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NUMERICAL ANALYSIS OF SLOPE STABILITY AND SETTLEMENT OF LOCAL ROAD EMBANKMENT CONSTRUCTED WITH CLAY AND MUNICIPAL SOLID WASTE

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ABSTRACT

The significant accumulation of Municipal Solid Waste (MSW) in Pakistan, coupled with inadequate handling and disposal practices, poses substantial health and environmental risks, creating an urgent need for sustainable utilization methods in civil engineering. The primary objective was to determine the optimal proportion of MSW (ranging from 5% to 25%) that could replace clay without compromising the stability and settlement of the shallow foundation. Numerical analysis was conducted using the advanced finite element software PLAXIS 2D. Three embankment scenarios were modeled: Case 1 (clay only), Case 2 (uniform clay-MSW mix), and Case 3 (alternate layers of clay (0.3m) and clay-MSW mix (0.7m)). A standard AASHTO single axle design load of 61 KN/m was applied to all models. The results indicate that both MSW content and the pattern of layer

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placement influence the slope stability and settlement response. The optimal percentage of MSW replacement was calculated to be between 15% and 20%. Specifically, replacing clay with 15% MSW in Case 2 yielded a Factor of Safety (FOS) of 1.26, and using 20% MSW in the alternate layers of Case 3 yielded an FOS of 1.28. Since these FOS values exceed the permissible limit of 1.25, the findings confirm that safe embankments can be constructed by integrating MSW with clay, offering a practical solution for the safe disposal and utilization of MSW by municipalities.

Key Words: Slope Stability, Settlement, Embankment, Municipal Solid Waste, Clay.

Introduction:

Globally, Municipal Solid Waste (MSW) comprises a mixture of discarded solid materials, including items like garbage, trash, and refuse, generated daily by both urban and rural populations (Awad-Allah et al., 2022). Currently, approximately 2 billion metric tons of MSW are produced worldwide, and projections by the World Bank suggest that this generation will increase significantly, reaching 3.4 billion metric tons by the year 2050 (Keskin et al., 2022). While MSW composition varies, it generally includes biodegradable and non-biodegradable components such as kitchen waste, paper, plastics, metals, and assorted debris. Of the MSW collected by municipalities, a substantial majority (roughly 70%) is deposited in landfills and dumpsites (Jahanfar et al., 2017).

In Pakistan, the growing population and rapid urban development have led to the substantial generation of MSW, amounting to approximately 50 million tons annually, with an expected increase of 2% each year (Nguyen et al., 2022). This accumulation poses a significant problem due to inadequate handling and improper disposal practices. Pakistan often lacks an effective waste management system, resulting in MSW being deposited at sites without proper landfills or being incinerated, which can lead to severe environmental issues (Stark et al., 2000). The inadequate handling of MSW creates various environmental and health concerns; for instance, waste piles become breeding grounds for disease vectors (insects, rats, worms). Furthermore, foul odors arise from the decomposition of moist waste, and water seeping through these waste piles contaminates groundwater, leading to unhygienic conditions and health risks (Rawat et al., 2019).

Given the significant accumulation and improper disposal of MSW, there is an urgent need to explore viable solutions for incorporating this material into civil engineering projects. One practical approach explored in this study is the utilization of MSW within embankments for local roads, blending it with clay to form a composite fill material (Omari, 2012). However, the geotechnical characteristics of MSW are known to exhibit considerable dispersion, primarily stemming from variations in waste type and its age. Consequently, accurately assessing and predicting the mechanical behavior of MSW requires a comprehensive understanding of its properties (Zhang et al., 2020).

The aim of this research is specifically to understand the slope stability and settlement

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response of an embankment of a local road resting on clay and a mixture of clay and Municipal Solid Waste using numerical modelling (Chauhan et al., 2017). The overall purpose was to evaluate the optimum percentage of MSW that could be partially mixed with clay without compromising the slope stability and settlement of the shallow foundation. To achieve this, the study focused on three primary objectives:

To evaluate the slope stability and settlement response of a standard clay embankment in rural road construction;

To analyze the slope stability of a road embankment constructed with clay mixed with different percentages of MSW; and

To analyze the corresponding settlement response.

To meet these objectives, numerical analysis was performed using the advanced finite element software PLAXIS 2D. This software allows for the analysis of two-dimensional problems related to deformation and stability in geotechnical engineering (Eid et al., 2000). The analysis was structured around three different embankment scenarios, with the aim of

determining the optimal proportion of MSW that could be combined with clay, ranging from 5% to 25%. Case 1 involved an embankment constructed solely with clay (Ashiq et al., 2024). Case 2 utilized clay mixed with various proportions of MSW (5% to 25%). Case 3 examined alternate layers of clay (0.3m) and a clay-MSW mix (0.7m), also ranging from 5% to 25% MSW. The Mohr-Coulomb Model (MCM) was employed for the material properties of the clay-MSW mixtures (Sangeetha et al., 2025). The ultimate goal was to establish that safe embankments could be constructed by integrating MSW with clay, while maintaining slope stability (Factor of Safety greater than the permissible 1.25) and minimizing settlement (below the permissible 51 mm). The results derived from this study would be helpful for municipalities in the safe disposal and utilization of MSW (Sharma et al., 2025).

