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Dynamic Behavior of Slope stability of Bioreactor Landfill

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Abstract. Disposal of municipal solid waste (MSW) is a huge problem because most developing and underdeveloped countries dispose of or dump the solid waste on open land without any protection or environmental control. To overcome this problem, conventional and engineered landfill systems are used to dump or dispose of solid waste to avoid an adverse environmental and health impacts. However, currently practiced landfill system needs to be upgraded to accommodate more advanced degradation of solid waste, leading to the establishment of a Bioreactor landfill system. Bioreactor landfill involves the recirculation of leachate into the MSW to enhance the microbial process which overall increases the waste degradation and stabilization. As per the report by the Press Information Bureau in 2016, India produces 62 million tons of solid waste with an average annual growth rate of 4%. About 60% of the landmass of India is prone to earthquakes of moderate to high intensity. Hence, it is necessary to study the behavior of seismic design of bioreactor landfill so as to design the landfills located in the seismic impact zones to resist the earthquake. The present study is focused to analyze the slope stability of bioreactor landfill with the changes in the dynamic properties of bioreactor waste mass with time and decomposition by using PLAXIS2D a Finite Element (FE) software. The dynamic slope stability analysis of bioreactor landfill is also performed by considering several geometry (i.e., slope angles, introducing bench/step of different widths and their combinations) with c-Phi reduction method. It is revealed that reduction in the slope angles increases the factor of safety (FoS). Further, introduction of bench/step along the slope of bioreactor landfill enhances the stability with gentle slopes. However, increase in width of bench/step does not influence in enhancing the stability of slope. Change in geotechnical properties of wastes in each layer at different decomposition age controls the dynamic slope stability of bioreactor landfill.

Keywords: Bioreactor landfill; Leachate recirculation; Seismic slope stability

1. Introduction

Waste management is an important concept related to waste disposal to maintain a clean environment. Several methods have been adopted to dispose of the wastes. However, the most commonly used standard methods to maintain the MSW are to dispose in landfill, incineration, generation of biogas, waste compaction, composting and disposal by barging out in the sea, etc. [1]. Bioreactor landfill is emerging as a major concept across the world because bioreactor landfill is a municipal solid waste landfill (MSWLF) in which liquids are added to facilitate the bacterial decomposition of waste materials [2].

The addition of liquid and air to enhance microbial processes results in to increase in waste degradation and stabilization. They are expected to i) reduce the amount of leachate and the costs associated with its management; ii increase the rate of commercial methane (natural gas) production for commercial purposes, and iii) reduce the amount of land required for landfill construction. The oxygen and moisture levels in bioreactor landfills are monitored and manipulated to increase the rate of decomposition by microbial activity.

An overall operation of bioreactor landfill system is relied on the addition of liquids or recirculation of leachate to raise the solid waste's moisture content at an optimal amount for breakdown and decomposition of MSW. The treatment of garbage through decomposition is the basic premise of a bioreactor landfill. Decomposition occurs in a shorter time frame of 5-10 years [3]. India's population is growing rapidly which is leading to the generation of the huge amount of waste. But, bioreactor landfill is not so popular in India despite several advantages. The Kanjurmarg landfill in Mumbai is the only active bioreactor landfill in India.

Dynamic stability of landfills is one of the major geotechnical tasks in landfill design and operation. Acceleration of the decomposition rate of waste due to leachate circulation greatly affects the characteristics of MSW. Hence, its impact on the dynamic behavior of slope stability of bioreactor landfill needs to be studied. Relevant previous studies related to bioreactor landfills slope stability analysis using several techniques are summarized in Table 1. Relatively few studies have been performed on the dynamic behavior of slope stability of bioreactor landfill. However, different types of degradation composition of MSW have not been considered, and analyses were performed mostly by adopting it uniformly throughout. Further, age of the entire MSW in landfills has been considered the same, however, it is varying depending upon disposal of MSW. Moreover, it differs according to types of material like; organic and inorganic wastes. Shear strength parameters are considered the same for each layer of waste deposition but they should differ depending upon age and rate of degradation [2-6]. Hence, a detailed study of dynamic behavior of bioreactor landfill is required by considering the changes in geotechnical properties with time and age. Further, optimization of geometry should be proposed based on the dynamic slope stability analysis of bioreactor landfill for its long-term integrity.

