M.TECH (GEOTECHNICAL ENGINEERING) VAIDEHI 2023

# ANALYSIS OF STABILITY OF SLOPE ON LANDFILL IN DELHI

DISSERTATION

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Submitted by

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## CANDIDATE'S DECLARATION

I, VAIDEHI, Roll No. 2K21/GTE/23, belonging to Master of Technology, Geotechnical Engineering, Delhi Technological University hereby declare that the project Dissertation titled "**Analysis of Landfill Slope Stability in Delhi**" which is submitted by me to the Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfillment for the award of degree of Master of Technology in the Geotechnical Engineering is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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# CERTIFICATE

I hereby certify that the thesis titled **“ANALYSIS OF STABILITY OF SLOPE ON LANDFILL IN DELHI”** which is submitted by VAIDEHI 2K21/GTE/23 CIVIL ENGINEERING DEPARTMENT, Delhi Technological University, Delhi, in partial fulfilment of the requirement for the award of the degree of Master of Technology, is a record of the Dissertation work carried out by the students under my supervision. To the best of my knowledge, this work has not been submitted in part or full for any Degree to this University or elsewhere.

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# ABSTRACT

The stabilization of an existing landfill in Delhi, for dry waste has been examined. The conventional method for stabilizing the slope of the dumps is to flatten the slope by pushing the crest inwards or stretching the horizontally oriented slope's toe outward. This is an impractical approach in Delhi due to the scarcity of usable land as landfill heights and volumes are very high, this is not a practical solution. The following elements have been taken into account when conducting a parametric study: (a) Height of landfill (constant), (b) Inclination of landfill (varying), (c) Factor of Safety (FOS). In order to determine the Factor of Safety (FOS) using Geo-Studio, the model is being constructed while maintaining the height of the landfill constant. The study's findings are used to identify an ideal solution. The study demonstrates that for the landfill to be stabilized at a constant height, the slope of the inclination angle must be less than 53°.

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# CHAPTER 1
# INTRODUCTION

## 1.1 GENERAL

Landfills for solid waste are essential in today's society because the collection and disposal of garbage in centralized areas helps to reduce dangers to public health and safety. Landfills for solid waste are governed differently than those for hazardous waste. A range of solid, semi-solid, and minuscule amounts of liquid wastes may be accepted. Before going through closure and post closure phases, landfills typically remain operational for decades. During these times, precautions are taken for reducing the environmental contamination risk.

Non-hazardous trash from different sources, including residences, companies, eateries, healthcare facilities, and educational institutions are taken by MSW (Municipal Solid Waste) landfills. Other toxic wastes, conditionally exempt hazardous waste from industries, minor amounts of hazardous trash from homeowners, and contaminated soil from petrol spills can all be dumped in many MSW dumps. Industrial facilities have the option to utilize their exclusive landfill site, commonly known as a captive landfill, for the proper disposal of non-hazardous waste generated during their operations. This waste may include sludge from paper mills and wood waste from wood processing plants.

## 1.2 HAZARD ASSESSMENT

Landfill data from the USEPA, the country generated over 250 million tonnes of solid garbage in 2012, which is 2.8 times more than it did in 1960. After 65 million tonnes of waste was recovered and 20 million tonnes of waste was composted, the remaining (66%, or 165 million tonnes) MSW was buried under landfills. The amount of landfill space required to bury this much rubbish is 135 $km^3$, using engineered methods of compaction &land filling (unit weight of 12 $KN/m^3$).

Existing landfills are under pressure to handle more waste as a result of the Not in My Back Yard (NIMBY) mentality. By raising the height and slope inclination, the landfill shape can be optimized to hold as much waste as possible [15].

The Factor of Safety (FOS) is the term used to describe the ratio between the summation of driving forces and moments to the summation of resisting forces and moments. Although there are uncertainties regarding safety of both artificial &natural slopes, it is a prevailing convention to employ a constant FOS when evaluating the slope stability, irrespective of the degree of uncertainties involved in the calculations. Common practice to use the same FOS for varying levels of calculation uncertainty in order to evaluate slope stability [17]. In contrast to probabilistic strategy, offering mean of uncertain parameters & separates a factor among low& high uncertain situations, this approach is referred to as deterministic. The probabilistic approach has enabled risk assessment and hazard evaluation of slopes. However, the risk is not always taken into account in geotechnical analysis of landfills [14].

## 1.3 LANDFILL IMPACTS

Municipal solid waste (MSW) quantity and quality are influenced by a number of variables, including population, way of life, dietary habits, standard of living, level of industrial and commercial activity, local cultural traditions, and climate. The seven most significant metro areas' MSW generation rates, expressed in terms of both daily and per-capita basis [28]. The environment will be severely impacted if this much of large volume of MSW is not managed properly, the environment will be severely impacted. Conflicts between environmental and developmental goals continue to plague waste management policies and practices. Solid waste specialists increasingly believe that unless additional measures are made to detoxify materials that have been dumped, today's society will be burdening future generations with the costs associated with addressing the effects of landfills. The watery solution called Leachates that develops as water percolates through landfill, are a major source of impact.

The National Capital Territory (NCT) landfills in Delhi are estimated to produce a substantial number of leachates annually, which is concerning for groundwater according to the Central Pollution Control Board (CPCB). Due to the lack of water on surface and unpredictable nature of the monsoons, dependency on groundwater resources has grown significantly over the past few years in many parts of India, particularly in the arid and semiarid regions. According to the international standard, where "1700 $m^3$/person/year" is considered to be "water-stressed" and "1000 $m^3$/person/year" is considered to be "water-scarce," India is already experiencing water stress & is predicted to experience extreme water shortage by 2050. The Asia's capital, Delhi and a region with tremendous population growth, has issues with both the quality and quantity of its groundwater, and is shown in Fig.1 [28].

The effect of the Bhalswa landfill leachate on groundwater has not been the subject of any published scientific research in the study region. There is a lack of published literature that presents systematic data demonstrating the effect on the population exposed to polluted groundwater in the vicinity of the Bhalswa dump. Although some unpublished reports on fluorosis and main ions were carried out by CPCB (2001), they do not provide a comprehensive data analysis.

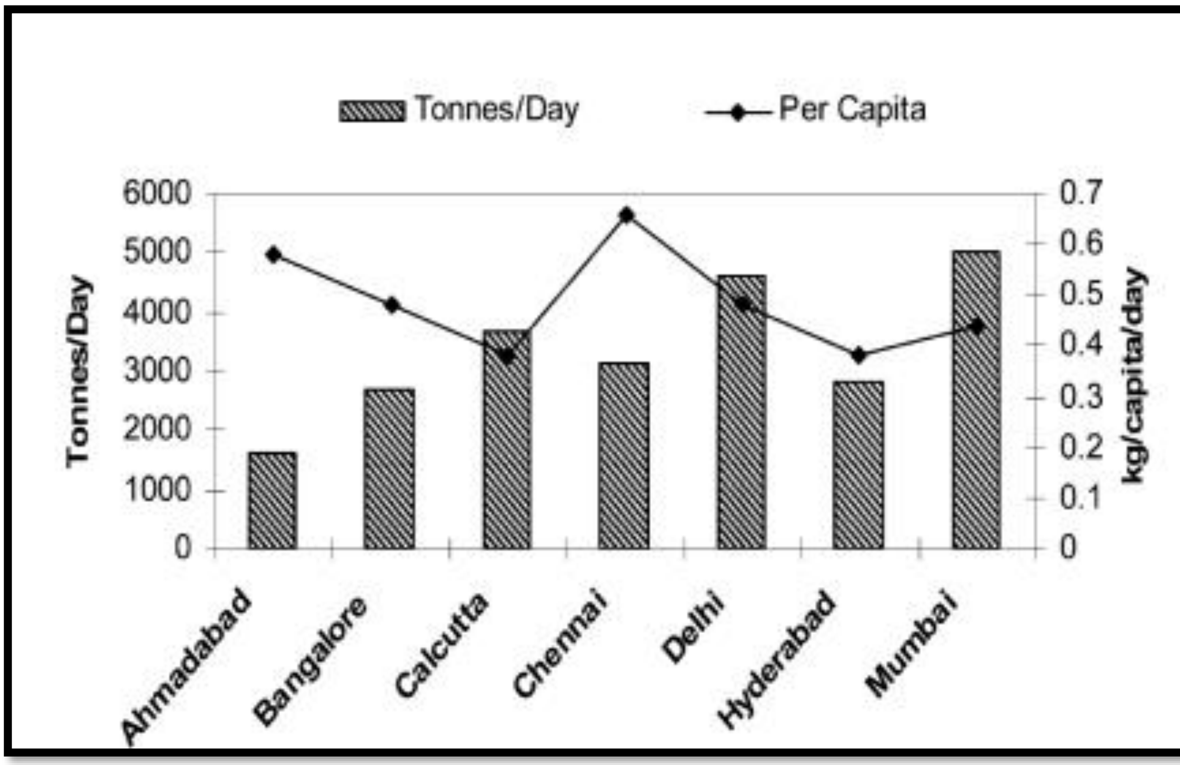


**FIG 1:** For the seven most densely inhabited metro areas in India, the MSW generation rates are both daily and per-capita **[28]**

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 LITERATURE REVIEW ON STABILITY OF LANDFILL

a. **Agarwal & M. Datta (2019),** in this paper the slope stability of an existing dump located in Delhi was assessed fewer than three distinct scenarios: Dry Waste, Pore Water Pressure, and Earthquake. The study results indicate that the existing slopes are stable when dry waste is present; however, instability can arise due to the development of pore water pressures resulting from rainfall infiltration during the rainy season or due to seismic forces. The research suggests that using reinforced soil berms is an effective approach for stabilizing waste dump slopes since there is limited space beyond the toe of the existing dump. The study reveals that flattening the slopes of the waste dump to make it stable requires reducing the inclination from 1.1(H):1.0(V) to 2.5(H):1.0(V). Decreasing the slope inclination leads to a reduction in the quantity of waste to be excavated by over 40% of the initial value. This method is more effective than the conventional approach of flattening the slope, given the limited space available beyond the toe of the dump.

b. **B. Dubey & E. McBean (2017),** this paper shows an innovative approach to evaluate the risk of slope failure in landfills. It introduces a novel method that utilizes probabilistic analysis to assess potential failure scenarios and the resulting fatalities. Moreover, this method comprehensively considers both the hazard and vulnerability aspects associated with landfill slope failure.

i. **Hazard aspects**: The assessment of hazard aspects involves conducting slope stability analysis for a vast range of potential scenarios related to the shear strength properties of MSW materials. This analysis utilizes the Monte Carlo method to determine the probability of having a factor of safety against slope stability that is less than one.

ii. **Vulnerability assessment aspect:** relies on calculating the run-out length and the resulting fatalities in the event of a specific slope failure scenario. It is determined by the ratio of the travel distance of the waste flow after failure to the distance at which fatalities occur due to waste movement, employing the Taylor series method.

