SLOPE STABILITY OF MSW LANDFILL USING CONSTITUTIVE MODEL

A. S. S. Raghuram[1]
B Munwar Basha[2]
[1]*Research Scholar,* [2]*Asst. Professor, Department of Civil Engineering, Indian Institute of Technology Hyderabad, Kandi, Sangareddy – 502 285.*
[2]*raghuram.ammavajjala@gmail.com* , [2]*basha@iith.ac.in*

ABSTRACT

Stability and deformation analysis of Municipal Solid Waste (MSW) landfills is cumbersome due to material heterogeneity. This heterogeneity is due to the presence of various materials with different properties. The MSW produces leachate and gases due to degradation of some of its components over a period of time. Due to the porous medium of the MSW, landfill gas and leachate can move freely in the pore spaces. Moreover, physical, chemical and biological processes make some components of MSW to degrade and some components stable. Therefore the behaviour of waste changes over the time dramatically. Several advanced mathematical models were developed to account for this complex behaviour of waste. As a consequence of complex behaviour, MSW has been modelled using the theories of soil mechanics to assess the settlement and strength of landfills collectively and to analyse the stability of MSW landfill. Current paper illustrates the stability of the MSW landfill as it is one of the important concerns in the design of landfills. The model is useful for evaluating the deformation and stability of landfills. Modelling and simulation of the deformation behaviour of MSW are carried out. A numerical model of MSW landfill is developed by using the two-dimensional explicit finite difference program namely FLAC 7.0. The results of the slope stability are presented in terms of unbalanced force ratio, stresses and displacements along the interface.

Key words: Constitutive Models, FLAC, MSW, Slope Stability, Unbalanced Force Ratio.

1 INTRODUCTION

The stability and settlement analysis of the MSW depends on the engineering properties. The stability of the MSW landfill can be found through shear strength. Moreover, the settlement of the landfill can be assessed by knowing the compressibility properties. Hossain et al. (2003) studied the importance of the compressibility of the MSW and consideration of degradation effects in the settlements of MSW. Machado et al. (2002, 2008) reported that the compressibility and shear strength of MSW are interrelated. The significance of the shear strength after incorporating biodegradation was studied by Hossain and Haque (2009). In this regard it is very important to consider the constitutive modelling of an MSW landfill. Many constitutive models were proposed by several researchers to predict the shear strength and settlements of MSW landfill. Sowers (1973) proposed basic soil mechanics based model to compute the settlement of MSW. Babu et al. (2010) reported stress-strain response of MSW landfill with time using a constitutive model works on modified Cam-Clay theory based on critical state soil mechanics along with non-associated flow rule. This model includes the mechanisms like primary compression, creep, biodegradation and mechanical compression. Therefore, present study on numerical modelling (FLAC 2D) makes use of the constitutive model to determine the shear stress along the failure surface.

2 OBJECTIVES

The main objective of the study is to present the advantage of considering the constitutive model for the analysis of MSW landfills, by comparing with the Mohr-Coulomb model using numerical analysis. In the present study, an existing constitutive model which was reported by Babu et al. 2010 is considered in the FLAC 2D. The model used in the study is primarily a modified Cam-clay model which also includes the effects of creep and biodegradation. Using the FISH function the constitutive equation is incorporated in FLAC to determine the variations of shear stresses and shear displacements along the interface. The modified Cam-clay model, is an in-built model in FLAC. It is improved to account for creep and biodegradation mechanisms of MSW landfill.

3 PROPERTIES OF MSW

The MSW material properties are collected from the literature. Table 1 presents the properties of MSW used in the present study.

