

Stability Analysis of Landslide-Prone Slopes Adjacent to MUET Buildings and Their Remediation

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Received: 09 November 2025, Revised: 24 May 2026, Accepted: 22 June 2026, Published: 01 July 2026

KEY WORDS	ABSTRACT
Slope Stability Numerical Modeling PLAXIS-2D Mohr-Coulomb Constitutive Model Concrete Piles Factor of Safety (FOS)	The Buildings at the Mehran University of Engineering and Technology (MUET), Jamshoro, pose a major concern because of the critically low safety conditions. This study analysed the stability of the slopes around Building A and Building B with PLAXIS-2D (Finite Element Modelling Software). The analysis showed that the slopes of Buildings A and B are unstable under natural conditions, with FOS values of 1.099 and 1.002, respectively. Moreover, the slopes were analysed under erosion conditions, and the result showed that on 15° erosion condition, instability increases, reducing FOS to 0.978 and 0.874, respectively. Analysis with building offsets of 0 m, 1 m, and 2 m was also carried out, and it indicated that 0 m offset is most critical. Steep slope angles of 65.7° (Slope A) and 68.2° (Slope B), along with Rocky clay soil of this region, further increase landslide risk, highlighting the adverse influence of slope geometry. Therefore, concrete piles were used as a remedial measure to resist the slope failure. Numerical modelling showed that concrete piles are effective in enhancing slope stability. From the various experimental models, a 1-meter-diameter and 25-meter length (12-meter above crest and 13-meter-long pile embedded at the top of the slope) gave the most promising results. The FOS rose to 2.1 for Building A and 1.8 for Building B, respectively, which reflected a stable slope condition. Piles installed along the slope crest acted as a barrier to lateral soil movement, increasing resistance to sliding forces and thereby reducing the risk of slope failure and potential damage to nearby structures. This approach provides a safe and economic solution. The results of this study indicate that the installation of concrete piles is an effective method for slope stabiliation in such geotechnical conditions.

1. Introduction

Civil engineering deals with the stability and safety of both natural and engineered structures such as hills, mountains, slopes, buildings, bridges, and highways. [1] The stability of structures built on slopes or on elevated terrain is considered only when they uphold their integrity to the anticipated loads and environmental factors. To evaluate and ensure structural safety, the concept of the Factor of Safety (FOS) is employed. Factor of Safety is a non-dimensional numerical value which signifies the difference between the actual strength of a structure and the loads or stresses that the structure can undergo. [2] Appropriate FOS values are specified for different types of structures, reflecting their functional requirements, potential risks, and the consequences of

failure. It is important to keep these factors within set limits to ensure the consistent performance and stability of both new and existing structures.[3]

Slope stability analysis is very important in geotechnical engineering, especially for projects that are close to sloping ground.[4] It makes sure that both natural and man-made slopes are built safely. If the slope analysis is wrong, the slope could fail. As a result, thorough soil studies are necessary to determine the actual soil conditions at the construction site.[5] Different triggering events like earthquakes and Landslides are happening ever more around the world, and they can have severe effects, such as fatalities, damage to infrastructure, displacement of communities, loss of environmental quality, and bad

effects on the water quality in rivers and streams. [6,7,8]

Geotechnical engineers should ensure that these structures are safe in order to prevent such disasters from happening. Slopes present significant hazard to geotechnical engineers since they form significant components of such objects as hills and road embankment.[9] The types of failures that may occur on the slope are numerous and include shear rotational, translational, compound, and wedge failures.[10,11,12] That is why slope stability analysis should be utilised to determine the stability of the slope. The Safety Factor of a slopes should never be less than one and should be upto 2.00 or more to prevent it from failure.[5,6,13,14,15]

This study evaluates the slope stability of existing buildings in Mehran University of Engineering and Technology, Jamshoro. The soil in Jamshoro is weak and swells.[16,17,18] Building infrastructure on these kinds of soils has caused a lot of damage and cost a lot of money to fix. So, treatment is needed to make its geotechnical features better. [19]

Concrete piles have been recognized as an effective remedial measure for slope stabilization because they provide deep structural support and enhance slope stiffness.[1] These piles transfer loads from unstable surface layers to more competent subsurface strata, acting as vertical reinforcements that resist translational and rotational movements of soil masses. Another study investigated that buttressing effects can also be generated by strategic placement of concrete piles, which minimizes lateral displacement and enhances the global factor of safety.[15,20] Thus, this research has shown that well-designed and installed concrete piles can reduce both short-term slope failure risks and improve long-term stability and resilience, which makes them a safe choice in geotechnical engineering practice.[4]

2. Materials and Methods

2.1 Site selection in MUET, Jamshoro

The initial step of our research was the selection of an appropriate site for investigation. The decision was based on factors including site proximity, study compatibility, and the feasibility of data and sample collection. Subsequent to site visits, final locations were chosen at the MUET Faculty Road, specifically within the Metallurgy and Coal Research Department of MUET, Jamshoro.[21] The site featured a roadway situated beneath steeper slopes, as shown in Figures 1.1, 1.2 and 1.3.