Integrating both the Probability of Failure (related to hazard aspects) and Probability of Fatality (related to vulnerability aspects) while assessing slope stability highlights an unacceptably high level of risk. This situation calls for immediate action by the responsible managers to address the issue at the dumpsite.

c. **A. Ansari & P. Daigavane (2020),** this paper emphasizes the need to prevent water-driven interactions between waste materials and the surrounding environment, particularly groundwater, in landfills. The paper focuses on landfill construction, stability, and failure. The environment is highly contaminated due to weak layers within the landfill caused by various factors, including improperly compacted soil layers, which contribute to failures. Therefore, it is recommended to avoid disposing of MSW in areas with steep slopes, hilly terrain, and sites located in wetlands, lakes, or streams.

d. **Singh SK & Shivangi.G (2016**), It has been observed that the daily quantity of municipal solid waste (MSW) generated in Delhi is currently 8360 tons, and it is projected to increase to 18,000 tons per day by 2021. The majority of waste in Delhi is disposed of in three primary sites: Bhalswa, Ghazipur, and Okhla. Landfills are managed through both chemical and biological processes, which aim to produce stabilized solids, liquid leachate, and gases. A comparison between the two methods revealed that the Default Method resulted in higher greenhouse gas emissions compared to the First Order Decay model. This suggests that the substantial amount of MSW in Delhi holds significant waste-to-energy potential, which, if harnessed, could help meet the increasing energy demands of Delhi.

e. **E. Koda & A. Kiersnowska (2020),** this paper is based on one of the biggest landfills in Poland that requires complex engineering works to extend the depositing capacity of the structure. The shear strength parameters of the subsoil and waste material used for analysis were based on geotechnical investigation and this analysis will help in stabilizing the slope of landfill. The slope stabilization of landfill can be stabilized using reinforcement methods which include geogrid, geocomposite and berms construction. Testing the geomaterials properties showed that there is no negative impact of anthropogenic soils on the properties and behavior of geogrids used in the study. Thus geomaterials can be effectively used in landfill areas to stabilize its slope.

f. **B.J. Ramaiah & G.V. Ramana (2016),** In this study dynamic properties of municipal solid waste from two dump sites located at Delhi is being studied using field and large scale laboratory tests. Large scale Undrained Cyclic Triaxial (CTX) tests were conducted on MSW specimens to investigate the effect of various parameters such as composition, confining pressure, number of loading cycles, loading frequency and saturation on the dynamic properties. Sample consisting of 25 to 35% fibrous waste content exhibit less reduction in stiffness with number of loading cycles compared with sample consisting of negligible fibrous content. This study observes that dynamic properties evaluated add to the growing database of the worldwide dataset and can be useful for evaluating the seismic stability.

g. **Biringen et. al. (2013),** this research presents a method for assessing slope stability in the extreme case of growth fault migration towards earthen embankments such as water reservoirs. The assessment is based on the assumption that if growth faults cross an embankment, the embankment fill and underlying foundation soils lose a particular percentage of their strength, Abased on clay content, liquid limit, clay size fraction, and effective normal stress. The assessment focuses on the long-term impacts of strength loss on slope stability as a result of slow development fault movement towards a water reservoir embankment.

h. **Murphy (1990),** in the existing MSW dumps, slope stabilization is a serious issue. The Factor of Safety (FOS) is the term used to describe the ratio between the summation of driving forces and moments to the summation of resisting forces and moments. Additionally, the angle of the landfill's slope rises as trash progressively tips from the top of the dump. In September 2017, a slope failure at one of Delhi's dump sites occurred. It was about 50 m high and had a 35° to 40° slope angle. Geo-Studio is being used to analyze and model the landfill failure and stabilization.

## 2.2 CONCLUSION

Landfill failures have occurred during construction, operation, and closure. The majority of the failure surfaces were found in the soil geo-synthetic interface or in waste materials. The height and side slope of the landfill are the primary driving geometrical elements that govern its stability. Frozen and flung objects could cause injury in cold climates. It has an effect on landfill stability.

# CHAPTER 3
# ANALYSIS OF LANDFILL SLOPE STABILITY

## 3.1 INTRODUCTION

The production of solid waste increased in both quantity and variety, and as a result, landfill sitting became a significant environmental problem. Catastrophic landfill slope failures have occurred all over the world in the last 20 years (such as at the Bandung dumpsite in Indonesia and the Payatas landfill in the Philippines), which suggests that additional landfill stability investigations and analyses are necessary to prevent loss of human life and significant environmental, operational, and financial burdens. Fortunately, no lives have been lost as a result of these failures, but they have resulted in serious environmental issues like the intrusion of landfill waste into lower grounds, road blockages, and leachate contamination of downstream rivers, which disrupts and negatively affects the lives of thousands of nearby residents [24].

These failures most likely have catastrophic effects, including loss of life, destruction of property, and contamination of the surface and groundwater. In order to maximize landfill capacity on one side while maintaining landfill stability on the other, geotechnical engineers face a difficulty. The review of landfill failure modes is done in this chapter, and then the stability parameters are defined. The failure mechanisms and previous landfill failures are examined in the following sections.

## 3.2 TYPES OF FAILURE MODES

Experiences indicate that translational failure is more likely to be catastrophic and frequent than rotational failure. Translational failure typically begins with a sizable sliding mass that deforms and splits into numerous independent pieces. The weak surfaces inside the waste materials or the interface between the waste liner and the waste can cause translational failure. The weak surfaces inside the waste materials may be those that divide it from layers of different seasons or from an affluent area (Stark, 2000). Translational failure in the waste-liner interface can be justified by different shear strengths between waste components and liners. The translational failure in the waste-liner interface can be explained by the different shear strengths of waste components and liners.

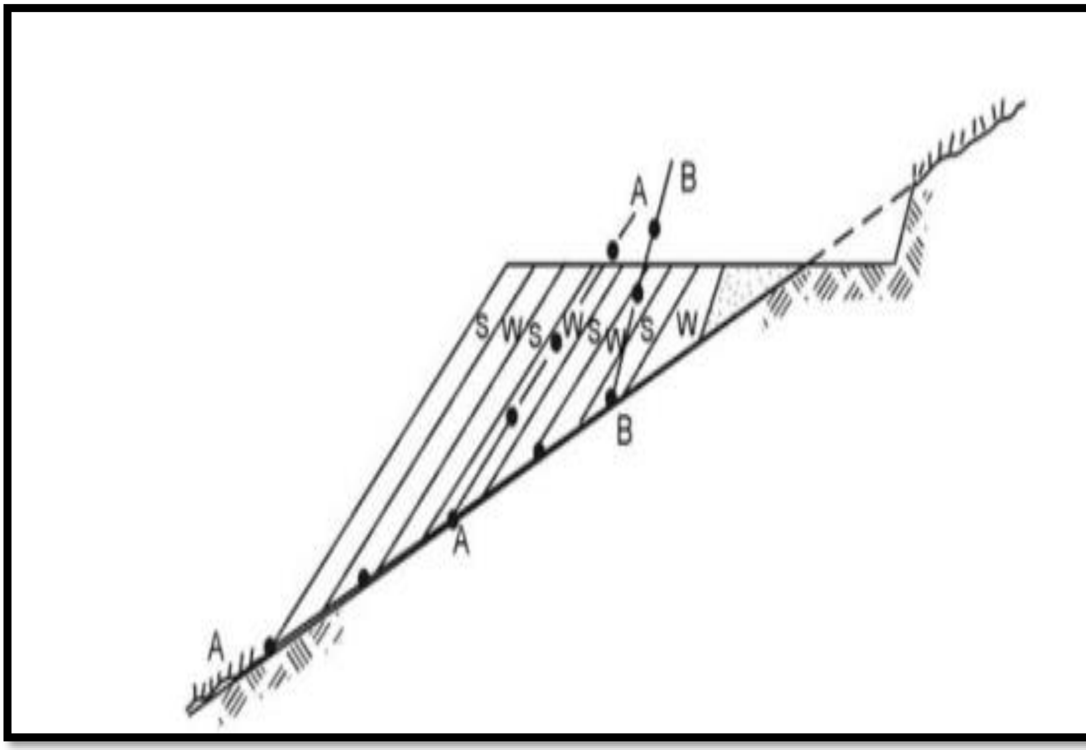


**FIG 2:** Waste composition in landfill **[18]**

Rotational failure is more common in homogenous materials such soft soil and clay, translational failure is more likely in landfills. Although very significant, the first two failures are known as veneer failures can be easily prevented through analysis and fixed at a fair price if they do happen. The severity of the other failure modes is greater.

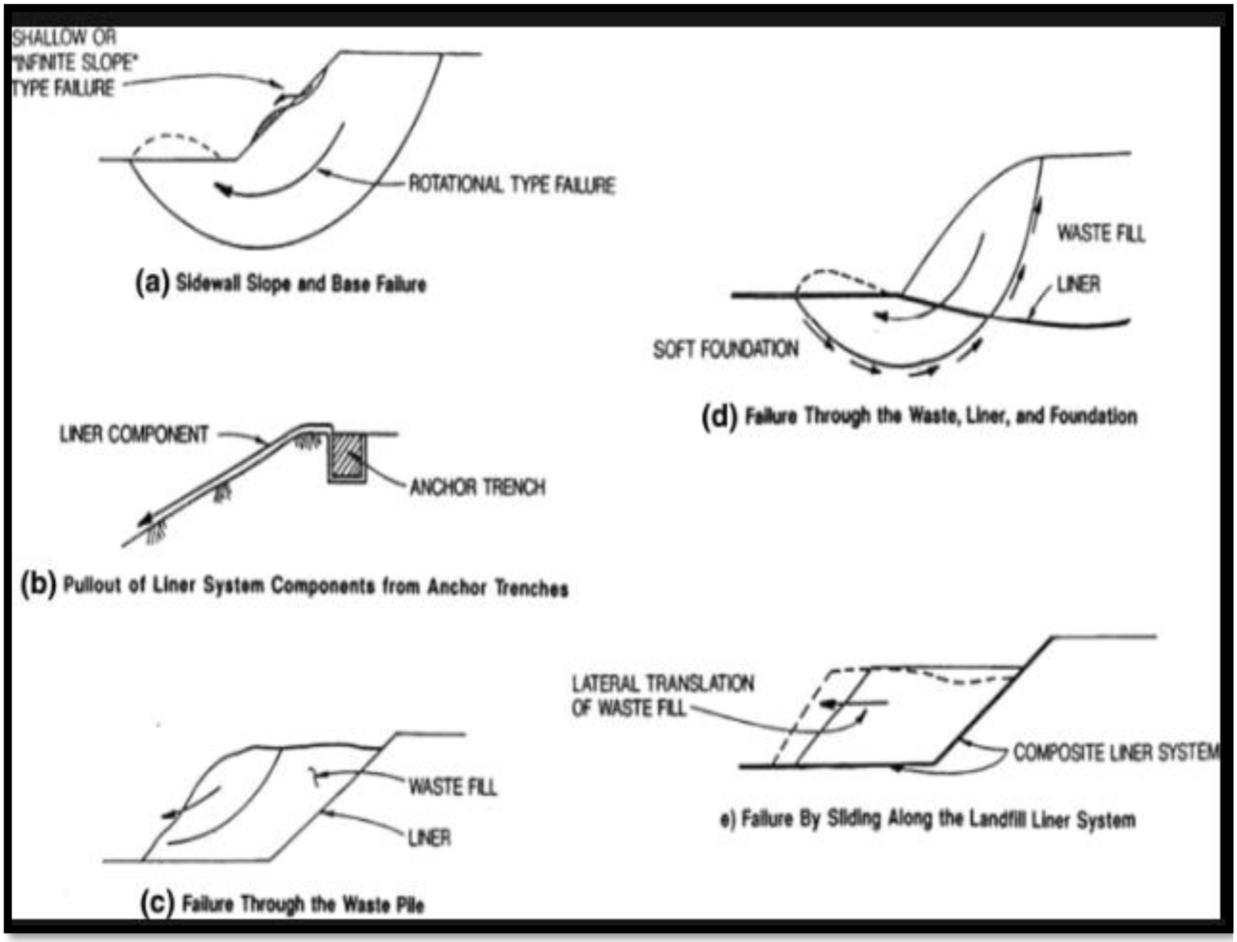


**FIG 3:** Failure modes in landfill

## 3.3 PARAMETERS AFFECTING SLOPE STABILITY

### ➢ GEOMETRY

The landfill's key driving geometrical elements that determine stability are height and side slope. Basically, the geometry of the site determines the shear strength of the waste materials. When slope and height are built to an unacceptably high level, a landfill will fail. Additional height and a steep side slope make it clear that dumpsites lack design and even engineered landfills lack design expertise.

### ➢ WASTE SHEAR STRNGRTH

All materials' shear strength mostly depends on the associated strain. "Strain-softening" is the name given to this occurrence. Simply put, the increase in load will cause the material to deform. Up until the resistance reaches the "peak value of the strength," further loads cause more deformation. In theory, the lack of trash compaction minimizes the surface flow of rain and speeds up the rate at which water percolates into the garbage. The excessive pore water pressure is mobilized by the infiltrated water, which also lowers the waste shear strength. High strength components including cardboard, metal, wood, and complete bottles were separated from the garbage, leaving sections of organic material and light plastic.

The largest difference between trash from poor and wealthy communities is the amount of ash, dust, and sweeping in poor communities as opposed to these components being insignificant in wealthier communities. It follows that it makes sense for the dump layers to be made up of successive layers of thick poor trash and thin wealthy garbage. Seasonal variations may result in a similar situation.

