Stress deformation analysis of MSW landfills

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ABSTRACT
Landfill stability and deformation analysis is one of the most important concerns in the municipal solid waste (MSW) landfill design and operation. Estimation of landfilling capacities based on deformation characterization of MSW assumes considerable significance in the estimation of additional landfilling capacity before closure. In the analysis, it is important to consider mechanisms such as primary compression, time dependent mechanical creep and biodegradation effects occurring in the MSW system. In this paper, a simple landfill cell is considered and stability and deformation analysis is performed based on the constitutive modeling approach. The implications on the slope stability and deformation response of MSW for a 5m high landfill cell are explained in terms of vertical and horizontal deformations, constitutive model, mechanical creep, and biodegradation. The effects of time on the strength and stability of the landfill cell are studied. The study shows that the analysis using constitutive modeling approach provides useful insights in the land-filling operations.

Keywords: municipal solid waste, stress and deformations, constitutive model, mechanical creep, biodegradation

1 INTRODUCTION
Analysis of mechanical response of Municipal Solid Waste (MSW) is an important component of landfill design and engineering. The response of MSW in terms of stability, settlement and stability under flow and circulation of leachate depends on the engineering properties. Mechanisms affecting the response of MSW include primary compression, mechanical compression and creep, and decomposition due to biodegradation of organic components. Hossain et al (2003) studied the compressibility behavior of MSW and showed that degradation effects need to be properly considered in the settlement response of MSW. Hossain and Haque (2009) presented results of experiments on shear strength of MSW and showed that shear strength values decrease with increase in biodegradation. Hossain and Haque (2009) studied the response of stability of MSW slopes within the bioreactor landfills, as a function of time and decomposition and predicted a factor of safety of less than 1 at advanced stages of degradation for a slope of 2:1. It is well recognized that the compression and shear strength of MSW are interrelated and there is a need to study the compression-strength behavior of MSW in stress-strain response and to assess the interaction between the waste and barrier systems (Machado et al 2002, 2008). Both stability and deformations have implications in short term and long term stability as well as landfill closure plans. For example, in short term requirements such as those in cell construction, they are useful in the assessment of stability of the cell and in assessing the potential volume changes in a slope profile. Similarly they are useful in long term stability in the assessment of additional volume that can be accommodated due to horizontal and vertical deformations in landfill mass. Both horizontal and vertical deformations arise as a result of the three mechanisms of immediate compression, mechanical creep and biodegradation and result in volume changes. The corresponding stresses and the stability of deformed landfill are also altered. It is important to study the volume changes occurring in the landfills to understand the behavior of MSW with time and also it can help in estimating landfilling capacities.

2 CONSTITUTIVE MODELS FOR MSW
Machado et al. (2002) proposed a constitutive model to simulate the mechanical behavior of MSW and considered that MSW behavior is controlled by two distinct parts, the mechanical behavior of the fibrous material and of the paste, using a coupled elasto-plastic model. Machado et al. (2008) improved the above model by considering the influence of biodegradation of organic matter in the mechanical behavior of MSW. Babu et al (2010a) proposed a constitutive model based on the critical state concept to understand the response of MSW and validated the response with reference to the data of Reddy et al (2009 a, b). Subsequently, Babu et al (2010b) illustrated the applicability of the model to predict time dependent settlement for a typical MSW
landfill. The predicted settlement results were compared with the predicted settlement results obtained using fourteen different reported models. It is shown that the predicted settlements can vary significantly depending on the model used and the parameter values selected. The following assumptions have been made in the development of the proposed constitutive model for MSW:

1) The mechanical behavior follows elasto-plastic behavior in the framework of the critical state soil model with associated flow rule;
2) The secondary compression is governed by the time dependent phenomenon and represented in an exponential function similar to the assumption of Gibson and Lo’s (1961) model, which is given by:

\[ e_v^c = b \Delta\sigma' (1 - e^{ct}) \]  