The present study has aimed to analyze the static and dynamic behavior of slope stability of the bioreactor landfills as a function of time and decomposition. Further the study is extended to understand the effect of different geometrical configurations on the dynamic behavior of bioreactor landfill.

Table 1. Summary of literatures review on stability of bioreactor landfill.

Author(s)	**Objectives**	**Key Observations**
Warith [1]	Performed the experimental study on bioreactor landfills.	Determined the effect of solid waste size, leachate recirculation and nutrient balance on the rate of municipal solid waste (MSW) biodegradation.
Zekkos et al. [2]	Unit weight of Municipal solid waste and hyperbolic relation was created to depict the MSW unit weight profile using field and large-scale laboratory data.	Investigated the factor affecting the unit weight of MSW unit weight. These factors are waste composition and construction practices, such as cover soil placement, compaction effort etc.
Haque [3]	Dynamic characteristics and stability analysis of bioreactor landfills using PLAXIS and GSTABLE were performed.	Concluded that the stability of bioreactor landfills should be evaluated using the strength characteristics determined as a function of time and decomposition rather than using average values.
Hossain and Oasim [4]	Analyzed the slope stability of bioreactor landfill using PLAXIS and GSTABLE for seismic conditions.	The FoS decreases for both static and seismic cases as the decomposition increased with time.
Hossain et al. [5]	Performed the deformation of bioreactor landfill using PLAXIS.	Revealed that the compressibility parameters can be used as a function decomposition to calculate settlement.
Hoyos et al. [6]	Studied dynamic properties of bioreactor landfills with degradation.	Assessed the dynamic propertiessuch as stiffness and damping ratio of MSW during the degradation in bioreactor landfills.
Srivastava et al. [7]	Performed reliability analysis of the effect of leachate recirculation and degradation on the stability of bioreactor landfills slopes.	Examined the increase in stability of the landfill slope with ages.
Reddy [8]	Studied the geotechnical properties of municipal solid waste at different phases of biodegradation.	Assessed the alteration of geotechnical properties of synthetic municipal solid waste (MSW) at various stages of degradationthrough experimental study.
Babu et al. [9]	Evaluating the influence of variable geotechnical properties of MSW on stability of landfill slopes by using FLAC.	Evaluated factor of safety with spatially varied geotechnical properties of MSW which are lower than the corresponding values evaluated for uniformly constant geotechnical properties of MSW.

Giri and Reddy[10]	Studied the effects of unsaturated hydraulic properties of MSW by adopting strength reduction technique to analyze the stability of bioreactor landfill slope in terms of (FOS) using FLAC program	Examined controlling factors such as pore water, capillary pressures, and moisture distribution etc. on the unsaturated hydraulic properties of MSW of bioreactor landfill slope during leachate recirculation.
Rajesh et al. [11]	Reliability-based assessment of municipal solid waste landfill slope and analyzed using FEM and PLAXIS.	Observed that as the degree of decomposition progress, time elapses, and the slope's FoS decreases significantly.
Ismail et al. [12]	Slope stability of landfill with waste degradation and the stability of landfill is analyzed using 2D PLAXIS.	Observed that the FoS reduces with steeper slope angle and vice versa. FoS decreases proportionally to increasing slope angles.
Jha and Kumar [13]	Analyzed slope stability analysis of bioreactor landfillof varying geometry using FEM approach.	Revealed that overall stability of bioreactor landfill, not only, depends on the material properties but slope geometry as well.
		Examined controlling factors such as pore water, capillary pressures, and moisture distribution etc. on the unsaturated hydraulic properties of MSW of bioreactor landfill slope during leachate recirculation.

2. Material Model and Validation of Model

2.1 Material Model, Mesh Generation and Boundary Conditions

Finite Element Method (FEM) is used for dynamic analysis of the slope stability of bioreactor landfills by considering several parameters such as change in material properties, slope geometries etc. In order to achieve the objectives, Mohr-Coulomb (M-C) model in PLAXIS2D, a FEM software, is adopted which includes five parameters; Young's modulus (E), Poisson's ratio (ν), Cohesion (c), Friction angle (ϕ) and Dilatancy angle (ψ). The 15 nodded triangular element is a very accurate element that gives good quality outcomes, even for challenging problems and hence is adopted in the present study for analysis (Fig. 1).