Literature Review

Municipal Solid Waste (MSW) encompasses all solid waste materials generated by human activities, generally considered useless or unwanted by individuals or businesses. The components of MSW exhibit considerable variability in terms of size, shape, and both physical and biochemical characteristics (Salahudeen et al., 2024). This inherent diversity presents a significant challenge when attempting to quantify the engineering properties of MSW. The mechanical properties of waste display wide dispersion due to factors such as differing sample compositions, variations in sample types (including age, unit weight, pre-treatment, shredding, and sorting), and the lack of universally accepted procedures for testing and interpreting resulting data (Trivellato et al., 2014). Consequently, a comprehensive understanding of MSW properties is essential for accurately assessing and predicting its mechanical behavior.

Characterization of the shear strength of MSW is critical for the design of slopes,

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embankments, landfills, and for seismic stability evaluations (Rawat et al., 2021). Growing safety concerns and fatal accidents arising from the undrained mechanical behavior of waste in older, poorly managed landfills have spurred recent interest in evaluating these shear strength parameters. Direct shear tests have historically been the preferred method for measuring MSW shear strength, largely due to the ease of handling large waste particles (Rawat et al., 2019). These tests have been conducted using both in-situ techniques on undisturbed samples and on recompacted samples. Direct shear tests have also been employed on large, compacted waste bales to evaluate shear resistance at the contact surfaces of coupled MSW materials. Triaxial compression tests are less common; when used, authors have often interpreted shear strength at various values of axial strains, typically up to a maximum of 20%, because the deviator stress often increases without reaching a discernible peak strength (Qi , 2017). It has been observed that the unit weight of the sample had only a minor influence on the measured shear strength.

Data concerning the temporal evolution of MSW shear strength is limited. Some observations suggest a slight decrease in the angle of shearing resistance or a decrease in apparent cohesion and friction following soaking in leachate or accelerated degradation (Koda et al., 2021). However, contradictory reports exist, suggesting higher shear strength parameters for old refuse samples compared to freshly deposited material. Overall, the literature highlights a wide variation in shear strength parameters of MSW, attributed to variations in test methods, sample age, composition, unit weight, and the assumptions made during data interpretation (Zhang et al., 2021). While in-situ direct shear tests on undisturbed samples can provide more realistic shear strength data for larger samples under actual conditions, they are difficult to

perform at great depths and may be unsuitable in terms of time and cost for obtaining representative data.

Regarding compressibility, the mechanism of compression in waste has been described by various authors (De Farias et al., 2022). The rate of landfill settlement is chiefly dependent on waste composition, operational practices, and factors affecting biodegradation. Total compression in MSW is generally considered to be a result of primary compression (expected during the initial days of placement) and secondary compression, which is primarily degradation-driven and can continue indefinitely (Abdulah et al., 2014).

The Elastic Modulus (Young's modulus) is a crucial mechanical property governing deformation behavior, describing a material's stiffness and quantifying its elastic deformation under stress before reaching its yield point (Mei et al., 2025). The low elastic modulus of MSW can potentially cause barriers to move into the waste until limit equilibrium conditions are established. Literature typically reports two forms of elastic modulus: a dynamic modulus (small strain shear modulus) required for seismic response analysis, and a static modulus required for settlement analyses (Olinic et al., 2014). Data on the static modulus of waste is sparse, although large one-dimensional compression cells

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(ranging from 0.60 m to 2.0 m in diameter) have been employed to estimate the constrained modulus of waste (Pradiptia et al., 2023).

This study employs Plaxis 2D, an advanced finite element method software developed at Delft University of Technology since 1987, intended for analyzing two-dimensional problems related to deformation and stability in geotechnical engineering. The software performs analysis assuming either plane strain or axi-symmetry, utilizing 6-noded or 15-noded triangular elements (Akbas et al., 2023). For a geotechnical simulation tool like Plaxis 2D, the accuracy of approximating reality heavily depends on the user's expertise concerning problem modeling, understanding the soil models and their limitations, the selection of model parameters, and the ability to judge the reliability of the computational results.

To describe soil deformations, a mathematical framework known as a material model is assigned (Mehdizadeh et al., 2020). While the Linear Elastic model, based on Hooke's law, is unsuitable for modeling soil due to its highly non-linear and irreversible behavior, it can be used for stiff volumes within the soil, such as concrete walls or intact rock formations. A significant limitation is that this model does not limit stress states, implying infinite strength.

The Mohr-Coulomb Model (MCM), a linear elastic perfectly plastic model, represents a 'first-order' approximation often used for soil or rock (Kumar et al., 2022). It requires five input parameters: Young's modulus (E) and Poisson's ratio (υ) for elasticity; friction angle (Ø) and cohesion (C) for plasticity; and the angle of dilatancy. The MCM is computationally efficient and provides a first estimate of deformations by assuming a constant average stiffness or stiffness that increases linearly with depth (Adajar et al., 2018). Although the MCM is limited-it does not account for stress-dependency, stress-path dependency, strain dependency of stiffness, or anisotropic stiffness effective stress states at failure are generally well-described using the Mohr-Coulomb failure criterion with effective strength parameters (Φ') and (C') (Blight et al., 2008).