Where \( b \) is the coefficient of mechanical creep; \( \Delta\sigma' \) is the change in mean effective stress, \( c \) is the rate constant for mechanical creep; and \( t' \) is the time since application of the stress increment. The time dependent biological degradation is given by Park and Lee et al. (1997)

\[ e_v^b = E_{dg} (1 - e^{-dt''}) \]  

Where, \( E_{dg} \) is the total amount of strain that can occur due to biological decomposition; \( d \) is the rate constant for biological decomposition and \( t'' \) is the time since placement of the waste in the landfill. Increment in volumetric strain is

\[ d\varepsilon_v = d\varepsilon_v^e + d\varepsilon_v^p + d\varepsilon_v^c + d\varepsilon_v^b \]  

Where \( d\varepsilon_v^e \), \( d\varepsilon_v^p \), \( d\varepsilon_v^c \) and \( d\varepsilon_v^b \) are the increments of volumetric strain due to elastic, plastic, creep and biodegradation mechanisms respectively. The elastic volumetric strain can be written as:

\[ d\varepsilon_v^e = -\frac{de_v^e}{1+e} = \kappa \frac{dp'}{1+e} \]  

Increment in plastic volumetric strain can be written as

\[ d\varepsilon_v^p = \left( \frac{\lambda - \kappa}{1+e} \right) \frac{dp'}{p'} + \frac{2\eta dp' \eta}{M^2 + \eta^2} \]  

Where \( \kappa \) is the swelling index; \( \lambda \) is the compression index; \( \eta \) is the stress ratio and \( M \) is the frictional constant. These increments in elastic and plastic volumetric strains are well established in critical state soil mechanics literature. This model has been extended by Babu et.al (2010) to consider effects of mechanical creep and biodegradation on MSW. Increment of volumetric strain due to creep is given by

\[ d\varepsilon_v^c = cb\Delta\sigma' e^{ct'} dt \]  

The total volumetric strain of the MSW is expressed as

\[ d\varepsilon_v = \frac{\kappa}{1+e} \frac{dp'}{p'} + \frac{2dp' \eta}{M^2 + \eta^2} + cb\Delta\sigma' e^{ct'} dt = E_{dg} e^{-dt''} \]  

The equation for the prediction of stress-strain becomes

\[ q = M\eta \left( \frac{p'}{p} \right)^{1+c0} \exp \left[ \frac{e_v - e_0}{1+e_0} \Delta\sigma' e^{ct''} + dE_{dg} e^{-dt''} \right] \left( \frac{\lambda - \kappa}{1+e_0} \right) \]  

Where \( p' \) is the mean effective stress and \( p'0 \) is the pre-consolidation pressure.

3 MSW LANDFILL CONDITIONS

A typical MSW landfill of 5 m height and slope 1H:1V on both sides is selected, which is assumed to be filled in five layers each at a thickness of 1 m. The engineering properties of MSW required for the analysis are evaluated based on standard geotechnical methods. The details on evaluation of properties are given in Lakshminathan et al (2013) and are in similar range as those available in literature. They represent the typical properties of MSW for Bangalore city.

4 MODELING AND ANALYSIS

Numerical analysis using finite element or finite difference methods such as Fast Lagrangian Analysis of Continua (FLAC) is a useful way to address many complex stress deformation problems using different constitutive models including modified cam clay model. A finite difference code capable of representing cam clay model with an extension to include effects of creep and biodegradation was used in the analysis. Numerical model is developed using FLAC2D version 5.0. Modified cam clay model formulation is based on a combined shear and volumetric yield function and associated flow rule.

![Fig 1: Finite difference grid of the MSW landfill](image-url)
creep and biodegradation, additional code is formulated to represent the behavior of MSW due to these mechanisms. The input parameters for the model are frictional constant M, slope of normal consolidation and swelling line (λ and κ), pre-consolidation pressure which determines the size of initial yield surface, parameters of creep and biodegradation mechanisms given in Table 1.