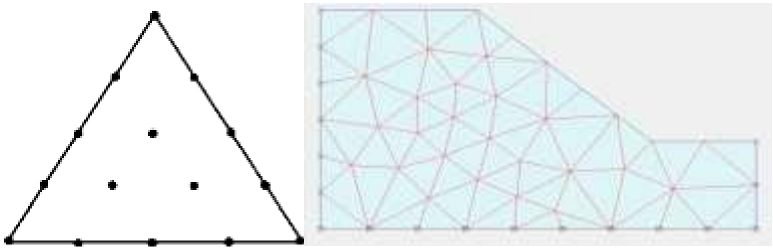

Fig. 1. An illustration 15 nodded triangular element (left) and cross-section of generated mesh (right).

2.2 Analysis and Model Validation

Experimental analysis of slope stability of bioreactor landfills has not been found in the literature. Hence, validation of the model has been conducted by comparing the results of two different software [3-4]. In the present study, validation of the model is performed by considering a simple slope model and comparing the FoS of manual calculation and the same obtained by numerical analysis.

In this approach, a simple geometrical model (Fig. 2) with geotechnical properties as presented in Table 2 is taken to determine the FoS manually by using Swedish Circle Method. Further, the same model is analyzed in PLAXIS2D by considering the Mohr-Coulomb model and the *c*-Phi reduction method to determine the FoS.

It is observed that the FoS is obtained to be 2.01. Comparing the FoS resulted from both methods, difference in result is observed to be 6.51% which is less than 10%, and hence, can be considered within the permissible limit for further analysis.

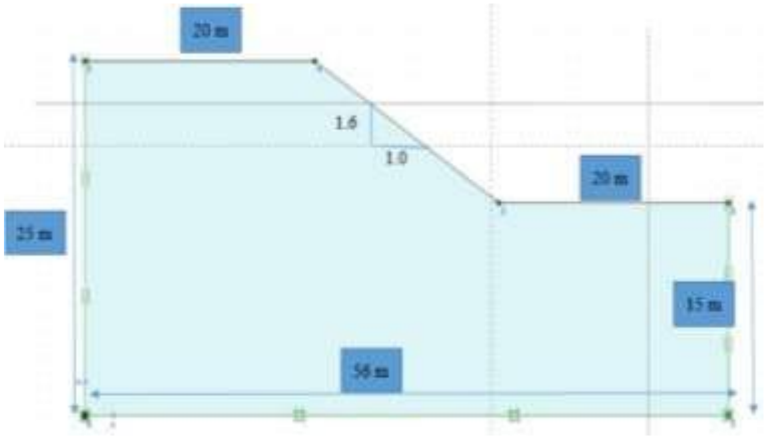

Fig. 2. Geometrical model of slope.

Table 2. Properties of material used in geometrical model for validation [13]

Parameters	Values
Unit weight (γ_{moist}) (kN/m^3)	18
Young's Modulus of Elasticity (E) (kN/m^2)	1260
Poison's ratio	0.30
Cohesion (c) (kN/m^2)	30
Friction angle (ϕ) (degree)	20

2.3 Model Geometry

In the present study, various combinations of geometrical models, adopted for analysis are presented in Table 3 and are shown in Figs. (3-6).

Table 3. Geometrical models of bioreactor landfill.

