

# Evaluation of Factors Influencing Slope Instability: Case Study of the R523 Road Between Thathe Vondo and Khalvha Area in South Africa



F. Sengani and T. Zvarivadza

## 1 Introduction

There are two types of slopes that can be found on the earth's surface, namely natural slopes and artificial or engineered slopes (Abramson and Thomas 2002). Natural slopes are formed usually over a long period of time, through many geological and geomorphological processes such as mountain building, glacial activities, tidal and river activity (Abramson and Thomas 2002). These slopes are stable if the soil has sufficient strength to resist the gravitational forces on the potentially sliding mass. Change in pore water pressure condition, slope geometry or engineering works may cause the natural slope to fail (Wills et al. 2008). Engineered or artificial slopes may be considered in three main categories: embankments, cut-slope, retaining walls and waste tips (Abramson and Thomas 2002).

### 1.1 Fundamentals of Slope Failure

Debris flow, slumps, mudflows and rock-falls are simply various names given for slope failures. Slope failure is the downslope movement of soil or rock material under the influence of gravity without the direct aid of other media such as water, air or ice (Skinner and Porter 1987). Water and ice, however, are frequently involved in slope failure by reducing the strength of rock and soil and by contributing to plastic and fluid behaviour of soils. Slope failure is a common phenomenon in all high and steep slopes. It can also occur at a very low angle.

---

F. Sengani (✉) · T. Zvarivadza  
School of Mining Engineering, The University of the Witwatersrand,  
Johannesburg, South Africa  
e-mail: [fhaturgeorge@gmail.com](mailto:fhaturgeorge@gmail.com)

The force of gravity plays a very crucial role in causing slope failure. When the gravitational force acting on a slope exceeds its resisting force, slope failure occurs (Monroe 1994). The resisting forces helping to maintain slope stability include the slope materials strength and cohesion, the amount of internal friction between the grains and any external support of the slope. These factors collectively define a slope's shear strength. Opposing a slope's shear strength is the force of gravity. Gravity operates vertically, but has component acting parallel to the slope, thereby causing instability. The greater the slope's angle, the greater the component of force acting parallel to the slope, and the greater the chance of slope failure to occur (Skinner and Porter 1987). The steepest angle that the slopes can maintain without collapsing is called the angle of repose. At this angle, the shear strength of the slope's material exactly counterbalances the force of gravity. For unconsolidated material, the angle of repose normally ranges from 25° to 40°. Slopes steeper than 40° must be consist of un-weathered solid rock or highly consolidated soil.

## 1.2 Types of Slope Movement and Instability

There are many types of slope movements, and sometimes they act alone, and sometimes they are combined. The importance of understanding the type of movement is twofold. First, it provides clues to what might be causing the movements, and second, it provides an understanding of the mechanism necessary to design/construct mitigation measures (Skinner and Porter 1987). There are many criteria available for distinguishing types of slope failure: they include velocity and mechanism of movement, character of the rock and soils, and type of slope failures, the shape of the moving mass and water content of the material (Skinner and Porter 1987). Table 1 shows the classification of slope failure.

**Table 1** Classification of slope failure (Monroe 1994)

Types of movement		Subdivision/material	Rate of movement
Falls		Rock-falls	Extremely rapid
Slides	Rotational	Slump	Extremely slow to moderate
	Translational	Rockslide	Rapid to very rapid
Flows		Mudflow	Very rapid
		Debris flow	Rapid to very rapid
		Earthflow	Slow to moderate
		Quick clay	Rapid to very rapid
		Solifluction	Slow
		Creep	Extremely slow
Complex movement			Slow to extremely rapid

## **2 Research Approach**

A field investigation was conducted to identify the unstable slopes, types of slope failure, type of material forming the slope and factors that contribute to slope instability of the cut-slope in the study area. Field slope stability assessment, geological mapping and soil sampling were conducted. The laboratory work was conducted towards an understanding of material behaviour, to determine the type of soil forming the cut-slope and how the soil will perform under the imposed conditions such as the presence of water, the rate of rainfall and direction of surface runoff. All these factors affect the behaviour of soils. Analysis of site samples with respect to how conditions would change over time provided an understanding of the existing and future conditions. Understanding of the behaviour of material was imperative for assessment of the stability of the cut-slope.

## **3 Results**

Various factors impacting the road construction along the study area were investigated; a summary of seven case studies is presented in this paper. In addition, the results of the study of soil properties are presented, followed by identification of slope stability and hazardous zones along Road R523.