Table 1: Properties of MSW

| PROPERTY                        | VALUE |
|---------------------------------|-------|
| Cohesion (kPa)                  | 5     |
| Friction angle (*)              | 30    |
| Bulk density (kN/m³), γ         | 10    |
| Modulus of elasticity (kN/m²), E | 30000 |
| Frictional constant, M          | 1.2   |
| Compression index (Lamda), λ    | 0.046 |
| Swelling index (Kappa), κ       | 0.0046|
| Strain due to biodegradation, E_{db} | 0.158 |
| Rate constant for biological decomposition (day⁻¹), d | 0.00114 |
| Coefficient of mechanical creep (m²/kN), b | 0.000572 |
| Rate constant for mechanical creep (day⁻¹), c | 0.00179 |

The procedure to simulate this type of problem is illustrated by performing the analysis in following steps:

1) Generate the grid and assign material model properties and boundary conditions to represent the physical system.
2) The first lift of the slope with all the parameters is considered to be normally consolidated at this stage as the material is just placed. The mean and deviator effective stresses are calculated (p and q).
3) The elastic, plastic, creep and biodegradation components of strain based on equations 4, 5, 6 and 7 are evaluated.
4) The pre-consolidation pressure is evaluated using the relation

\[
p'' = \left[ \frac{\kappa}{\kappa'} + 1 \right]^{\frac{1}{\gamma}} \frac{\sigma'}{\exp\left( \frac{\kappa' - \kappa}{\gamma} + \frac{\Delta \sigma\kappa'}{\gamma} + \frac{E_{db} \kappa'}{(1+\kappa')} \right) (1+\kappa)}
\]

(10)

5) Previous value of pre-consolidation pressure (Since the waste was normally consolidated the previous pre-consolidation pressure value was the mean effective stress p') is replaced by the value obtained from the above equation.
6) Using the current value of pre-consolidation pressure determine the yield surface, the equation of which has also been changed and given by equation 9.
7) Sequential addition of the material in stages (five stages) to the problem domain.

5 RESULTS AND DISCUSSIONS

5.1 Factor of safety

As most of the landfills are located nearby highly populated areas it is essential to estimate the stability of landfills with increase in fill age to foresee any landfill failures in the future. The stability of the slope is calculated with limit equilibrium methods of slope stability using Taylor’s stability charts, slope stability software (SLIDE version 5) and numerical models (Mohr-coulomb model and MSW constitutive model). The results of the analysis expressed in terms of factor of safety are given in Table 2. Limit equilibrium methods are compared with the numerical models. These methods calculate the factor of safety based on static equilibrium whereas the numerical models are based on constitutive law and stress-strain relationships. The main limitation of limit equilibrium methods is that they do not consider deformations in the slope. In numerical models the factor of safety is evaluated using strength reduction method. The method comprises of reducing the strength parameters of the MSW to determine the factor of safety value that brings a slope to a verge of failure.

Table 2: Factors of safety using standard soil mechanics methods and FLAC

| Method                  | Factor of safety |
|-------------------------|------------------|
| Taylor’s stability number | 1.57             |
| Bishop simplified       | 1.60             |
| Janbu simplified        | 1.56             |
| FLAC(Mohr-coulomb)      | 1.54             |
| FLAC (Proposed model)   | 1.55             |

The results presented in Table 2 show that the values from the different methods are in the same range, confirming the accuracy of finite difference model considered in the present study for further analysis. However, limit equilibrium methods only give values of factor of safety and do not provide information on deformations. Since the proposed model incorporates mechanisms of primary compression, creep and
biodegradation, the latter two being time dependent mechanisms, the effect of time on the behavior and stability of the MSW slope can be estimated. Table 3 shows the results of factor of safety varying with fill age and different mechanisms incorporated.