Table.1 Properties of MSW

Property	Value
Cohesion, c (kPa)	5
Friction angle, ϕ (°)	30
Bulk density, γ (kN/m^3)	10
Modulus of elasticity, E (kN/m^2)	175000
Frictional constant, M	1.2
Compression index, λ	0.22
Swelling index, κ	0.035
Strain due to biodegradation, E_{dg}	0.158
Rate constant for biological decomposition, d (day^{-1})	1.14×10^{-3}
Coefficient of mechanical creep, b (m^2/kN)	5.72×10^{-4}
Rate constant for mechanical creep, c (day^{-1})	1.79×10^{-3}

4 CONSTITUTIVE MODEL

The constitutive model used in the present study is exclusively for MSW landfills and basically an extension for modified cam-clay model which includes creep and biodegradation phenomenon. The following equation represents the present modified Cam clay model:

$$q = Mp\sqrt{\left(\frac{p'_o}{p_1}\right)^{\left(\frac{\lambda}{\lambda-\kappa}\right)} \exp\left[\left(\frac{e_o - e}{1+e_o} + \Delta\sigma bce^{-ct} + dE_{dg}ce^{-dt}\right)\left(\frac{\lambda-\kappa}{1+e_o}\right)\right] - 1} \quad (1)$$

where, p = mean effective stress, q = mean deviatoric stress, M = slope of critical state line which is equal to $\frac{6\sin\phi}{3-\sin\phi}$, e_o = initial void ratio of MSW, e = final void ratio, $\Delta\sigma$ = change in mean effective stress, λ = compression index, κ = swelling index, E_{dg} = strain due to biodegradation, d = rate constant for biological decomposition, b = coefficient of mechanical creep, and c = rate constant for mechanical creep.

5 MODELING IN FLAC

A 30 m height of the MSW landfill as shown in Fig. 1 is considered for the present study for numerical analysis using FLAC 2D A numerical code is written in FISH language which represents the present constitutive model. The MSW is placed in three layers as shown in Fig. 2. The staged formation of the MSW landfill is shown with three different layers. Now it is required to simulate in six stages. As the soil below the base of the MSW landfill is considered to be stiff, the bottom boundary is assumed to be fixed in both horizontal (X) and vertical (Y) directions. Moreover, it is assumed that the top and sides of landfill are to move as it represents the realistic boundary conditions.

6 FLAC PROCEDURE

The following is the detailed procedure to simulate the constitutive model in FLAC:

1) Generate the grid, assign material properties and boundary conditions.
2) The first stage or first layer of the slope is modelled and considered to be normally consolidated as the MSW is freshly deposited.
3) Now calculate mean effective stresses (p), deviatoric stresses (q) and change in effective stresses ($\Delta\sigma$) due to sequential addition of MSW layers.
4) The preconsolidation pressure is evaluated using the following equation.

$$p'_o = \left[\left(\frac{\Delta q}{Mp'_1}\right)^2 + 1\right]^{\left(\frac{\lambda-\kappa}{\lambda}\right)} \frac{\Delta p'_1}{\exp\left(\left[\frac{e_o - e}{1+e_o} + b\Delta\sigma e^{-ct} + E_{dg}e^{-dt}\right](1+e)\right)} \quad (2)$$

5) The previous value of pre-consolidation pressure is replaced by the value obtained in Eqn. 2 and compute the value of q using Eqn. (1).
6) Then the next stage of MSW landfill is placed over the first layer, and same procedure is followed for the rest of two layers.

7 RESULTS AND DISCUSSIONS

7.1 Unbalanced Force Ratio (UFR):

It is noted that the FLAC 2D does not compute the factor of safety using the modified cam clay models. Therefore, the results in terms of the unbalanced force ratio and shear stresses along the interface obtained using Mohr-Coulomb and Modified Cam-clay models are presented in the current investigation. The unbalanced force ratio (UFR) is the ratio of unbalanced force to the magnitude of applied force. It can be noted that the UFR ratios for Cam-clay model and Mohr-Coulomb model are 9.725 x 10^{-4} and 9.83 x 10^{-4} respectively. As both the UFR ratios are less than 10^{-3}, which indicates that the MSW slope is stable.

