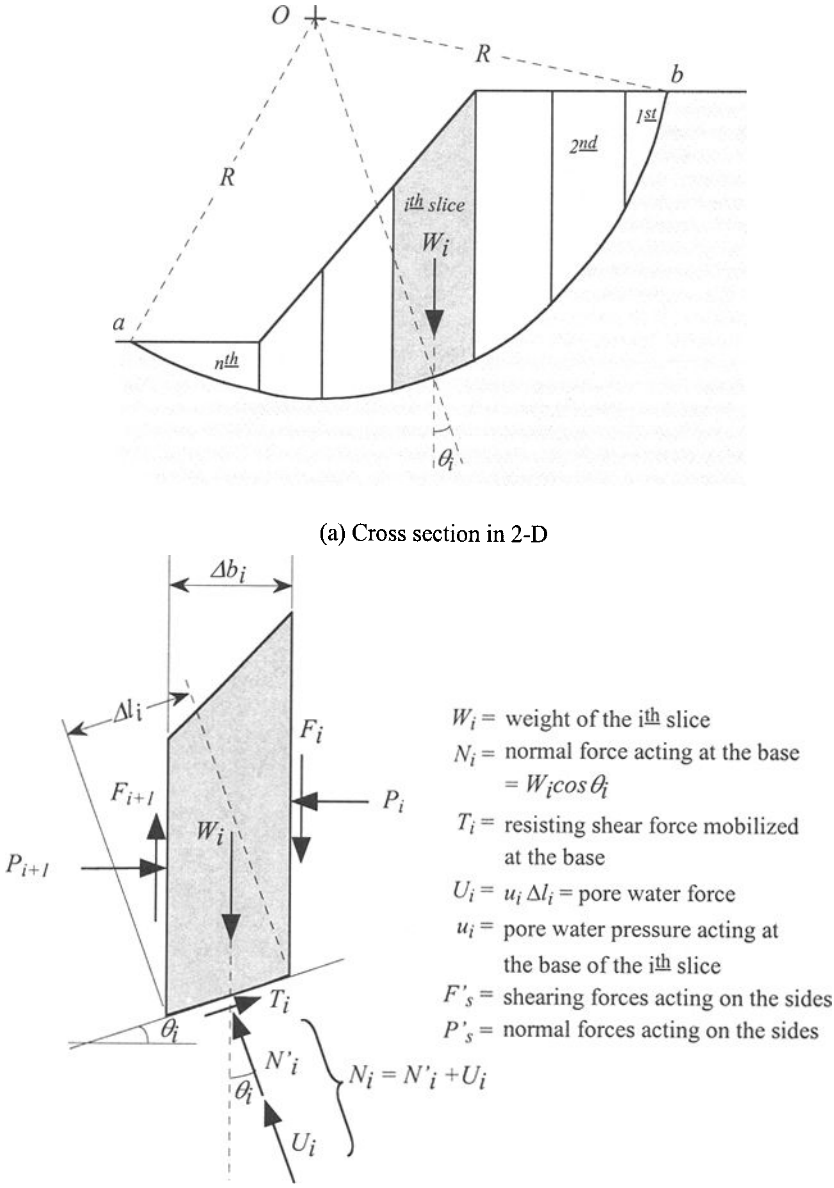
where

$$m_i = \cos\theta_i\left(1 + \frac{\tan\phi\tan\theta_i}{FS}\right) \tag{1b}$$

Conversely, for the analysis of the case histories to follow which failed in a translational manner, the simplified Janbu method will be used. This derivation is also readily available in the literature, e.g., see McCarthy (1982), and leads to a similar equation for the FS-value but now modified with an f_o-value.

$$FS = \left(f_o\right)\frac{\sum_{i=1}^{n}\left[c\Delta b_i + \left(W_i - u_i\Delta b_i\right)\tan\phi\right]\frac{1}{m_i}}{\sum_{i=1}^{n} W_i \sin\theta_i} \tag{2}$$

where "m_i" is defined in Equation (1b) and f_o = function of the curvature rate of the failure surface and the type of soil, see McCarthy (1982).