Fig. 1.1 Location sites under investigation.



Fig. 1.2 Site Slope A of investigation.



Fig. 1.3 Site Slope B of investigation.

2.2 Geometric calculation of slope

It's very important to understand the slope's geometry because it has a big effect on how stable the slope is. Theodolite surveying was used at first to get accurate data on the angle. The angle of slopes was found out as $\theta = 65.7^\circ$ or $65^\circ 42' 10''$ for Slope A and $\theta = 68.2^\circ$ or $68^\circ 13' 00''$ for Slope B, After that, a measuring tape was used to find the length of the inclined surface, which was 42' 6" or 12.958 ~ 13 m and 46' or 14 m, respectively. This was done to make sure the distance measurements were correct. Trigonometric Theorems were utilised to find both the vertical height and the horizontal distance of the slope after having these two vital measurements. After calculating geometric data, the geometry of the slope

was concluded in PLAXIS-2D software as shown in Figures 2.1 and 2.2.

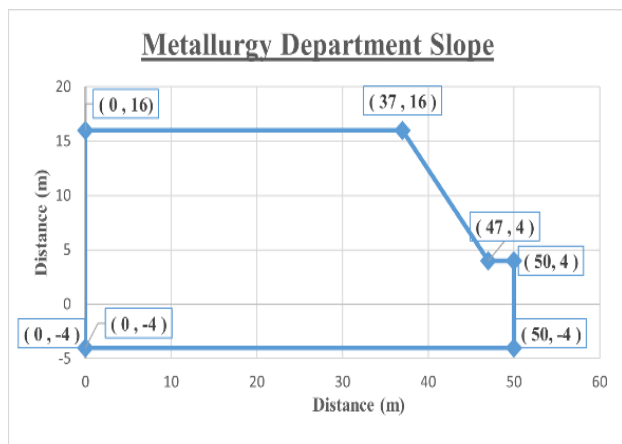


Fig. 2.1 Geometry of slope A

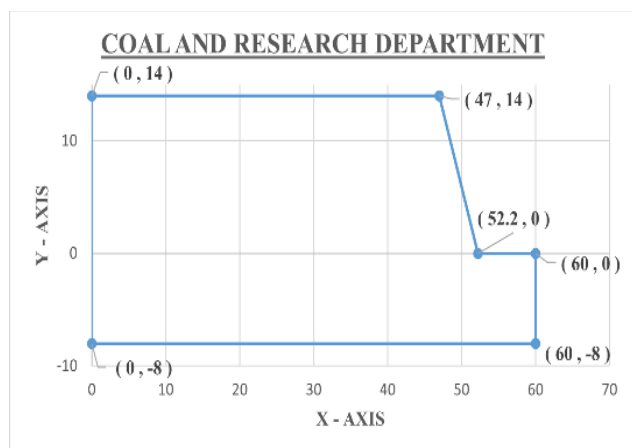


Fig. 2.2 Geometry of slope B

These geometric calculations lead to the essential data required for further studies of stability and simulations.

2.3 Sample collection:

The Sample was collected by the Pit Method, as shown in Figure 2.3.



Fig. 2.3 Site selection and sample collection

2.4 Estimation of soil parameters:

After the collection of the soil sample, the preliminary tests were conducted that were needed to incorporate into the PLAXIS-2D software for assigning the soil and are enlisted in Table 1.



Fig. 2.4 Site selection and sample collection

Table 1

Soil Simulation Parameters.

Angle of friction	(ϕ)	39.69°	-
Cohesion	(C)	26.57	kPa
Young's Modulus of Elasticity [1]	(E)	25000	kN/m ²
Poisson's Ratio [1]	(ν)	0.3	-
Optimum Moisture Content	(O.M.C)	15.2	-
Max Dry Density	(γ_d)	18.6	kN/m ³
Saturated density	(γ_{sat})	21	kN/m ³
Soil type	(AASHTO Classification)	Rocky Clay	(A-7-6)
Liquid Limit	(Casagrande Method)	54	%
Plastic Limit	(Thread Method)	34	%
Plasticity Index	(P.I)	20	%
Specific Gravity (G)	(Pycnometer Method)	2.61	-

Table 2

Concrete Pile Simulation Parameters

Young's Modulus of Elasticity [2]	3.0 E4	MPA
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Poisson's Ratio [2]	0.15	-
Density [2]	24	kN/m ³

2.5 Use of PLAXIS-2D:

PLAXIS-2D, a powerful finite element software made specifically for geotechnical uses, has been used to fully analyse the stability of the slope at MUET Jamshoro. To fully understand slope stability, simulations and tests were done on several models to find the most important parameters.[8,9,22]