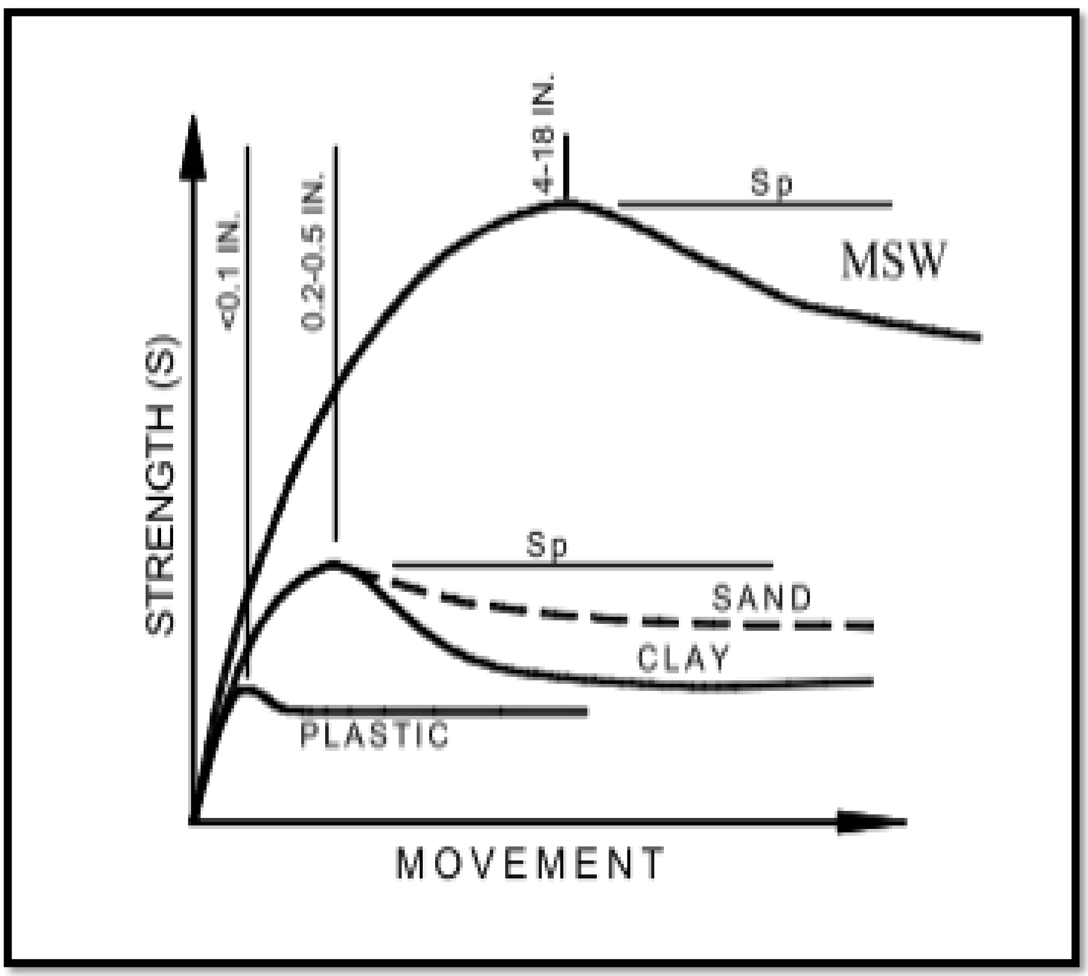


**FIG 4:** Strain-Softening of the landfill materials **[22]**

## ➢ CLIMATE

There are two points of contention regarding the impact of local climate on landfill stability:

**a.** Heavy rainfall during the rainy season and fire issues during the dry season are major issues in tropical nations that face landfill collapse (Philippine, Indonesia). The 2005 landfill disaster in Bandung, Indonesia was caused by three days of constant, torrential rain and concerns with prior landfill fires.

**b.** Freezing and tossing may be problems in cold areas. Stability of landfills is impacted by this occurrence. The effective shear strength will decrease and pore water pressure will rise as a result of freezing of the slope toe & tossing of the slope peak. Additionally, the hydraulic conductivity of the compacted clay might be negatively impacted by freeze-thaw (Omari, 2012).

**TABLE 1:** The NCT Delhi rainfall breakdown by month

| | Jan | Feb | Mar | Apr | May | June | July | Aug | Sep | Oct | Nov | Dec | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Normal Rainfall** | 14.6 | 13.3 | 10.0 | 5.6 | 9.3 | 38.9 | 190.7 | 197.5 | 106.5 | 19.5 | 2.9 | 4.5 | 613.3 |
| **Avg. no of rainy days** | 1.3 | 1.1 | 0.9 | 0.6 | 0.9 | 2.2 | 7.5 | 8.0 | 4.2 | 0.9 | 0.1 | 0.4 | - |

## ➢ LINEAR SHEAR STRENGTH

The types, levels, and methods of functioning of landfill liners vary. Compacted Clay Liner (CCL) and Geo-synthetic Clay Liner (GCL) are the results of the most basic classification. As was already mentioned, soil and plastic (Geo-synthetic) have significantly lower peak values for shear strength than waste materials. Due of this feature, translational failure in landfills is more likely than rotational failure. The two liquid-related triggers for landfill failures are "excessively wet foundation soil" and "wet clay beneath the geo-membrane."

## 3.4 LANDFILL FAILURES

Dumpsite or landfill failure analysis is a relatively recent idea. It could be because the landfill sizes weren't large enough for triggering the failure, & previous failures weren't lethal. In numerous instances of these failures, there was no scientific investigation carried out to ascertain the root cause of the failure. Because such events are socially unacceptable, governments generally do not mention them. However, several catastrophic landfill slope failures have recently happened, particularly in high rainfall countries like the Indonesia, Philippines, &even the United States. These failures resulted in significant human loss along with massive economic & environmental costs for local governments and adjacent people and employees.

## 3.5 SLOPES' STABILITY ANALYSIS METHODS

Limit equilibrium and finite element analysis are typically the two types of analyses used to evaluate the stability of geotechnical structures. Limit equilibrium is the force and moment basis, whereas the finite element method is based on stress and deformation. Compared to the strength parameters of limit equilibrium ones, the waste stress-strain parameters for finite element analysis are hardly accessible. Additionally, limit equilibrium has been the main focus of most slope stability methods [25]. The slices method is by far the most useful limit equilibrium approach for studying slope stability. The key factor affecting the normal stress on the slide surface in this method is the mass above the surface. The sliding mass must be divided into multiple vertical slices, and the equilibrium of each slice must be calculated in terms of force and moments in order to calculate the safety factor. To identify the lowest factor of safety, which belongs to the most crucial slide mass in the slope, this method must be done numerous times [33].

**TABLE 2:** Landfill Failure

| *No.* | *Reported by* | *Region* | *Year* | *Waste Vo.* | *Failure Mode* | *Life Loss* | *Reason* |
|---|---|---|---|---|---|---|---|
| 1 | Gillani, 2013 | Iran, Shiraz | 2013 | N/A | Rotation | 11 | The firework on the burned waste materials in landfill, caused exceeding pore water pressure and collapse |
| 2 | Blight, 2008 | Indonesia, Bandung | 2005 | 2.7 million | Translation | 147 | The reason is the extraordinary large portion of light waste (plastics) combined with disturbed water balances due to leachate circulation. |
| 3 | Blight, 2008 | Philippines, Payatas | 2000 | 1.2 million | Rotational | 330 | 10 days Heavy rain, Low waste density, Water percolation instead of drainage, reducing waste shear strength |
| 4 | Koerner and Snoog, 2000 | US | 1997 | 100,000 | Rotation | - | The increase of leachate head behind the clay backfill trench, due to the presence of both the clay layer within the waste mass and the clayey backfill material within the trench, was most likely the triggering mechanism of the failure. |
| 5 | Koerner and Snoog, 2000 | Africa | 1997 | 300,000 | Translation | - | The failure occurred after 48-hour of rainfall. The triggering mechanism was felt to be excessive liquid waste placement into the already-saturated wood bark between the old and the recent sections of the landfill. |
| 6 | Koerner and Snoog, 2000 | South America | 1997 | 1.2 million | Translation | - | the increase in leachate head within the waste mass due to the aggressive leachate injection operations. |
| 7 | Blight, 2008 | Colombia, Bogota | 1997 | 800,000 | Translation | - | pore pressure caused by recirculation of leachate |
| 8 | Blight, 2008 | South Africa, Durban | 1997 | 160,000 | Rotation | - | pore pressure caused by co-disposal of liquid wastes |
| 9 | Koerner and Snoog, 2000 | US, Mahoning | 1996 | 100,000 | Translation | - | The triggering mechanism of the failure was apparently a progressively increasing wet bentonite layer of the unreinforced geo-membrane GCL. |
| 10 | Koerner and Snoog, 2000 | US, Rumpke | 1996 | 1.2 million | Translation | - | The additional buildup of leachate head in the landfill due to ice formation at the exposed waste face near the toe of the slope |
| 11 | Koerner and Snoog, 2000 | Europe | 1994 | 60,000 | Translation | - | Excessive wetness of the clay component of the HDPE geo-membrane to CCL interfaces. It was reported that the geo-membrane was placed during a very wet period when the CCL was already at high water content. |
| 12 | Koerner and Snoog, 2000 | Turkey, Umbanye | 1994 | 12,000 | Translation | 39 | Excessive leachate level buildup (estimated to be 5 m) within the old, decomposed waste caused by water infiltrating from adjacent surface water ponds |
| 13 | Koerner and Snoog, 2000 | US, Maine | 1989 | 500,000 | Rotation | - | After approximately 120 mm of rain fall for ten days prior to the incident. |
| 14 | Koerner and Snoog, 2000 | US, Kettleman | 1988 | 490,000 | Translation | - | Rainfall during construction and waste placement, as well as the consolidation water expelled from the CCL, was reported to have caused an excessively wetted geo-membrane to CCL interface. |
| 15 | Koerner and Snoog, 2000 | US | 1984 | 110,000 | Rotational | - | It was marginally stable before heavy rainfall occurred over A 3 day period. rapid rise in water table within the waste mass from elevation +0.0 m to +3.2 m. |
| 16 | Blight, 2008 | Yugoslavia, Sarajevo | 1977 | 200,000 | Translation | - | N/A |

**TABLE 3:** Slice Method

| *Method* | *Factor of Safety (FOS)* Force equilibrium | Moment equilibrium | *Inter-slice force assessment (H=Horizontal, V=Vertical)* |
|---|---|---|---|
| Ordinary | - | Yes | Ignore both H, V |
| Bishop's Simplified | - | Yes | V ignored, H Considered |
| Janbu's Simplified | Yes | - | V ignored, H Considered |
| Janbu's Generalised | Yes | - | Both H, V Considered |
| Spencer | Yes | Yes | Both H, V Considered |
| Morgenstern-Price | Yes | Yes | Both H, V Considered |
| Lowe-Karafiath | Yes | - | Both H, V Considered |
| Corps of Engineers | Yes | - | Both H, V Considered |

# CHAPTER 4
# STUDY AREA

## 4.1 GENERAL

India's capital, Delhi, covers 1483 $km^2$ and is situated at latitudes 28°35'N and longitude 77°12'E at an altitude of 218 m above mean sea level. The Aravalli and the Gangetic Plain are at Delhi, ridges merge, creating a geological landscape with both quartzite bedrock and alluvial plains. Delhi's climate is classified as semi-arid and is marked by extremely dry conditions that are accompanied by hot summers and chilly winters. In addition, it frequently sees strong rains, having an annual average rainfall of 714.6 mm. In Delhi, the depth of the groundwater varies from 15 to 20 meters. With a population close to 14 million, Delhi is expected to produce 7000 metric tonnes of trash per day. Depending on the economic situation of the community, Delhi generates between 150 and 600 grams of solid trash per person every day. The majority of this waste comes from homes, businesses, and hospitals.

Three municipal organizations, The Municipal Corporation of Delhi, The New Delhi Municipal Corporation, and The Delhi Cantonment Board, handle waste in Delhi. Every MSW generated in the city is sent to landfill sites in Ghazipur (East Delhi), Bhalswa (North Delhi), and Okhla (South East Delhi), respectively.