(a) Cross section in 2-D

(b) Forces acting on the ith slice

Figure 1 - Cross Section in 2-D Showing Circular Arc Subdivided into Slices and Analysis of the ith Slice.

To solve case histories using either the simplified Bishop or the simplified Janbu methods in 2-D, the commercially available computer program GEOSLOPE V4 will be used.

2.2 Three-Dimensional Procedures

Contrasted to 2-D procedures, one can also perform a stability analysis using a 3-D procedure, see Hutchinson and Sarma (1985). Required is the site topography at a number of cross sections within the potentially critical, or actually failed, situation. Due to the nature of the landfill failures to be presented (they are relatively short in their axial direction), it is felt to be important to consider 3-D procedures in order to provide a contrast to the FS-values obtained.

A 3-D isometric sketch of the base of a rotational failure surface is shown in Figure 2(a). The entire surface is subdivided into columns of dimensions Δx by Δy by h_i (the column height from base to top) throughout the 3-D space involved in the failure, see Figure 2(b). From this point a number of different calculation methods can be followed.

For the analysis of the case histories to follow which failed in a rotational manner, the simplified Bishop method will be used. The difference from the previously described situation of Eqn. 1 is now the procedure is based on 3-D space. The FS-equation follows. Its derivation is available in Hutchinson (1981), Hungr (1987), Hungr, et al. (1989), Hungr (1997) and Soong, et al. (1998).

$$FS = \frac{\sum_{i=1}^{n}\left[c\Delta A_i + \left(N_i - u_i\Delta A_1\right)\tan\phi\right](R)}{\sum_{i=1}^{n} W_i x - \sum_{i=1}^{n} N_i x'\left(\frac{\cos\theta_i}{\cos\alpha_{y,i}}\right)} \tag{3a}$$

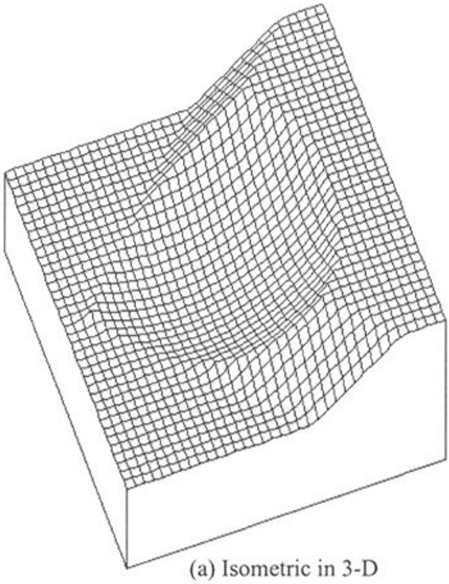
where

$$N_i = \frac{W_i - \left[\frac{(c - u_i\tan\phi)(\Delta A_i)(\sin\alpha_{y,i})}{FS}\right]}{m_i} \tag{3b}$$

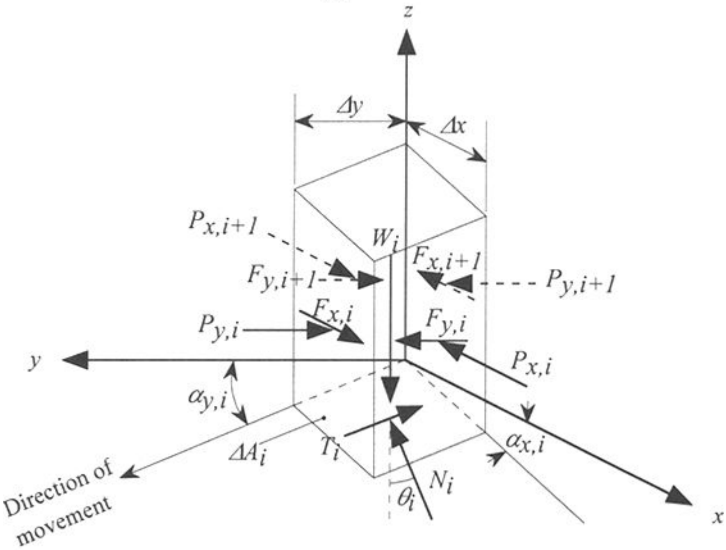
and

$$m_i = \cos\theta_i\left(1 + \frac{\sin\alpha_{y,i}\tan\phi}{FS\cos\theta_i}\right) \tag{3c}$$

For the analysis of the case histories to follow which failed in a translational manner, the simplified Janbu method will be used. The derivation is an extension of Eqn. (2) based on 3-D space which leads to the following equation, see Hungr (1989).