The MCM requires four basic parameters familiar to geotechnical engineers and obtainable from basic soil tests:

Young's modulus (E) [KN/m2]: Used as the basic stiffness modulus.

Poisson's ratio (υ): The ratio of transverse contraction strain to longitudinal extension strain.

Cohesion (c) or un-drained shear strength (c) [KN/m2]: Used to model effective cohesion (c), performing an effective stress analysis in PLAXIS when behavior is set to undrained.

Friction angle (Ø) [degrees]: Used to model the effective friction of the soil in combination with c, applicable for both drained soil behavior and when the material behavior is set to Undrained (A).

In summary, given the considerable dispersion and diversity of MSW geotechnical

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characteristics stemming from variations in waste type and age, numerical modeling using software like PLAXIS 2D and constitutive models such as the Mohr-Coulomb Model is necessary to estimate the optimal proportion of MSW that can be effectively blended with clay to create a composite soil suitable for a local road embankment fill material (Disfani et al., 2013).

Research Methodology

This project was carried out using one of the widely used geotechnical software that is Plaxis 2D. It is a user-friendly geotechnical program offering a realistic simulation of construction stages and detailed post-processing, making it a complete solution for our daily geotechnical design and analysis. With the help of Plaxis 2D, a line load was applied on the embankment laid on the clayey soil using staged construction technique (Majeed et al., 2023). First of all the load analysis was only carried out on the clay soil and then after some partial replacement of Municipal Solid Waste (MSW) was carried out in in different percentages of 5%, 10%, 15%, 20% and 25%. The load was applied gradually on the embankment of 1m thickness.

The Standard load of a single axle loaded truck given by AASHTO was applied on it. The factor of safety and the settlement analysis were carried out from the graph.

Flow chart for working procedure of PLAXIS 2D is described as under (Figure 1). Three cases of calculations for factor of safety and settlement were performed. The depth of embankment is 1m. The side slope is 1:3. The road is 4m wide. In case 1, only clay is filled in embankment as shown in (Figure 3.2). In case 2, embankment was filled with clay and different percentages of MSW i.e., 5%, 10%, 15%, 20% and 25% as shown in (Figure 2). In case 3, the alternating layers of clay (0.3m) and mix of clay and MSW (0.7m) is provided as shown in (Figure 3). It is assumed that the ground water lies at a great depth. Therefore, it is not considered in the numerical modeling procedure.

The diagram in Figure 1 illustrates the grid structure of the Finite Element Model for the local road embankment. The mesh was progressively made finer to reduce the impact of coarseness on the computed outcomes.

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Figure 1 Calculation procedure of numerical modeling

