A Review on Slope Stability Analysis

Mrittika Chakraborty[1], Prince Rathod[2]
Department of Civil Engineering
Parul Institute of Engineering & Technology, Parul University, Limda, India
Email: *mrittika.chakraborty27@gmail.com[1], prince.rathod@paruluniversity.ac.in[2]*
DOI:- https://doi.org/10.47531/SIC.2022.39

Abstract

Slope stability analysis is a rapidly developing area of study in geotechnical engineering as it has gained importance after some major slope failure catastrophe. Providing a slope that is economical and safe is a great concern in the construction industry. A slope is considered stable if the forces available to resist the movement are greater than the force driving the movement. A number of slope failures in recent years call for slope analysis and possible preventive measures.

The paper aims to provide an overview of the research work carried out, which focuses on the factors affecting the slope stability like sudden seepage pressure, erosion, tectonic activities, etc., mechanism of the slope failure e, numerical analysis. Also, the paper aims to review the common methods to mitigate the failure.

Keywords: - *Slope Stability, Slope failure, Preventive measures*

INTRODUCTION

A surface inclined at some angle from the horizontal, which may be a rise or fall, is called a slope. There are two types of slope (1) Infinite and (2) Finite slope. In nature, only a finite slope exists. These finite slopes are further divided into two: (1) natural (2) man-made. The man-made slopes are generally gentler and are constructed with respect to time, cost and quality. Whereas the natural slopes are steeper, the failure of this natural slope is a major concern of geotechnical engineers as they cause fatality and economic losses. The failure of the slope is primarily due to an increase in the shear stress or a decrease in the shear strength. There are various methods of slope stability analysis like Limit Equilibrium Method (LEM), Finite Element Method (FEM) and Numerical method of modelling (NMM). The LEM or the analytical techniques have been in practice for a long, but to analyse these natural slope failures calls for an integrated analysis of analytical techniques and FEM or NMM.

REVIEW OF PREVIOUS WORK DONE

This section comprises some of the literature used for studying slope stability analysis.

A. Stability Analysis of a Recurring Slope Failure along the NH-5, Himachal Himalaya, India.

(Singh et al., 2018) in their paper "Stability Analysis of a Recurring Slope Failure along The NH-5, Himachal Himalaya, India." They conducted an extensive study of the repetitive soil slope failure along the National Highway (NH)-5 in the Jhakri region of Himachal Pradesh. The absence of any previous stability investigation of this recurring slope failure calls for an integrated geotechnical and numerical approach to understand the instability factors.

A slope failure study in this region is important because a wide range of slope movements keep pacing. There is a strong relationship between tectonic movement and erosional activity. The Himalayas region shows a wide range of complex landslides, of which about 30% of landslides in the world are potent of causing a huge fatality and economic losses. (Li 1990; Dahal et al. 2009) Human activities like deforestation, poor design construction, hydropower projects etc., have added up the landslide event. (Haigh et al. 1989). The area of the Rampur- Jhakri of Shimla district is the zone where the landslides are predominantly shallow is mostly initiated by the rainfall and is caused by the major debris depositions, which has a glacial-fluvial origin. The constant Jhakri slope failure during every monsoon causes transport disruption and communication loss for a long time. (Himachal Pradesh State Disaster Management Authority (HPSDMA) 2012).

Therefore, the researchers have studied the slope failure mechanism and investigated the causes through a field and geotechnical investigation. Using the Limit Equilibrium Method (LEM), Slide v7.0, an analysis of a pre-failure and post-failure slope is carried out to demonstrate the failure surface and deduce the most probable critical failure surface for both conditions, respectively. From the geotechnical investigation parameters like particle size (silt= 19.07% to 37.93%; sand= 15.21% to 19.07%; clay=1.6% to 4.86%), Atterberg Limit (LL=24% to 29%; PL= 18%to 21%; PI=7%), cohesion (9.81 kPa), angle of internal friction (32°), coefficient of permeability (0.0026m/h), natural moisture content (12.80%), Unit weight (13.30 kN/m3), bulk density (1420 kg/m3), saturated unit weight (17.14 kN/m3) and their values were deduced.

