

# Reliability Analysis of Municipal Solid Waste Landfill Slopes

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**ABSTRACT:** It is well known that geotechnical properties of MSW are highly variable and in the present study, the stability of a typical MSW landfill slope (1V:3H and Height = 30.5 m) considering spatial variation of geotechnical parameters is studied in probabilistic framework. The analysis is performed using random field theory combined with numerical analysis and Monte Carlo Simulations (MCS) are carried out to obtain the statistics of the performance parameter, i.e., factor of safety, which is required in the reliability analysis of MSW landfill. The role of spatial variation of the geotechnical properties of waste and the effect of biodegradation with time and degree of decomposition are examined. The results showed a decrease in the reliability indices with increase in variation of MSW properties as well as with degree of decomposition. The study highlights the need for consideration of multilayered slope stability analysis, with spatial variation in waste properties and degree of decomposition as these factors provided reduced reliability index values when compared to the results obtained considering single waste layer for the whole depth.

## INTRODUCTION

Slope stability of a msw landfill mainly depends on the geotechnical properties of waste. Because of waste degradation, the geotechnical properties, such as, unit weight and shear strength characteristics, vary with time as well as degree of decomposition, which is of vital concern from the point of view of slope stability issues. By carrying out the slope stability analysis, it is required to design a safe landfill that is stable under permitted operating conditions. To ensure long term stability, with due consideration of various sources of uncertainties involved in the estimation of geotechnical parameters, it is suggested that the calculated factor of safety should be in the range of 1.5 – 3.0 (bowles 1996). It is well understood that the approach is simple and straightforward but does take into account the variability in an appropriate manner (duncan 2000). On the other hand, in a probabilistic approach, the performance

of the structure resulting from different failure criteria is expressed in a probabilistic framework, i.e., either probability of failure ( $p_f$ ) or in terms of safety index known as reliability index ( $\beta$ ).

The development of reliability based procedures is receiving considerable attention and guidelines on the targeted reliability indices have been suggested in literature. USACE (1997) made specific recommendations on target probability of failure ( $p_f$ ) and reliability indices ( $\beta$ ) in geotechnical and infrastructure projects and suggested that a value of at least 3.0 is needed for an above average performance. Methods of reliability analysis such as first order reliability method (FORM), second order reliability method (SORM), Point Estimate Method (PEM), and Monte Carlo simulation (MCS) are available in literature (Baecher and Christian 2003).

## UNCERTAINTIES IN MSW PROPERTIES

Quantitative assessment of uncertainty modeling requires the use of statistics as well as probabilistic modeling, which relies on sets of measured data. The uncertainty in the measured data is expressed in terms of sample mean ( $\mu$ ) and variance ( $\sigma^2$ ). The coefficient of variation ( $CoV\%$ ), which is obtained by dividing the sample standard deviation ( $\sigma$ ) by the sample mean ( $\mu$ ), is commonly used in quantifying the geotechnical uncertainty analysis. In the present study, from available literature (Zekkos 2005, Stark et al.2009), the range of statistical parameters, i.e., mean ( $\mu$ ), standard deviation ( $\sigma$ ), and coefficient of variation ( $CoV\%$ ) in the unit weight ( $\gamma$ ) and shear strength parameters, i.e., cohesion ( $c$ ) and angle of internal friction ( $\phi$ ) are evaluated as reported in Table 1.

TABLE 1 Range of statistical parameters, i.e., mean ( $\mu$ ), standard deviation ( $\sigma$ ) and Coefficient of Variation ( $CoV\%$ ) of MSW obtained from published data

	Unit Weight ( $\gamma$ )kN/m <sup>3</sup>	Cohesion ( $c$ ) kPa	Friction angle ( $\phi$ )
$\mu$	9.17 – 13.09 (11.13)	6.63- 29.85 (18.23)	27.6° – 36.93° (32.27°)
$\sigma$	1.86 – 3.38 (2.62)	3.81 – 24.0 (13.91)	6.11° – 9.66° (7.89°)
$CoV$	20.24-25.81% (23.54%)	57.41 – 80.40% (68.9%)	22.14% – 26.17% (24.16%)