Before being used for rubbish disposal or dumping, these locations were not systematically developed. Additionally, before choosing these sites, no environmental impact assessment had been done.

**Table 4:** Characteristic Property of Landfills

| Sr. No | Features | Okhla | Bhalswa | Ghazipur |
|---|---|---|---|---|
| 1. | Year | 1996 | 1992 | 1984 |
| 2. | Area (Hec) | 16.9 | 26.2 | 29.6 |
| 3. | Slope(º) | 70º-80º | 60º-70º | 60º-70º |
| 4. | Height(m) | 30-40 | 18-20 | 26-30 |
| 5. | Latitude | 28°30’42” N, 77°16’ 59” E | 28°44’27.16” N, 77° 9’27.92” E | 28°37’22.4” N, 77° 19’ 25.7” E |
| 6. | Type of Dump | Household with C and D waste | Household, vegetable market, C and D waste | Household, animal waste from poultry, fish market. |

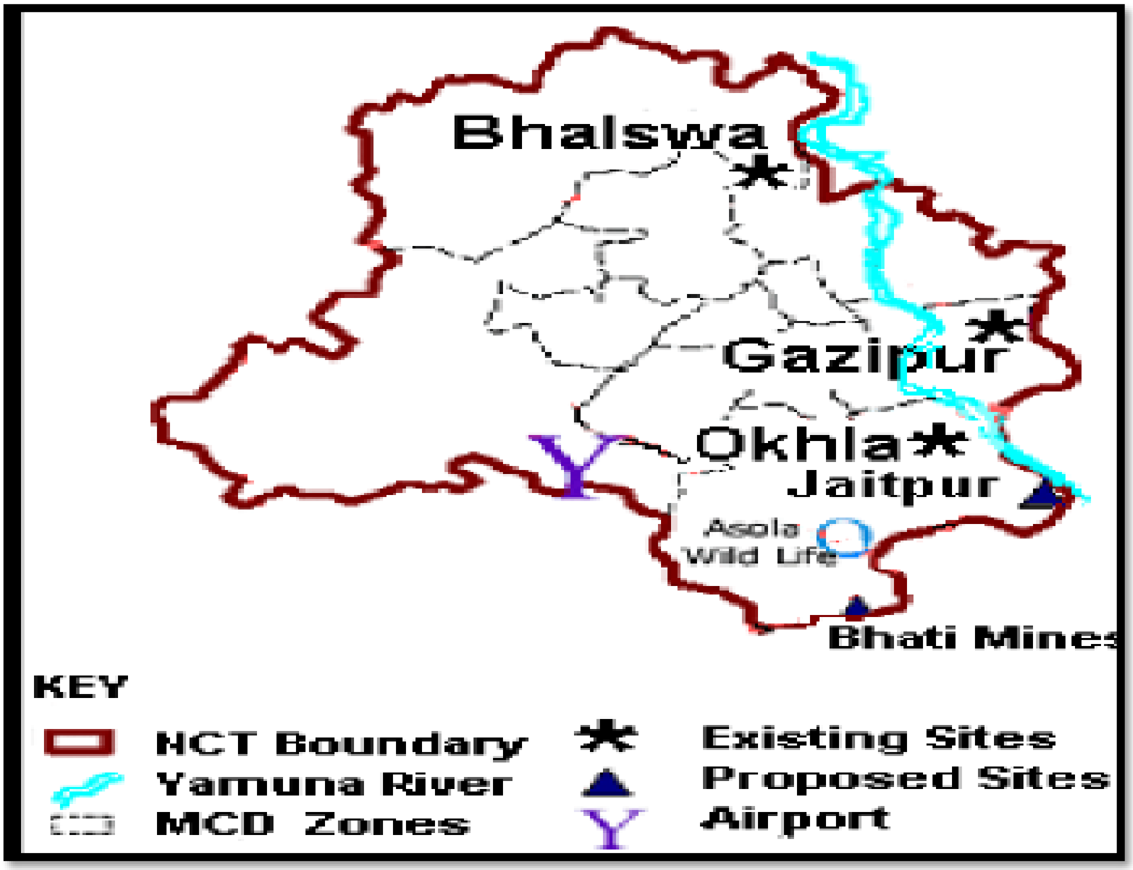


**FIG 5:** Delhi landfill map

## 4.2 GEOLOGY OF THE AREA

The hydro geological condition in the area, which is characterized by the occurrence of quartzite hard rocks and alluvial formation, governs the availability of groundwater there. The following diverse physiographic units and the groundwater's hydro-geological configuration are other factors that affect the presence of groundwater. On either side of the ridge, the alluvial deposits that cover the quartzite bedrock are of a different type. Clearly defined river sediment deposits can be found in the Yamuna flood plain. About 48 $km^2$of the closed Chhatarpur alluvial basin are filled with alluvium that was produced from the nearby quartzite ridge.

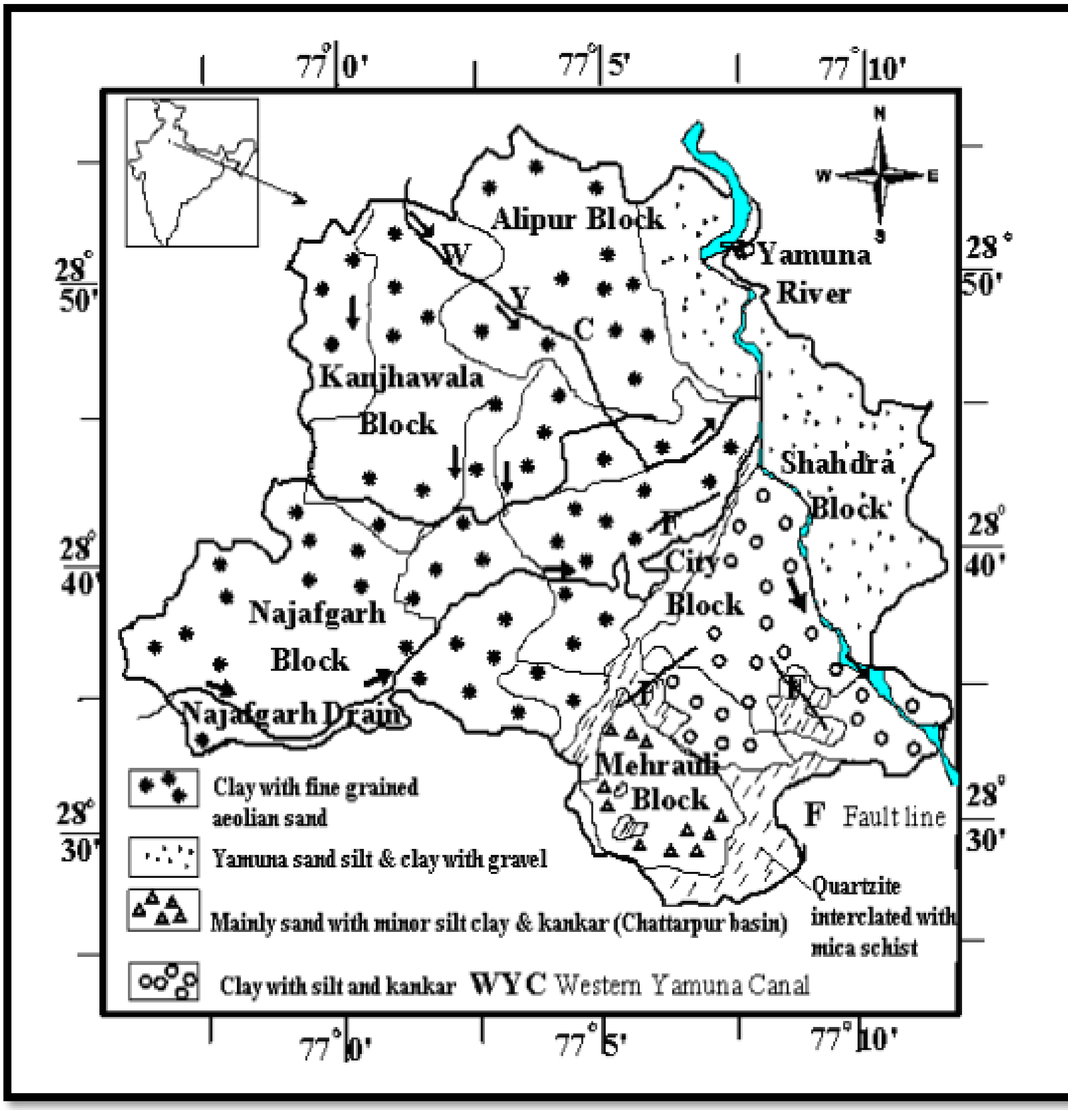


**FIG 6:** Geology of the area

## ➢ SOIL CHARACTERISTICS

In the studied area, alluvial soils predominate. In the research location, deposits from flood plains and precipitation both affect how quickly the soil weathers. The topography, drainage system, geo-hydrological conditions, and mineral content of the soil all have a large role in the enormous variances in soil types. Sandal loam is found in the area of Okhla dump, silt loam is found in Bhalswa landfill, and clay, silt, and clay loam are all present in the soils of the current study. The majority of these soils are calcareous and quite alkaline in composition.

- **HUMIDITY**

The Indian Meteorological Department in New Delhi, India, is where the humidity data (from 1990 to 2004) is also gathered. Understanding the local humidity is crucial for studies on groundwater quality. While July and August see high levels of humidity, other months in a tropical country experience humidity level that are rather typical.

- **GROUNDWATER**

Despite having a small aerial footprint, the NCT of Delhi, has a diverse geological &geographical environment that results in varying GW conditions in different regions. In terms of landform differences, the region is traversed by ridge areas. The western Delhi alluvial plain, the closed Chhatarpur basins, and the Yamuna flood plains are all very important for regulating the occurrence and transport of groundwater (CGWB, 1995).

A common groundwater situation is the existence of salty water aquifers situated at shallow depths between 20 meters and 50 meters below the ground surface in many areas. In shallow aquifer zones, the groundwater is in a phreatic state; nevertheless, in deep aquifer zones, the groundwater is frequently in semi-confined or restricted states. Shallow fresh water aquifers between 40 and 50 metres deep that are found in the Yamuna flood plains and the Chhatarpur basin function as a single unconfined aquifer system. Block confined and semi-confined aquifers are found at this kind of depths in Najafgarh, in the western half of the region.

## 4.3 ANALYSIS OF WASTE PARAMETERS

For MSW dumps tests are performed using shear strength parameters of MSW. In laboratory tests, large direct shear test boxes (300* 300 mm) were used, and two cases of horizontal displacement (25 & 55mm) are given shear strength characteristics. Slope stability is controlled by the key parameters; therefore, the analysis takes into account the small displacement parameter, which translates to a horizontal displacement of 25 mm (8.3%) in the large shear test box. Cohesion intercept (c) = 13 $KN/m^2$, Angle of Shearing Resistance (ɸ) = 30° and Unit Weight of MSW (ɣ) = 12 $KN/m^3$ are the variables taken into account (Agarwal, 2019).

The Morgenstern Price Method is used to do the analysis. In this instance, the FOS is calculated using the limit equilibrium approach.
The stability analysis is conducted under following circumstances:

**a)** Height of waste (H) = 120m
**b)** Inclination of waste (θ) = 33.69°, 38.66°, 45°, 48.81°, 51°, 53.13°

**FIG 7:** Bhalswa Landfill

# CHAPTER 5
# MATERIALS AND METHODOLOGY

## 5.1 GENERAL

The amount of waste items in Delhi city also grows daily as the population grows. They are all situated close to the Yamuna River's bank. The sampling sites are chosen such that they accurately the length, breadth, and kind of dumping occurring in various areas to obtain a uniform image of the research area. Pre- and post-monsoon sampling was done in and near these waste sites every year from 2004 to 2007 during the pre- and post-monsoon seasons. Every season, a total of roughly 70 ground water samples were gathered.

## 5.2 NUMERICAL MODELING

Geo-Studio 2020 Software is used in this study to evaluate the landfill slope. The slope's stability was assessed using the Slope/W tool prior to stabilisation, and the second step involved creating a slip surface, where the interslice force function is heavily influenced by the degree of deformation that the potential sliding mass needs to undergo in order to initiate movement. This technique is based on limit equilibrium. The factor of safety for any type of movement may be considerably impacted by the slip surface. Using this technique, the Factor of Safety (FOS) can be determined.