Model Types	Constant Geometrical Parameter	Varying Geometrical Parameter	Remarks
1	Width of bench/step in slope (i. e. 3 m)	Slope angles are varying such as 2:1, 3:1 and 4:1 for each cases.	Fig. 3
2		Non-uniform slopes above and below the bench/step.	Fig. 4

3	Two bench/step of 10 m width	Uniform slopes of 1:1.	Fig. 5
4		Non-uniform slopes of 1:1, 2:1 and 3:1.	Fig. 6

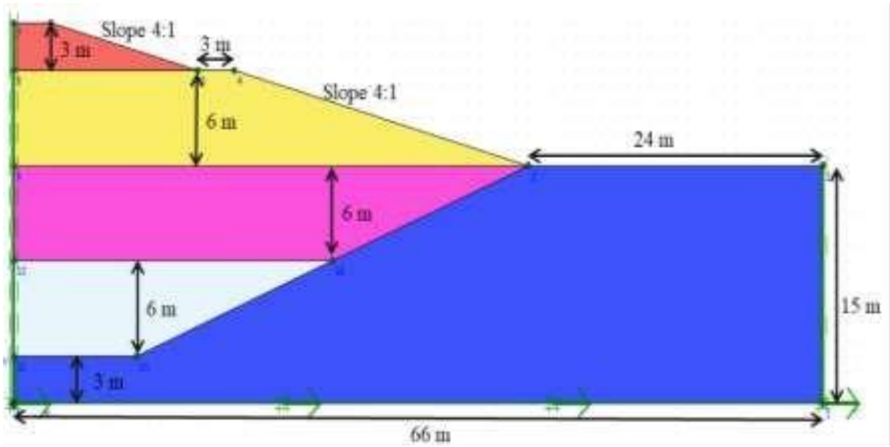

Fig. 3. Geometrical model of bioreactor landfill with bench and uniform slopes.

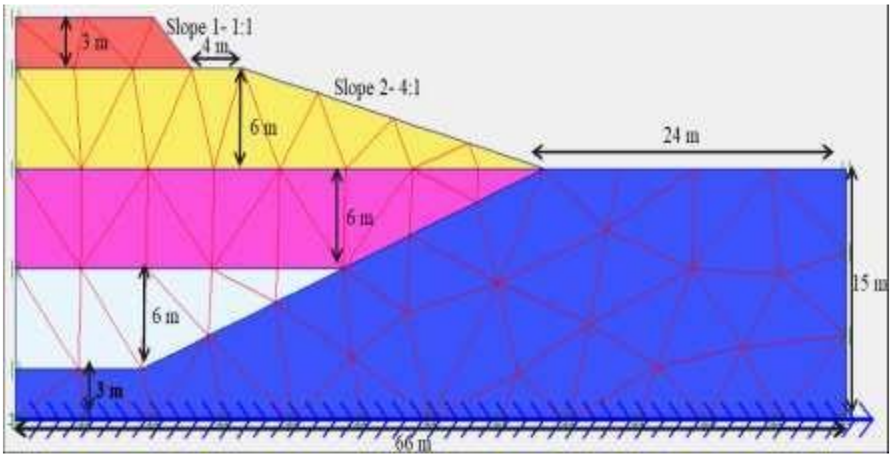

Fig. 4. Geometrical model of bioreactor landfill with bench and having varying slopes.

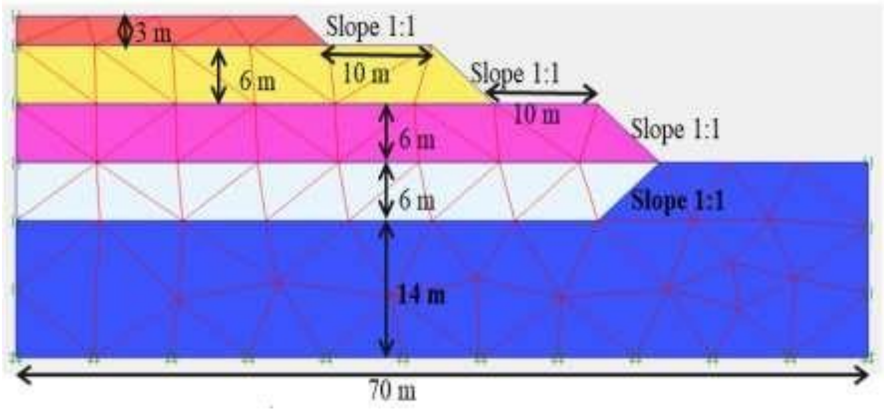

Fig. 5. Geometrical model of bioreactor landfill with two bench and uniform slopes.