2.6 Method of Analysis: Mohr-Coulomb model:

The Mohr-Coulomb model is an easy and useful way to mimic how things really work with just some soil properties. It is a first-order approximation of how soil behaves, so it is useful for figuring out how much soil will change shape when loads are put on it. The Mohr-Coulomb model is different from other models because it is simpler and doesn't need as many input parameters. [5,16,18]

A lot of researchers use this model to explain how soil behaves when it is elastic and perfectly plastic. When Hooke's law is used to find Young's modulus (E) and Poisson's ratio (ν), the relationship between stress and strain is linear in the elastic range. The failure criterion is affected by two factors: the friction angle (ϕ) and the cohesiveness (C). [13,23,24] A value derived from a non-associated flow rule is also used to characterise the flow rule, simulating true irreversible volume changes owing to shearing.

3. Results and Discussion

3.1 Numerical Modelling Results

Stability of the slopes at MUET Jamshoro has been examined in detail in PLAXIS 2D, which is a strong and efficient finite element software with specific geotechnical applications. The stability of the slopes at MUET Jamshoro was analysed in detail using PLAXIS 2D, a strong finite element software specifically designed to work with geotechnical work. The important parameters were identified by manually testing the models until we had a fairly close picture of the stability of the slopes. The factor of safety, which is a crucial metric of the overall stability of slopes, was calculated thoroughly in each of the models. The bearing pressure of a shallow foundation falls between 100 to 200 kPa (1 to 2 tons/ft²) [16,18,22] . It was noted that loading factors of 200 kPa and a building offset of 0 m have negative impacts on the slopes in this experimental study. The incorporation of these

loads in the analysis was made to depict the worst-case scenario. The solution to the issue was to employ concrete piles in various configurations to determine the greatest FOS, and this rendered the slopes stable.

3.1.1 Analysis of Natural Slope: A

The untreated slope was simulated by placing various loads on it to observe how the natural slope will respond to such loads when the natural slope is on a 0 m offset. This simulation provides a significant beginning point in trying to determine the stability of the slope itself. The analysis provides us with valuable knowledge on how the slope would behave under normal loading conditions by observing the slope in its natural condition.

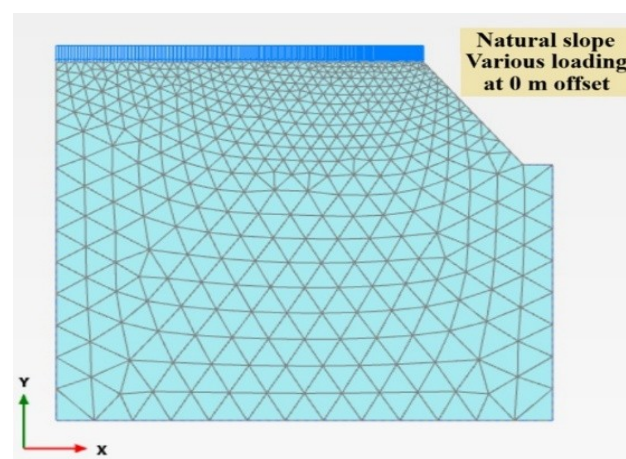


Fig. 3.1 Slope A: various loading with 0 m offset

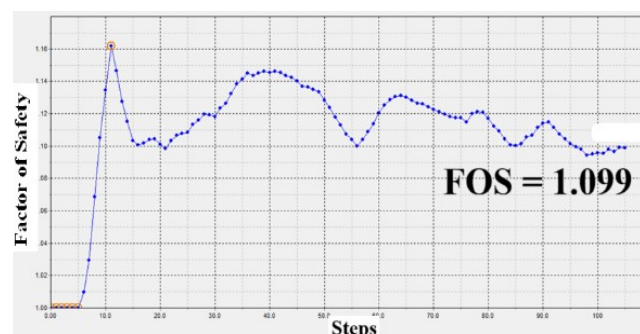


Fig 3.2. FOS: 200 kpa loading and 0 m offset

Table 3

Untreated FOS Analysis: Slope at Building: A

LOAD (kPa) / Offset (m)	Factor of Safety (FOS)		
	0	1	2
100	1.345	1.444	1.487
150	1.224	1.301	1.382
200	1.099	1.186	1.263

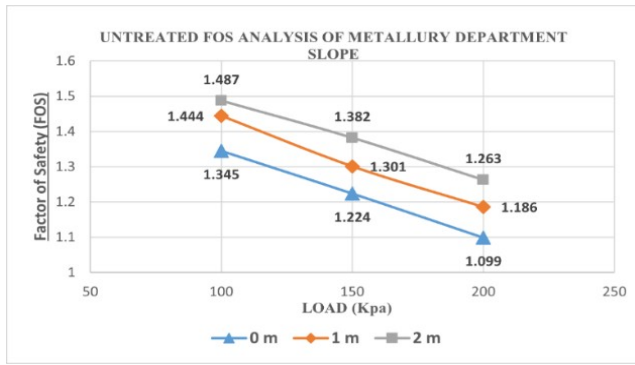


Fig 3.3 Graph Load(Kpa) v/s FOS: Building A

Building slope at various loads such as 100 Kpa, 150 Kpa and 200 Kpa was studied, and the Factor of Safety was obtained as 1.099 at 200 Kpa loading. This indicates that FOS is highly significant at 0 m offset, and this is very dangerous and requires treatment to remain stable and resist loading. [18]