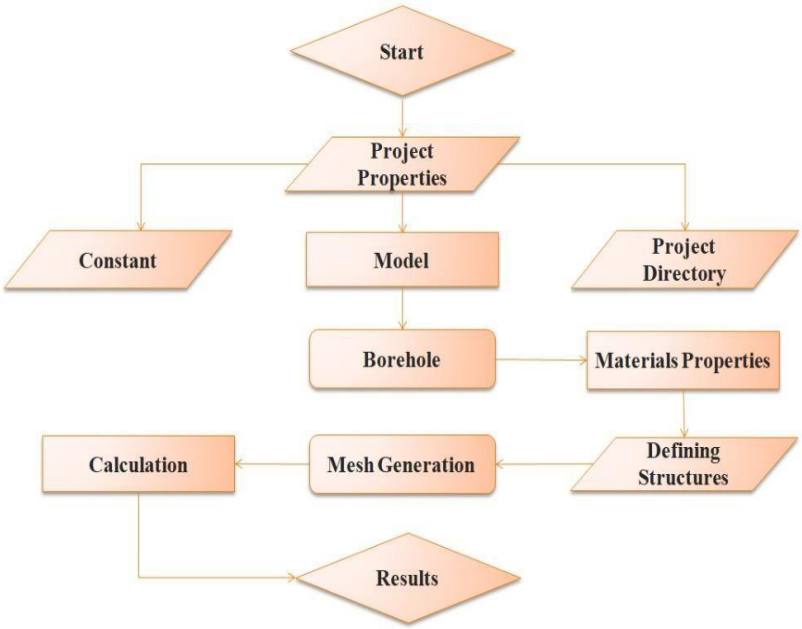

Figure 2 Cross- Section of Road Embankment with Clay

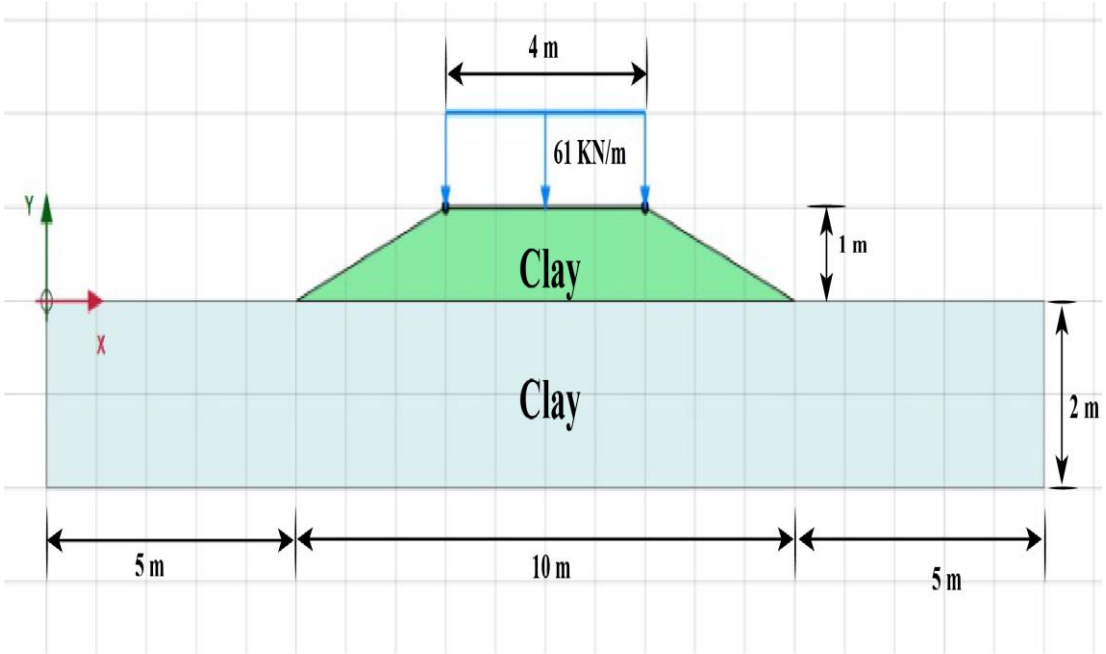

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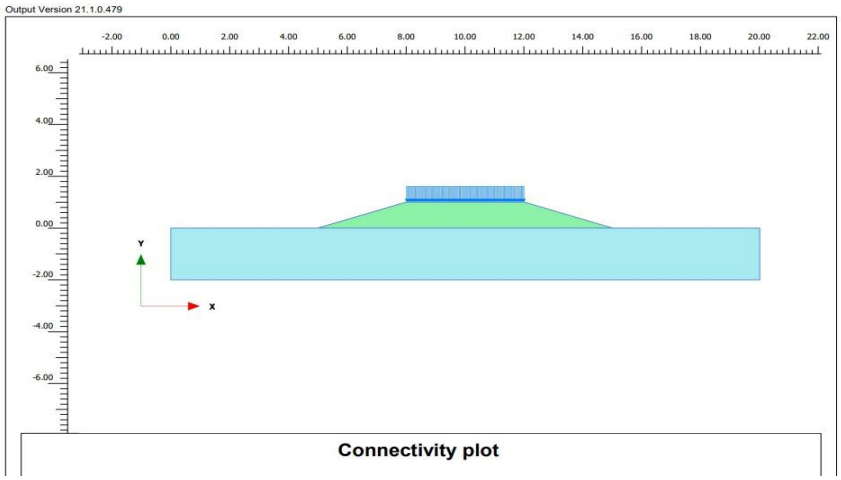
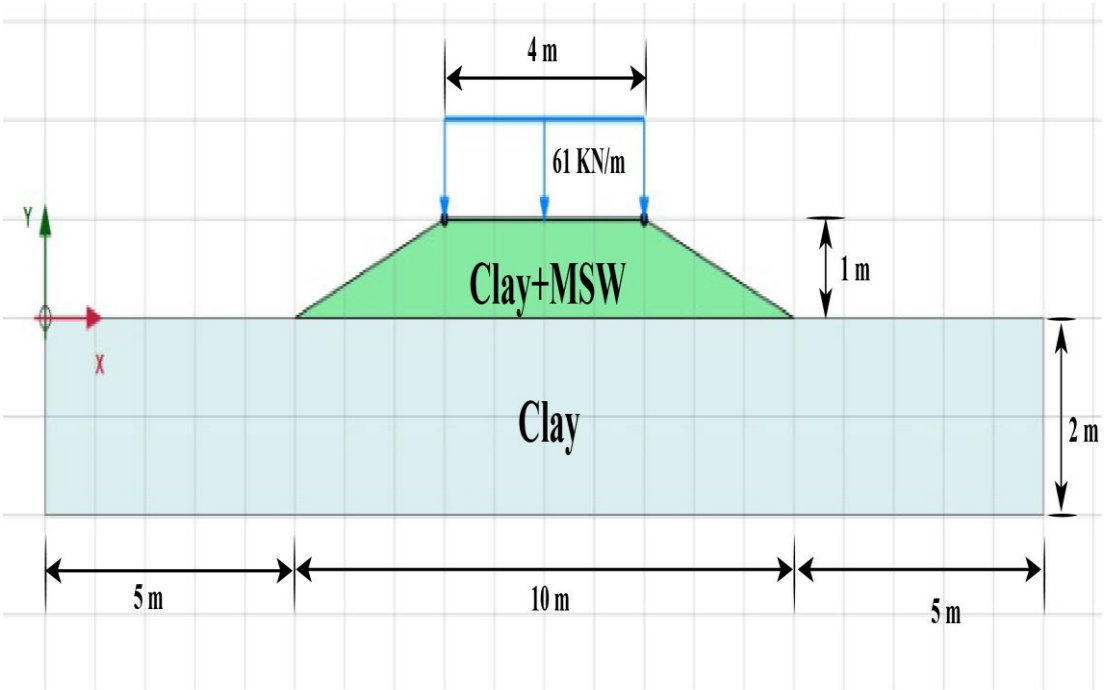
Figure 3 Proposed Placement of Road Embankment with Clay and MSW