Table 3: Variation of factor of safety with different mechanisms and time.

| Time(days) | 100  | 365  | 3650 |
|------------|------|------|------|
| Primary compression | 1.55 | 1.55 | 1.55 |
| Primary compression + creep | 1.75 | 1.90 | 1.95 |
| Primary compression + creep + biodegradation | 1.64 | 1.85 | 2.00 |

The results show that as time or fill age increases the factor of safety increases. Factor of safety value varies depending on the mechanism dominant in MSW. The effect of creep and biodegradation mechanisms is to enhance the stability of the MSW slope as it is evident from the table above. Creep mechanism includes rearrangement of particles due to which MSW slope acquires higher factor of safety. The mechanism of biodegradation also increases the overall stability of slope however gives comparatively smaller values for 100days and 365 days , this may be because as time progresses waste degrades due to which void ratio increases and the corresponding rearrangement of particles negates the stability induced by the creep mechanism. Hence the conventional slope stability methods ignoring the creep and biodegradation such as simple Mohr-Coulomb model underestimate the factor of safety of MSW slope which increases from its initial value with time. As more and more MSW gets degraded the MSW slope acquires a stable configuration.

To give a better understanding of these changes in factor of safety with fill age, the values of shear stresses corresponding to different mechanisms are computed and presented in Table 4. Three values of shear stresses at different depths viz. at 1m depth, 3m and 5m below the crest of cell geometry are evaluated using the constitutive model and Mohr-coulomb in Table 4.

From Table 4 it can be noted that as the fill age of MSW increases the shear stresses decrease which implies that that the factor of safety increases. Hence this argument quite agrees with trend of safety values we obtained in Table 3. Also the shear stresses have large values near the toe of the slope and decrease as the height of the slope increases. The Mohr-coulomb model gives higher values of shear stresses and hence is associated with lower value of factor of safety of 1.54.

The model is not capable of estimating time dependent behavior of MSW. For mechanisms such as creep and biodegradation, the shear stresses decrease with time.

Table 4: Variation of shear stresses with different mechanisms and time.

| Mechanism | 1m depth | 3m depth | 5m depth |
|-----------|----------|----------|----------|
| Mohr-coulomb (kPa) | 0.68 | 2.23 | 7.38 |
| Primary compression (kPa) | 0.42 | 1.42 | 1.86 |
| Primary compression + creep (kPa) | 0.57 | 2.00 | 2.79 |
| Primary compression + creep + biodegradation (kPa) | 0.55 | 0.98 | 1.49 |
| Primary compression + creep + biodegradation (kPa) | 0.41 | 0.87 | 1.42 |

5.2 DEFORMATION ANALYSIS

In the present literature settlement of MSW landfills are associated with vertical settlements only. However for landfills horizontal as well as vertical deformations are crucial to monitor many aspects of landfilling operations. Hence it is important to estimate both the vertical and horizontal deformations. The vertical and horizontal deformations of a point on the crest of the MSW slope are evaluated and presented in Table 5 and Table 6 respectively.

Table 5: Vertical deformations due to different mechanisms with respect to time.

| Time(days) | 100  | 365  | 3650 |
|------------|------|------|------|
| Primary compression (mm) | 309 | 309 | 309 |
| Primary compression + creep (mm) | 1053 | 1109 | 1239 |
| Primary compression + creep + biodegradation (mm) | 1687 | 1808 | 2329 |

It is observed that the deformations of the MSW slope increase with fill age. The mechanism of primary compression is completed before 100 days and hence the values corresponding to 100 days and beyond are
constant. In case of mechanisms involving biodegradation and creep, the deformations are functions of time and increase with fill age. The mechanisms of creep and biodegradation dominate the behavior of MSW with time and hence induce considerable deformations in the slope.