3.1.2 Analysis of 15° Erosion Susceptible Slope: A

The untreated slope was modelled carefully to view its behaviour under various loads depending on the eroded slope. This simulation is a significant starting point to calculate the stability of the slope by itself. Based on the slope as it is currently, the analysis provides helpful information on how the slope would behave under normal loading conditions at 0 m offset, which would result in the slope eroding by 15 degrees.

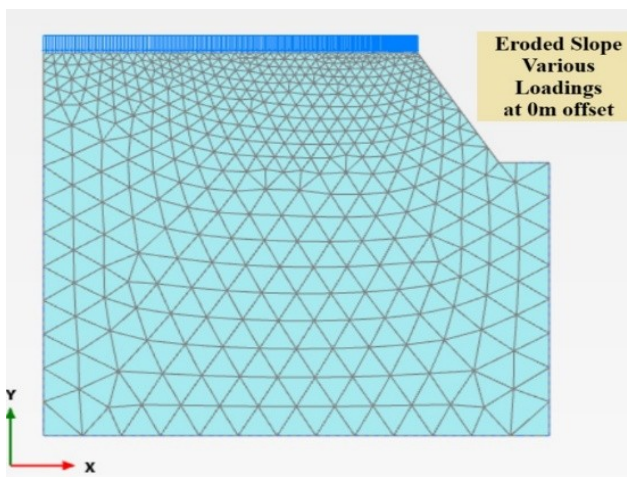


Fig. 3.4 Eroded Slope A: various loading with 0 m offset

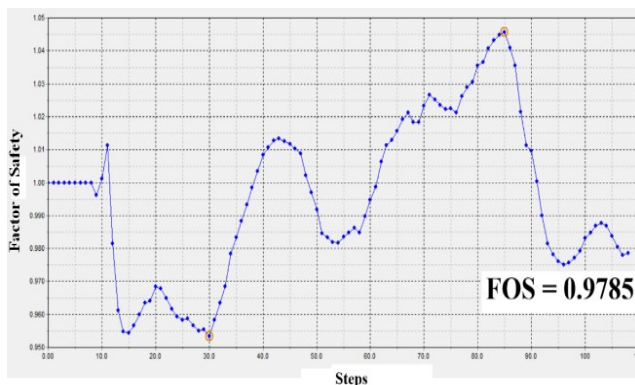


Fig 3.5 Eroded Slope A: 200 kPa loading with 0 m offset

Table 4

Untreated 15° Eroded FOS analysis of slope at Building: A

LOAD (kPa) / Offset (m)	Factor of Safety (FOS)		
	0	1	2
100	1.236	1.236	1.331
150	1.091	1.151	1.262
200	0.9785	1.041	1.132

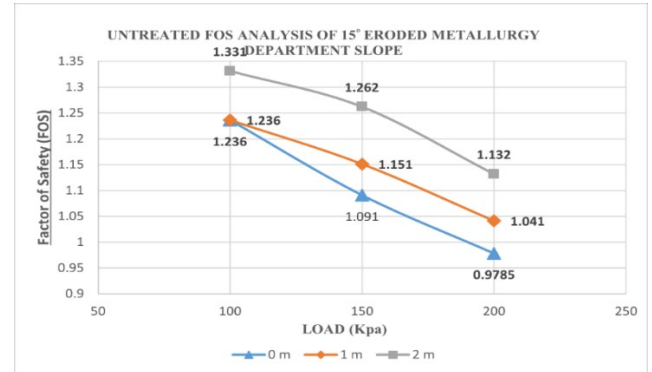


Fig 3.6 Graph Load(Kpa) v/s FOS: Eroded Building A

Following observation of the eroded slope of a building under varying loads at an offset of 0 m, such as 100 Kpa, 150 kPa, and 200 kPa. The Factory of Safety, at 200 kPa loading, is believed to be 0.9785. This implies that FOS will matter a lot as the slope angle will become steeper and the building will shift towards the top of the slope. This has demonstrated reduced FOS following weathering, which is highly risky and requires management to maintain stability and withstand loading. [18]

3.2.1 Analysis of Natural Slope: B

Untreated slope B was closely modelled to observe the behaviour of the natural slope during varying loading conditions with a 0 m offset. This simulation is a highly significant beginning point to the process of determining the stability of the slope in its own right. Through the slope in its untreated form, the examination provides us with valuable data regarding how the slope would behave under the normal loading conditions.