A Scanning Electron Microscope (SEM) analysis also has been carried out to understand the surface morphology of the soil sediments. Energy-dispersive X-ray spectroscopy (EDS) was also carried out along with SEM. The EDS study concluded by stating that there is high Mg, Al, Fe, K, Si. There is a close-knit of the failure types, critical surface, gradient, height, slope geometry, pore water pressure lithology contributing to the landslide mechanism. (Picarelli and Abolmasov, 2014). The slope section selected for the study had a steep gradient and semi-circular failure surface.

The geometry of the shallow slope is more relatable with the factors like failure type, critical failure type and amount of mass displaced. (Frattini and Crosta 2013; Chen et al. 2016). A graph plotted for the Jhakri slope (North and South section). The geometry of the failure indicates a highly unstable condition in the south section of the slope in both pre and post-failure conditions. Benching has been proposed for the southern section, exhibiting critical stability in dry conditions.

The northern section of the slope exhibits critical stability in a dry state at a smaller height. The slope height and slope angle with the slope geometry indicate that the slope section is unsafe in a dry state.

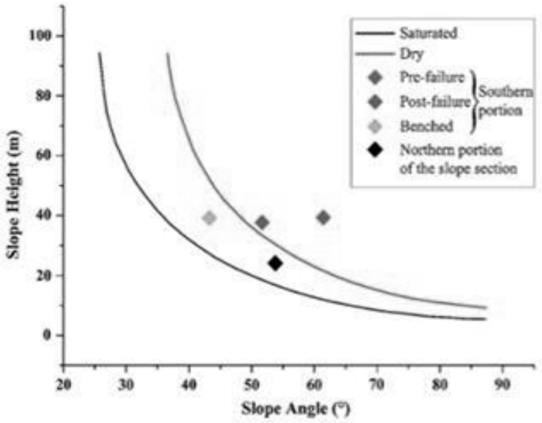

Figure 1 Critical slope height versus slope angle relation for soil slope geometry (after Hoek and Bray 1981)

The shallow slope failure activated by a rainfall infiltration has four phases: (a) Movement of the water to the failure zone or bedrock soil interface zone (surface flow, interflow), (b) cohesion loss or slide occurring through the layers of soil. (c) material mobilisation. (d) the collapse of the material. (Ellen 1988).

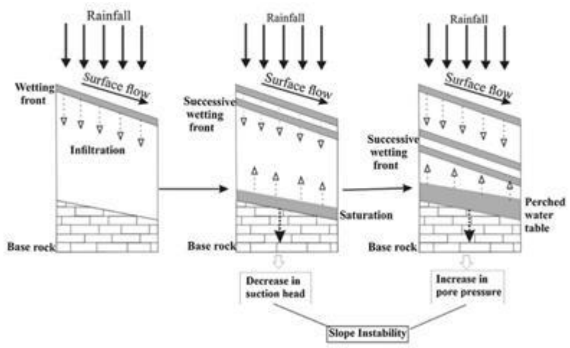

Figure 2 A sequential schema of shallow landslide initiation (after Malet et al. 2005; Kuriakose et al. 2009)

To define the rainfall threshold, two empirical approaches based on the rainfall measurement were considered. They are (1) precipitation obtained for specific rainfall events (Guzzetti et al., 2007). (2) antecedent rainfall measurement (causing the slope to fail) (Iverson 2000; Godt et al. 2006). From the examination conducted, it was concluded that the antecedent rainfall of 91mm for 30 days would cause the failure of the slope without any preventive measure. In post-monsoon conditions, the slope will reactivate if it receives rainfall of 110mm. For stability analysis of the slope, LEM was carried out as it is an accurate and versatile method. For the FoS computation, Bishop's Simplified (BS) and Morgenstern-Price (MP) methods were considered. The analysis concluded that the slope is unstable; even after the failure in the southern section, the preventive measure of reinforced benching was proposed, and it was found that the slope is stabilised.