### ***3.1 Road Construction***

Based on the observation and historical information concerning the geographical features of the study areas, it was noted that the road construction in the study areas has resulted in a wide variety of environmental impacts along the road R523. It had altered the surface drainage patterns and increased runoff generation. The improper road construction in the study area causes the concentration of water at the foot of a cut-slope, and this provides additional weight to the slope which in turn increases the driving force which causes slope failure. The alteration of surface drainage patterns results in the increase of speed of surface runoff and therefore a high probability of water washing soil down to the road, blocking the surface drainage ditch. As a result, the foot of the slope became waterlogged. When the soil is over-saturated with water, slope failure occurs.

The observed significant geomorphic impacts of road construction along the road R523 include the destabilization of side-cast material downslope, also making the slope steeper than before. Thus, the road construction has resulted in undercutting of natural slopes that were at the angle of repose, creating new steeper cut-slopes that are unstable and susceptible to failure. When the slope steepness is

increased, the shear stresses in the soil within the slope also increases and reduces stability, resulting in slope failure (Abramson and Thomas 2002).

### 3.2 Case Study of a Slope Failure Area

During field observation, the evidence of a previous slope failure was noticed (see Fig. 1) in the study area where slope failures are not active. There were also mitigation measures implemented after slope failure occurred. In this case, the gabion wall to prevent future slope instability was built. The gabion wall was noted to be effective where two-tiered steps were employed. It was found to be ineffective where less than two-tiered walls were employed. The ineffectiveness of the gabion was noted by through a slope failure that had been reactivated. As a result, the failure of the gabion was noted to have led to the road interruption due to soil slides which blocked the road.

Furthermore, analysis of factors that contributed to the slope failure along the study areas has indicated that water pressure also plays a major role in the weight of the soil. The previous study by Duncan and Wright (2005) has shown that water that fills the cracks developed on the surface of the slope has high possibility to decrease the shear strength of the soil as pore pressure in the slope increases.



**Fig. 1** Slope failure at R523 road

Based on the observation, in most of the areas where slope failure was more pronounced, several cracks were noted and a number of short streams were also noted. It was believed that the slope failure in the study areas was highly influenced by the presence of a large quantity of water flowing around the areas. It was also observed that most of the slope failure took place during the rainy season.

### 3.3 Soil Physical Properties

#### 3.3.1 Particle Size and Size Distribution

Based on the laboratory analysis, the soil particle size distribution of the study areas was found to be significantly richer in silt and clay contents (see Table 1). The clay content of the soil varied between 27.89 and 40.95%, silt content between 40.03 and 51.96%, whereas sand content ranged from 13.94 to 26.97%. Furthermore, analysis has shown that the soil texture of the study area can be classified as a silty clay (S1), silty clay loam (S2) and clay loam (S3, S4, S5 and S6). The soil was classified using the US Department of Agriculture System (USDA) classification system. Due to the above-mentioned characteristic of the soil in the study area, it was then concluded that the area is therefore prone to land-sliding. This is because when clay soil is over-saturated due to heavy rain, the soil is usually subjected to swelling and this ultimately results in land-sliding phenomenon. Furthermore, when these soils get dried, it is mostly subjected to shrinkage which will result in a change in the volume of the soil mass; thus, the soil fragments of varied dimensions will be subjected to movement (Table 2).

#### 3.3.2 Atterberg Limits

The Atterberg limits are a set of index tests performed on fine-grained soils to determine the relative activity of the soils and their relationship to moisture content

**Table 2** Physical properties of soil within the study

Site no.	Sample no.	Particle size distribution			Atterberg limits		
		Sand % (>63 $\mu\text{m}$ )	Silt % (63–2 $\mu\text{m}$ )	Clay % (<2 $\mu\text{m}$ )	LL	PL	PI
1	Sp.1	13.94	44.94	40.95	39.74	30.76	8.98
2	Sp.2	15.92	51.96	33.86	38.32	29.44	8.88
3	Sp.3	25.74	45.98	27.89	52.39	42.42	9.97
4	Sp.4	24.02	43.89	32.01	56.36	37.82	18.54
5	Sp.5	30.01	40.03	29.98	54.15	43.19	9.58
6	Sp.6	26.97	41.87	30.93	53.39	37.58	15.81

(Wills et al. 2008). The laboratory results of measured liquid limit (LL), plastic limit (PL) and plastic index (PI) of studied soil samples were variable. The LL found ranged from 38.2 to 56.38%, PL from 29.44 to 44.56% and PI ranged from 8.88 to 12.6. The plastic limit is the division between a semi-solid and plastic state for the soil material. Therefore, the plastic limit of 44.56% was found to be the highest water content at which the soil begins to behave in a plastic manner. The liquid limit is the division between plastic and liquid state for the soil material. Therefore, a liquid limit of 38.2% was found to be the lowest moisture content at which the soil will flow at very low shear forces.