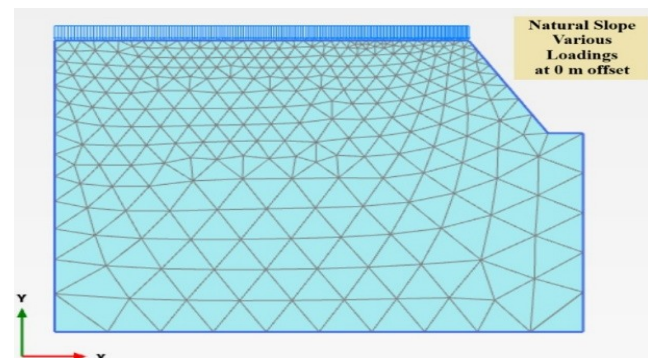


Fig 3.7 Slope B: various loading with 0 m offset

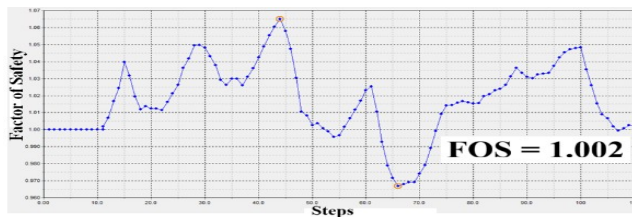


Fig 3.8 FOS: 200 kPa loading and 0 m offset

Table 5

Untreated FOS analysis of slope at Building B

LOAD (Kpa) at	Factor of Safety (FOS)		
	0 m offset	1 m offset	2 m offset
100	1.162	1.225	1.247
150	1.073	1.13	1.167
200	1.002	1.052	1.086

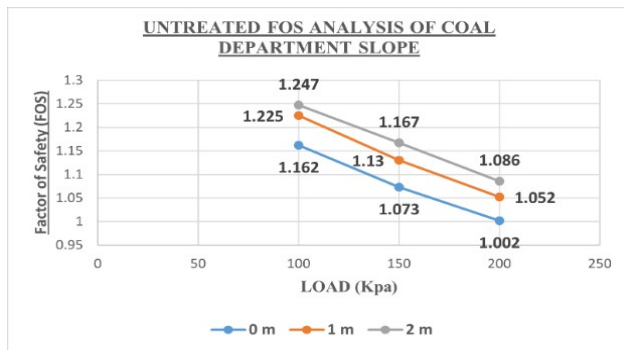


Fig 3.9 Graph Load(Kpa) v/s FOS: Building B

The slope B was analysed using various loads, such as 100 kPa, 150 kPa, and 200 kPa, with 0 m offset. The factory of safety has a rating of 1.002, indicating that it is highly important and that the slope is extremely dangerous and requires to be treated in order to remain constant and not to be affected by loading. [18]

3.2.2 Analysis of 15° Erosion Susceptible Slope: B

In order to determine the behaviour of the eroded slope in various loading conditions, the untreated slope was carefully modelled. Such a simulation can be a very important initial step towards an understanding of the inherent stability of the slope. With the effect of 15 degrees of slope erosion, the analysis, which looks at the slope in its untreated state, offers important insights into how the slope would respond to typical loading conditions at a 0 m offset.

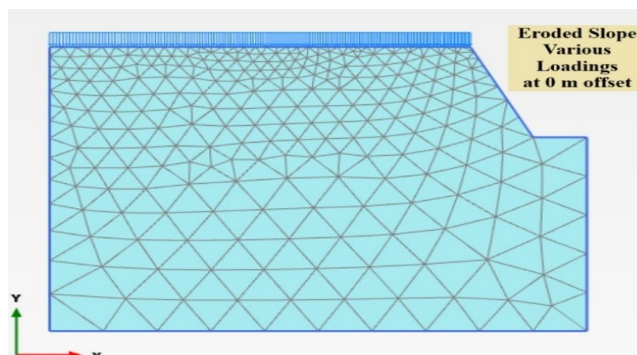


Fig 3.10 Eroded Slope B: 200 kpa loading with 0 m offset

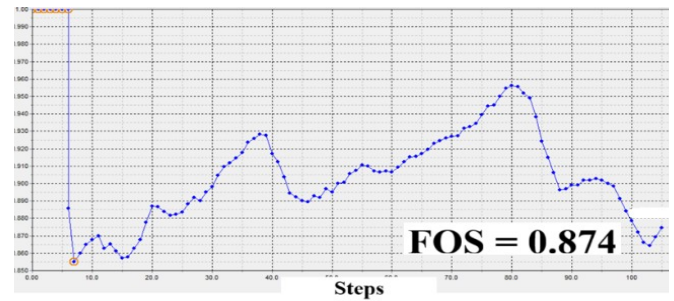


Fig 3.11 Eroded Slope B: 200 kPa loading with 0 m offset

Table 6

Untreated 15° Eroded FOS Analysis of slope at Building: B

LOAD (kPa) at	Factor of Safety (FOS)		
	0 m offset	1 m offset	2 m offset
100	1.037	1.07	1.111
150	1.023	1.00	1.02
200	0.874	0.901	0.929