## 5.3 STABILTY ANALYSIS

The Slope/W tool of the Geo-Studio software, which is based on the limit equilibrium approach, is used to assess the stabilisation of slope. Although there are other ways to determine the stability of a landfill, we will use the Morgenstern-Price approach in this study. This approach is employed because it benefits from taking moment and force balance into account.

The following list of Mohr-Coulomb failure criteria can be used to calculate the stabilisation factor and safety factor for the landfill:

$$\tau_f = C + \sigma n \tan\theta$$

Where, C is effective cohesion, θ is angle of internal friction

A slope stability analysis has been performed to investigate the influence of height and slope inclination without a berm at the base of the slope at a height of 120 meters. Each heading is divided into three conditions. It is the circumstances:

**a)** Slope under earthquake loading Slope under earthquake loading

**b)** Dry Slope

**c)** Slope under pore water pressure (Ru = 0.1)

## 5.4 GEOMETRICAL ANALYSIS

In this work, six geometry models were created for the numerical analysis. Although, the height of the landfill (H=40m) stays constant, the inclination of the landfill (θ) varies at various angles such as, 33.69°, 38.66°, 45°, 48.81°, 51°, 53.13°. For each angle, the stability of the landfill is determined i.e. FOS (>1) shows a stabilized slope, whereas FOS (<1) shows an unstabilized slope.

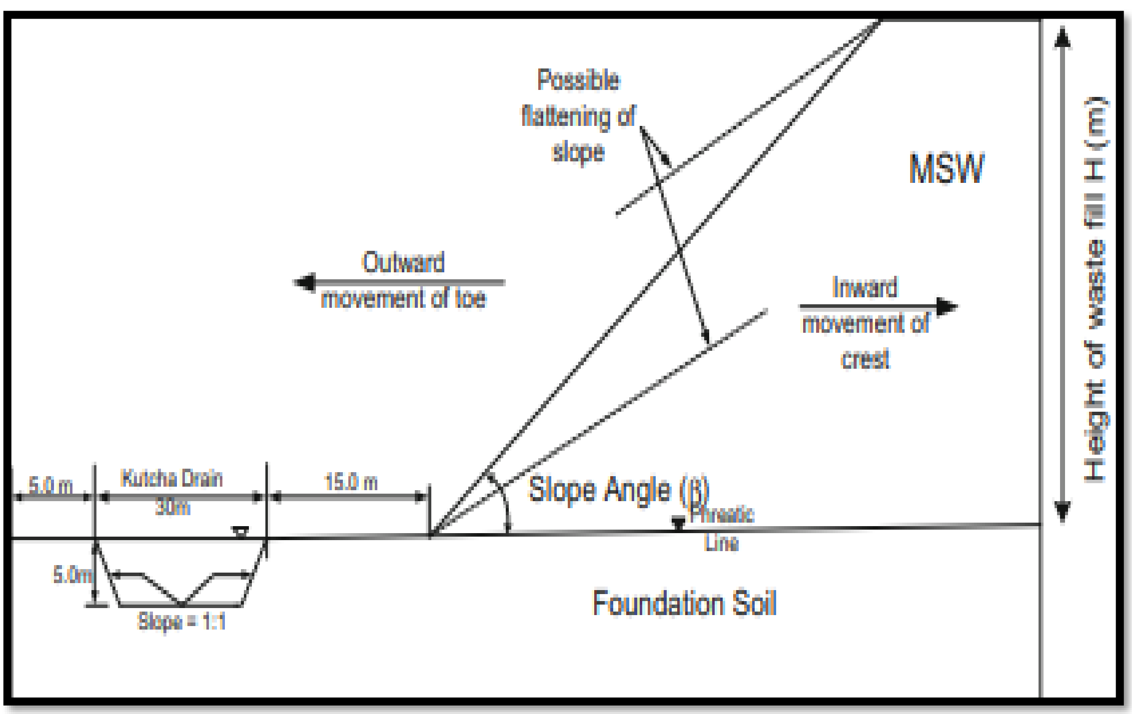


**FIG 8:** Section for Analysis

# CHAPTER 6
# SOFTWARE ANALYSIS

## 6.1 GENERAL

Commercial software called Slope/W is used to analyze slopes. Stability analysis is the most frequent numerical analysis used in the field of geotechnical engineering. This is partly due to the fact that stability is undoubtedly a primary concern in every civil engineering project. The slices method's concepts are simple to understand, and it's simple to use the approaches in software. Even a spreadsheet can be used to complete the simplest procedures. So, shortly after computers were invented, slope stability software became accessible. It is now feasible to manage analyses with ever-increasing complexity thanks to modern limit equilibrium tools.

Understanding the specifics of the method is considerably aided by graphically displaying all of the intricate forces on every slice of the prospective sliding mass or by visualizing distribution of various parameters across the slip surface. While the graphical display of calculated data has helped to clarify the method and, in particular, the distinctions between the various approach available, it has also brought to light several drawbacks in the formulations for limit equilibrium. The approach is possibly being pushed too far beyond its original intended goal, as evidenced by the limits that have been exposed. The technique of slices was first designed for a scenario where gravity (the weight of the slice) has the greatest impact on the normal tension along the slip surface.

## 6.2 SLOPE/W

SLOPE/W is a part of Geo-Studio, a comprehensive collection of geotechnical tools. One of the most effective aspects of this integrated method is that it permits the use of finite element calculated pore-water pressures and stresses in a stability study, among other sorts of assessments of a much larger and more complicated spectrum of issues. Even though SLOPE/W may be used as a standalone product and does not require the usage of this advanced feature, employing it as a part of a comprehensive suite of geotechnical software programmers' increases the program's potential.

## 6.3 LIMIT EQUILIBRIUM METHOD

The method of slices has a wide variety of solution methods that have been created over time. In essence, they are all rather similar. The variation in approaches can be attributed to several factors such as the static equations employed, the included interslice forces, and the expected relationship between interslice shear and normal forces.

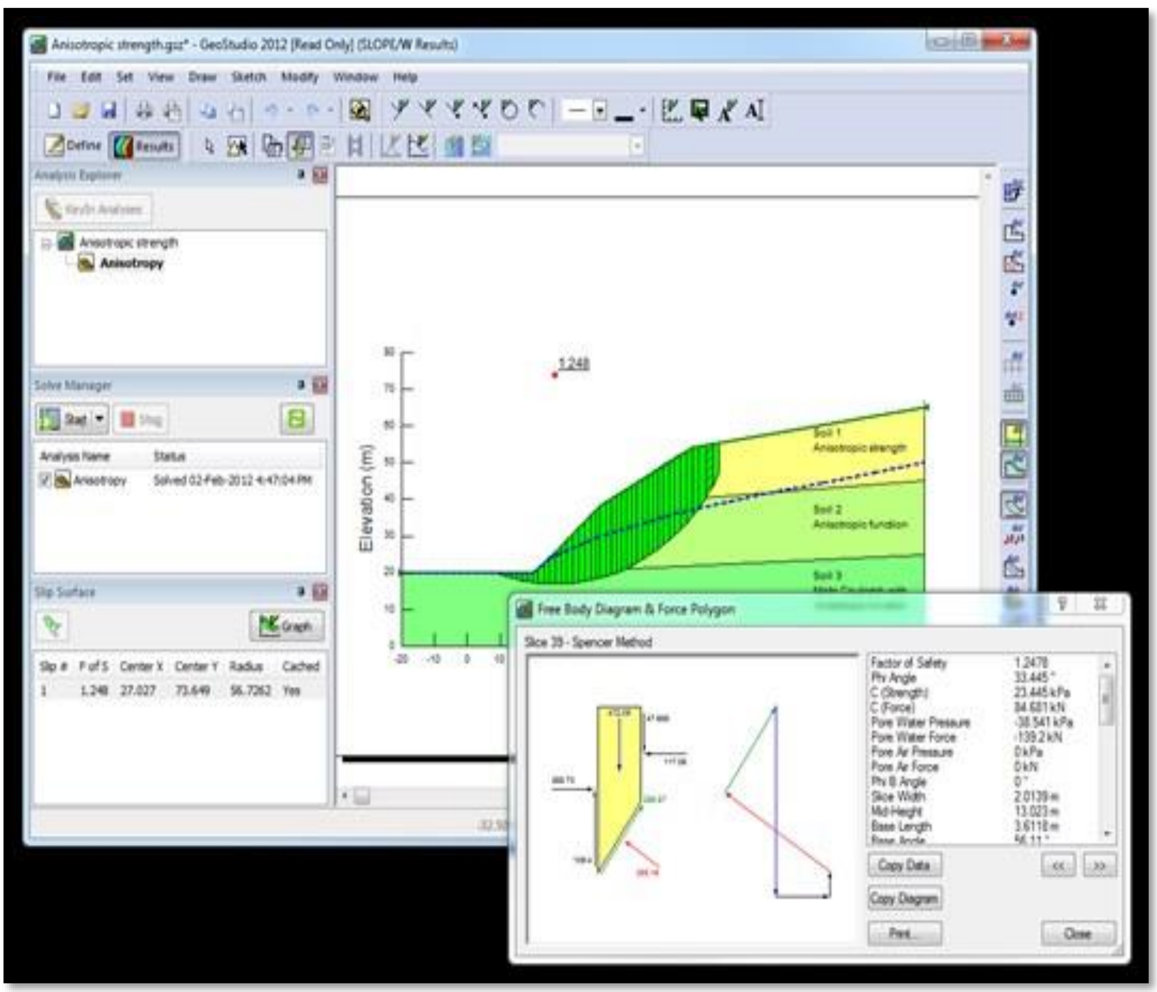


**FIG 9:** Slope Stability by Geo-Studio

# CHAPTER 7

# CASE STUDY: BHALSWA LANDFILL, DELHI

## 7.1 GENERAL

There are three active landfills in Delhi City, located at Bhalswa, Okhla, and Ghazipur. There isn't any technology control on the solid waste disposal in these locations except from the manual compost. The Bhalswa dumpsite, which has been in operation since 1994, is situated in the northwest of Delhi. This dumpsite collected roughly 3000 tonnes per day between 1994 and 2011. Since 2011, 1200 tonnes of garbage per day have been diverted to Narela Bawana, another landfill. In the east and north, clusters (slums) surround the site, while in the south and west; drainage runs along to the site.

The Bhalswa dumpsite has attained an approximate elevation of 40 meters, and the steep inclines on its sides are readily apparent, with certain cross-sections exhibiting angles as steep as 60°. The primary sources of inbound garbage are residences and business locations. This landfill site can be classified as a second-class site in terms of the range of friction coefficient due to poor compaction and the presence of strong waste materials such as stone and brick components.

In this case study, the friction coefficient has a normal distribution with a mean of 0.14 and a standard deviation of 0.02. The frequency of rainfall is considered to be 0.01 as an annual trigger mechanism.

**TABLE 5:** Waste Components in Bhalswa Landfill

| Components of Waste | Average (%) |
|---|---|
| Paper | 3.80 |
| Metal | 0.2 |
| Biomaterials | 50.40 |
| Plastic | 4.50 |
| Glass | 1.50 |
| Stone, Ash and Bricks | 32.5 |


**FIG 10:** Bhalswa Dumpsite Section

## 7.2 DISCUSSION

The first failure scenario resulted in the highest "Hazard" value, whereas the vulnerability assessment yielded zero for this particular scenario. As a result, the most likely failure (FOS<1) is not always the most crucial. A high vulnerability and a high probability failure resulted in the occurrence of the most serious failure. Six failure scenarios are observed in this cross-section, assuming translational failures, were examined using the Slope/W & DAN-W programmers', providing the probabilities of failure & mortality, respectively. One person in that residential area would perish for every meter as the waste materials generated by the failure process moved closer to the neighborhood.

