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Analysis of Slope Stability in Municipal Solid Waste Landfills Using Fuzzy Logic

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Abstract: One of the fundamental challenges in municipal waste management is ensuring the long-term stability of landfills. Slope instability in these structures can lead to irreparable consequences, including environmental pollution, infrastructure destruction, and public health threats. Therefore, accurate assessment and prediction of slope behavior in these structures is of particular importance. In this study, a new method based on fuzzy logic has been proposed to assess and predict slope stability in landfills. Fuzzy logic, as a powerful tool in modeling complex and uncertain systems, allows for more accurate analysis of landfill behavior. In order to conduct the present study, various steps were taken, including data collection, modeling with fuzzy logic, determining model coefficients, and model validation. In the first step, field data were collected from various excavations such as slope geometry, soil mechanical properties, groundwater level, loading due to waste, etc. Then, a fuzzy logic model was developed to analyze slope stability. In this model, input parameters such as slope, elevation, soil type, and groundwater level were described as linguistic variables and converted into fuzzy numbers using membership functions, and finally, fuzzy rules were defined to express the relationships between inputs and output (slope stability or instability). In the next step, field and laboratory data were used to determine the coefficients of the fuzzy model, and using optimization methods, the model parameters were adjusted in such a way that the model output was consistent with the observed data. In the last step, the developed model was validated using new data. For this purpose, the model results were compared with the observed data and the accuracy and reliability of the model were evaluated. The results show that the developed model will be able to predict the probability of slope instability with high accuracy and identify areas with high risk of instability in landfills. Also, it was determined that by analyzing the sensitivity of the model, important factors that affect slope stability can be identified. According to the model results, appropriate solutions can be provided to improve slope stability, such as changing the slope angle, soil reinforcement, and drainage. As a general conclusion, based on the observations of the present study, it can be said that using fuzzy logic in analyzing the slope stability of landfills is a new and efficient approach that can significantly contribute to improving urban waste management and reducing risks from slope instability.

Keywords: slope stability, landfill, fuzzy logic, optimal slope.

RESEARCH HISTORY

In recent decades, with the rapid progress of urbanization processes and the increase in disorder in waste production and management, landfills have become important as central institutions in the process of urban waste disposal and management. While these structures play a key role in waste treatment and disposal, they also face major challenges and problems. The increase in waste volume, environmental pollution, and violation of slope stability of these landfills are issues that require careful investigation and new solutions in the field of waste management and slope stability. Given the extent of these challenges and their extensive impacts on the environment and public health, the need to find effective and intelligent solutions for the optimal management of landfills is particularly important. In this context, this research attempts

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to examine the fundamental challenges and problems associated with landfills, focusing on increasing slope stability and improving their management performance. This measure not only helps improve waste management but also minimizes negative impacts on the environment and public health.

Numerous studies have been conducted in the field of slope stability analysis in municipal solid waste landfills using fuzzy logic.

In their article titled "Geotechnical Design of Sustainable Landfills and Integrated Waste Management Facilities", Powrie and Watson (2014) reviewed the principles and methods of geotechnical design of landfills with sustainability and environmental considerations in mind. They presented a comprehensive approach to the design of covers, gas collection systems and water drainage networks. They also examined the requirements for monitoring and maintaining landfills after closure. They emphasized that considering environmental and social aspects, along with economic considerations, is key to sustainable landfill design[1].

Inciarte-Mundo (2014) in their article titled "Slope Stability Analysis in Municipal Solid Waste Landfills" evaluated different methods for analyzing and predicting slope stability in landfills. They investigated the effect of parameters such as physical and mechanical properties of the waste, landfill geometry, and hydrological conditions on slope stability. The results of their research can be useful in the safe design and management of landfills[2].

Shariatmadari et al. (2018) in their article titled "Investigation of the Effect of Tensile Strength of Fiber Section on Shear Strength of Municipal Solid Waste" investigated the strength properties of municipal solid waste. They performed direct and triaxial shear tests on waste samples to determine parameters such as adhesion, angle of internal friction, and modulus of elasticity. The results showed that these parameters are a function of density, biodegradability, and moisture content of the waste [3].

In their article titled "Effect of Fiber Content on Compressive and Tensile Strength of a Mixture of Incinerator Ash and Glass Fibers," Portela et al. (2020) investigated the use of glass fibers to improve the mechanical properties of ash from incineration. They produced mixtures with different percentages of glass fibers and conducted compressive and tensile strength tests on them. The results showed that adding fibers improved compressive and tensile strength to a certain extent. They suggested using this optimized mixture as a building material[4].

In a study titled "Effect of Rainfall Intensity and Slope on Infiltration and Surface Runoff in Rainfed Areas of Kalaleh Region, Golestan Province," Ramaei Ramyar et al. (2018) acknowledged that with increasing rainfall intensity and slope, the average infiltration intensity decreased and the average runoff coefficient increased. The effect of rainfall intensity and slope, separately and reciprocally, on the average infiltration intensity and surface runoff intensity was found to be significant with a confidence level of 0.99 [5].

Naeimi et al. (1400) in a study titled "Evaluation of the effects of landfills on the environment using geotechnical factors, case study: Qochan landfill" acknowledged that by analyzing the Iranian matrix, it was determined that the number of negative algebraic mean effects and consequences is equal to 3 and 5, respectively. Among them, the negative effect and consequence less than -1.3 in the column and row are related to land leveling and preparation, bed rupture, and wall stability, respectively. According to geotechnical studies, the stability factor of landfill walls needs to be improved [6]. Naeimi et al. (1400) in a study titled "Evaluation of the effects of landfills on the environment using geotechnical factors, case study: Qochan landfill" acknowledged that the increase in waste production due to population growth and unprincipled burial in landfills is one of the most important problems created in urban societies. Environmental impact assessment has been a welcomed tool for predicting and reducing the destructive and harmful effects of construction projects [7]. A study conducted by Sampurna et al. in 2016 investigated the stability and deformation of engineered landfills using the Mohr-Coulomb model in FLAC2D software. This paper deals with a detailed analysis of the stability of landfills, because there are problems such as heterogeneous composition, incorrect assessment of shear strength parameters, the effect of mechanical creep and indecomposability on the resistance response, and also ignoring issues related to material variability. In this study, the response surface methodology (RSM) was used to investigate the effect of variability of strength and stiffness parameters on the stability of landfills. The effect of variation of specific gravity with depth was also specifically investigated and the results showed that the reliability index decreases with increasing parameter variability. Also, considering the variation of specific gravity with depth provides more reliable estimates of the safety factor and deformations [8].

In a paper by Payne et al. (2018), the seismic stability of municipal solid waste (MSW) landfills on different types of underlying soils was investigated. In this study, a detailed analytical method was developed to calculate the seismic safety factor. This method provides the necessary relations for calculating the safety factor using the two-part wedge mechanism and the limit equilibrium method. The acceleration results calculated using this method showed very good agreement with the results of the DEEPSOIL software. The findings indicated that the type of underlying soil has a significant effect on the seismic stability of landfills [9].