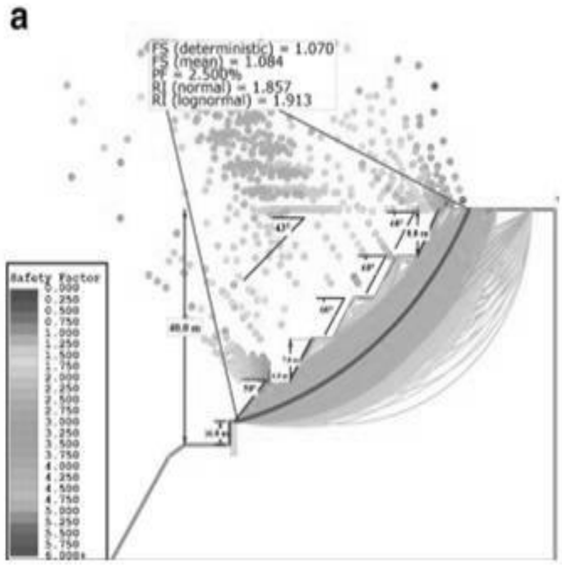

Figure 3 Slip surfaces from LEM result for a proposed benched slope

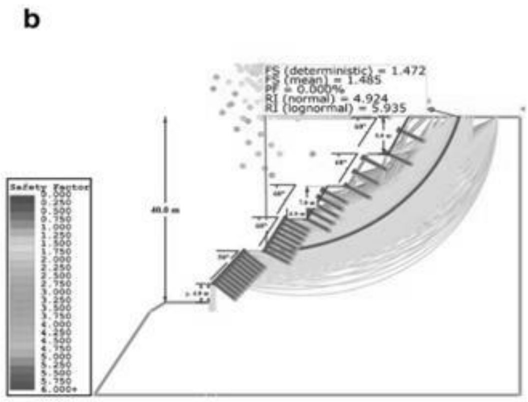

Figure 4 Slip surfaces from LEM result for a proposed reinforce benched slope

The angle, height and width of the bench are determined using the hit and trial method. Furthermore, a sensitivity analysis is carried out to know the sensitivity of the FoS. The results indicated that the pre-and post-failure slope's reliability index (RI) is negative in both BS and MP methods. Therefore, the preventive measures use both benching and soil nailing to check the RI. The bench angle is kept at 60° with five benches, and the overall slope is kept at 43°. The soil nails used are 5 m long with a tensile capacity of 200kN tensile strength. In benched slope, the RI is less than 3 in both BS and MP methods which means the slope is unstable. But a reinforced slope is having a RI of 5.004 and 4.924 in both BS and MP methods, respectively.

B. Rain- Triggered Slope Failure of the Railway Embankment at Malda, India

(Raj & Sengupta, 2014) their paper "Rain-triggered slope failure of the railway embankment at Malda, India." They examined the railway embankment failure at Malda, which cause the derailment of the train.

The height of the railway embankment was a maximum of 4.4m with a slope of 2(H):1(V). The width of the top of the slope is 6.7m and is designed to take an axial load of 25t of the train, which is a distributive load of 94.5 kPa. 30% of the sudden impact load is already included in this load which is a requirement of Indian Railways. (RDSO, 2003). The districts receive rainfall of 2,000 to 4,000 per year (IMD, 2012). On 28th September 1995, Malda received the maximum rainfall in the history of intensity 23.75 mm/h. (Khaladkar et al., n.d.)

The prime factor for the failure of this railway embankment slope was the rainfall the district received. So the researchers established a soil-water content and matric suction relationship for the embankment soil, and also a numerical simulation with FE-code GEO-STUDIO (GEO-SLOPE, 2007) was performed. A significant reduction in the factor of safety was indicated by numerical analysis, which was dependent on the intensity and duration of rainfall. The stability analysis of the slope is also carried out using the LEM methods: the Morgenstern-Price method, Janbu's method, Ordinary slice method and Bishop's simplified method.

From the Geotechnical analysis, it was observed that the soil has an effective cohesion of 0.2 kPa and an effective angle of internal friction φ' of 29.5°. The graph shows that the soil is well-graded.