## OBJECTIVES OF PRESENT WORK

The objective of the present work is to perform the probabilistic slope stability analysis of the MSW landfill slope with due consideration of spatial variation of geotechnical parameters. The study is conducted using random field theory combined with finite difference numerical code, Fast Lagrangian Analysis of Continua, FLAC 5.0 (Itasca, 2007). Two-dimensional non-Gaussian homogeneous random field is generated by Cholesky decomposition technique. Monte Carlo

simulations are performed to determine the statistics of the response of the MSW landfill slope, evaluated in terms of factor of safety, and, the stability of the landfill slope is reported in probabilistic terms, i.e., reliability index ( $\beta$ ). The results of the analysis are compared and discussed in the light of traditional factor of safety approach, in which the geotechnical parameters are considered as uniformly constant throughout the analysis domain.

## SPATIAL VARIATION AND RANDOM FIELD MODELING

It is well understood that the second moment statistics, i.e., mean ( $\mu$ ) and variance ( $\sigma^2$ ), alone are not sufficient to describe the spatial variation of geotechnical properties, which vary in the 2- or 3-dimensional space. The spatial variation of the *in situ* property, represented by the mean ( $\mu$ ), coefficient of variation ( $CoV\%$ ), and auto-correlation distance ( $\delta_z$ ), is well represented by the random field theory. For the spatial variability modeling, a parameter, i.e., an auto-correlation distance ( $\delta_z$ ) is defined as “the distance within which the soil property exhibits relatively strong correlation”. It is noted that for low values of  $\delta_z$  the domain is similar to erratic field and as  $\delta_z$  increases the field becomes more homogeneous. For representing a log-normally distributed continuous random field for selected geotechnical property, which is represented by parameters such as mean ( $\mu_c$ ), standard deviation ( $\sigma_c$ ), auto-correlation distance ( $\delta_z$ ). The implementation of the modeling procedure in the numerical code is done by developing a subroutine in ‘FISH’ code in *FLAC* (Itasca, 2007). The procedure is explained in Haldar and Sivakumar Babu (2008) and Srivastava (2009).

The numerical analysis for the stability analysis of *MSW* landfill slope is performed after dividing the physical domain of the problem into finite difference mesh of quadrilateral elements. The unbalanced force of each node is normalized by gravitational force acting on that node. A simulation is considered to have converged when

the normalized unbalanced force of every node in the mesh is less than  $10^{-3}$ . In the present analysis, to model the constitutive behavior of *MSW*, elastic perfectly plastic model based on Mohr–Coulomb failure criteria, with associated flow rule, is used. The stability of the slope is calculated in terms of global *factor of safety*, which is evaluated using strength reduction technique.

Considering spatial variation of geotechnical parameters, the statistical information about the mean and variance of the calculated *factor of safety* is obtained from a number of Monte Carlo Simulation (*MCS*) runs. It is noted that the variance of factor of safety significantly reduces as number of simulations increased and the analysis is conducted for different numbers, varying from 100 to 1000. In the present analysis, 100 Monte Carlo simulations were found to be sufficient and are performed. The code runs 100 times and in each run the ‘FISH’ program (subroutine), which assigns different realizations of spatially variable field, in finite difference grids. The distribution of factors of safety and variance are obtained and probability of failure is evaluated and the corresponding reliability index is evaluated.