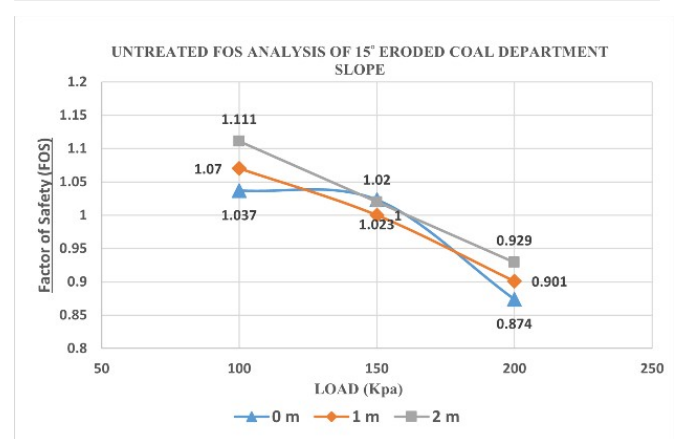


Fig 3.12 Graph Load(Kpa) v/s FOS: Eroded Building B

Following an analysis of the eroded building slope at different loads (100, 150, and 200 kPa) on a 0 m offset. The factory of safety is estimated to be 0.874 at 200 kPa loading, indicating that FOS is critical. This is because the building's offset from the slope's crest will decrease as the angle of the slope increases, resulting in lower FOS after weathering. This is extremely dangerous and requires treatment to withstand loading and maintain stability. [18]

3.3 Use of Piles in Slope in PLAXIS-2D:

To minimise the chance of slope failure on the Building Slope B, concrete piles of different lengths and diameters were used as an important safety measure at several locations in the slope profile. Piles are known for making a slope more stable by strengthening its load distribution mechanism, shear resistance, and bearing capacity. The main goal of the simulation was to find the best location, diameter, and length for the pile to make it safer [4], [8], [12]. Precise simulation focuses on specific key pile configurations, as analysis indicates that the critical position is at a 0 m

offset under a load of 200 kPa.[16,18] We looked at several models very closely to see how different pile diameters, lengths, and locations affected the rise in the factor of safety [22, 24,25]. The purpose of the study was to come up with a safe and efficient method of applying concrete piles to protect the area affected and to ensure that the area is more resistant to slope instability in the long run.

3.3.1 Use of Concrete Piles on Slope A:

Following numerous serious simulations of PLAXIS-2D models, which involve altering the size and positions of the piles at the summit of the slope, it was established that the most appropriate mechanism of maintaining the slope steady is by having a pile diameter of the piles to 1 meter and placing the pile at the summit of the slope. This arrangement contained the greatest Factor of Safety (FOS), ranging from 1.91 to 2.0. An FOS near 2.0 indicates that the piling system is performing well to stabilise the slope and prevent its failure. According to these findings, it is obvious that piles prove to be a significant component in the design of the slope as they render it stronger, less prone to failure and more stable in the long run.[18, 22]

Table 7

Treated FOS Building Slope B With Different Pile Lengths

Load (Kpa) / Dia	0.5 m			0.75 m			1 m		
Pile Length from base	20 m	25 m	30 m	20 m	25 m	30 m	20 m	25 m	30 m
100	1.9	1.9	1.9	2	2	2.1	2.1	2	2.1
150	1.7	1.7	1.6	2	2	1.8	2.1	2	2
200	1.5	1.5	1.5	1.8	1.8	1.7	2.0	2.1	1.9