(a) Isometric in 3-D



(b) Forces acting on the ith slice

Figure 2 - Isometric Section in 3-D Showing a Rotational Failure Surface and Analysis of the ith Column.

$$FS = \frac{\sum_{i=1}^{i=n} [c\Delta A_i \cos\alpha_{y,i} + (N_i - u_i \Delta A_i)\tan\phi \cos\alpha_{y,i}]}{\sum_{i=1}^{i=n} N_i \cos\theta_i \tan\alpha_{y,i}} \tag{4}$$

For both the simplified Bishop and the simplified Janbu methods in 3-D, the computer program CLARA 2.31 will be used, see Hungr, et al. (1989) and Hungr (1997).

2.3 *Commentary*

In contrasting slope stability investigations by 2-D versus 3-D methods the elimination or inclusion of side forces on the failure slices is the obvious major issue. The necessary elimination of these side forces when using 2-D analysis invariably gives lower FS-values than when including them in 3-D analyses. In light of this situation, customary engineering design practice has favored the use of 2-D analysis. The reasons are as follows:

(i) Design methods using 2-D analysis are significantly less complicated and simpler to perform.
(ii) Computer codes based on 2-D analysis are readily available, whereas three dimensional computer codes are much less common, see Stark and Eid (1998).
(iii) Computer codes based on 3-D analysis are comparatively expensive.
(iv) Data input for analyses using 3-D computer codes necessarily must be more detailed and complete, e.g., the complete original and final topography must be known or estimated.
(v) The general perception is that FS-values obtained by 2-D analysis are only slightly more conservative than their 3-D equivalents (e.g., by 5 or 10%), so design-wise the error is marginally safe and within the estimated accuracy of input variables such as interface shear strengths and moisture levels.

The case histories to be described are necessarily brief in order to accommodate a reasonably sized technical paper. Hopefully, the salient features of each case history are presented so that an accurate perspective can be gained. More complete details of each case history are available in Soong and Koerner (1999) and the references that are cited herein.

3. *Unlined Landfill Failures*

As shown in Table 1, there are listed five unlined landfill failures. All sites were underlain by fine grained silt and clay subgrade soils of low hydraulic conductivity, but generally not a compacted clay liner meeting current regulatory standards. It is important to note, that there were no geosynthetics involved in any of the five case histories to be presented. To gain a perspective of the configuration of the failures, the 2-D cross sections of these five case histories are shown together in composite form in Figure 3.

In presenting and analyzing these case histories the following will be the process:

(i) The field situation (before and after failure) is described.
(ii) The failure surface is identified and if circular or rotational, the simplified Bishop method will be used. Conversely if the failure surface is translational, the simplified Janbu method will be used.
(iii) Known parameters of unit weight and shear strength will be used whenever they are available.
(iv) A 3-D analysis is then performed using the CLARA 2.31 computer code including a variation of the unknown parameters until a FS = 1.0 (i.e., incipient failure) is reached. The logic being that this incipient failure value had to be reached at some time before the failure occurred.
(v) The site-specific "triggering mechanism" is then applied (which may have been working even in the preceding step) and the program is re-run thereby obtaining a FS < 1.0.
(vi) A 2-D analysis is then performed using the GEOSLOPE V4 computer code with the same parameters as in item (iv) above to obtain the corresponding FS-value.
(vii) The same site-specific triggering mechanism as in item (v) above is applied and the 2-D program re-run to obtain the corresponding FS-value.
(viii) A wedge factor (*WF*) is calculated which is defined as follows, for both incipient failure and for the inclusion of the triggering mechanism.

$$WF = FS_{3\text{-}D}/FS_{2\text{-}D} \tag{5}$$

(ix) It is important to note that the above described analysis procedure is quite arbitrary. An alternative method would be to include the triggering mechanism in the 3-D analysis to arrive at a FS = 1.0 condition as the base line. Without the triggering mechanism this would result in a FS > 1.0. Again the 2-D analysis would always be less than the 3-D analysis. The result of this alternative approach would be that the wedge factors would be somewhat smaller than presented herein.

