Landslide Disaster Risk Reduction Through Slope Stabilization: A Case Study of eThekwini, KwaZulu Natal, South Africa

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Abstract. Landslides are a severe geological hazard which mainly occur when the forces which cause downward earth movement of a slope exceed the strength of the constituent materials. The main causes of landslides can be broadly categorized as hydrogeological, morphological and physical. The triggering mechanisms include human activities and natural causes such as excessive rainfall or snowfall, volcanic activity and seismic actions. In April 2022, a subtropical depression along the coastal region of eThekwini, KwaZulu Natal, South Africa caused intense precipitation averaging 200–450 mm over a five-day period. The cyclone impact resulted in the deadliest and most catastrophic landslides in recent times and unprecedented infrastructural damage.

The mass earth movements and associated deposits caused significant geomorphic alterations. In the aftermath of landslides, disaster risk reduction approaches are vital in minimizing the impact and for preventing further mass movements. In order to rehabilitate the failed slopes, this study investigated the geometries, geotechnical and morphological characteristics of the residual slopes. A susceptibility model of the zone was developed to classify the risk of sliding and an earth support system was designed to stabilize the slope. The computations demonstrated that landslide disaster risk reduction can be achieved through measures which predict and mitigate the likelihood of slope failure in geohazard areas.

Keywords: landslide · slope stability analysis · disaster risk reduction · safety factor · ground anchors

1 Introduction

The term 'landslide' is often loosely used to define any form of mass movement of rocks, ice and/or soils. Different authors have proposed classification systems which distinguish the mass movement according to the type of deformation and material [2, 6]. One of the latest landslide classifications developed by Hungr et al. [3], recognizes that there are six types of earth movements, namely; fall, flow, slide, slope deformation, spread and topple. A landslide can therefore be a complex phenomenon involving one or several of these movements or transitioning from one type of movement to another over

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time. The common factor in the different forms of landslides is that they occur when the shear stress exceeds the shear strength of the constituent materials in a slope. This condition of shear failure is attained when there is either an increase in destabilizing forces or a reduction of resisting forces or both.

Shear stresses on a slope can be increased by human activities which impose loads such as construction, agriculture and vibrations from blasting, machinery or mining. Other contributing factors entail disturbing previous landslides, poorly planned or inadequate drainage systems, wildfires and deforestation. Natural factors which upsurge destabilizing forces include volcanic eruptions and dynamic loads from earthquakes. Morphological factors which increase landslide propensity comprise hilly or mountainous terrain, coastal cliffs and unstable geologic conditions. The regional geology of eThekwini coupled with the tropical cyclone have been identified as the main causes of the multiple landslides which occurred in 2022. Table 1 presents the summary of landslide classifications after [3].

Table 1. Landslide classification

Movement type	Description	Mode of failure	
		Rock	**Soil**
Fall	Movement of isolated blocks or chunks of soil by gravity	Rock/ Ice fall	Boulder/ Debris/ Fine Soil fall
Flow	Movement of liquified material such as mud flows, can be slow (several years) or rapid	Rock/ Ice avalanche	Debris/ Mud/ Earth/ Peat flow/ Debris Avalanche
Slide	Deformation due to shear failure, the sliding mass generally remains intact. Movement may be parallel to the surface (planar) or rotational	Rotational/ Planar/ Wedge/ Compound/ Irregular	Rotational/ Planar/ Compound
Slope deformation	Slow catastrophic movements that involve the entire slope or sizeable sections	Mountain/ Rock slope deformation	Creep/ Solifluction/ slope deformation
Spread	Subsidence due to cracks developing and expanding laterally	Slope spread	Liquefaction
Topple	Rotation of blocks from a vertical face	Block/ Flexural	Coarse and fine soils topple

1.1 Landslide Geological Risks of eThekwini

eThekwini is a coastal metropolitan with a population of approximately 4 million people comprising of Durban city and its neighboring towns. The landscape predominantly consists of hills and mountains, steep slopes and 18 major river systems, with the Indian Ocean adjacent to the city. The geology of eThekwini consists of three major groups which heighten its landslide risk; the Berea, Natal and Pietermaritzburg formations [1]. The Berea formation are mainly non-plastic red sand, subordinate white or yellow sand and basal conglomerate. Due to the little to no fines content, they are highly erodible and form gullies when subjected to incessant groundwater. The deep gullies which were formed in different parts of the region causing immense infrastructural damage ensuing the rainfall and flooding, indicated deep seated erosion.