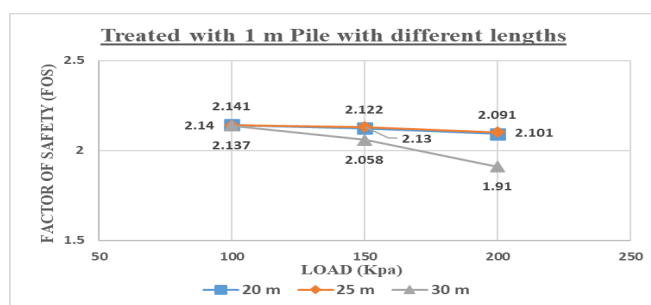


Fig 3.13 Graph Load(kPa) v/s FOS: 1 m Pile treated Building A

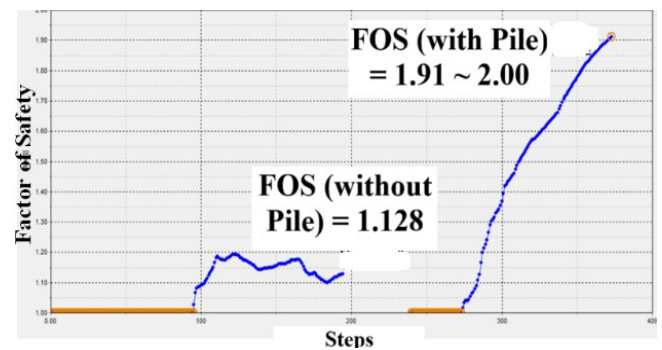


Fig 3.14 FOS with and without piles on Building A

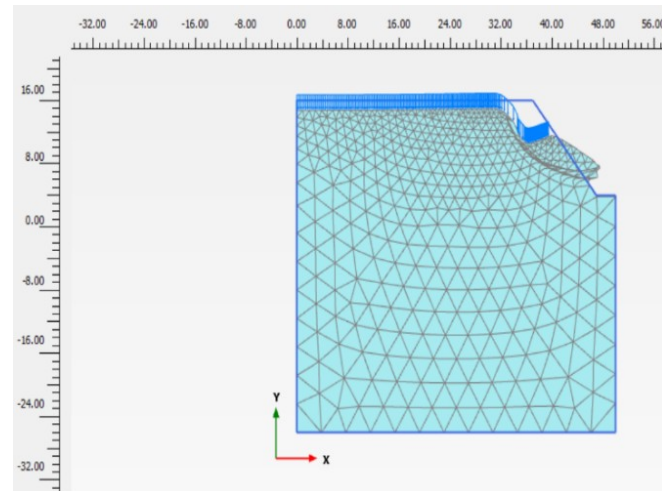


Fig 3.15 Building slope: A, without pile

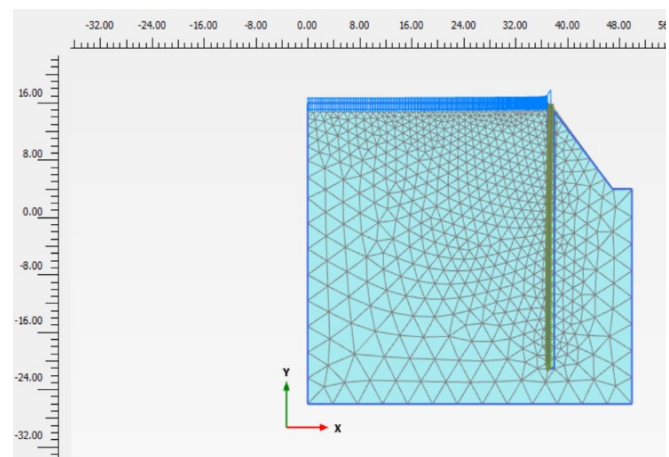


Fig 3.16 Building slope: A, with pile

3.3.2 Use of Concrete Piles on Slope B:

Following a lot of modelling in PLAXIS-2D using models 3, 4 and 5, in which the diameter and the position of the piles were varied, it was discovered that the most appropriate method of maintaining the slope stable was to use piles with a diameter of 1 meter and position them at the top of the slope. With this setup, the Factor of Safety (FOS) reached its highest point, which was about 1.639. The pile system has kept the slope stable and protected against possible failures; it has reached a FOS close to the critical level of 2.0. These findings show that piles are an important part of the slope's design because they improve its overall structural integrity, lower the chance of failure, and keep it stable over time.[18,22]

Table 8

Treated FOS Building B Slope With Different Pile Lengths

Load (Kpa) / Dia	0.5 m			0.75 m			1 m		
Pile Length from base	20 m	25 m	30 m	20 m	25 m	30 m	20 m	25 m	30 m
100	1.4	1.4	1.4	1.6	1.5	1.6	1.7	1.7	1.7
150	1.2	1.2	1.2	1.4	1.4	1.3	1.8	1.8	1.8
200	1.1	1.1	1.1	1.3	1.2	1.3	1.7	1.8	1.6