In 2021, Shu et al. published a paper on slope failures in municipal solid waste (MSW) landfills, which examined the combined effects of leachate and gas pressure from organic matter decomposition on slope stability. By providing a simple method for calculating gas pressure and using a circular model to analyze these effects, this study showed that gas pressure in a landfill depends on factors such as gas production rate, waste gas conductivity, and landfill depth. The results show that considering gas pressure significantly reduces the slope safety factor, and this problem is more severe in deeper landfills [10].

Jahanfar et al. (2017) have assessed the risk of slope failure of landfills and have presented a new method for probabilistic analysis of failure scenarios and related losses. In this study, researchers introduced a new method for risk assessment using probabilistic analysis of failure scenarios and potential losses. The conceptual framework of this method included selecting appropriate statistical distributions for the shear strength of municipal solid waste materials and rheological properties to analyze potential failure scenarios. The properties of the waste materials were used to analyze the probability of slope failure and the length of the waste movement path in a specific scenario to calculate the risk of potential losses. The application of this new method in risk assessment with a case study of a landfill in a densely populated area of New Delhi, India showed that the risk is very high and urgent measures are necessary to reduce it before a catastrophic event occurs [11].

In a study conducted by Pourkhosravani et al. in 2017, Geographic Information System (GIS) and fuzzy logic were used to find a suitable location for a landfill in the city of Firozabad. In this study, factors such as geology, water resources, land use, and distance from residential areas were examined. After combining and weighting these factors, maps were prepared to determine suitable and unsuitable landfill areas. The results showed that the southeast, northeast, and part of the northwest were the best options due to suitable geological conditions and distance from residential and agricultural areas [12].

Ansari et al. (2021) examined the construction, stability, and failure of landfills, focusing on case studies from different countries, including Poland, Turkey, the Philippines, China, and Sri Lanka. The aim of this study was to understand the factors affecting landfill failure and the importance of their proper design and maintenance. The analysis showed that the rapid growth of waste generation and economic constraints have led to the creation of landfills with inadequate environmental protection, such as leachate collection systems and weak liners, which lead to severe environmental pollution [13].

In a paper published by Basuka and Sinarta in 2021, the use of a landfill as a site for construction was investigated. The main objective of this research was to evaluate the ability of the landfill to withstand construction loads and to investigate the stability of the landfill slope. The results of the research showed that the settlement of the waste was up to 45 cm with a load of 1250 kg/m2. Therefore, special attention should be paid to the high settlement in the design of the foundation in these areas. Also, this research showed that the slope of the landfill did not significantly change in stability because the safety distance was observed and the slope was not high [14].

An article published by Mirhaji et al. in 2019 investigated the effect of seismic isolation of the soil bed on the dynamic responses and permanent displacements of the municipal landfill embankment. The aim of this research was to evaluate the performance of geosynthetic liners and seismic isolation systems in improving the seismic behavior of the landfill. For this purpose, shaking table tests were conducted on a municipal solid waste landfill insulated with geosynthetic liners, as well as numerical modeling. The results showed that seismic isolation by reducing the friction coefficient significantly reduced the level of translational acceleration and seismic displacements and protected the structure against seismic conditions [15].

Pandey et al. (2017) in a paper investigated the geotechnical properties of municipal solid waste (MSW) consisting of different compositions with diverse properties. The study focused on the role of physical properties and mechanical strength of waste in the stability of landfills and the environmental impacts due to leachate and heavy metal leakage into soil and groundwater. The results showed that the cohesion value ranged from 27 to 53 kPa and the internal friction angle ranged from 7 to 22 degrees. Also, the safe slope angle was calculated to be between 27 and 55 degrees and the safe bearing capacity was between 118.54 and 301.16 kN/m2 for a height of 20 meters and a safety factor of 3 [16].

In a study, Seddighi et al. (2018) investigated the Nazlu landfill located in West Azerbaijan province from a geotechnical perspective and conducted dynamic and static analyses to assess the stability of its slopes. This study analyzed the behavior of the landfill in two states: empty and full of waste. The results of the analyses indicated the appropriate stability of the landfill. As a result, the landfill was modeled as an earthen material and different physical and mechanical properties were considered for each layer of waste .[17].

Haddad et al. (2017) in a study addressed the challenges of municipal solid waste management and the need to evaluate non-standard landfills. Researchers have investigated various methods, including geophysics, field studies, and laboratory experiments, with the aim of identifying and monitoring these areas. CPTU (standard penetration cone) and ERT (electrical resistance tomography) methods have been introduced as proposed methods for identifying landfills. The selection of the appropriate method depends on the characteristics of the site and the type of waste. The researchers suggested that first, using geophysical and mapping methods, suitable areas for drilling should be identified. Then, the site characteristics should be determined by sampling and laboratory tests [18].

An article published by Ismail et al. in 2019 analyzed the stability of municipal solid waste (MSW) landfill slopes in two types of landfills: conventional and bioreactor. This research investigated the effects of waste degradation and changes in their geotechnical properties on the stability of landfill slopes. For stability analysis, the finite element method was used and the safety factor obtained from it was used to evaluate the condition of the slopes. The results showed that the geotechnical properties of waste such as moisture content, unit weight, shear strength, and hydraulic conductivity have an effect on slope stability [19].

In 2017, Ravi Teja et al. analyzed the causes of the Kosheh landfill slope failure from a geotechnical perspective. In this study, a probabilistic model was presented to identify the causes of failure using the first reliability method (FORM) and statistical parameters such as mean and coefficient of variation. The analyses were performed using the Morgenstern-Price method and various combinations of shear parameters were investigated to simulate field conditions. The results showed that the decrease in shear strength due to waste decomposition over time was the main cause of failure. At the time of failure, the average shear strength parameters included $\varphi = 10°$ and $c / \gamma H = 0.15$ and the variability (COV) was 35% and 30%, respectively. The failure occurred in a rotational manner and at a distance of more than 100 m from the bottom of the landfill. The decomposition of plastic waste and its covering with fresh organic waste also led to brittle failure [20].

Considering the previous research studies and the shortcomings they had in the research, this research has attempted to address them and eliminate a large part of them. Therefore, the innovations of this research can be categorized as follows:

- Identifying factors affecting the stability of landfill slope
- Providing a method based on fuzzy logic for analyzing slope stability
- Designing a fuzzy model for calculating the optimal and stable slope of the landfill
- Providing a method for calculating the optimal slope in which the landfill has sufficient stability and at the same time has the highest waste disposal capacity.