## RESULTS OF ANALYSIS

In the present study, the influence of spatial variation of geotechnical parameters on the stability of the 30 m high municipal solid waste landfill (with slope angle 1V:3H and 6.0 m bench at 15 mid height) is studied. The whole system is placed on native silty clay ( $c = 50$  kPa,  $\phi = 30^\circ$ ,  $\gamma = 16$  kN/m<sup>3</sup>). Bray et al (2009) noted that water content is potentially an important factor influencing the stability of the landfills, but for water contents at or below the field capacity, which is a predominant condition for the *MSW* landfills, it was not found to be a key factor. Hence, the present analysis does not take into consideration the effect of presence of water content. However, in bioreactor landfills where waste may be saturated or nearly saturated, significant excess pore pressures could be produced due to highly compressible nature of *MSW*. The probabilistic slope stability analysis of

*MSW* landfill is performed considering the following cases:

1. The mean values of material properties for the waste layer are taken from Table 1. Initially, the stability of the landfill slope is worked out in terms of traditional *factor of safety* with baseline properties of *MSW* ( $\gamma = 11.13$  kN/m<sup>3</sup>,  $c = 18.23$  kPa,  $\phi = 32.27^\circ$ ) for the full depth of the fill (30 m) in a single layer. Further, a parametric study on the probabilistic assessment of the stability of landfill slope is performed, considering spatial variation of geotechnical properties, with mean ( $\mu$ ) values equal to baseline properties, coefficient of variations (*CoV*%) as provided in Table 2 and correlation distances ( $\delta_c$ ), i.e., 0m, 0.5m, 1.0m, 1.5m, and results are compared and discussed.
2. To study the impact of degree of decomposition (*DoD*%) and corresponding variation in the geotechnical properties, on the stability of the *MSW* landfill slope, the geotechnical properties of the *MSW* of 30 m landfill are linearly varied with depth. The total landfill depth (30 m) is considered to be placed in 10 layers, each 3 m thick. The traditional *factor of safety* of the landfill slope is evaluated for the mean values of the geotechnical parameters evaluated at the center of the each layer. A parametric study on the probabilistic assessment of the stability of landfill slope is performed considering spatial variation of geotechnical properties in each layer with mean ( $\mu$ ) values (obtained at the center of the each layer as shown in Fig.1), coefficients of variation (*CoV*%) as provided in Table 2 and correlation distances ( $\delta_c$ ), i.e., 0m, 0.5m, 1.0m, 1.5m, and results are compared and discussed.

TABLE 2 Coefficients of variation (*CoV*%) considered in the input geotechnical parameters for probabilistic slope stability analysis of *MSW* landfill

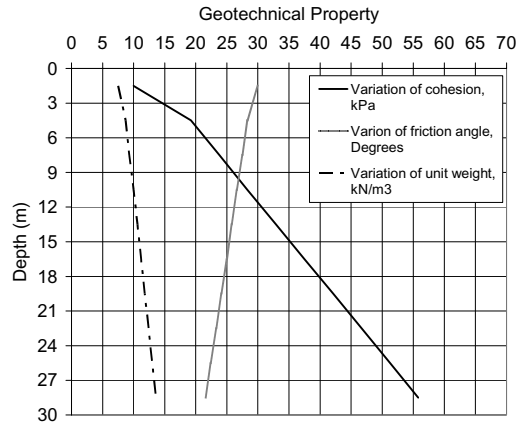
Cases	Unit weight ( $\gamma$ )	Cohesion (c)	Friction angle ( $\phi$ )
1	10%	50%	10%
2	15%	60%	15%
3	20%	70%	20%

4	25%	80%	25%
5	30%	90%	30%

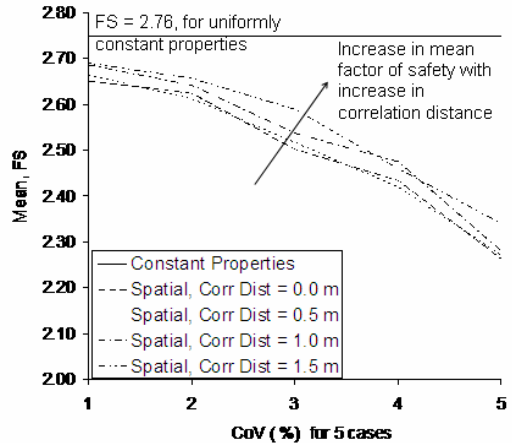
For Case [1] study, the tradition *factor of safety* for uniformly constant properties is evaluated as 2.76, which is more than the minimum acceptable limit of 1.5. Fig 2 shows the influence of coefficient of variation ( $CoV\%$ ) and correlation distance ( $\delta_c$ ) in the evaluation of mean *factor of safety* of *MSW* landfill slope for spatially varying geotechnical properties. The results are also compared with the traditional *factor of safety* value, in which the geotechnical properties are considered to be uniformly constant. It can be noted that with an increase in coefficient of variation, the mean value of factor of safety decreases and on the other hand, the *factor of safety* value increases as the correlation distance increases. From the calculated mean and variance of the *factor of safety* values from 100 Monte Carlo simulations, the reliability index ( $\beta$ ) for normally and log-normally distributed  $FS$  are obtained.