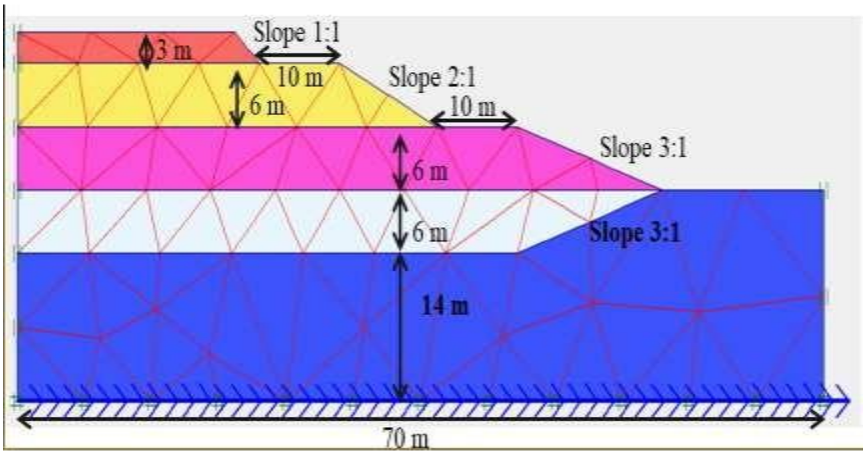

Fig. 6. Geometrical model of bioreactor landfill with two bench and non-uniform slopes.

2.4 Material Properties

2.4.1 Static Input Parameters

Parameters used in the FEM analysis for the different phases of decomposition are presented in Table 4.

Table 4. Material properties of different phases of bioreactor landfill systems at drained condition [6].

Material Set	Unit Weight (kN/m^3)	Permeability ($m/day*10^{-3}$)	Poison's Ratio	Shear Wave Velocity (V_s) (m/sec)	Friction angle (degree)	Stiffness (kN/m^2)
Phase I	11.0	860	0.25	23.7	33	1260

Phase II	11.8	86	0.40	30.3	27	3092
Phase III	12.6	86	0.42	71.7	25	18752
Phase IV	14.1	8.6	0.45	73.6	24	22579
Natural ground	15.9	1	0.35	11.6	30	609

2.4.2 Dynamic Input Parameters

For the dynamic analysis, the 1990 Upland earthquake struck at 23:43:00 UTC on February 28 having a magnitude of 5.4 is selected. This earthquake has hit west of the San Andreas Fault System, injuring thirty personsand causing $12.7 million in losses. The earthquake spectrum and its characteristics are presented in Fig. 7 and Table 5.

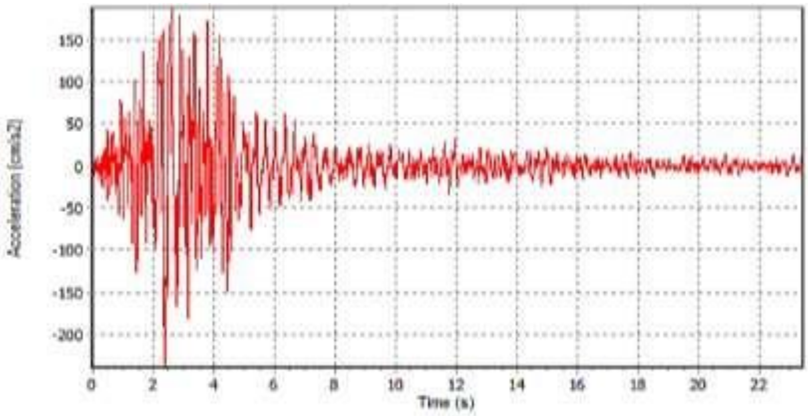

Fig. 7. Earthquake Spectrum (Adopted from Plaxis2D).

Table 5. Characteristics of 1990 Upland earthquake.

Components	Upland Earthquake
Magnitude	5.40
Peak acceleration value (g)	0.23
Duration (s)	19.40
Frequency (Hz)	200
Prescribed Displacement (m)	0.01

2.5 Analysis Cases

The entire depth of the MSW is divided into four different layers [5-6]. Each layers are allowed to undergo uniform degree of decomposition. Table 6 presents the various cases of decomposition scenarios considered in the analysis.