In previous research, studies have been conducted using experimental and laboratory methods in the field of slope stability analysis in municipal solid waste landfills. Studies have also been conducted using numerical methods. Given the increasing use of artificial intelligence in new studies and the existence of various laboratory and numerical data in previous studies, it seems that it is possible to analyze the slope stability of landfills with this method. This research uses this method. This method is able to cover unknown paths and complete the necessary data for slope stability analysis using logical induction.

RESEARCH METHODOLOGY

In order to assess slope stability at a landfill using fuzzy logic, the steps of the research method are expressed in Figure 1, with each step being fully described.

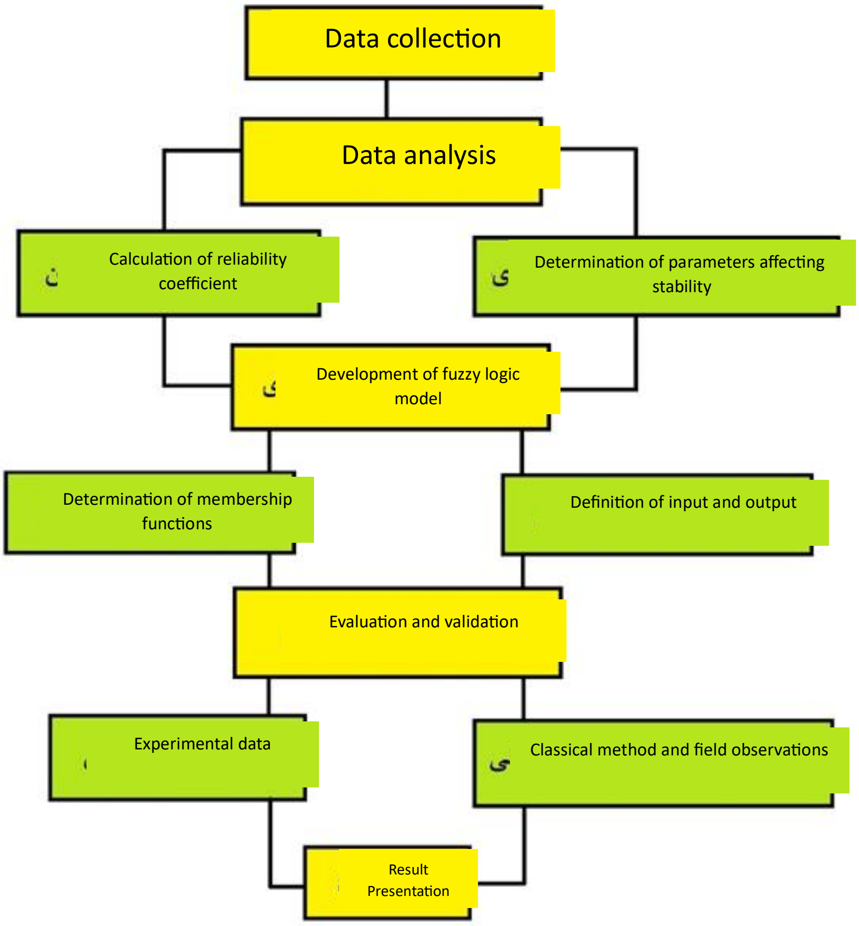

Figure 1. Process diagram for writing an article

CONDUCTING FIELD STUDIES AND DATA COLLECTION

The first step of this research method is to conduct extensive field studies and collect the necessary data from the studied landfills. In this step, first, several landfills are selected as case studies. These sites should be diverse in terms of geological, climatic and operational characteristics so that the results can be generalized to different environments. Then, important geotechnical data such as soil characteristics, shear strength, internal friction angle and soil cohesion are collected through field and laboratory tests on soil samples. This data is essential for determining soil strength parameters and analyzing slope stability. In addition, the slope of the landfill slopes is measured using mapping and remote sensing methods such as LiDAR. Finally, information on soil moisture, leachate leakage and other factors affecting slope stability such as precipitation, relative humidity and wind will be collected through on-site measurement and monitoring stations. This data is essential for identifying key stability factors and entering them into the fuzzy logic system. Collecting accurate and comprehensive data at this stage will play a vital role in developing a successful fuzzy logic model[21].

DATA ANALYSIS

After collecting field data, the next step is to analyze this data using statistical and mathematical methods. In this stage, the parameters affecting slope stability are first identified. These parameters include the slope slope, geotechnical soil properties such as the angle of internal friction (φ) and cohesion (c), and environmental factors such as moisture, leachate, rainfall, and wind.

Then, using theoretical and empirical relationships in geotechnical engineering, the Factor of Safety for slope stability is calculated for each of the case studies. One of the common relationships for calculating the factor of safety in the circular failure analysis method is the Mohr-Coulomb relationship:

$$\tau = c + \sigma \tan(\varphi) \quad (1)$$

Where τ is the shear stress, c is the adhesion, σ is the normal stress, and φ is the angle of internal friction.

Also, in the maximum shear strength method, the safety factor is calculated from the following equation:

$$fs = \frac{(c'A + N' \tan(\varphi')}{T} \quad (2)$$

where A is the failure surface, N' is the effective normal force, φ' is the effective internal friction angle, and T is the shear force.

Using these relationships and the geotechnical data obtained, the stability safety factor can be calculated for various conditions. Usually, a safety factor greater than 1.5 for static conditions and greater than 1.1 for seismic conditions indicates acceptable stability [21].

DEVELOPMENT OF FUZZY LOGIC MODEL

A fuzzy logic model is an intelligent system based on fuzzy set theory that is used to model complex systems with uncertainty and ambiguity. In this model, input and output variables are defined as fuzzy sets with specific membership functions. Membership functions indicate the degree to which each variable value belongs to a specific fuzzy set. Then, fuzzy logic rules that describe the relationships between input and output variables are formulated based on expert knowledge and field experiences. These rules are formed from linguistic and qualitative expressions. For example, "If the slope is high and the soil cohesion is low, then the slope stability confidence factor will be low" [22].

In the fuzzy inference stage, by combining fuzzy logic rules and input values, the fuzzy output of the system is calculated. This fuzzy output must be converted into a non-fuzzy and definite value, which is done using non-fuzzification methods such as the center of gravity or the central mean. Fuzzy logic models have the ability to model nonlinear systems, integrate qualitative and quantitative knowledge, and describe uncertainties and ambiguities. This model can describe complex relationships between different variables in the form of simple and understandable rules. Also, due to its rule-based structure, it has high interpretability. To increase the accuracy and validity of the fuzzy logic model, real field and laboratory data are usually used to optimize the membership functions and rules. This validation and optimization process continues iteratively until the final model is obtained [22].

After data analysis, the next step is to develop a fuzzy logic system for slope stability assessment. In this step, the input and output variables of the fuzzy system are first defined. The input variables can include the slope slope, geotechnical soil properties (internal friction angle and cohesion), soil moisture, leachate leakage rate, rainfall, and other factors affecting stability. The output variable is usually the slope stability confidence factor. In the next step, appropriate membership functions are determined for each of these fuzzy variables. The Gaussian membership function is considered for this research[22].