Figure 3 shows the influence of change in the coefficients of variation ( $CoV\%$ ) on the reliability index ( $\beta$ ) values calculate for the spatially varying geotechnical parameters (typical results are obtained for correlation distance ( $\delta_c$ ) = 0 m).

The results of the reliability analysis are also compared with the minimum acceptable limit of 3.0 (for above average performance level as per USACE 1997 recommendations). It can be noted that the reliability index values for lognormally distributed  $FS$  is more than the values obtained for normally distributed  $FS$ . For normally distributed  $FS$ , the reliability index value is below the acceptable limit of 3.0 for case 4 and case 5.

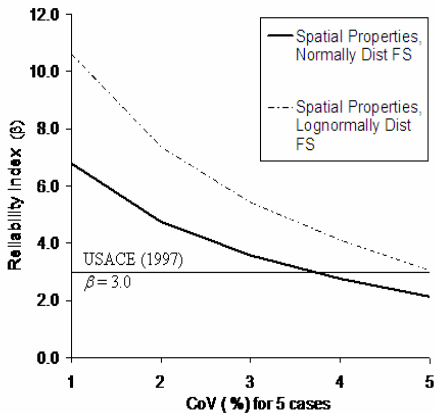


**Fig.1** Variation of geotechnical properties of *MSW* with respect to depth



**Fig.2** Influence of coefficient of variation and correlation distance in the calculated mean factor of safety of the landfill slope

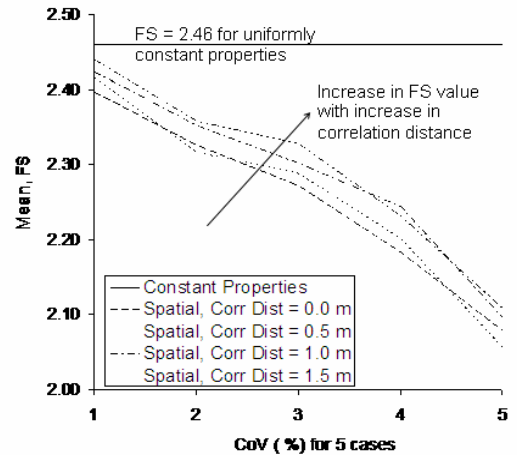
For the case [2] study, the *factor of safety* for the multilayered landfill slope is evaluated as 2.46. It should be noted that it is lower than the corresponding value of *factor of safety* ( $FS = 2.76$ ) evaluated for single depth of *MSW* landfill slope. Hence, it can be stated that the stability of the *MSW* landfill slope should be performed with due consideration to layering of *MSW* deposits and degree of decomposition ( $DOD\%$ ), which simulates the general practical situations also.



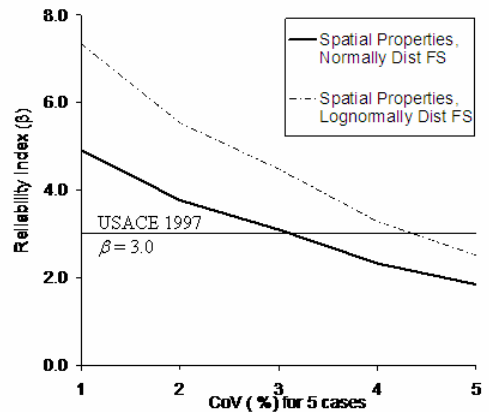
**Fig.3** Reliability index ( $\beta$ ) values for the MSW landfill slope with spatially varying geotechnical parameters