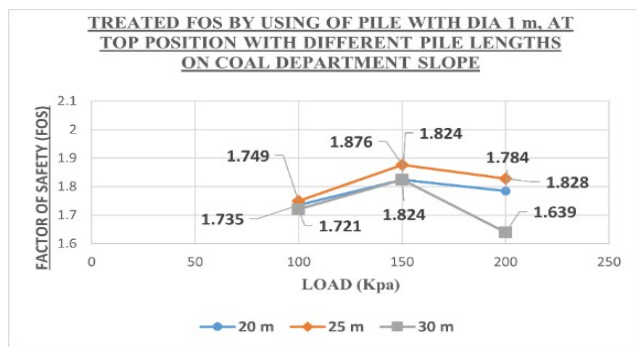


Fig 3.17 Graph Load(kPa) v/s FOS: 1 m Pile treated Building B

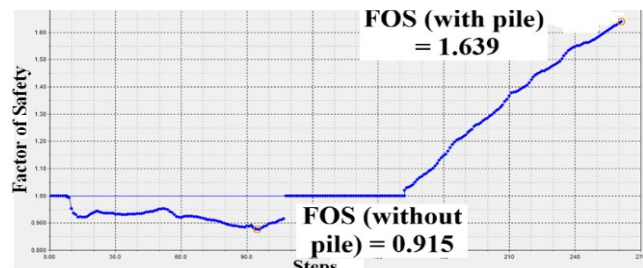


Fig 3.18 FOS with and without piles on Building B

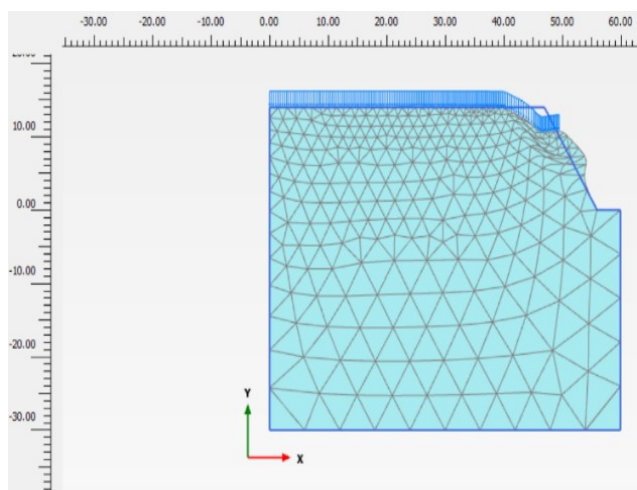


Fig 3.19 Building slope: B, without pile

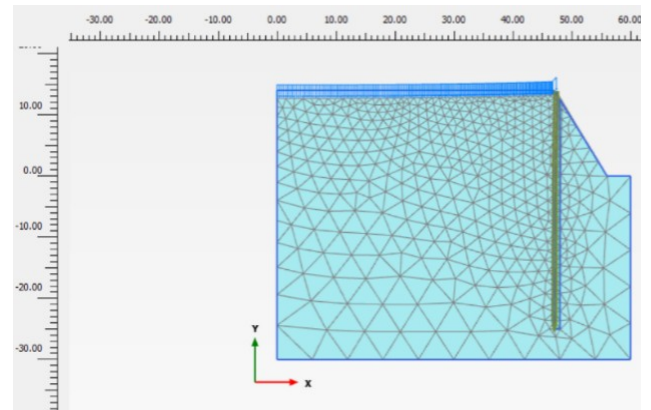


Fig 3.20 Building slope: B, with pile

4. Conclusion

- I. This study has investigated that these particular buildings located in the vicinity of MUET, Jamshoro, are vulnerable to landslides due to their self-weight being imposed on the Rocky clay soils of Jamshoro. The PLAXIS-2D analysis demonstrated that the slopes of both Buildings A & B were unstable, with a Factor of Safety (FOS) of 1.099 and 1.002 respectively, under natural conditions.
- II. Slopes were also analysed for 15° erosion condition as it is imminent from the condition of the facing of the slopes. The Analysis demonstrated that the slopes of both Buildings A & B were more unstable then in natural condition, with a Factor of Safety (FOS) of 0.978 and 0.874, respectively.
- III. Both slopes were analysed under natural and eroded conditions with building offsets of 0 m, 1 m, and 2 m. PLAXIS-2D results showed that a 0 m offset, where buildings are directly at the slope edge, is the most vulnerable. The steep slopes, 65.7° for Slope A and 68.2° for Slope B, further increase the risk of landslides due to the existence of the weak clay soil. These findings highlight that slope geometry significantly affects slope safety.
- IV. The slope stability calculations and various models have shown that putting in piles has greatly increased the Factor of Safety (FOS). Concrete Piles raised the FOS for Buildings A & B to promising levels of 2.1 and 1.8, respectively. Using Concrete Piles kept the weak soil stable and act like soil reinforcement when it was

under the gravitational load, enhancing the soil's shear strength stronger.

- V. PLAXIS-2D assessment indicated that the optimal pile configuration consists of piles with a length of 25 m and a diameter of 1 m, positioned at the top of the slope, 12 m above ground level from the crest and embedded 13 m into the slope embankment. This configuration was found to provide the maximum factor of safety under the given conditions and is considered effective in enhancing the slope's shear strength to prevent failure.

5. Limitations And Future Recommendations

This research is based on PLAXIS 2D modeling, which is widely used for analyzing slope stability and provides a reliable understanding of soil behavior under two-dimensional conditions. Furthermore, it focuses on one specific cause of slope instability, i.e., the self-weight of buildings, allowing a clear and simplified evaluation of how self weight affects slope stability. Therefore, the future recommendations are given below:

- I. A detailed seismic analysis of the study area should be conducted to evaluate the impact of earthquake-induced forces on slope stability.
- II. The analysis should be extended to PLAXIS 3D to capture three-dimensional effects such as pile spacing, group interaction, and spatial variability of soil properties.

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