Then, based on expert knowledge, field experiences and data analysis results, a set of fuzzy logic rules is formulated. These rules specify the relationships between input and output variables. For example:

If the slope is high and the soil cohesion is low and the moisture content is high, then the stability confidence factor of the slope is low. Finally, using the central mean fuzzy inference method, the output of the fuzzy logic system (stability confidence factor) is calculated. The next step is the evaluation and validation of the developed fuzzy logic model. In this step, the results obtained from the fuzzy logic system are compared with classical engineering methods and field observations. Also, part of the data is set aside for model validation. If necessary, the membership functions and fuzzy logic rules are adjusted and optimized to increase the accuracy of the model. This iterative process continues until the final and reliable fuzzy logic model is obtained[22].

FUZZY MEMBERSHIP FUNCTIONS

1. Gaussian Membership Function

The Gaussian membership function is one of the most common membership functions in fuzzy logic, with a curve shape similar to the normal distribution in statistics. This function is defined using two main parameters: the center of the function (c), which represents the value of the variable with the highest membership degree of one, and the width parameter or standard deviation (σ), which controls the width of the curve and its dispersion.

The mathematical relationship of the Gaussian membership function is as follows:

$$\mu(x) = \frac{\exp{(-x-c)^2}}{2\sigma^2} \quad (3)$$

where c is the center of the function and σ is the width parameter of the function [23].

In this function, the value of the Gaussian membership function varies between 0 and 1. The closer the value of x is to c, the higher the membership degree and the closer it will be to 1. As the distance of x from c increases, the membership degree decreases. The parameter σ plays a key role in determining the shape and width of the Gaussian curve. The larger σ is, the wider and more elongated the Gaussian curve becomes. Due to its smooth and continuous shape, the Gaussian membership function is very suitable for modeling ambiguous phenomena and uncertainties in real systems. This function has wide applications in various fields such as signal processing, fuzzy control systems, and fuzzy inference systems [23].

2. Fuzzy centroid inference method:

The fuzzy centroid inference method is one of the most common defuzzification methods in fuzzy logic systems. In this method, the final and non-fuzzy value of the system output is determined by calculating the central point or centroid, the area covered by the fuzzy logic.

The mathematical formula of the centroid method is as follows:

$$x^* = \sum \frac{\mu(x).x}{\mu(x)} \quad (4)$$

Where x* is the final value of the fuzzy output, μ(x) is the degree of membership of the fuzzy output, and x is the value of the output variable.

Therefore, in this method, first the product of each output value and its fuzzy membership degree is calculated. Then the sum of these products is divided by the sum of the degrees of membership to obtain the central point or center of gravity of the area under the curve, which will be the final and fuzzy output value[23].

The center of gravity method is one of the most accurate defuzzification methods because it considers all points under the fuzzy output curve. This method maintains the continuity of the output well and is very suitable for continuous systems. Although this method is computationally more expensive than other methods, it has higher accuracy and is used in many sensitive and precise applications such as control and decision-making systems[23].

3. Mean of Maximum Inference Method:

The Mean of Maximum Inference Method is another common defuzzification method in fuzzy logic systems. This method uses the mean of the values of the output variable that have the maximum membership degree in the output fuzzy set to calculate the final and non-fuzzy value. The mathematical formula of this method is as follows:

$$x^* = \sum \frac{x}{n} \tag{6}$$

where x* is the mean value of the non-fuzzy output, x is the output variable values in the region of maximum membership function and n is the number of these values.

Therefore, in this method, first the interval or intervals of the output variable that have the maximum membership degree (usually equal to 1) are identified. Then the average of these output values with the maximum membership degree is calculated, which will be the final and non-fuzzy output value. The central mean method is a simple and direct method for defuzzification that has a lower computational burden than the center of gravity method. This method is suitable for systems whose output is not continuous or has a limited number of possible values for the output. However, this method is less accurate than the center of gravity method because it only considers the output values with the maximum membership degree [23].

3.2.4 Validation of Fuzzy Logic Model

After developing a fuzzy logic system for slope stability assessment, the next step is to evaluate and validate the model. This step is very crucial because it ensures that the developed model has sufficient accuracy and precision to be used in real conditions.

First, the results obtained from the fuzzy logic system are compared with classical and traditional geotechnical engineering methods as well as observations and real data from landfills. This comparison shows whether the results of the fuzzy logic system are consistent with the existing valid methods or not.

In this section, the main and important formula used to compare the results of the fuzzy logic system with classical methods is the calculation of the Factor of Safety in traditional geotechnical methods. One of the common relations for calculating the factor of safety in the circular failure analysis method is the Mohr-Coulomb relation:

$$fs = \frac{(c'A + N'\tan(\varphi')}{T} \tag{6}$$

Where:

FS Slope stability safety factor

c' Effective soil cohesion

A Failure surface

N' Effective normal force
φ' Effective soil internal friction angle
T Shear force

This relationship divides the slip resistance forces (c'A + N'tanφ') by the shear force driving the slip (T) to calculate the stability safety factor [24].

The safety factor calculated from these traditional relationships can be compared with the stability safety factor values obtained from the fuzzy logic system. The smaller the difference between these two values, the greater the agreement of the fuzzy logic system results with the valid and conventional methods.

Then, a part of the available data that has not been used in the model development is used to validate the fuzzy logic model. This experimental data is given as input to the model and the model outputs are compared with the actual values. The amount of deviation and error of the model at this stage indicates its level of validity and accuracy [24].

In this section, to calculate the deviation and error of the fuzzy logic model with respect to the actual data, the mean absolute error (MAE) is calculated using the following relationship:

$$MAE = \sum \frac{|y\_actual - y\_predicted|}{n} \qquad (7)$$

Where:
y_actual: actual value of test data
y_predicted: predicted value by fuzzy logic model
n: number of test data

MAE calculates the mean absolute magnitude of the difference between the actual and predicted values by the model. The smaller the MAE value, the less deviation and error the fuzzy logic model has from the actual data and the higher the accuracy and validity of the model[5].

To calculate MAE, first the sum of the absolute magnitudes of the differences between the actual and predicted values for all experimental data is calculated. Then this sum is divided by the total number of experimental data to obtain the mean error. This formula is one of the most common criteria for evaluating the error in modeling, and MAE values below a certain threshold are usually considered acceptable. If the difference between the model outputs and the actual data is unacceptable, it is necessary to adjust and optimize the fuzzy logic rules, membership functions, and other model parameters. This process can be performed by various methods such as genetic algorithms, meta-heuristic methods, or Yadovi tuning by experts[24]. After making the necessary adjustments, the model must be re-validated to ensure that its accuracy is improved. This adjustment and validation cycle continues until the desired and acceptable accuracy is achieved for the fuzzy logic model.