Table 6: Horizontal deformations due to different mechanisms with respect to time

| Time (days) | 100    | 365   | 3650  |
|------------|--------|-------|-------|
| Primary compression (mm) | 607    | 607   | 607   |
| Primary compression + creep (mm) | 1902   | 2174  | 4388  |
| Primary compression + creep + biodegradation (mm) | 2937   | 3414  | 8368  |

5.3 Volume Changes in MSW Slope With Time
The vertical and horizontal deformations of the MSW slope with time due to different mechanisms result in the change in shape of the original profile. In this study volume changes occurring in the MSW slope with time are evaluated. This study of volume change in landfill is essential to estimate the capacities of landfills and provide guidance in landfill closure plans. Also it may help in understanding and mitigating the landfill capacity problems. Considering cell geometry of 5m high and 1:1 slope, the original volume of the MSW slope is found to be 75 m³. The expected volume change of the slope with fill age is presented in Table 7. Figure 2 show the deformed landfill section with time.

Table 7: Volume changes with time.

| Time (days) | Original volume (m³) | New volume (m³) | Volume change (%) |
|------------|----------------------|-----------------|------------------|
| 100        | 75                   | 61.14           | 18.48            |
| 365        | 75                   | 42.56           | 43.24            |
| 3650       | 75                   | 30.39           | 59.47            |

Fig 2: volume changes at 100 days, 1 year and 10 years

The results show that as the fill age of the slope increases there is considerable change in the volume of MSW slope. Consider for example, at a fill age of 100 days the volume change is only 18% while at the end of 10 years (3650 days) it is about 60%. Hence, a considerable amount of MSW has degraded. This type of analysis is useful in the assessment of additional volume that can be accommodated in filling capacity.

5.4 INFLUENCE OF LIFT THICKNESS
The waste lift thickness is an important aspect in land-filling operations. In order to examine the effect of lift thickness in landfill stability, the landfill cell selected for this study is assumed to be filled in different lift thicknesses of 0.5m, 1m and 2.5 m. Factor of safety is evaluated at different lift thicknesses and the results indicate that as time increases the factor of safety increases. However at smaller lift thickness the safety value is high compared to higher lift thickness.

Table 8: Influence of lift thickness

| Lift thickness (m) | 100 days | 365 days | 3650 days |
|-------------------|----------|----------|-----------|
| 0.5               | 1.70     | 2.20     | 2.65      |
| 1.0               | 1.64     | 1.85     | 2.00      |
| 2.5               | 1.56     | 1.75     | 1.90      |
Vertical and horizontal deformations of a point on the crest of the cell are evaluated at different lift thicknesses and time. These results show that deformations increase with time, also larger deformations are associated with larger lift thickness.

Table 9: Vertical deformations in mm.

| Lift thickness (m) | 100 days | 365 days | 3650 days |
|-------------------|----------|----------|-----------|
| 0.5               | 1090     | 1587     | 2132      |
| 1.0               | 1687     | 1808     | 2329      |
| 2.5               | 1870     | 1989     | 3578      |

Table 10: Horizontal deformations in mm

| Lift thickness (m) | 100 days | 365 days | 3650 days |
|-------------------|----------|----------|-----------|
| 0.5               | 2336     | 3124     | 6230      |
| 1.0               | 2937     | 3414     | 8368      |
| 2.5               | 3245     | 4290     | 8750      |

6 CONCLUSIONS

In this study, a constitutive model which incorporates mechanical compression, mechanical creep, and biodegradation-induced compression and based on critical state soil mechanics principles is implemented in numerical analysis program FLAC to predict the stress-deformation behavior of composite lined landfill systems. Finite difference analyses were performed on a typical landfill cell to evaluate the stress/displacement response as MSW was placed in increments on the landfill cell base. Based on the results obtained, the following conclusions can be drawn:

- The stability analysis shows that as the fill age of MSW landfill increases the factor of safety increases.
- The changes in the stress-deformation response of MSW with time are governed by the mechanisms dominant at that instant.
- At the end of 1 year the change in volume of MSW landfill is found to be about 44% and at the end of 10 years about 60%. Hence, a considerable quantity of MSW undergoes degradation.
- As the lift thickness increases the factor of safety decreases. The settlements were large for larger lift thickness and relatively small for smaller lift thickness.

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