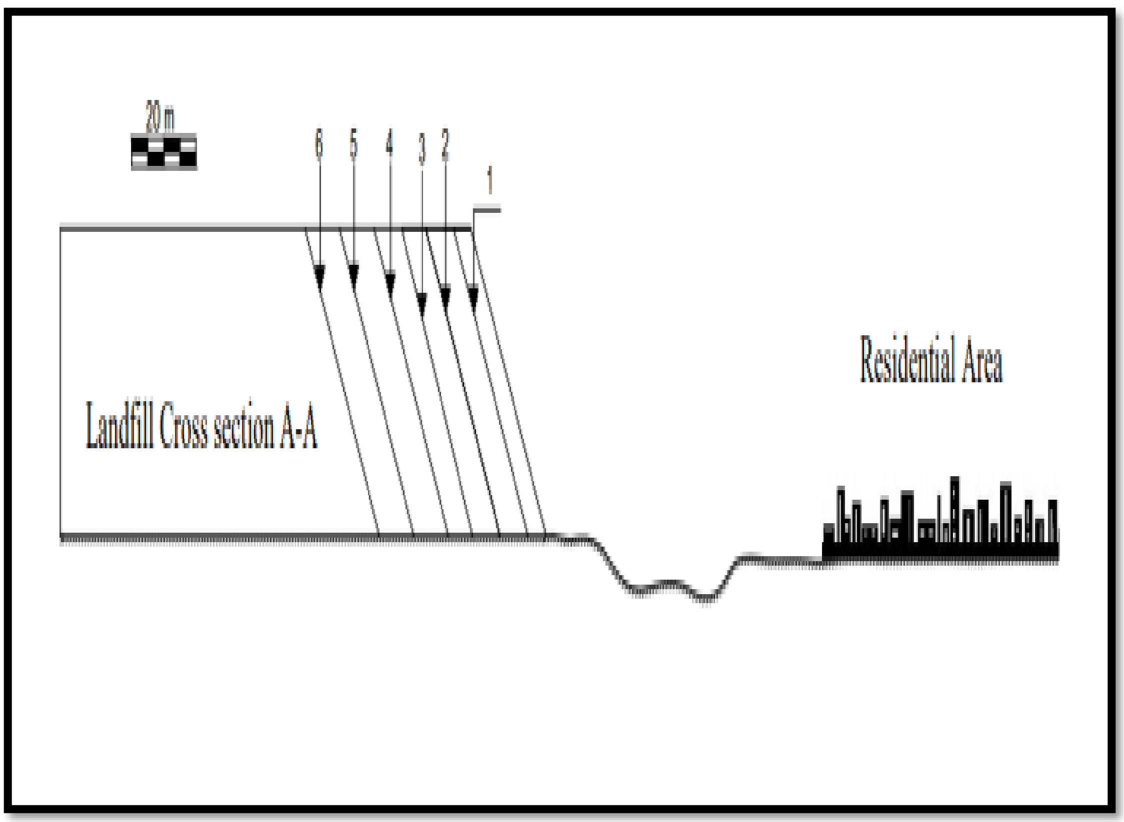


**FIG 11:** Landfill Failure Risk

## 7.3 CONCLUSION

The risk assessment of landfill slope failure involves calculating two factors, namely Hazard and Vulnerability, based on specified criteria. The input data for the slope stability analysis, including friction angle, unit weight and cohesion, are utilized to evaluate the risk (probability of landfill failure) for specific cross-sections of the landfill. Normal distributions of the friction angle and frictional coefficient are employed as inputs for the run-out analysis, resulting in the calculation of vulnerability (likelihood of loss of life during the landfill failure process) using the Taylor series method.

The geotechnical properties of the trash, such as friction angle, pore water pressure, unit weight and cohesiveness, play a major role in the stability of MSW landfills. Although it’s typical to utilize regular constant values of MSW features in the analysis of stability, one should take into account the heterogeneous nature of MSW as well as its geographical and temporal variability. Using a probabilistic approach for stability analysis allows for the incorporation of geotechnical uncertainties related to MSW, as opposed to deterministic analysis of stability which relies on constant input values.

In this study, a probabilistic approach was utilized to assess the stability of landfill slopes, taking into consideration the uncertainties in MSW geotechnical properties. The analysis involved combining risk and vulnerability to establish waste slope stability parameters, and the aim was to determine the likelihood of failure (hazard) and the probability of fatalities (vulnerability) using probabilistic waste rheology data. As a case study, this technique was utilized to assess the danger in an Indian landfill.

# CHAPTER 8
# RESULTS & DISCUSSION

## 8.1 RESULTS

Parameters used for designing the models using Geo-Studio are given below:

**TABLE 6:** Parameters for Slope/W Analysis

| Waste Parameters | Value |
|---|---|
| Cohesion intercept (c) | 13 $KN/m^2$ |
| Unit Weight of MSW (ɣ) | 12$KN/m^3$ |
| Angle of Shearing Resistance (ϕ) | 30° |

The geochemical parameters of groundwater have been attempted to be determined using numerical analysis of hydro geochemical data (Lawrence & Upchurch 1982).
For the parametric categorization of modeling studies, factor analysis and correlation are frequently utilized in numerical or statistical ideas (Balasubramanian et al. 1985).
(a) Only a finite number of variables may be taken into account, (b) Major ions are typically limited to specific variables by convention, and (c) Employing certain procedures can yield stronger correlations, with statistical data generally offering a more accurate depiction than graphical data.

The variations in FOS for various slope inclinations at constant height are presented through models using Geo-Studio:

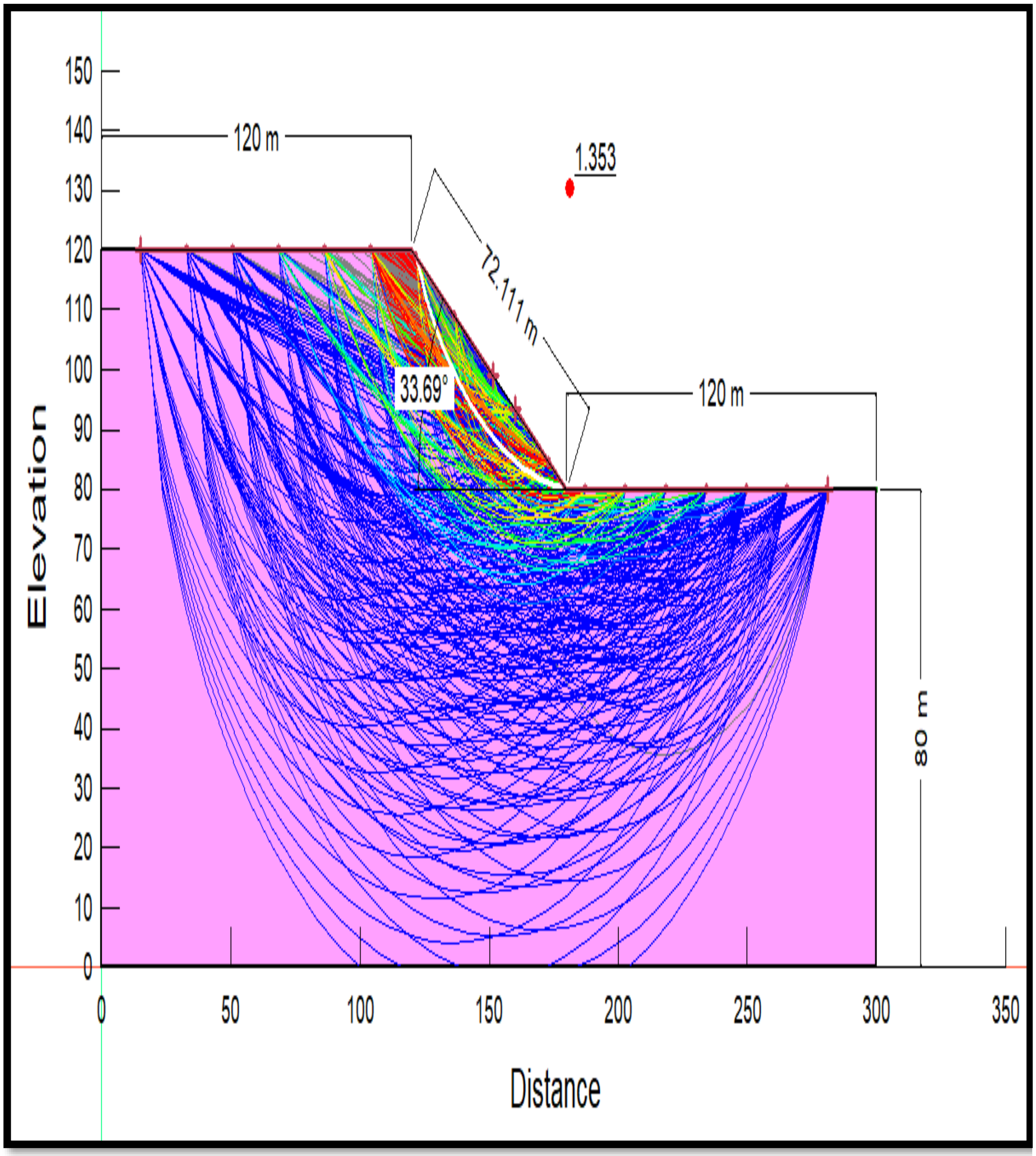


**FIG 12:** SLOPE INCLINATION 33.69° HAVING FOS 1.353 (STABLE)

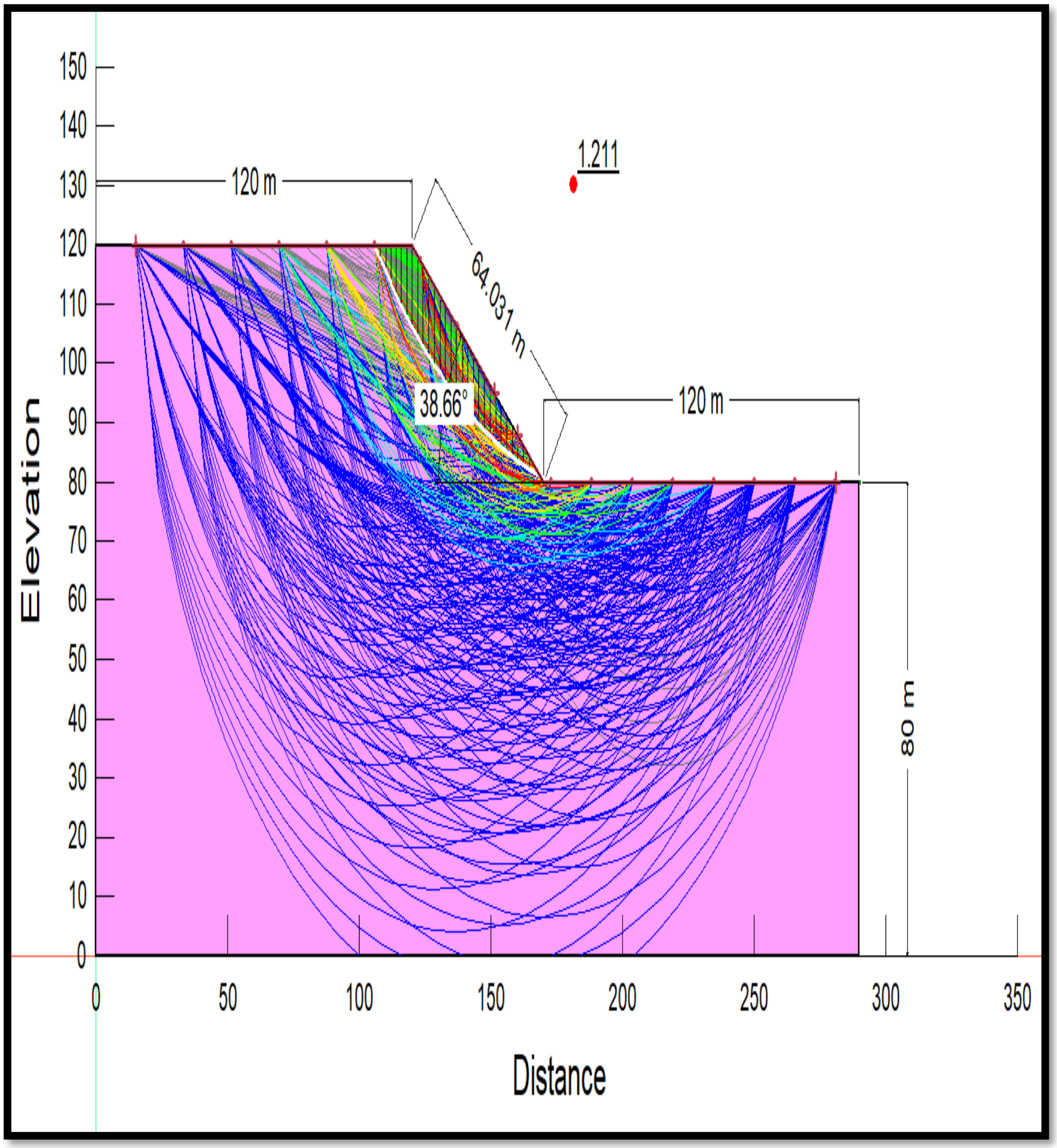


**FIG 13:** SLOPE INCLINATION 38.66° HAVING FOS 1.211 (STABLE)

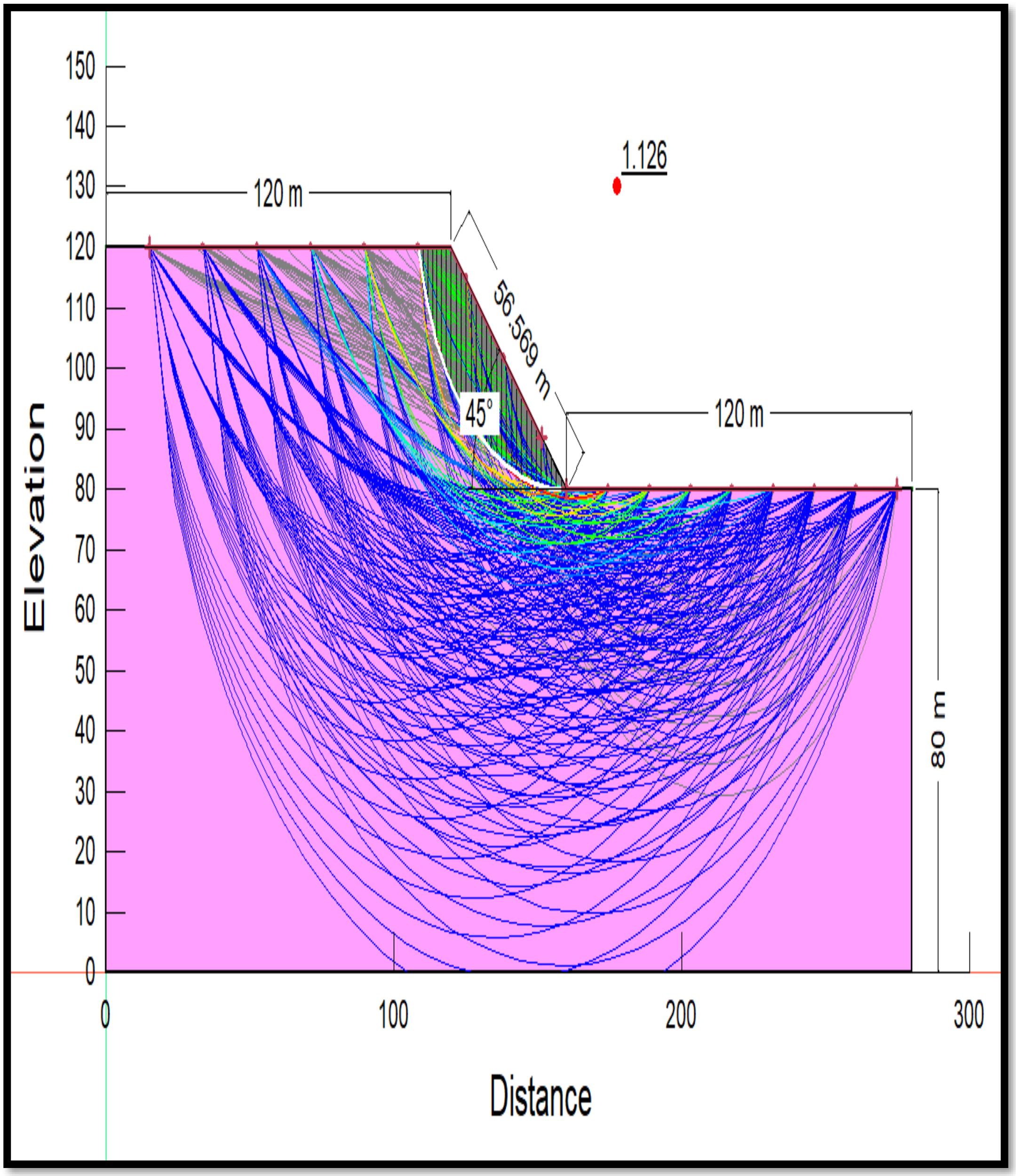


**FIG 14:** SLOPE INCLINATION 45.00° HAVING FOS 1.126 (STABLE)

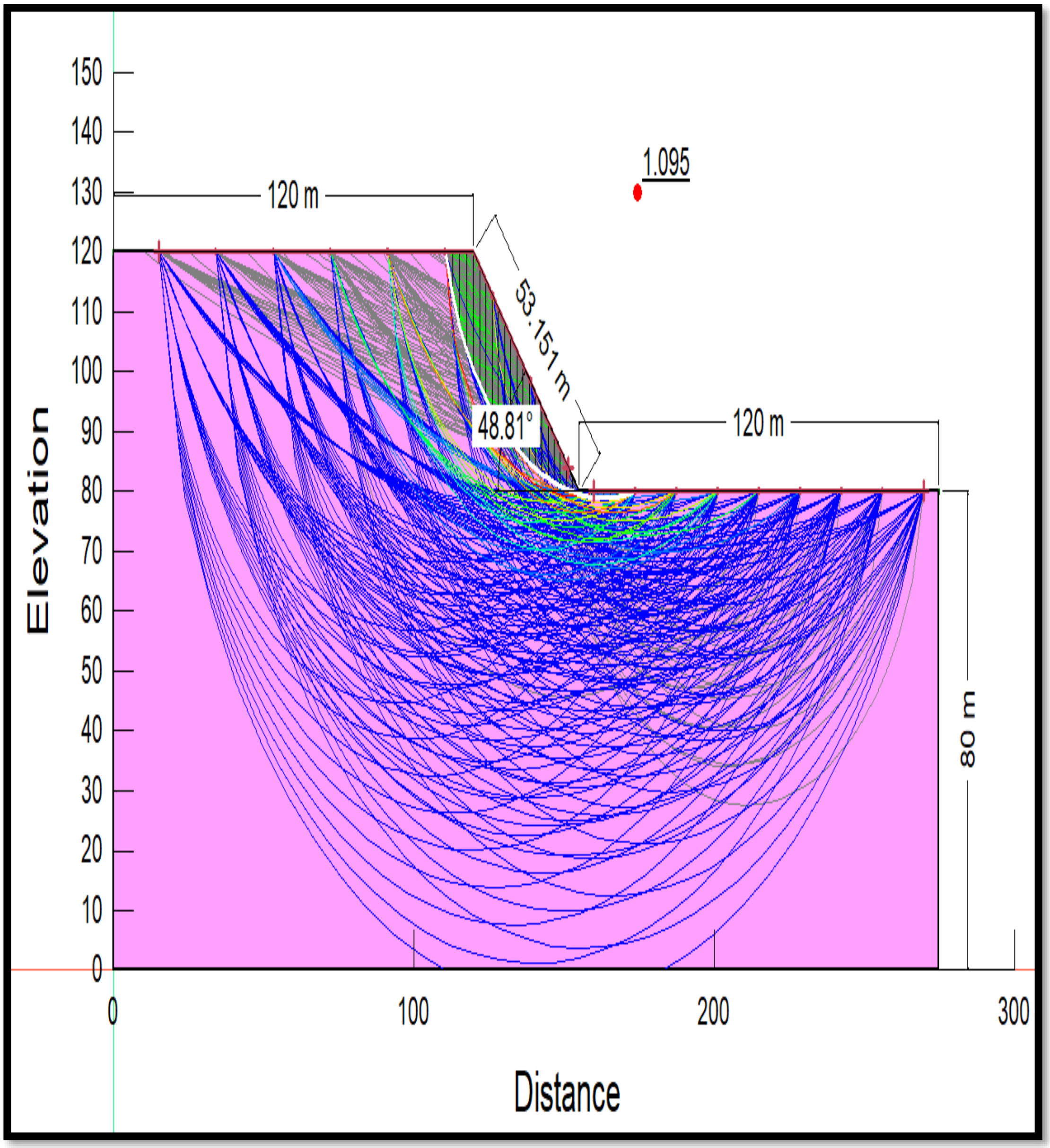


**FIG 15:** SLOPE INCLINATION 48.81° HAVING FOS 1.095 (STABLE)

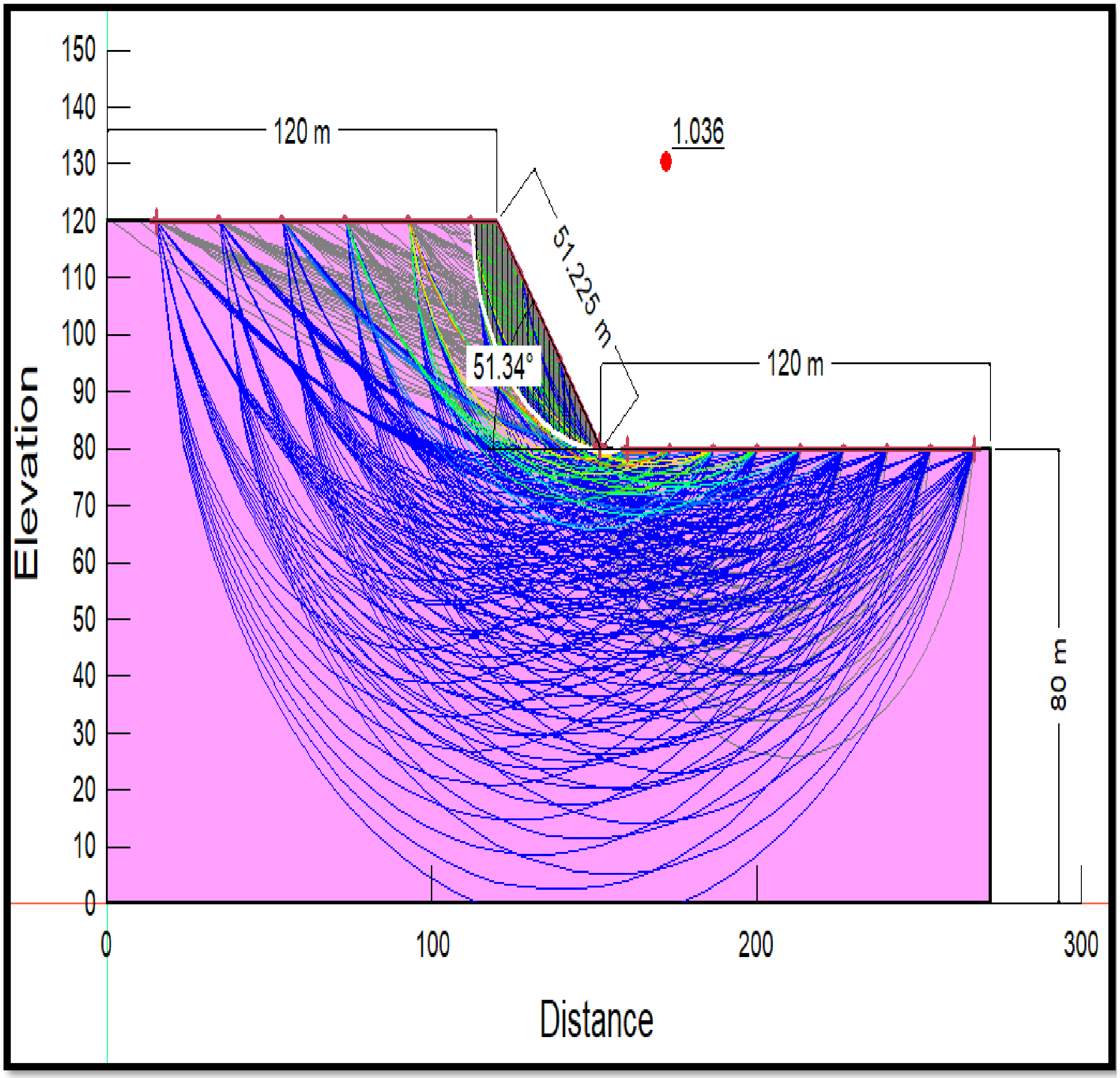


**FIG 16:** SLOPE INCLINATION 51.34° HAVING FOS 1.036 (STABLE)

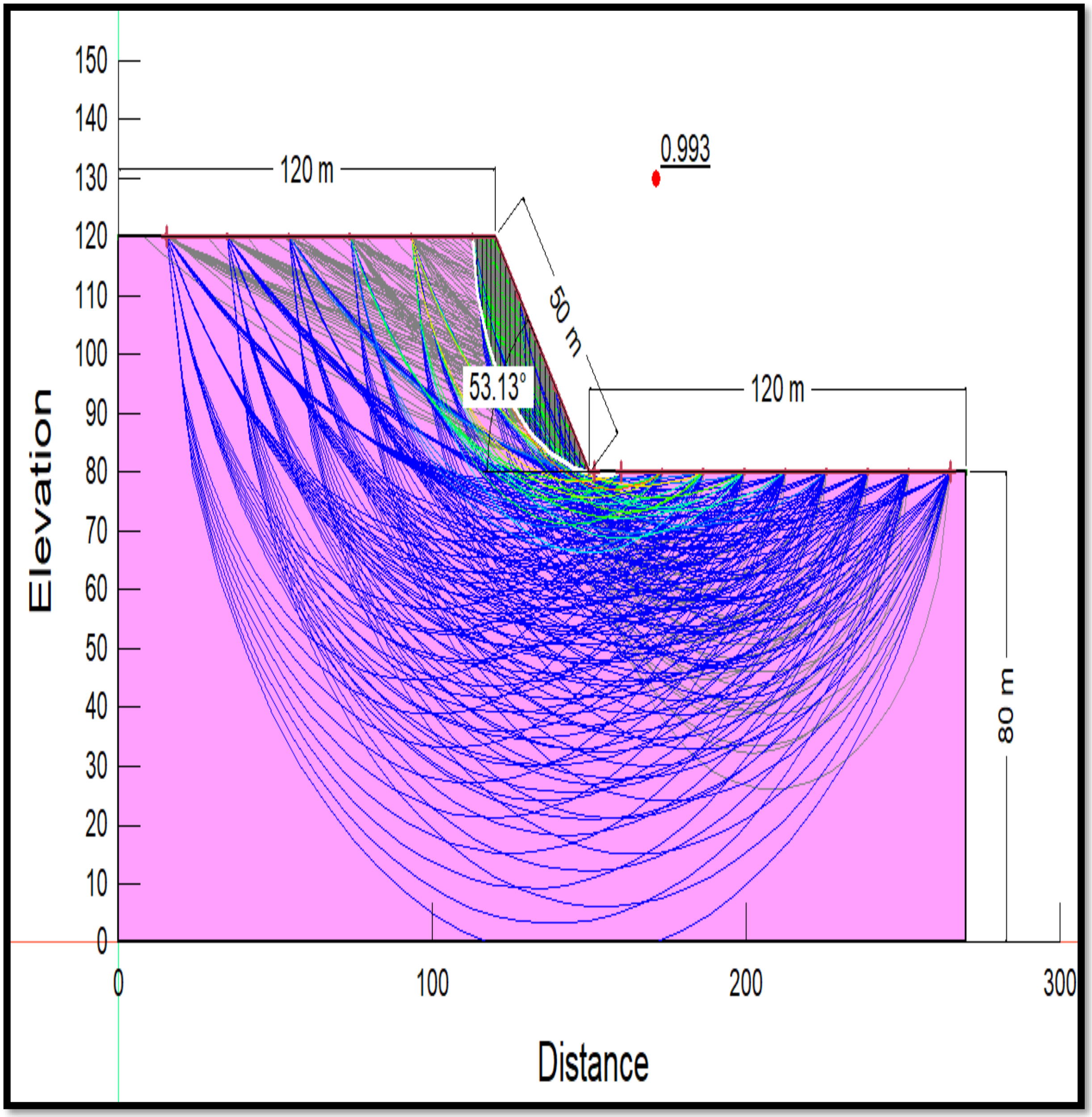


**FIG 17:** SLOPE INCLINATION 53.13° HAVING FOS 0.993 (UNSTABLE)

## 8.2 DISCUSSION

It is clear from the above-mentioned analysis's that the FOS decreases noticeably when the slope inclination increases while the height remains constant. It can be concluded that safe slope inclination is less than 53º. Slope inclination (θ<53º) gives unstable slope by providing FOS (<1) whereas slope inclination (θ>53º) gives stable slope by providing FOS (>1). The stabilization of the slope is improved by using this technique.

**TABLE 7:** Analysis of Model

| Sr. No | Height of Landfill (m) | Inclination of Landfill (θ) | Factor of Safety (FOS) |
|---|---|---|---|
| 1. | 120 | 33.69º | 1.353 |
| 2. | 120 | 38.66º | 1.211 |
| 3. | 120 | 45.00º | 1.126 |
| 4. | 120 | 48.81º | 1.095 |
| 5. | 120 | 51.00º | 1.036 |
| 6. | 120 | 53.13º | 0.993 |

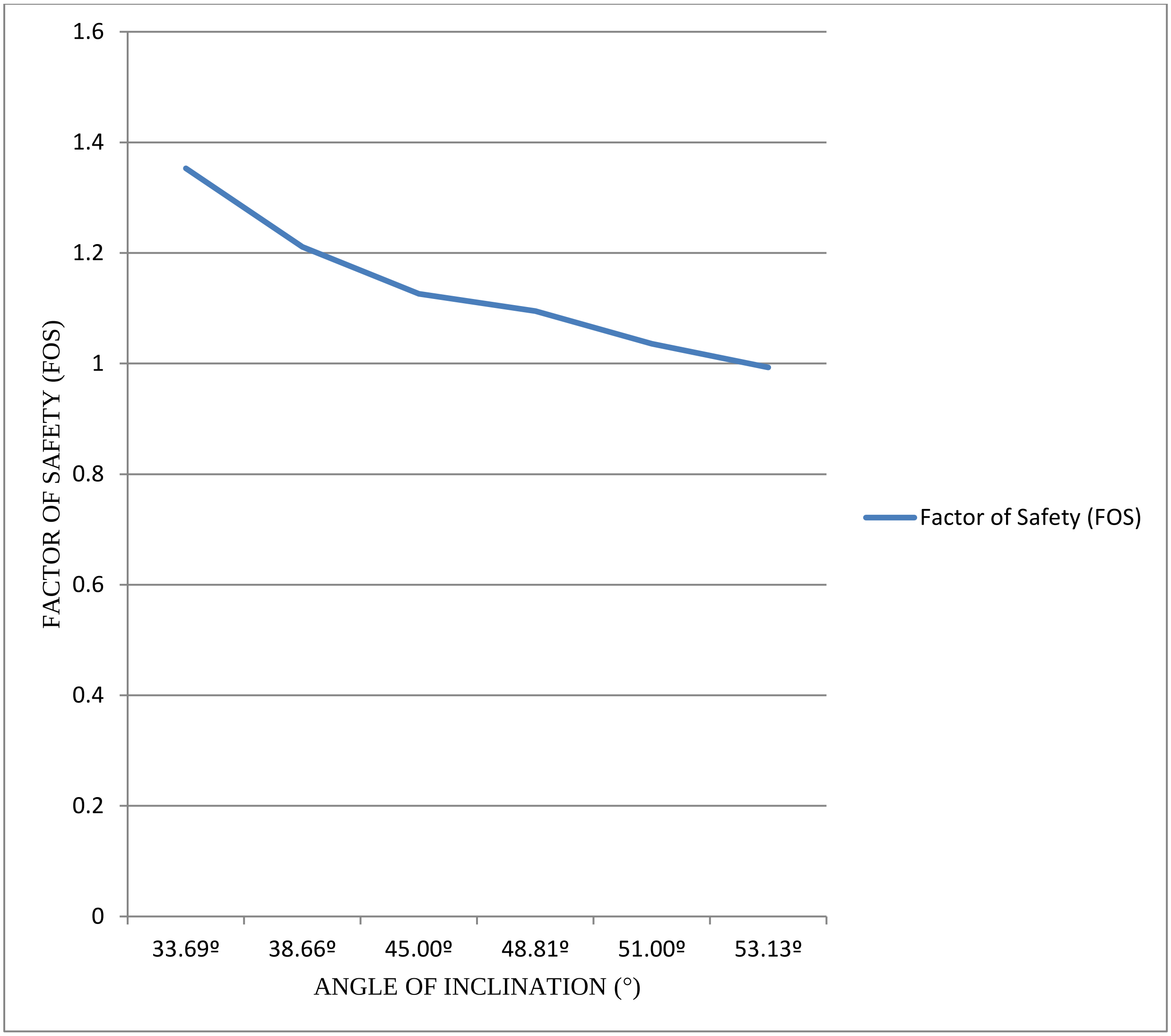


**FIG 18:** Graph of FOS for variation in angle of inclination

# CHAPTER 9

# SUMMARY OF THE PROJECT

## 9.1 CONCLUSION

This study uses numerical modeling to analysis the stability of landfill at different angle of inclination. The study concluded that:

i. A stable slope is seen when angle of inclination is less than 53º having FOS greater than unity.

ii. An unstable slope is seen when angle of inclination is more than 53º having FOS less than unity.

iii. As a result, more than 40% of the original amount of waste that needs to be excavated is reduced.

iv. Due to the minimal space needed beyond the dump's toe, this technique is preferable to the traditional one of leveling the slope.

The research area was chosen because it was thought of being affected by landfill dumping; it has almost identical aquifer systems and lithology and is located a few kilometers from two garbage sites. The sampling locations close to the dump were selected to reflect potential influences from the past, present, and future. Considering the unstructured nature of Delhi, its positioning within the flood plain of the Yamuna River, and its alluvial lithology that heightens the susceptibility to pollutant leaching, the placement of landfills within highly urbanized regions of the city is inevitable. As a consequence, the impact of these landfills on the extensive population cannot be escaped in the capital city of India. Investigation of the quality of the ground water in the area of a particular landfill in Delhi enabled us to recommend some effective strategies for limiting potential harm up to a certain point & potential precautions must be taken for landfill planning in the future. It might be best to close both active landfills right away to stop creating further pollutant sources.