Additional summary and conclusion items will be postponed until all ten case histories (unlined and lined) have been presented.

3.1 Case History "U-1"

Case history U-1 is a municipal waste landfill that failed in 1984. The failure was rotational and involved approximately 110,000 m^3 of solid waste. Divinoff and Munion (1986) and Erdogan, et al. (1986) have reported on this case history.

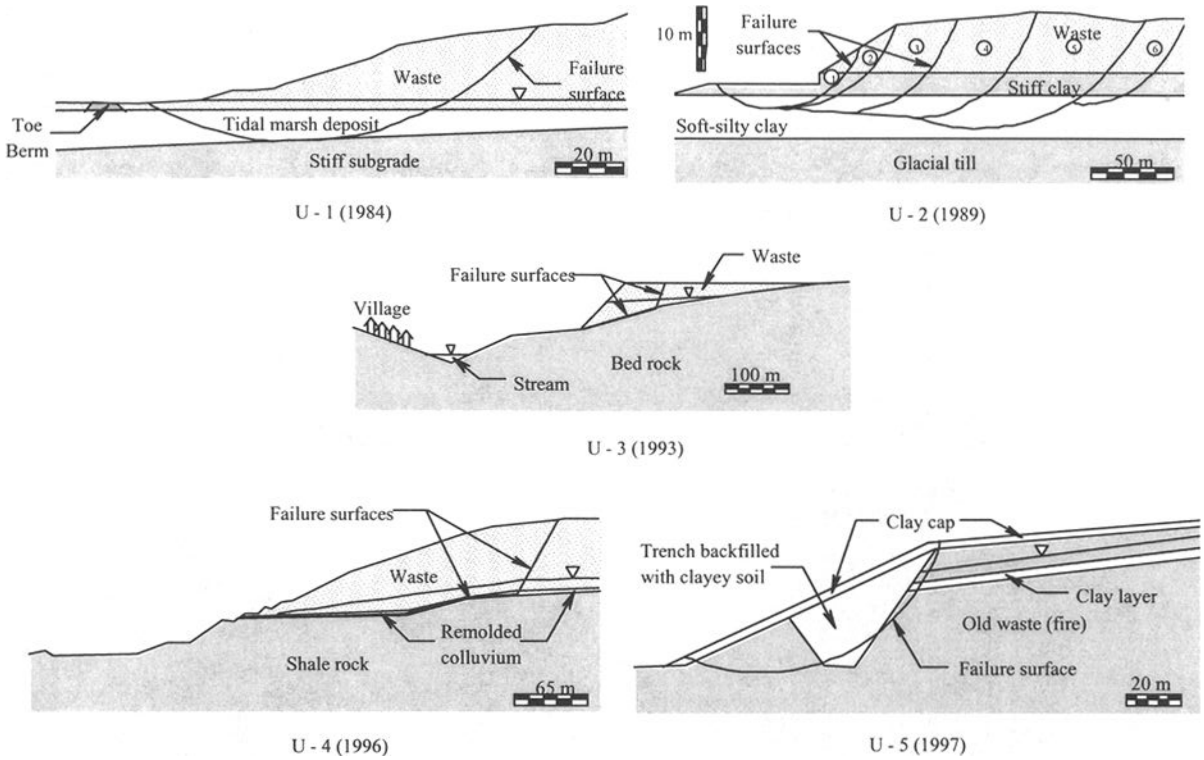


Figure 3 -- Cross Sections in 2-D of Unlined Landfill Failures Analyzed and Assessed in This Study (Horizontal and Vertical Scales are Equal for Each Sketch and Indicated Accordingly)