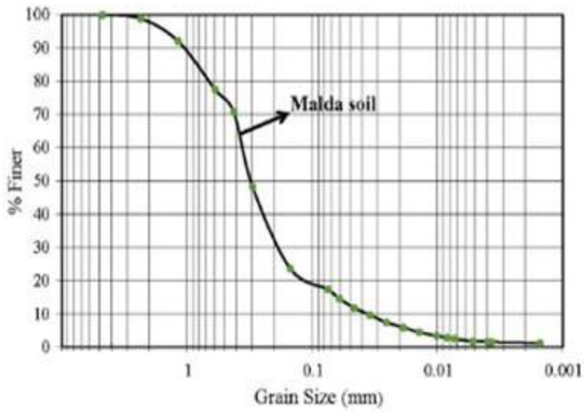

Figure 5. Grain size distribution of the embankment soils

Tension meters were used to determine the soil-water characteristic curve using a standard method (ASTM, 2004). The hydraulic conductivity with suction was found to be 8.4 x 10-4 cm/s. Empirically a relationship was established between the hydraulic conductivity and suction pressure (Genucheten, 1980).

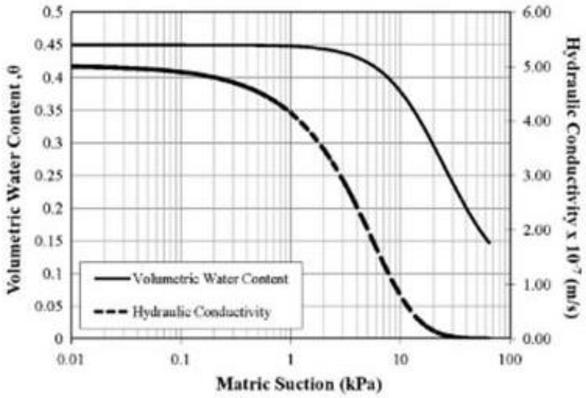

Figure 6 Variation of volumetric water content and hydraulic conductivity with suction pressures for the Malda soil

From the numerical analysis, it was observed, the embankment does not fail with the rainfall of 2 mm/h for 20h, but if this intensity of rainfall exceeds, then the FoS drops rapidly. Theoretically, the embankment fails after receiving a rainfall of 4 mm/h of intensity for 8h. The slope remains stable at 3h if this intensity increases to 8 mm/h.

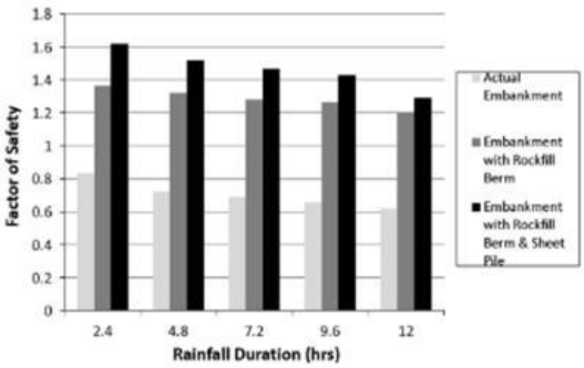

Figure 7 The factor of safety of the Malda embankment with proposed modifications for 25 mm/h rainfall events

Stabilising the embankment with a 2 m wide free-draining rockfill berm on top of the slope can sustain a rainfall of 25 mm/h intensity for 12h to enhance this stabilisation 5 m long sheet pile driven to protect the toe of the slope.

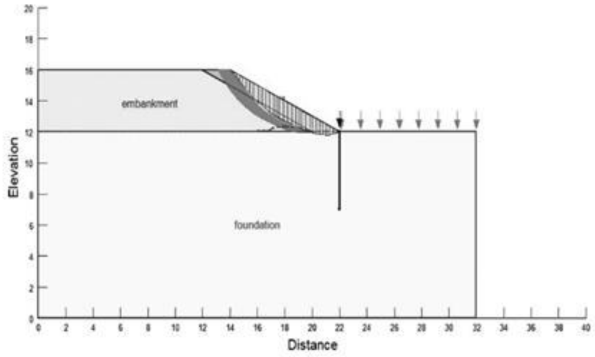

Figure 8 Critical sip surface within the embankment with rockfill berm and sheet piling in place

C. A hillslope failure analysis: A case study of Malingaon village, Maharashtra, India

(Shah et al., 2019) in their paper on "A hill slope failure analysis: A case study of Malingaon village, Maharashtra, India", they studied and concluded that the landslide catastrophe of 30th July 2014 was triggered due to excessive rainfall un-scientific method of agricultural practice by the dwellers.