In order to limit leachates from Okhala and Bhalswa landfill & prevent ground water contamination, proper management must be implemented to separate out or eliminate hazardous solid wastes before dumping.

## 9.2 FUTURE SCOPE

Future study on risk analysis, failure mobility, and slope stability of landfill failures can concentrate on various elements that can be summed up as follows:

i. Future research may examine the friction angle and cohesiveness as dependent variables on one another, which could result in a merged probability distribution in spite of the independent distributions found in this study.

ii. Future research could use three-dimensional programmers to offer mobility and slope stability analysis, risk estimations, and other data that would likely be more precise for landfill design.

iii. The computation and assessment of risk in this study focused on human life loss. But characteristics and environmental surface & ground water pollution are potentially sensitive factors, necessitating additional study to assess the risk.

iv. For the purposes of this study, the identical distributions of waste material unit weight, friction angle, and cohesion have been applied to several spatial and temporal contexts. For classifying these characteristics range for various landfill scenarios, like high and low normal stress in landfills, old or fresh garbage, compacted or uncompacted waste, etc., would be useful in future studies.

v. The technique would be relevant for other landslip categories, like debris-flow, avalanche& rock-flow, even though this research concentrated on landfill failure risk analysis.

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# LIST OF PAPER

1. **ANALYSIS OF STABILITY OF SLOPE ON LANDFILL IN DELHI.**
   Vaidehi and A.K. Gupta, "ANALYSIS OF STABILITY OF SLOPE ON LANDFILL IN DELHI", 4$^{th}$ International Conference on Waste Management (RECYCLE 2023) (18-19 MAY) **(PRESENTED)**.

RECYCLE 2023

4th International Conference on Waste Management

CERTIFICATE OF PARTICIPATION

This is to certify that

*Vaidehi*

presented Oral Presentation on the topic **Analysis Of Landfill Slope Stability At Bhalswa, Delhi** in Recycle 2023, The 4$^{th}$ International Conference on Waste Management, Organised by Waste Management Research Group, Indian Institute of Technology Guwahati on 18$^{th}$ and 19$^{th}$ May 2023.

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