Table 6. Various cases of decomposition scenarios.

Cases	Layer 1	Layer 2	Layer 3	Layer 4
Case 1	Phase I	Phase II	Phase III	Phase IV
Case 2	Phase II	Phase III	Phase IV	Phase IV
Case 3	Phase III	Phase IV	Phase IV	Phase IV
Case 4	Phase IV	Phase IV	Phase IV	Phase IV

3. Result and Discussion

3.1 Effect of varying slope angles on the bioreactor landfill stability having bench/step

The FoS of bioreactor landfills of varying cases and geometry (Fig. 3) are analyzed by using dynamic conditions and are presented in Fig. 8.

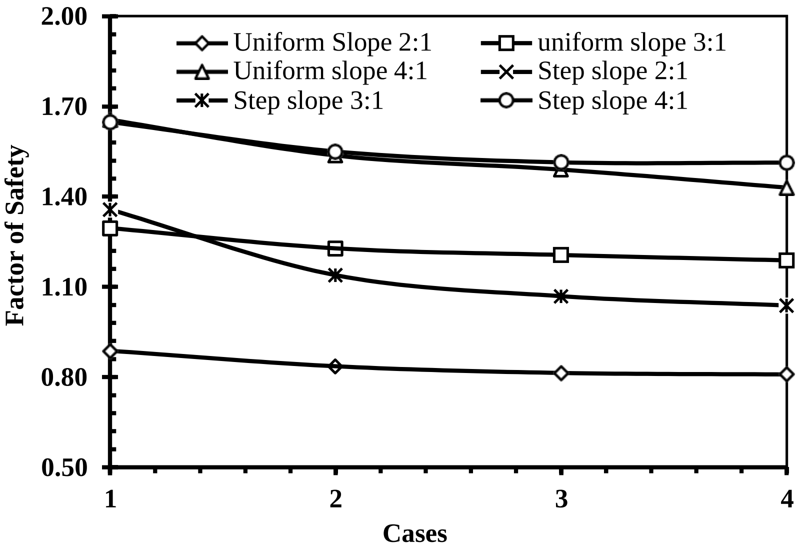

Fig. 8. Dynamic analysis of bioreactor landfill for different geometrical conditions and cases.

Slope with bench/step has a higher FoS value as compared to the same with a slope without a step in the case of slope 4:1. The FoS value for slope 2:1 after introducing step is coming to be zero for all cases, indicating the complete failure of slope. However, FoS is less for 2:1 and 3:1 with step in slope as compared to the same with the normal slope in all cases. The FoS increases with slopes and decreases with cases (i.e. change in material properties of layers). The FoS of bioreactor landfill has been observed to be less than 1 for all cases (i.e. decomposition rate and timing) of slope 2:1. However, FoS is increasing with a reduction in slope angles (from 2:1 to 4:1) of layer 2 for all cases. In comparison to all slope geometries and cases, the bioreactor landfill system having combinations of steeper angle in slopes with bench/step are pronounced to be unstable compared to the same with gentler slope angles. However, decomposition rate and time and thereby changes in geotechnical parameters of each layer have influenced significantly to the stability of bioreactor landfill for any slope geometry.

3.2 Effect of non-uniform slope geometry on dynamic stability of bioreactor landfills

The geometrical model of the bioreactor landfill slope is shown in Fig. 4. In this problem, width of bench/step is kept constant (i.e., 4 m), but slope above (i.e., designated as slope 1) is kept constant i.e., 1:1 and below (i.e., designated as slope 2) of bench/step is varying i.e. 2:1, 3:1 and 4:1, respectively. Materials properties of cases are presented in Table 4.

It is observed that the FoS of bioreactor landfill has observed to be less than 1 for all cases (i.e. decomposition rate and timing) (Fig. 9). Further, it is revealed that the FoS increases with reduction in slope angles (from 2:1 to 4:1) for all cases. Further, the drastic reduction in the FoS is observed with change in the cases from 1 to 4. This confirms that the decomposition rate and time and thereby changes in geotechnical parameters of each layers have significantly influenced the stability of bioreactor landfill for any slope geometry.