The geological composition of this slope is basaltic strata. (Singh et al., 2016). The geotechnical investigation of the soil samples from the bottom, middle and top of the slope revealed the parameters to be specific gravity (2.8- 2.25), bulk density (0.62 g/cm3), dry density (1.35g/cm3- 1.26g/cm3), Atterberg limit (LL= 52.5%; PL= 31.75%- 27.88%; PI=20.75%- 24.62%), cohesion (0.13kg/cm2- 0.42 kg/cm2), angle of internal friction (4.35°- 36.4°). The specific gravity of the soil samples infer that the soil has a high amount of sand particles, but with respect to the water content, the soil is sandy-clayey soil. (Sathe, S. S., & Mahanta, C. 2019).

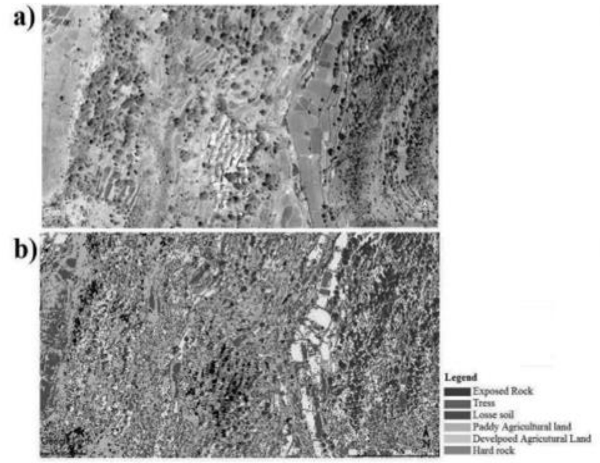

Figure 9 Land use land cover map of Malingaon before the occurrence of landslide in the year 2014 (a and b)

To recognise the vulnerability of the slope, images from Google Earth map 2018 were introduced into Arc GIS 9.1 and analysed before and after the landslide. The comparison showed that the landslide was in the area where the agricultural land was developed. This developed agricultural land caused a lot of loose soil in the surrounding of the hill, which also contributed to the hill slope failure work includes numerical analysis, seepage analysis, geotechnical properties of soil samples from various depths of the slope.

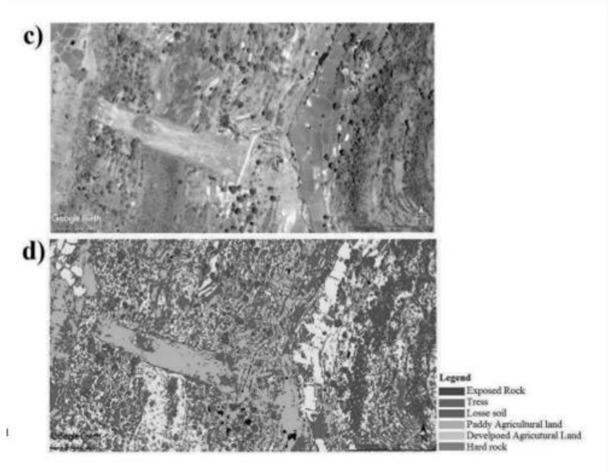

Figure 10 Land use land cover map of Malingaon before the occurrence of landslide in the year 2014 (c and d)

Observed in the numerical analysis. In all cases, the failure mode matched well with that observed in the experiments [6]

CONCLUSIONS

From the review of the papers, a conclusion can be drawn that geotechnical parameters like- particle size, Atterberg limits, cohesion, angle of internal friction is important in determining the factor of safety of the slope. Also, in a tropical country like India, the failure of slopes is governed by the seepage of the rainwater.

REFERENCES

1. ASTM (2004). Standard guide for measuring matric potential in the vadose zone using tensiometers. ASTM standard D3404-91. American Society of Testing Materials, West Conshohocken, PA.
2. Chen XL, Liu CG, Chang ZF, Zhou Q (2016) The relationship between the slope angle and the landslide size derived from limit equilibrium simulations. Geomorphology 253:547–550
3. Dahal RK, Hasegawa S, Yamanaka M, Dhakal S, Bhandary NP, Yatabe R (2009) Comparative analysis of contributing parameters for rainfall-triggered landslides in the Lesser Himalaya of Nepal. Environ Geology 58(3):567–586
4. Ellen SD (1988) Description and mechanics of soil slip/debris flow in the storm. In: Ellen SD, Wieczorek GF (eds) Proceedings of the conference on landslides, floods and marine effects of the storm of January 3–5, 1982, in the San Francisco Bay Region, California, Washington, USA, USGS professional paper 1434:03–112
5. Frattini P, Crosta GB (2013) The role of material properties and landscape morphology