PRESENTING COMPARATIVE RESULTS

Histogram of Soil Internal Friction Angles

This graph shows the distribution of internal friction angles for different soil samples. The horizontal axis shows the internal friction angle (degrees) and the vertical axis shows the frequency of these angles. The internal friction angles vary between 25 and 45 degrees, with most samples falling within the 30 to 40 degree range. The internal friction angles of different soil samples vary between 25 and 45 degrees. Soils with higher internal friction angles (closer to 45 degrees) have greater resistance to sliding and therefore provide greater slope stability.

Soil Cohesion Graph

This graph shows the cohesion of different soil samples. The horizontal axis is the sample index and the vertical axis is the soil cohesion in kilopascals. Different samples are shown with different cohesion values. The cohesion of different soil samples was measured in the range of 0 to 40 kPa. This graph shows that some samples have very low cohesion while others have high cohesion. Based on the cohesion graph, the cohesion of the studied soils is in the range of 0 to 40 kPa. Since some samples have low cohesion, these soils are more prone to sliding. As a result, high cohesion (close to 40 kPa) helps to improve the stability of the slope.

Soil Shear Strength Graph

The shear strength of different soil samples is displayed in this graph. The horizontal axis is the sample index and the vertical axis is the shear strength in kilopascals. The shear strength of different soil samples varies between 100 and 200 kPa. This graph indicates the ability of the soil to resist shear stresses.

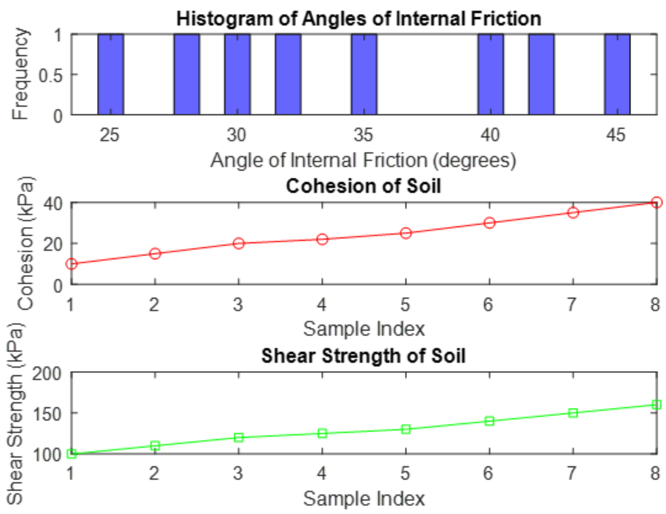

Figure 2. Histogram of soil internal friction angles - soil cohesion diagram - soil shear strength diagram

SOIL MOISTURE OVER TIME GRAPH

The changes in soil moisture over time are displayed. The horizontal axis is days and the vertical axis is the percentage of soil moisture. The changes in soil moisture over time are displayed, indicating an increase or decrease in soil moisture over a certain period of time. This graph shows that changes in soil moisture can affect slope stability. High moisture reduces soil shear strength and increases the risk of landslides. Therefore, controlling soil moisture is essential to maintain slope stability.

PRECIPITATION OVER TIME GRAPH

The changes in precipitation over time are displayed. The horizontal axis is days and the vertical axis is precipitation in millimeters. The changes in precipitation over time are displayed, which can indicate precipitation patterns over a certain period of time. Heavy and continuous rainfall can increase soil moisture and lead to a decrease in slope stability.

WIND SPEED OVER TIME GRAPH

The changes in wind speed over time are displayed. The horizontal axis is days and the vertical axis is wind speed in kilometers per hour. Displaying changes in wind speed over time, which can indicate climate changes and the effects of wind on the environment.

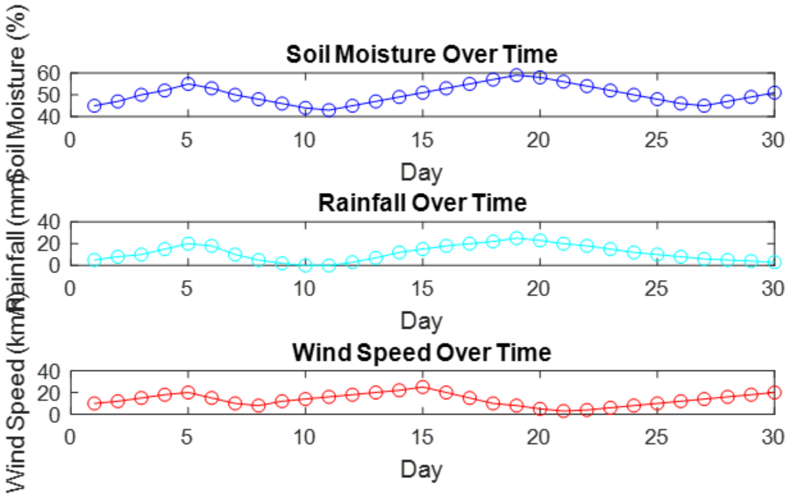

Figure 3. Soil moisture graph over time - Precipitation graph over time - Wind speed graph over time

DRAINAGE LEAKAGE OVER TIME GRAPH

The changes in drainage leakage over time are displayed. The horizontal axis is days and the vertical axis is the drainage leakage rate in liters per day. Displays the drainage leakage rate over a specific time period, indicating the changes and fluctuations in drainage leakage over time.

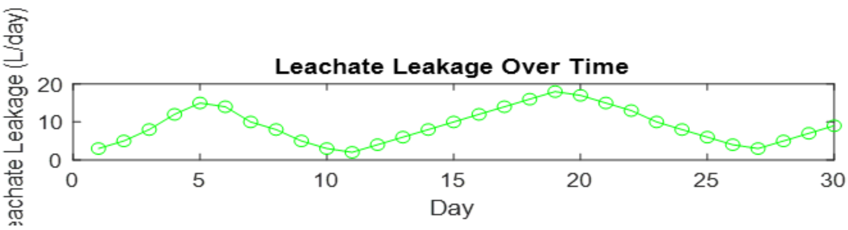

Figure 4. Drainage leakage graph over time

THE GRAPH OF SAFETY FACTOR VERSUS SLOPE ANGLE

The relationship between the safety factor and slope angle is shown. The horizontal axis is the slope angle (degrees) and the vertical axis is the safety factor. Examining the relationship between the safety factor and slope angle shows that as the slope angle increases, the safety factor decreases. This graph shows that as the slope angle increases, the safety factor decreases. In other words, steeper slopes (with a greater angle) are less stable and more likely to slip.