In this case, we will use different percentages of municipal solid waste i.e 5%, 10%, 15%, 20%, and 25% alongwith clay.

Figure 4 Proposed Placement of Road Embankment with Clay and MSW mix with clay in alternate layers



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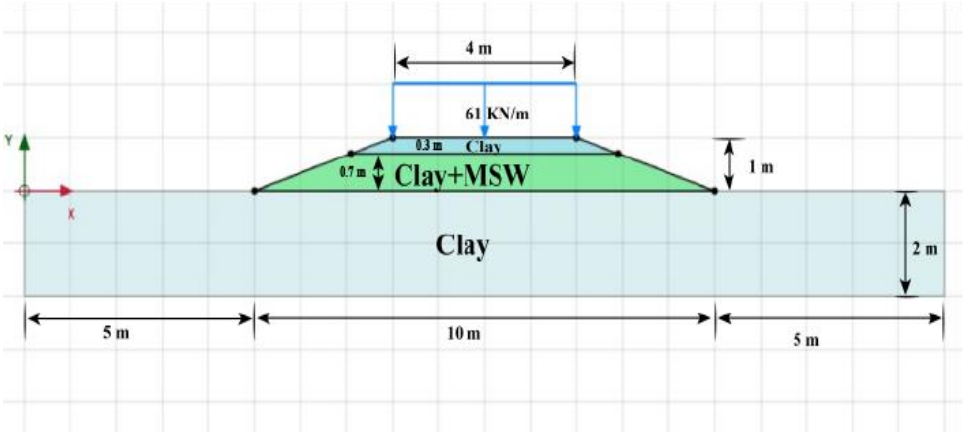

Figure 5 Mesh of the Local Road

The goal of this research is to use some of the clay and mix it with different amounts of MSW (Municipal Solid Waste), which could be anywhere, from 5% to 25%. We first figured out how heavy the clay gets when it's all soaked with water, and that turned out to be 18 KN/m**2** on average. Now, we want to find out how strong and how much the ground settles under embankments when we use these clay-MSW mixtures. To do this, we're using a model called the Mohr Coulomb Model (MCM). We also have some specific details about the clay that the MCM needs to work correctly.

In **Table 1**, the response of the concrete footing was determined using Linear Elastic Model. The material properties of concrete are also described in Table 1.

For different mixes of clay and MSW, the values of cohesion, friction angle, modulus of elasticity, saturated unit weight, and unsaturated unit weight are described in Table 2.

Table 1 Material properties of clay and concrete embankment

Parameter	Symbol	Clay	Concrete	Unit
Type of behavior		undrained	Non-porous	-
Weight above phreatic level	γ(unsat)	17	24	KN/m^3

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Weight below phreatic level	γ(sat)	19	-	KN/m^3
Permeability x-direction	Kx	0	0	m/day
Permeability y-direction	Ky	0	0	m/day
Poisson's ratio	*N*	0.30	0.15	-
Friction angle	Φ	30^0	-	Degrees
Cohesion	C	15	-	KN/m^2

Table 2 Material properties of various mixes of clay and MSW

Soil Type	**C (KN/m2)**	**Φ (0)**	**E (KN/m2)**	**γsat (KN/m3)**	**γunsat (KN/m3)**
Clay	15	30	20000	19	17
Clay+5%MSW	14	28	18000	18.61	16.66
Clay+10%MSW	13	24	16000	18.24	16.32
Clay+15%MSW	12	22	14000	17.8	15.98
Clay+20%MSW	11	20	12000	17.48	15.64
Clay+25%MSW	10	18	10000	17.1	15.3

Results

This study aims to use numerical analysis to find out the maximum mix of clay in a road embankment that can be replaced with MSW while still supporting regular loads. The standard single axle load for a road embankment recommended by AASHTO is 18,000 lbs. The truck load is generally transferred to the embankment. The breadth of road is 4 m. Therefore, the maximum design load on embankment is taken as 18000 lbs (61 KN/m). The permissible settlement of road embankment is 51 mm (2 inch) . The ideal proportion of Municipal Solid Waste (MSW) can be determined by considering both the maximum design load that the embankment can support and the acceptable amount of settlement.