7.2 Magnitude of shear stresses along the interface

The magnitudes of shear stresses, shear displacements, normal stresses and normal displacements are computed along the interfaces. As the slope is not linear, the number of interfaces considered for the analysis are 13. The interfaces from 1 to 9 represent the bottom geomembrane liner and 10 to 13 represents the top cover of landfill. The interfaces (1, 2), (3, 4, 5, 6) and (7, 8) are the same as it has same magnitude of shear stresses, but different normal stresses and normal displacements. This may be attributed to the presence of two different soils i.e. MSW and silty clay. Therefore, the FLAC considers the two interfaces, top of silty clay layer (i.e. interface 1) and the bottom of MSW (i.e. Interface 2). The results presented in Table 2 show the magnitudes of the shear stresses, normal stresses, shear displacements and normal displacements along the interfaces.

The results presented in Fig. 3 shows the shear stresses at interface using modified Cam clay model. It can be noted from Fig. 3 that the magnitude of maximum shear stresses along the interface are 4.42, 17.2 and 8.14 kPa for the interfaces 2, 3 and 7 respectively. It is noted from Fig. 3 that the shear stress is minimum at interface 3 i.e. in the side slope of landfill. It can be attributed to the maximum shear displacement of 37.2 mm from Fig. 5.

It can be observed from Fig. 4 that the magnitude of the maximum shear stresses along the interface are 6.66, 12.7 and 4.43 kPa for the interfaces 2, 3 and 7 respectively using Mohr-Coulomb model. An observation that can be made from Fig. 5 that the shear stress is minimum at interface 7. The corresponding shear displacement can be noted as 5.38 mm. It can be noted from Figs. 3 and 4 that the shear stresses computed using modified Cam clay model are very high than the shear stresses obtained with Mohr-Coulomb model. Consideration of constitutive model has considerable influence on the overall stability of landfills. Therefore, this study highlights the importance of considering modified Cam clay model while modelling the MSW landfills.

7.3 Magnitude of shear displacements along the interface

The results presented in Figs. 5 and 6 show the magnitudes of shear displacements along the interface computed using modified Cam clay model and Mohr-Coulomb failure criterion. The maximum shear displacements along the interface can be noted from Fig. 5 are 37.2, 22 and 9.62 mm at the interfaces 2, 3 and 7 respectively. It can be noted from Fig. 6 that the maximum shear displacements obtained using Mohr-Coulomb failure criterion are 11.2, 14.3 and 5.38 mm at the interfaces 2, 3 and 7 respectively. An important observation that can be made from Figs. 5 and 6 that the shear displacements obtained with Mohr-Coulomb failure criterion are less than the stresses computed using modified Cam clay model. The shear displacements at interface 2 as shown in Figs. 5 and 6 has

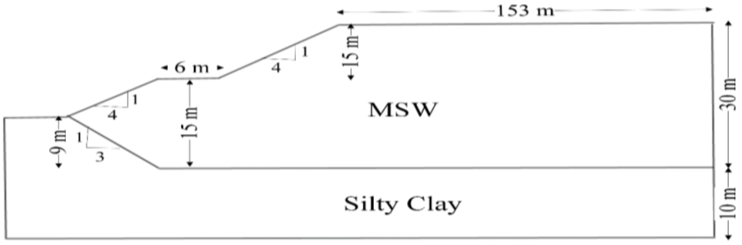

Fig. 1 MSW landfill geometry.