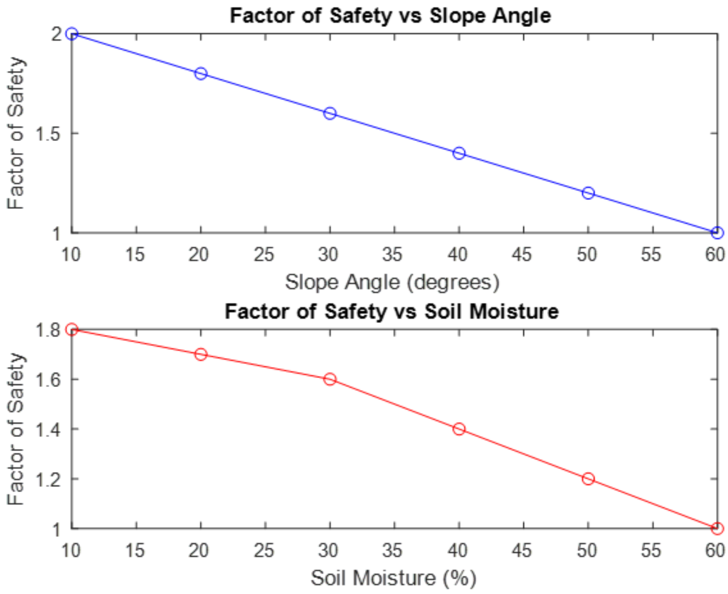

Figure 5. Graph of safety factor versus slope angle

SAFETY FACTOR VS. SOIL MOISTURE GRAPH

The relationship between the safety factor and soil moisture is shown. The horizontal axis is the percentage of soil moisture and the vertical axis is the safety factor. Examining the relationship between the safety factor and soil moisture shows that increasing soil moisture can lead to a decrease in the safety factor.

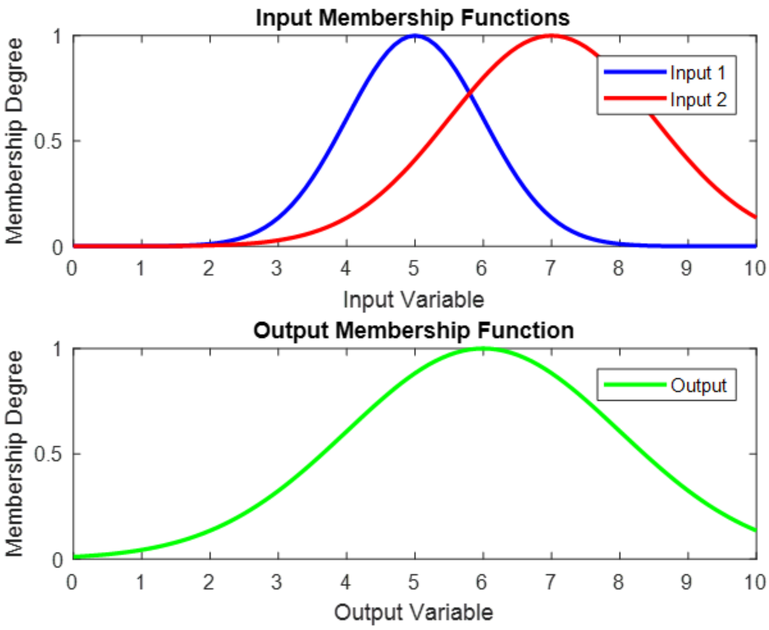

Figure 6. Safety factor versus soil moisture chart

OUTPUT DIAGRAM OF FUZZY INFERENCE SYSTEM

The output of the fuzzy inference system is shown in comparison with two different inputs. The membership diagrams of the input and output variables are also shown along with the fuzzy system with different rules. This diagram shows the output of the fuzzy inference system based on two different inputs. The membership diagrams of the input and output variables are also shown along with the fuzzy system with different rules.

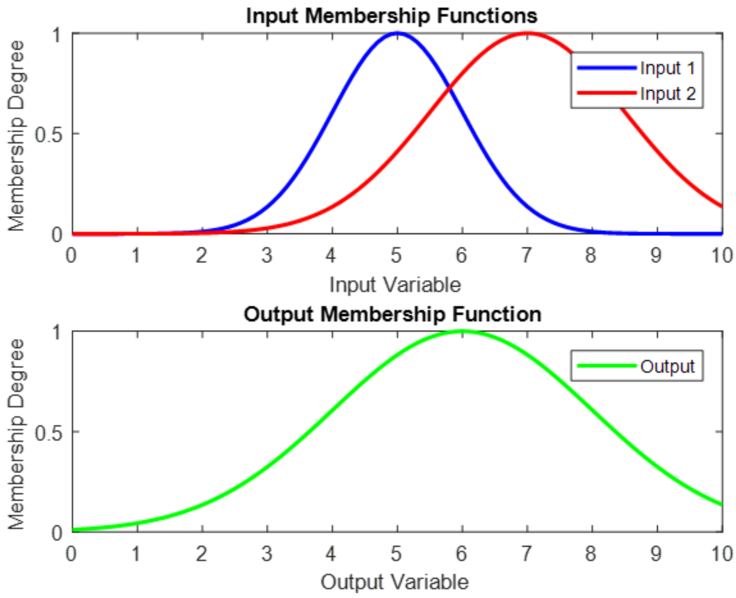

Figure 7. Output diagram of the fuzzy inference system

COMPARISON OF RESULTS OF TRADITIONAL METHOD AND FUZZY SYSTEM

This graph shows a comparison between the results of traditional method and fuzzy system for safety factor. The horizontal axis is the slope angle (degree) and the vertical axis is the safety factor. Two data sets (traditional method and fuzzy system) are compared with each other. This graph shows a comparison between the results of traditional method and fuzzy system for safety factor. The differences and similarities between the two methods can be seen.

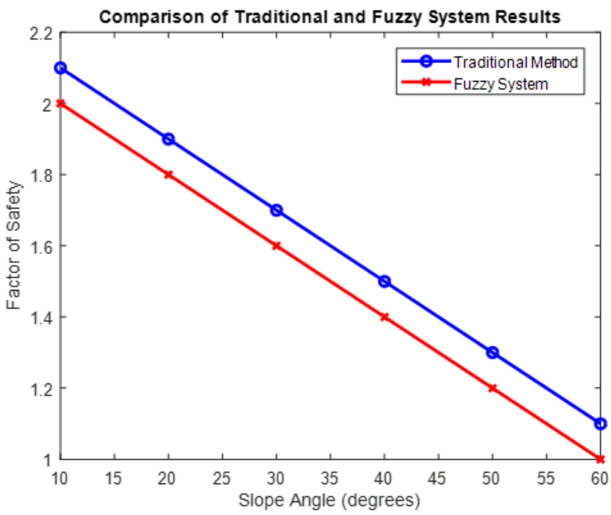

Figure 8. Comparison of results of traditional method and fuzzy system

VALIDATION OF FUZZY MODEL WITH REAL DATA

This graph shows a comparison between real data and fuzzy model for the factor of safety. The horizontal axis is the slope angle (degree) and the vertical axis is the factor of safety. Two data sets (fuzzy model and real data) are compared with each other. The comparison between the results of the fuzzy model and real data for the factor of safety shows that the fuzzy model fits the real data well. The fuzzy model designed in the research is compared with real data, which shows that this model can predict the factor of safety well. These models are used to analyze the slope stability of landfills and can help identify critical conditions and suggest preventive measures.