Numerical analysis of bearing capacity and settlement of embankment was performed for following three cases:

Case 1: Only clay is filled in embankment as shown in (Figure 2).

Case 2: Embankment was filled with clay and clay and MSW mix with 5% to 25% (Figure 3).

Case 3: The alternating layers of clay (0.3m) followed by mix of clay and MSW (0.7m) from 5% to 25% are provided (Figure 4).

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Table 3 and 4 respectively present the values of bearing capacity, settlement, and load for cases 1-3.

For case 1, we created an embankment with only clay to compare the slope stability and settlement of the proposed model of our embankment. The standard load of 18,000 lbs was applied as an UDL 61 KN/m. The settlement recorded for this model was 14 mm and factor of safety recorded was 1.52, i.e. more than the permissible (1.25).

Table 3 Factor of Safety, settlement, and load of embankment (cases 1-2)

Soil type	Load Applied in UDL (KN/m)	Settlement (mm)	Increase in settlement w.r.t to clay in %	FOS
Clay	61	14		1.52
Clay+5% MSW	61	15	7	1.50
Clay+10% MSW	61	20	42	1.41
Clay+15% MSW	61	25	78	1.26
Clay+20% MSW	61	48	242	1.14
Clay+25% MSW	61			1

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For case 2, clay is mixed with MSW and the similar load recommended by AASHTO of 61 KN/m was applied on it. The factor of safety came out to be a bit shorter than recommended when we went for 20% MSW, i.e. (1.14). The settlement was 48 mm, yet within limitations.

The correspondence increase in settlement is 242% with respect to embankment with clay. However, the factor of safety of the embankment is within permissible limit of 1.25 if the clay is replaced with 15% MSW .

So, replacing clay with 15% of MSW under standard loading conditions give the factor of safety 1.26 (>1.25) and the value of settlement 25 mm. This implies that with reference to both slope stability and settlement, clay in the road embankment can be replaced with 15% of MSW.

For case 3, the alternate layers of 0.3m of clay and 0.7m of clay and msw mix is provided, and the similar load recommended by AASHTO of 61 KN/m was applied on it. The factor of safety came out to be a bit shorter than recommended when we went for 25% MSW, i.e. (1.19).

The correspondence increase in settlement is 392% with respect to embankment with clay. However, the factor of safety of the embankment is within permissible limit of 1.25 if the clay is replaced with 20% MSW . So, replacing clay with 20% of MSW under standard loading conditions give the factor of safety 1.28 (>1.25) and the value of settlement 48 mm. This implies that with reference to both slope stability and settlement, clay in the road embankment can be replaced with 15% of MSW.

Table 4 Factor of Safety, settlement, and load of embankment (case 3)

Soil type	Load Applied in UDL (KN/m)	Settlement (mm)	Increase in settlement w.r.t to clay in %	FOS
Clay	61	14		1.52
Clay+5% MSW	61	16	114	1.47
Clay+10% MSW	61	31	221	1.39
Clay+15% MSW	61	43	307	1.3
Clay+20% MSW	61	48	342	1.28

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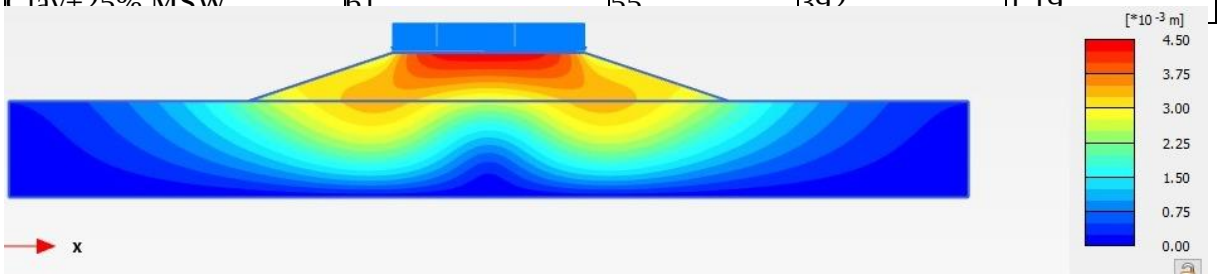
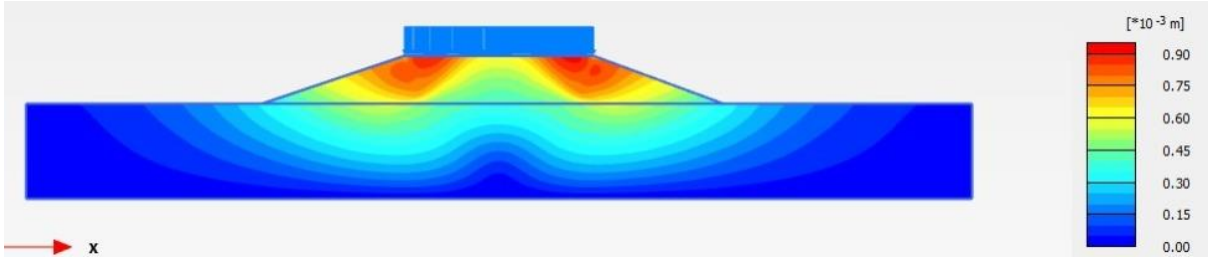
Clay+25% MSW	61	55	392	1.19



The settlement pattern of case 1, case 2 and case 3, when the clay was partially replaced with 15% MSW and 20% MSW is shown in Figures 6,7, and 8 respectively. It can be



observed that maximum settlement occurred below the embankment.