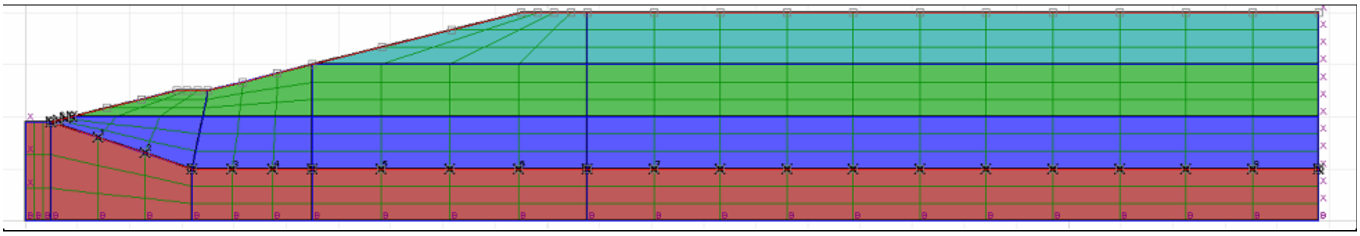

Fig. 2 FLAC model grid.

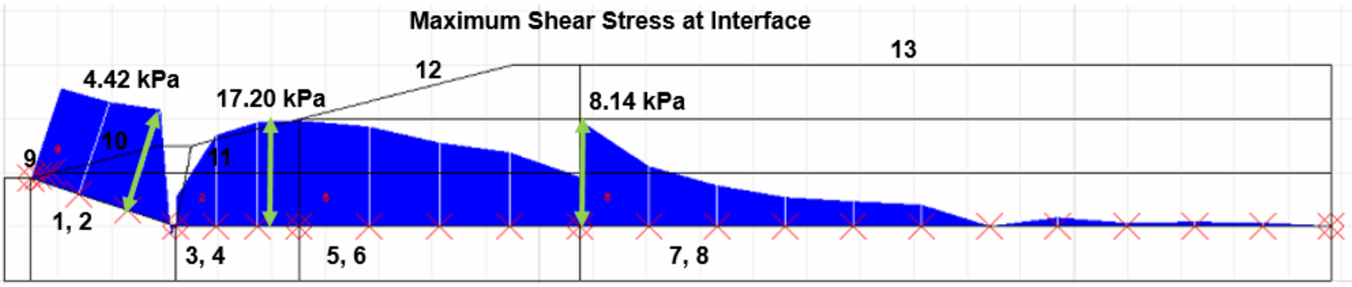

Fig. 3 Magnitude of shear stresses along the interface using modified Cam clay model.

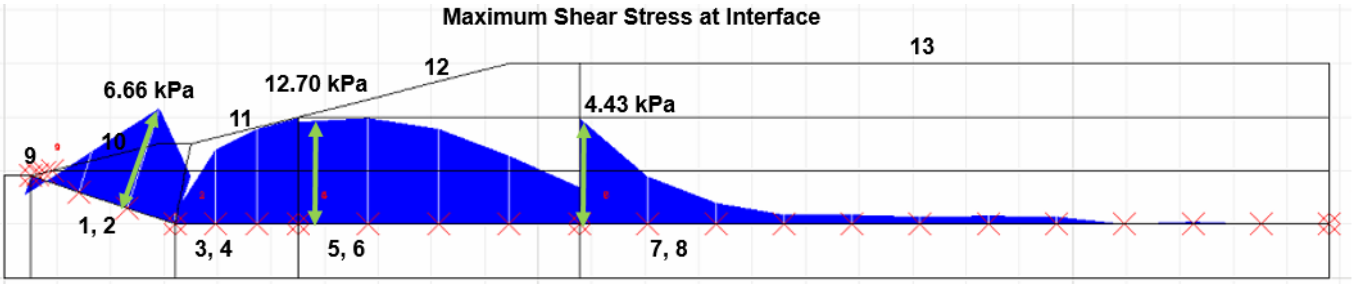

Fig. 4 Magnitude of shear stresses along the interface using Mohr-Coulomb model.