Figure 4 shows the influence of changes in coefficient of variation ( $CoV\%$ ) and correlation distance ( $\delta_z$ ) on the calculated mean *factor of safety* for multi layered *MSW* landfill slope with spatially varying geotechnical properties in each layer. It can be noted that the calculated mean *factor of safety* for multilayered *MSW* landfill slope (with spatially varying properties) is lower than the corresponding values obtained for single depth of *MSW* landfill slope (with spatially varying properties) as evaluated in case [1] study.

Figure 5 shows the influence of change in coefficient of variation ( $CoV\%$ ) on the reliability index ( $\beta$ ) values calculated for multilayered *MSW* landfill slope with spatially varying geotechnical parameters in each layer (results are presented for correlation distance ( $\delta_z$ ) = 0 m). It can be noted that the consideration of spatial variation of geotechnical parameters in each layer of multilayered landfill slope provides reliability index values lower than the corresponding values obtained for single depth of *MSW* landfill slope. The results of the reliability analysis with log-normally distributed input parameters are acceptable.



**Fig.4** Influence of change in coefficient of variation and correlation distance



**Fig.5** Reliability index ( $\beta$ ) values for multilayer MSW landfill slope with spatially varying geotechnical parameters in each layer

## CONCLUSIONS

The two important probabilistic characteristics of the soil spatial variability, i.e., coefficient of variation and auto-correlation distance are studied. Monte Carlo simulation technique, combined with numerical analysis, is a very useful approach in this regard and provides realistic treatment to the reliability analysis of landfill slopes.

The results of the analysis indicate that deterministic slope stability as well as probabilistic slope stability of the MSW landfill with spatially varied geotechnical properties are lower than the corresponding values evaluated for uniformly constant geotechnical properties. It is also noted that consideration of multilayered landfill slope, with linear variation of properties in each layer depending upon degree of decomposition, and, with spatial variation of properties in each layer, provided lower stability values.

## REFERENCES

- Baecher G.B. and Christian J.T. (2003) *Reliability and statistics in geotechnical Engineering*. John Wiley
- Bowels J.E. (1996) *Foundation analysis and Design*. 5th ed. McGraw-Hill Book Co. NY
- Bray J.D., Zekkos D., Kavazanjian Jr. E., Athanasopoulos, G.A. and Riemer M.F. (2009) Shear strength of municipal solid waste. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 135(6), 709-722.
- Dawson E.M., Roth W.H. and Drescher A. (1999) Slope Stability Analysis by Strength Reduction. *Géotechnique*, 49(6), 835-840.
- Duncan J.M. (2000) Factors of safety and reliability in geotechnical engineering. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 126(4), 307-316.
- Griffiths D.V. and Fenton G.A. (2007) *Probabilistic Methods in Geotechnical Engineering*. Springer.
- Haldar S. and Sivakumar Babu G. L. (2008) Effect of soil spatial variability on the response of laterally loaded pile in undrained clay. *Computers and Geotechnics*, 35, 537 – 547.
- Itasca (2007) *FLAC 5.0 Reference Manual*, Itasca Consulting Group, Minneapolis.
- Srivastava A. (2009). *Risk analysis of earth dams under static and earthquake loadings*. Ph.D. Thesis, Department of Civil Engineering, Indian Institute of Science, Bangalore India.
- Stark, T. D., Nejan, H-S, Li, G. (2009) Shear strength of municipal solid waste for stability analysis, *Environmental Geology*, Vol. 57, No. 8, pp. 1911 – 1923.
- USACE (1997) *Engineering and design: introduction to probability and reliability methods for use in geotechnical engineering*. Department of the Army, Washington, D.C. Engineering Circular No. 1110-2-547.
- Zekkos D. P. (2005) *Evaluation of static and dynamic properties of municipal solid-waste*. Ph.D. thesis, Department of Civil and Environmental Engineering, University of California, Berkeley, California.