Figure 6. Settlement pattern of embankment with clay only (case 1).

Figure 7. Settlement patterns of embankment with clay and 15% MSW (case 2).

Figure 8. Settlement patterns of embankment with alternate layers of clay and clay and 20% MSW (case 3).

The factor of safety charts of case 1, case 2 and case 3, when the clay was partially replaced with 15% MSW and 20% MSW are shown in Figures 9, 10 and 11 respectively.

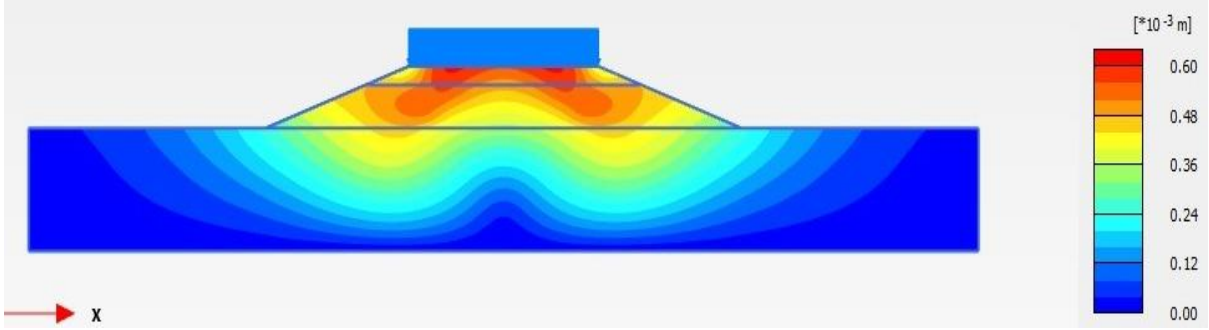


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Figure 9. Factor of Safety chart for clayey embankment (Case 1)

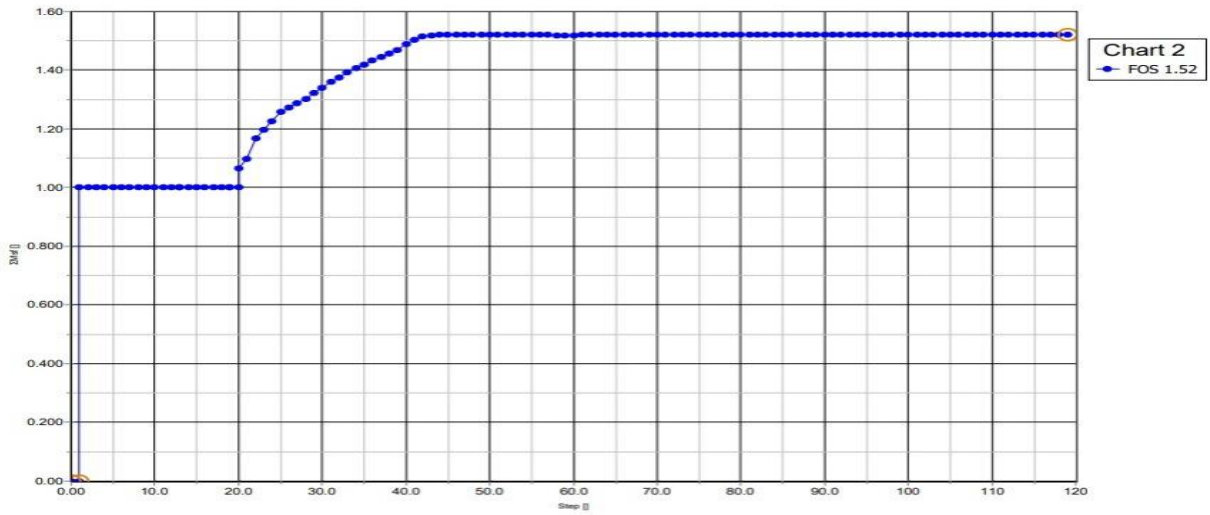
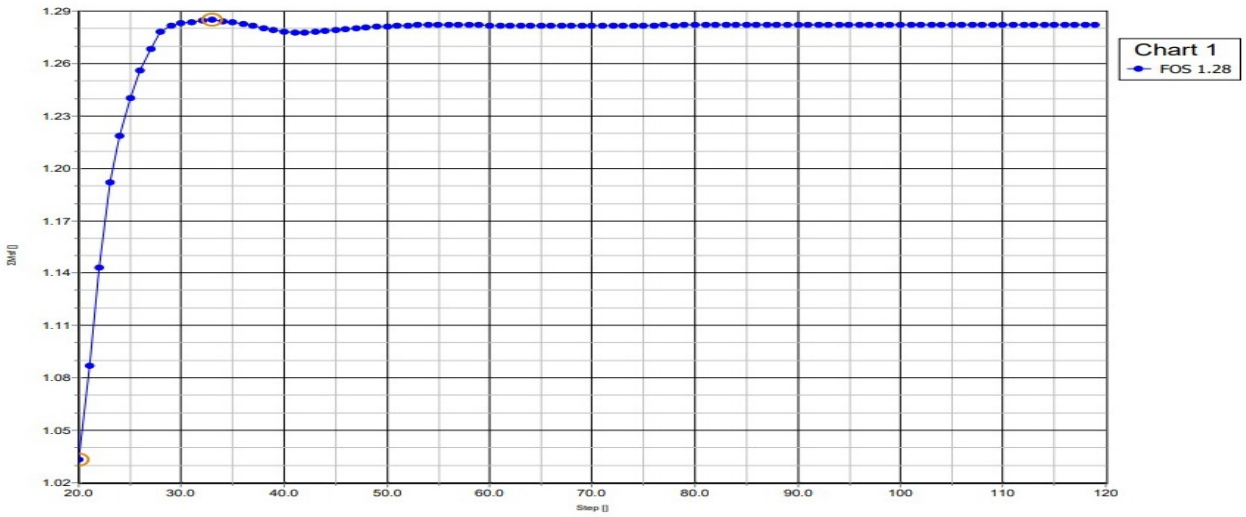