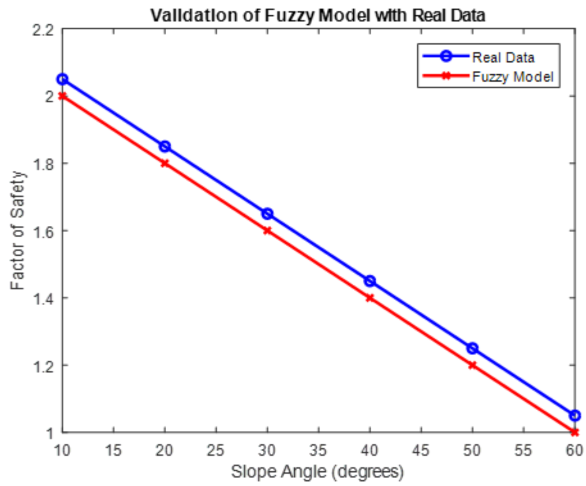

Figure 9. Validation of the fuzzy model with real data

INFERENTIAL SYSTEM DESIGN

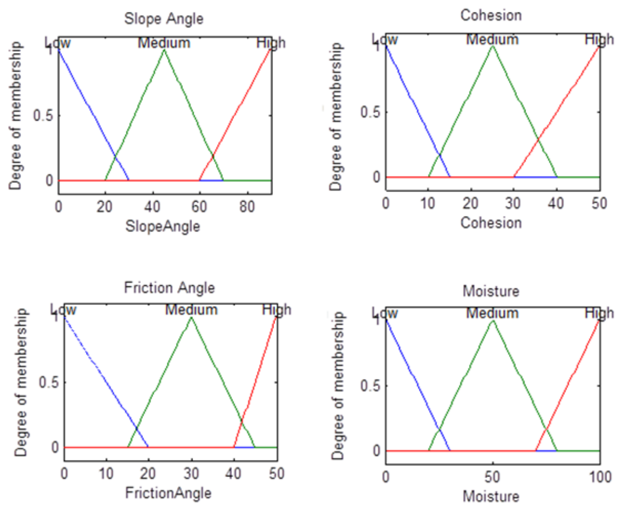

Figure 10. Representation of membership functions in the inferential system of slope angle-adhesion-internal friction angle-humidity

DISPLAYING GRAPHS OF INPUT MEMBERSHIP FUNCTIONS

Low Slope angle between 0 and 30 degrees.
Medium Slope angle between 20 and 70 degrees.
High Slope angle between 60 and 90 degrees.

As the slope angle increases, stability decreases. Higher angles usually result in a lower safety factor.

Cohesion

Low Cohesion between 0 and 15 kPa.

Medium Cohesion between 10 and 40 kPa.

High Cohesion between 30 and 50 kPa.

Higher cohesion increases slope stability because more force is required to slide.

Friction Angle

Low Internal friction angle between 0 and 20 degrees.

Medium Internal friction angle between 15 and 45 degrees.

High Internal friction angle between 40 and 50 degrees.

A higher angle of internal friction means that the soil is more resistant to slipping.

Moisture

Low Humidity between 0 and 30 percent.

Medium Humidity between 20 and 80 percent.

High Humidity between 70 and 100 percent.

Increased moisture can lead to reduced slope stability because water acts as a lubricant and reduces the shear strength of the soil.

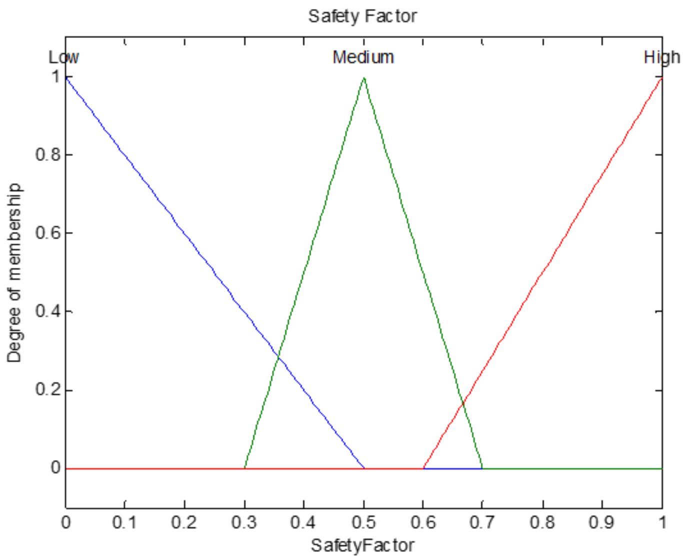

Figure 11. Safety factor of the inferential system

SAFETY FACTOR

Low Safety factor between 0 and 0.5.

Medium Safety factor between 0.3 and 0.7.

High Safety factor between 0.6 and 1.

A high safety factor indicates greater slope stability. The higher the safety factor, the lower the probability of slippage and failure.

Result:

Safety Factor: 0.5294

Given the inputs (slope angle of 30 degrees, adhesion of 20 kPa, angle of internal friction of 25 degrees, and humidity of 40 percent), the calculated safety factor is 0.5294.

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This safety factor is in the moderate range, meaning that the slope is relatively stable but there is a possibility of slipping and failure under certain conditions.

Overall conclusion:

1. Slope angle: The lower the slope angle, the greater the stability. For high angles, stability decreases and the safety factor becomes lower.
2. Adhesion: High adhesion increases stability and the safety factor.
3. Internal friction angle: A high internal friction angle also contributes to greater stability.
4. Humidity: Increased humidity can reduce slope stability.

OPTIMAL INFERENCE SYSTEM

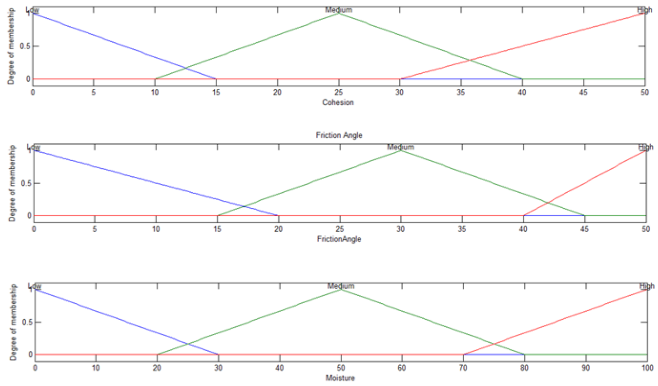

Figure 12. Fuzzy system inputs for calculating the optimal slope

Low cohesion results in a lower optimum slope because the shear strength is lower. Medium and high cohesion results in a higher optimum slope because the shear strength is higher and the soil can withstand steeper slopes.