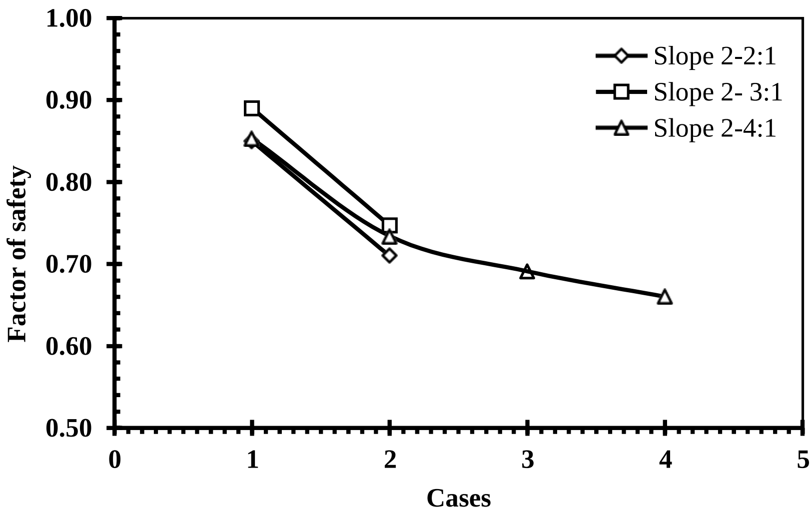

Fig. 9. Dynamic stability of non-uniform slope geometry in bioreactor landfill.

3.3 Effect of slope geometry in stability of bioreactor landfill

In this study, width of bench/step is kept constant (i.e., 10 m) and the slope 1, slope 2, slope 3 (kept constant i.e. 1:1 for case 1) (Fig. 4) and varying slopes of 1:1, 2:1, 3:1 for case 2 (Fig. 5), respectively. Similar materials properties of all cases are adopted as presented in Table 4.

The FoS value for all cases of slope is less than 1 which shows more critical situation (Fig. 10). The FoS value decreases with changing cases from 1 to 4. It indicates that as phase increases or decomposition increases, stability of landfills decreases. However, decomposition rate and time, and thereby changes in geotechnical parameters of each layers have significantly influenced the stability of bioreactor landfill for any slope geometry. Further, it is revealed that varying slope angles provide the better FoS as compared to the uniform slopes above and below the bench/step of bioreactor landfill. Comparing the effect of bench/step widths on the stability of bioreactor landfill (Fig. 9 and 10), it is observed that higher the width of bench/step in slope causes lesser FoS. Overall, dynamic stability of bioreactor landfill depends on both material properties of each phases (i.e. cases) and geometry.

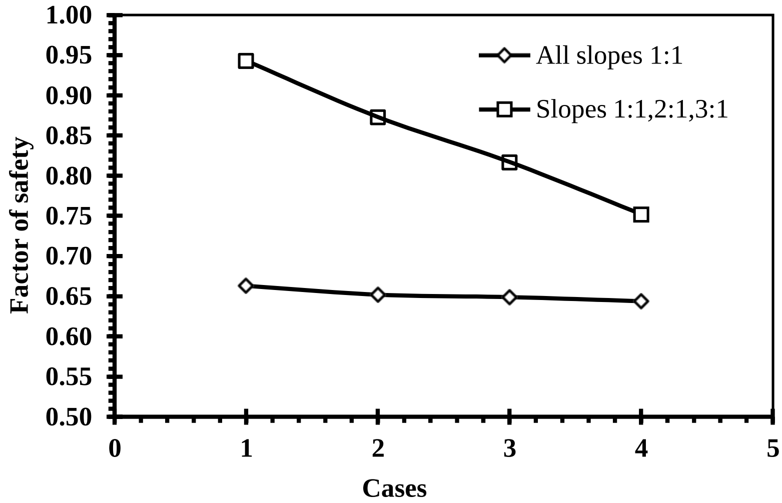

Fig. 10: Dynamic stability of varying slope geometry with 10 m width of bench/step in bioreactor landfill

4. Conclusion

Present study has analyzed the dynamic stability of bioreactor landfill considering both change in geometry and material properties using FEM analysis. Followings are conclusions that can be drawn from the study:

- The bioreactor landfill system having combinations of steeper angle in slopes with bench/step are pronounced to be unstable compared to the same with gentler slope angles.
- The FoS value decreases with changing cases which confirms that stability of landfills decreases with an increase in decomposition rate. Reduction in slope angle increases the stability of bioreactor landfills.
- Lowering the slope angle improves the bioreactor stability of landfill. However, bioreactor landfills with multiple stages of decomposition and gentler homogeneous slope angles by integrating one bench/step is more favourable in terms of stability. Furthermore, extending the width of the step/bench in the

bioreactor landfill's slope has been shown to be impractical for all slope angles.

Overall, It is observed that uniform slope of 4:1 in bioreactor is more stable in comparison to other slope geometry. Further, dynamic slope stability of a bioreactor landfill system is influenced not only by decomposition rate and time and changes in geotechnical properties of wastes, but also by slope geometry. However, further research is still needed considering the various dynamic parameters for different earthquake spectrums.

References

1. Warith, M.: Bioreactor landfills: experimental and field results. Waste management, 22(1), 7-17 (2002).
2. Zekkos, D., Bray, J. D., Kavazanjian Jr, E., Matasovic, N., Rathje, E. M., Riemer, M. F., & Stokoe, K. H.: Unit weight of municipal solid waste. Journal of Geotechnical and Geoenvironmental Engineering, 132(10), 1250-1261 (2006).
3. Haque, M. A.: Dynamic characteristics and stability analysis of municipal solid waste in bio-reactor landfills. The University of Texas at Arlington (2007).
4. Hossain, M., Haque, M., Qasim, S., & Hoyos, L.: Seismic Stability of Bioreactor Landfill with Decomposition—A Numerical Modeling. In Proceedings of the 4th International Conference on Earthquake Geotechnical Engineering, Thessaloniki, Greece, Balkans (pp. 25-28) (2007).
5. Hossain, M. S., Gabr, M. A., & Haque, M. A.: Deformation of MSW Bioreactor Landfills: Properties and Analysis Approach. In GeoCongress 2008: Geotechnics of Waste Management and Remediation (pp. 216-223) (2008).
6. Hossain, M. S., Haque, M. A., & Hoyos, L. R.: Dynamic properties of municipal solid waste in bioreactor landfills with degradation. Geotechnical and geological engineering, 28(4), 391-403 (2010).
7. Srivastava, A., Babu, G. S., Reddy, K. R., & Kulkarni, H. S.: Effect of leachate recirculation and extent of degradation on the stability of bioreactor landfill slopes. In Geo-Risk 2011: Risk Assessment and Management (pp. 720-727) (2011).
8. Reddy, K. R., Hettiarachchi, H., Gangathulasi, J., & Bogner, J. E.: Geotechnical properties of municipal solid waste at different phases of biodegradation. Waste Management, 31(11), 2275-2286 (2011).
9. Babu, G. S., Reddy, K. R., & Srivastava, A.: Influence of spatially variable geotechnical properties of MSW on stability of landfill slopes. Journal of Hazardous, Toxic, and Radioactive Waste, 18(1), 27-37 (2014).
10. Giri, R. K., & Reddy, K. R.: Slope stability of bioreactor landfills during leachate injection: Effects of unsaturated hydraulic properties of municipal solid waste. International Journal of Geotechnical Engineering, 8(2), 144-156 (2014)
11. Rajesh, S., Babel, K., & Mishra, S. K.: Reliability-based assessment of municipal solid waste landfill slope. Journal of Hazardous, Toxic, and Radioactive Waste, 21(2), 04016016 (2017).
12. Ismail, S., Taib, A. M., Rahman, N. A., Hasbollah, D. Z. A., & Ramli, A. B.: Slope Stability of Landfill with Waste Degradation. International Journal of Innovative Technology and Exploring Engineering, 9, 393-398 (2019).
13. Jha A. K., Kumar D.: Influence of slope geometry and decomposition time-age on stability of Bioreactor Landfills – Numerical Analyses. Proceedings of Indian Geotechnical conference (2021).