Figure 10. Factor of Safety chart for clay and 15% embankment (case 2).

Figure 11 Factor of Safety chart for clay and 20% embankment (case 3).



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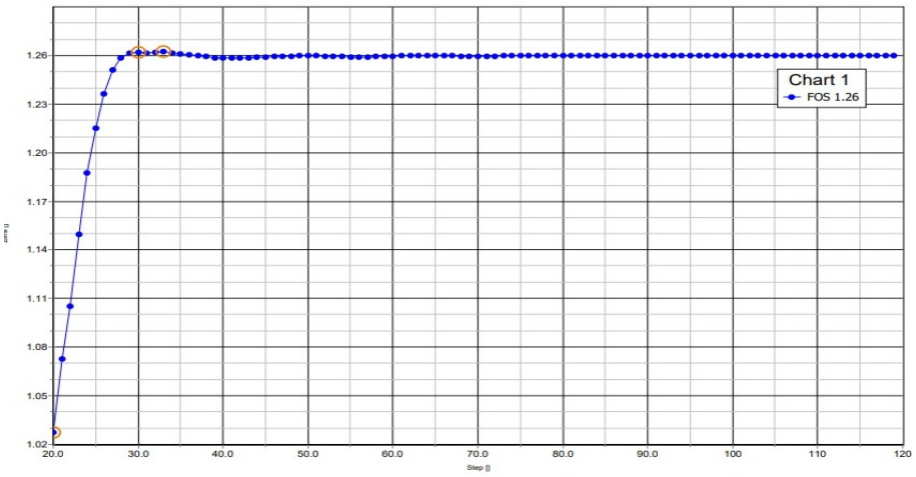
Conclusion and Suggestions:

In this study, numerical analysis was performed to assess the slope stability and settlement of a road embankment resting on clay and various mixtures of clay and Municipal Solid Waste (MSW). The MSW content ranged from 5% to 25%. The overall purpose of the research was to evaluate the optimum



percentage of MSW that could be partially mixed with clay without compromising the slope stability and settlement of the shallow foundation (Ivasuc et al., 2015). The results of the numerical analysis suggest that the slope stability and settlement response of the road embankment are dependent on two factors: the content of MSW and the pattern of placement used for the layers of clay and clay MSW mixture.

The primary finding is that the optimum percentage of MSW that can replace clay was calculated as 15% to 20%. Depending on the specific pattern of the placement of layers used in the model, the ultimate factor of safety (FOS) corresponding to this optimum percentage range of MSW was found to be between 1.26 and 1.28. Improving the slope

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stability and settlement behavior of an embankment constructed using a clay and Municipal Solid Waste (MSW) mix involves several key considerations for future implementation. Proper compaction techniques must be employed during the construction phase to maximize the density of the embankment material. This process will enhance slope stability by actively reducing the potential for settling. Consideration should be given to incorporating geosynthetic materials such as geogrids or geotextiles within the embankment. These materials can improve overall stability by reinforcing the structure. Careful engineering and monitoring of the embankment's drainage system are essential. This is necessary to prevent excess water from weakening the clay-MSW mix, which is a major factor that can lead to undesirable settlement and instability. Regular inspection and maintenance are crucial to address any potential issues promptly and ensure the long-term stability of the structure.

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