Low internal friction angle results in a lower optimum slope because the resistance to sliding is lower. Medium and high internal friction angle results in a higher optimum slope because the soil can resist sliding more.

Low moisture content results in a higher optimum slope because dry soil has higher shear strength. Medium and high moisture content results in a lower optimum slope because water acts as a lubricant and reduces the shear strength of the soil.

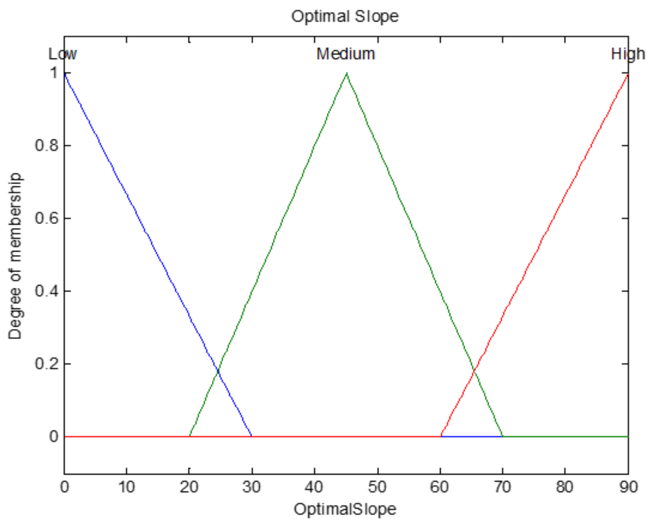

Figure 13. Optimal slope

Low optimum slope for conditions where the soil has low cohesion and internal friction angle and high moisture content. Medium optimum slope for average soil conditions. High optimum slope for conditions where the soil has high cohesion and internal friction angle and low moisture content.

CONCLUSION

- The angle of internal friction of different soil samples varies between 25 and 45 degrees. Soils with a higher angle of internal friction (close to 45 degrees) have greater resistance to sliding and therefore provide greater slope stability.
- The cohesion of the studied soils is in the range of 0 to 40 kPa. Since some samples have low cohesion, these soils have a higher tendency to slide. As a result, high cohesion (close to 40 kPa) helps to improve slope stability.
- Changes in soil moisture can affect slope stability. High moisture reduces the shear strength of the soil and increases the risk of sliding. Therefore, controlling soil moisture is essential to maintain slope stability.
- Heavy and continuous rainfall can increase soil moisture and lead to reduced slope stability. As the slope angle increases, the safety factor decreases. In other words, steeper slopes (with a greater angle) are less stable and more likely to slip.
- Low cohesion results in a lower optimum slope because the shear strength is lower. Medium and high cohesion results in a higher optimum slope because the shear strength is higher and the soil can withstand steeper slopes.
- Low internal friction angle results in a lower optimum slope because the resistance to sliding is lower. Medium and high internal friction angle results in a higher optimum slope because the soil can resist sliding more.
- Low moisture content results in a higher optimum slope because dry soil has a higher shear strength. Medium and high moisture content results in a lower optimum slope because water acts as a lubricant and reduces the shear strength of the soil.

RESEARCH HYPOTHESIS

Hypothesis 1: It seems that using fuzzy logic, it is possible to calculate the appropriate and stable slope of the pit.

Based on the research findings; 1- Soils with a higher internal friction angle (close to 45 degrees) have greater resistance to sliding and therefore provide greater slope stability. 2- Since some samples have low cohesion, these soils have a greater tendency to slide. As a result, high cohesion (close to 40 kPa) helps improve slope stability. 3- The shear strength of different soil samples varies between 100 and 200 kPa. This graph indicates the ability of soil to resist shear stresses. 4- High moisture content reduces soil shear strength and increases the risk of sliding. Therefore, controlling soil moisture is essential to maintain slope stability. 5- Heavy and continuous rainfall can increase soil moisture and lead to a decrease in slope stability. 6- Displaying changes in wind speed over time, which can indicate climate changes and the effects of wind on the environment. 7-Displaying the amount of drainage leakage over a specific time period, which indicates changes and fluctuations in drainage leakage over time. 8-Investigating the relationship between the safety factor and slope angle shows that the safety factor decreases with increasing slope angle. The results showed that the safety factor decreases with increasing slope angle. In other words, steeper slopes (with a greater angle) are less stable and more likely to slip. 9- Investigating the relationship between the safety factor and soil moisture shows that increasing soil moisture can lead to a decrease in the safety factor.

Comparison between the results of the fuzzy model and real data for the safety factor shows that the fuzzy model matches the real data well. The fuzzy model designed in the research has been compared with real data, which shows that this model can predict the safety factor well. These models are used to analyze the slope stability of landfills and can help identify critical conditions and suggest preventive measures. The overall conclusion shows that:

1. Slope angle: The lower the slope angle, the greater the stability. For high angles, the stability decreases and the safety factor decreases.
2. Adhesion: High adhesion increases stability and the safety factor.
3. Internal friction angle: A high internal friction angle also contributes to greater stability.
4. Humidity: Increased humidity can reduce slope stability.

Hypothesis 2: It seems that the stability of the landfill slope can be analyzed more accurately with fuzzy modeling.

Based on the optimal inference system, it can be said that; low cohesion results in a lower optimal slope because the shear resistance is lower. Medium and high cohesion results in a higher optimal slope because the shear resistance is higher and the soil can withstand steeper slopes. Low internal friction angle results in a lower optimal slope because the resistance to sliding is lower. Medium and high internal friction angle results in a higher optimal slope because the soil can show more resistance to sliding. Low moisture content results in a higher optimal slope because dry soil has more shear resistance. Medium and high moisture content results in a lower optimal slope because water acts as a lubricant and reduces the shear resistance of the soil.

Low optimum slope for conditions where the soil has low cohesion and internal friction angle and high humidity. Medium optimum slope for average soil conditions. High optimum slope for conditions where the soil has high cohesion and internal friction angle and low humidity.

The results of the present study are consistent with the research of Wang et al. (2013) who investigated the factors affecting slope stability in landfills. It is consistent with the research of Mando (2014) based on evaluating different methods for analyzing and predicting slope stability in landfills. They investigated the effect of parameters such as physical and mechanical characteristics of waste, landfill geometry and hydrological conditions on slope stability. With the results of the research of Naimi et al. (1400) because the necessary modification and improvement are necessary for the stability of the wall and appropriate results and solutions are presented to improve the conditions. With the results of the research of Eskandari et al. (1392) that the results of the land classification map also consider the production capacity of soils. The results showed that the proposed optimal method has appropriate accuracy and can be used as a new method for locating excavation pits.

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