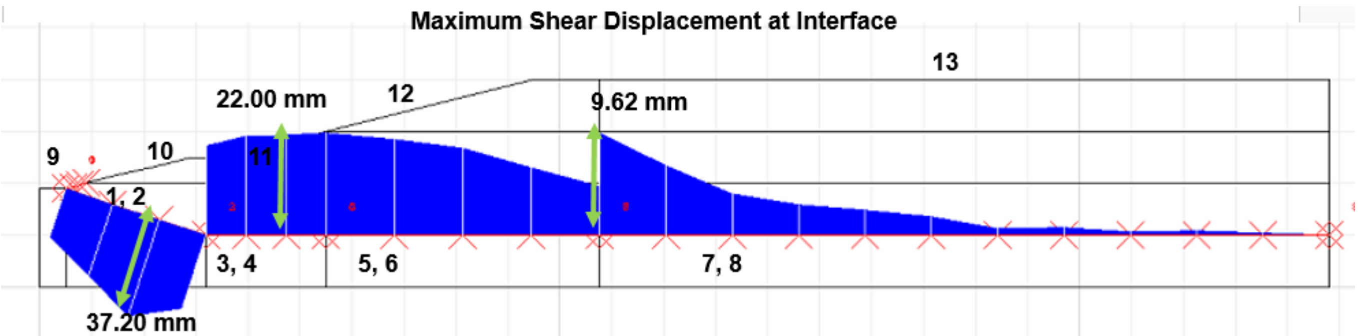

Fig. 5 Magnitude of shear displacements along the interface using modified Cam clay model.

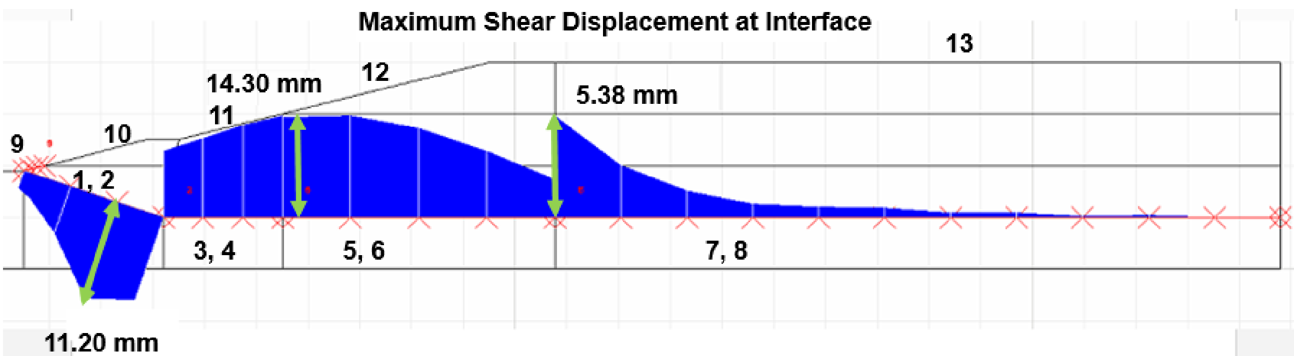

Fig. 6 Magnitude of shear displacements along the interface using Mohr-Coulomb model.

Table 2 Comparison of stresses and displacements of constitutive model with Mohr-Coulomb model