The Natal formation consists of sandstones with a high liquefaction potential; a process whereby the soil undergoes sudden loss of strength in response to changes in stress conditions. It is envisaged that the uncontrolled flooding liquified the sandstones which consequentially triggered the landslides. The Pietermaritzburg group is characterized by thin layers of dark-grey carbonaceous shale and siltstone. These shales have a low hydraulic conductivity due to the high clay content and consequently take long to consolidate when saturated. Under undrained conditions, they lose their cohesiveness forming a slippery surface which culminates in landslides.

The 2022 landslides were the deadliest in South Africa, with a death-toll of 459 and displacing more than 40 000 people. Subsequently, rehabilitation techniques were required to remediate the widespread damage. The rehabilitation of areas that have been altered by landslides is an intricate process which often requires disaster risk reduction (DRR) approaches [7]. DRR procedures encompass identifying the landslide triggers, analyzing the stability of the residual slopes and implementation of landslide mitigation measures for unstable slopes. This study presents the DRR measures which were undertaken on one of the road embankments which represented similar failures that were caused by the landslides across eThekwini. Figure 1 presents the landslide damage at Umdloti beach which was one of the worst affected areas.

Fig. 1. 2022 eThekwini landslides – Umdloti beach [4].

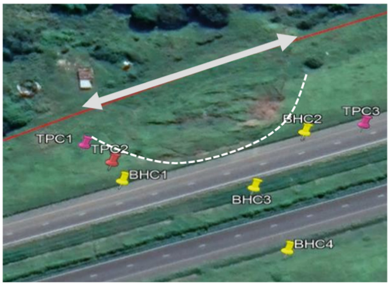

Fig. 2. Case study embankment a) Translational flow slide b) Borehole and tests pit positions

2 Geotechnical Investigation

A translational flow slide developed on a 11 m high embankment of a highway which is adjacent to the Ngane River near Umkomaas. The failure surface of the embankment was approximately 3 m deep and 60 m long. The shape of the failure surface suggested that there was a firm underlying layer necessitating the depth to bedrock to be determined. The investigation comprised of core drilling 4 No. boreholes, test pits and geophysical surveys as shown in Fig. 2.

Longitudinal tension cracks were observed on the road shoulder which when filled with water increase excess pore pressures and reduce shear resistance. There was also water discharge from a damaged subsurface stormwater drainage pipe onto the fill material and this might have exacerbated the slope failure. From the soil profile, it was determined that the geology mainly comprised of 3 layers; silty sandy gravel fill up to an average depth of 5.5 m which was underlain by 1.8–3 m of Berea sand and gravel followed by a 12 m bottom layer of residual Pietermaritzburg shales. The location of this specific site on the contact zone between Berea sands and Pietermaritzburg shales could have also been a liquefaction trigger. In addition, the shales tend to have unfavorable dip angles (dip slopes) which are unstable.

3 Slope Stability Analysis

After identifying the possible failure causes, the second stage of the DRR procedure was to assess the stability of the residual slopes. The slope stability analysis was undertaken using RocScience Slide 2 software as shown in Fig. 3. Three limit equilibrium methods of analysis were considered: Bishop, Janbu and Morgenstern. The analysis showed that for internal stability, the residual slope was highly unstable with Janbu yielding a minimum factor of safety (FS) of 0.41. It was also observed that the failure plane was located between the Berea sands and Pietermaritzburg shales which concurred with the geotechnical investigation. For the global stability, the FS was 0.75. Hence, both cases yielded a FS less than (1) signifying unstable conditions. SAICE [5] stipulates that the minimum permissible FS for highway embankments is 1.5. Therefore, there was need for slope stabilization to protect the road and pavement from further collapse.