on landslide size distributions. Earth Planet Sci Lett 361:310–319

6. GEO-SLOPE Intl. Ltd. (2007). Seepage modelling with SEEP/W: an engineering methodology. 2007 edition, GEO-SLOPE Intl. Ltd, Calgary, Alberta, Canada
7. Godt JW, Baum RL, Chleborad AF (2006) Rainfall characteristics for shallow land sliding in Seattle, Washington, USA. Earth Surf Process Landf 31:97–110
8. Guzzetti F, Peruccacci S, Rossi M, Stark CP (2007) Rainfall thresholds for the initiation of landslides in central and southern Europe. Meteor Atmos Phys 98:239–268
9. Haigh MJ, Rawat JS, Bartarya SK (1989) Environmental indicators of landslide activity along the Kilbury road Nainital, Kumaun Lesser Himalaya. Mt Res Dev 9:25–33
10. Himachal Pradesh State Disaster Management Authority-HPSDMA (2012) Activity Report (2007–2011). Government of Himachal Pradesh, Department of Revenue (Disaster Management Cell). www. hpsdma.nic.in
11. Hoek E, Bray JW (1981) Rock slope engineering, 3rd edn. Institute of Mining and Metallurgy, London
12. IMD (2012) Monsoon 2012: a report. IMD MET monograph no. 13/2013, Pai DS, Bhan SC (eds) National Climate Centre, Indian Meteorological Department, Government of India, Pune, India
13. Iverson RM (2000) Landslide triggering by rain infiltration. Water Resource Res 36(7):1897–1910
14. Khaladkar, R. M., Mahajan, P. N., & Kulkarni, J. R. (n.d.). Alarming Rise in the Number and Intensity of Extreme Point Rainfall Events over the Indian Region under Climate Change Scenario Indian Institute of Tropical Meteorology.
15. Kuriakose SL, Sankar G, Muraleedharan C (2009) History of landslide susceptibility and a chorology of landslide-prone areas in the Western Ghats of Kerala, India. Environ Geol 57(7):1553–1568
16. Li T (1990) Landslide management in the mountain area of China, ICIMOD Kathmandu. Occasion Paper no. 15, p 50
17. Malet JP, Asch TWJV, Beek RV, Maquaire O (2005) Forecasting the behaviour of complex landslides with a spatially distributed hydrological model. Nat Hazards Earth Syst Sci 5(1):71–85
18. Picarelli L, Abolmasov B (2014) Introduction: recognition and mechanics of landslides. In: Sassa K et al. (eds) Landslide science for a safer geo-environment, vol 1. Springer, Switzerland, pp 295–296
19. RDSO (2003) Guidelines for Earthwork in Railway Projects. Guidelines no. GE: G-1, Ministry of Railways, Govt. of India, Geotechnical Engineering Directorate, Research Designs and Standards Organization, Lucknow, India
20. Sathe, S. S., & Mahanta, C. (2019). Groundwater flow and arsenic contamination transport modelling for a multi aquifer terrain: Assessment and mitigation strategies. Journal of Environmental Management, 231, 166–181.
21. Raj, M., & Sengupta, A. (2014). Rain-triggered slope failure of the railway embankment at Malda, 789–798. https://doi.org/10.1007/s11440-014-0345-9
22. Shah, C. R., Sathe, S. S., Bhagawati, P. B., & Mohite, S. S. (2019). A hillslope failure analysis: A case study of Malingoan village, Maharashtra, India. Geology, Ecology, and Landscapes, 00(00), 1–6. https://doi.org/10.1080/24749508.2019.1695714

23. Singh, A. K., Kundu, J., & Sarkar, K. (2018). Stability analysis of a recurring soil slope failure along NH-5, Himachal Himalaya, India. Natural Hazards, 90(2), 863–885. https://doi.org/10.1007/s11069-017-3076-z