	Mohr-Coulomb				Modified Cam-Clay			
Property / Interface No	Shear Stress (Pa)	Shear Displacement (m)	Normal Stress (Pa)	Normal Displacement (m)	Shear Stress (Pa)	Shear Displacement (m)	Normal Stress (Pa)	Normal Displacement (m)
1	-6.61×10^{3}	-1.12×10^{-2}	-1.40×10^{5}	-4.91×10^{-2}	-5.20×10^{3}	-3.71×10^{-2}	-1.47×10^{5}	-1.25×10^{-1}
2	-6.66×10^{3}	-1.12×10^{-2}	-1.39×10^{5}	-5.38×10^{-2}	-4.42×10^{3}	-3.72×10^{-2}	-1.52×10^{5}	-1.30×10^{-1}
3	-1.27×10^{4}	-1.40×10^{-2}	-2.05×10^{5}	-6.80×10^{-2}	-1.72×10^{4}	-2.20×10^{-2}	-2.05×10^{5}	-1.65×10^{-1}
4	-1.25×10^{4}	-1.80×10^{-2}	-2.05×10^{5}	-7.38×10^{-2}	-1.72×10^{4}	-2.77×10^{-2}	-2.05×10^{5}	-1.80×10^{-1}
5	-1.27×10^{4}	-1.43×10^{-2}	-2.88×10^{5}	-9.44×10^{-2}	-1.72×10^{4}	-2.20×10^{-2}	-2.93×10^{5}	-1.97×10^{-1}
6	-1.27×10^{4}	-1.85×10^{-2}	-2.88×10^{5}	-1.04×10^{-1}	-1.72×10^{4}	-2.77×10^{-2}	-2.93×10^{5}	-2.15×10^{-1}
7	-4.43×10^{3}	-5.38×10^{-3}	-2.95×10^{5}	-9.62×10^{-2}	-8.13×10^{3}	-9.62×10^{-3}	-2.97×10^{5}	-1.97×10^{-1}
8	-4.42×10^{3}	-6.82×10^{-3}	-2.95×10^{5}	-1.06×10^{-1}	-8.13×10^{3}	-1.24×10^{-2}	-2.97×10^{5}	-2.15×10^{-1}

changed its sign indicating a sudden change in the gradient of the slope as can be seen from Fig. 2. However the stresses shown in Table 2 at all interfaces are negative showing the stresses are compressive in nature as modified cam clay model cannot sustain tensile stresses.

8 CONCLUSIONS

- This paper has presented the applicability of the elastic-plastic model “Modified Cam Clay” for the prediction of the MSW behavior in landfills. The present modified Cam clay model considered in the study is included the effects of creep and biodegradation phenomenon. The FLAC 2D does not compute the factor of safety using the modified cam clay models. The stresses and displacements along the interface of the MSW landfill were studied using modified Cam clay and Mohr-Coulomb models and the following are the main conclusions.
- It is noted from the current study that the shear displacements obtained with Mohr-Coulomb failure criterion are less than the stresses computed using modified Cam clay model. Therefore, the adapted Modified Cam Clay is able to improve the general characteristic response of MSW.
- The shear stresses computed using modified Cam clay model are significantly higher than the stresses obtained using Mohr-Coulomb.

REFERENCES

Babu, G. L. S., Reddy, K. R., and Chouksey, S. K. (2010a), “Constitutive model for municipal solid waste incorporating mechanical creep and biodegradation-induced compression.” *Waste Manage.* (Oxford), 30(1), 11–22.

Babu, G. L. S., Reddy, K. R., and Chouksey, S. K. (2011). “Parametric study of MSW landfill settlement model.” *Waste Manage.* (Oxford), 31(6), 1222–1231.

Babu, G. L. S., Reddy, K. R., Chouksey, S. K., and Kulkarni, H. (2010b). “Prediction of long-term municipal solid waste landfill settlement using constitutive model.” *Pract. Period. Hazard. Toxic Radioact. Waste Manage.*, 10.1061/(ASCE)HZ.1944-8376.0000024, 139–150.

Chouksey, S. K., and Babu, G. (2014), “Constitutive model for strength characteristics of municipal solid waste.” *Int. J. Geomech.*, 10.1061 /(ASCE)GM.1943-5622.0000351, 04014040.

Hossain, M. S., and Haque, M. A. (2009b), “Stability analyses of municipal solid waste landfills with decomposition.” *Geotech. Geol. Eng.*, 27(6), 659–666.

Machado, S. L., Carvalho, M. F., and Vilar, O. M. (2002), “Constitutive model for municipal solid waste.” *J. Geotech. Geoenviron. Eng.*, 10 .1061/(ASCE)1090-0241(2002)128:11(940), 940–951.

Muni Budhu (2010). *Soil Mechanics and Foundations*, Wiley publishers, U.S.