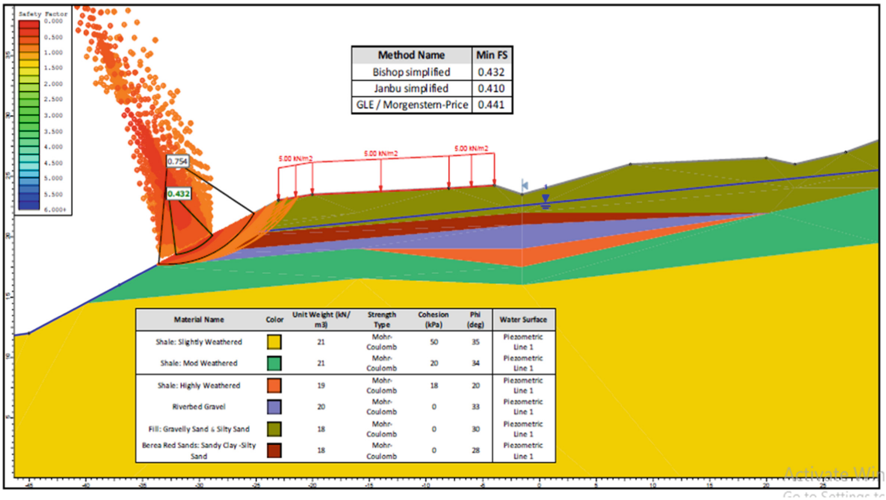

Fig. 3. Slope stability analysis of residual slope

4 Slope Stabilization

The final DRR stage was aimed at slope stabilization. Several factors were considered in determining the suitable stabilization system which included appropriateness for the site-specific geologic conditions, ease of installation, long-term performance and cost. Governed by these factors, it was determined that the slope would be stabilized using self-drilling grouted ground anchors with the following specifications:

1. The full depth of excavation of 7 m was to be undertaken in stages not exceeding 1.75 m.
2. An initial temporary lateral earth support system of self-drilling anchors with shotcrete facing. The 38 mm diameter and 12 m long ground anchors were to be installed in an inclined position of −15° to the horizontal, spaced at 1.5 m horizontally and vertically.
3. Removal of saturated fill and backfilling with imported granular G7 material compacted to 93% maximum dry density in layers not exceeding 300 m.
4. Installation of vertical wick drains between the soil and shotcrete to prevent porewater pressure build-up behind the wall and horizontal drains to intercept ground water between Berea sands and Pietermaritzburg shales.
5. Permanent 150 mm grade 25 MPa shotcrete facing reinforced with welded steel mesh.

Figure 4 presents the ground anchor stabilized slope. It can be observed that the lateral earth support system increased the stability of the slope by approximately 4 times from 0.41 to 1.56. This implied that the embankment had been adequately stabilized and the DRR objectives had been achieved.

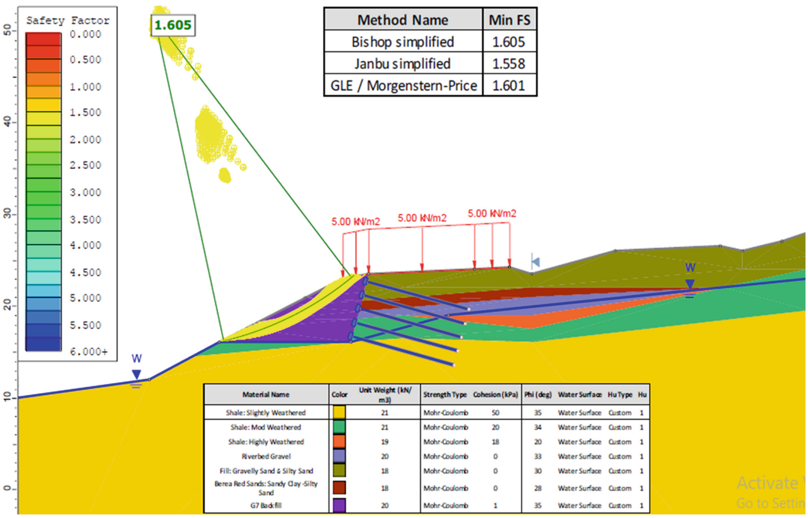

Fig. 4. Ground anchor stabilized slope

5 Conclusion

The coastal region of eThekwini, South Africa has a long-standing history of landslide occurrences. Its geology which predominantly comprises of highly erodible sands, low permeability clays and liquifiable sandstones increases landslide propensity. The tropical cyclone which inundated the region in 2022 led to extensive earth movements which severely altered the landscapes. In this study, a DRR approach was undertaken to mitigate the consequential impacts of a highway embankment where a translational slide had occurred. After identifying the site-specific triggers, the stability of the residual slope was analyzed. The analysis revealed that the embankment was in a high-risk state with low FS values of 0.41 and 0.75 for the internal and global stability respectively which indicated imminent failure. To prevent further mass movement the embankment was reinforced with 38 mm ground anchors spaced at 1.5 m. The stability analysis revealed that the reinforced slope was sufficiently stabilized with a FS of 1.56. Due to climatic changes which are characterized by intensified rainfall events, the frequency of landslide occurrences is likely to increase. Based on the findings of this study, DRR is a key procedure which can be used to attenuate the impacts of landslides particularly in high-risk areas.

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