Based on the results, it was noted that if the water content of the soil in the study area was reduced below the plastic limit of 44.56%, the soil behaved as a semi-solid material, thus increasing the resisting force on the soil, and therefore soil failure was not going to occur. If the water content of soil slope's surface increases above the liquid limit, which is likely to occur in the summer season, in this case, the soil turns to behave as a viscous fluid. As a result, such soil has a high possibility of experiencing failure.

### 3.4 Slope Stability and Hazardous Zones Along Road R523

One of the guiding principles of slope stability assessment stated that 'the past is the key to the future'. When evaluating landslide hazards future slope failures could occur as a result of the same geologic or geotechnical, geomorphic and hydrologic situations that led to past and present failures (Hadjin 2002).

Based on this assumption, a quantitative classification system was used to determine and identify stable and hazard zones in the study area. This system was based on the consideration of five main factors that are believed to substantially affect the stability of slopes. The slope stability assessment was performed on seven

**Table 3** Results of slope stability assessment (input data)

Site no.	Parameters				
	Geologic formation	Slope aspect	Precipitation (Avg. Ann) (mm)	Land-use	Height (m)
1	Silty clay	South-east	120.64	Bush	6.70
2	Silty clay loam	North-east	120.64	Less-dense bushland	8.20
3	Clay loam	South	120.64	Woodland	27.90
4	Clay loam	North	120.64	Woodland	34.5
5	Clay loam	South	120.64	Woodland	17
6	Clay loam	South-east	120.64	Woodland	15.60
7	Sandstone	North-east	120.64	Less-dense bushland	36.50

**Table 4** Results of total rate state of stability

Site no.	Position		Factors					
	Latitude	Longitude	Geologic formation	Slope aspect	Precipitation (Avg. Ann) (mm)	Land-use	Height (m)	Total score
1	22° 56' 48"	30° 21' 19.8"	5	15	10	15	16	61
2	22° 55' 59.6"	30° 20' 34.2"	5	15	10	15	16	61
3	22° 55' 58.2"	30° 20' 27.7"	5	10	10	10	4	39
4	22° 55' 56.1"	30° 20' 23.7"	5	8	10	10	4	37
5	22° 55' 41.4"	30° 20' 9.5"	5	10	10	10	13	48
6	22° 55' 42.7"	30° 19' 38.9"	5	15	10	10	13	53
7	22° 55' 37.1"	30° 17' 58.3"	15	15	10	15	4	59

cut-slopes along the road R523, and the results are summarized in Tables 3 and 4. The overall slope stability was obtained by summing the rates of all contributing parameters, these results are shown in Table 4, and five classes of stability and hazard can be found in Table 3.

Based on the qualitative classification system results, slopes at site no. 3, 4, 5 and 6 were classified as unstable slopes which made the most hazardous section along the road R523 and these slopes need to be stabilized to improve their stability. It was noticed that the slopes at these sections had a high probability of experiencing failure. This was evident due to that almost all slope failure in the study area was occurring in the area of previous slope failure.

The slopes at site no. 1, 2 and 7 were classified as fairly stable slope after summing all five factors believed to affect their stability. These slopes also fall within the class of slope with moderate hazard, based on Table 3. The stability of these slopes needed some improvements as to prevent the possibility of future slope failure. The slope at site no. 7 was totally different from other slope due to being entirely composed of fractured sandstone while others slopes are composed of soil.

## 4 Conclusions

It was concluded that based on the recorded data and field observation, the slope failure was prone to occur during heavy rainfall. It was noted that the rainfall turns to trigger slope failure due to the increase in water pressure within the soil pores. Furthermore, analysis has shown that the slope failures identified in the field were rotational slump failures, and they occurred close to the road. It was then concluded that the natural slopes were disturbed during road construction since the natural drainage pattern was altered. This contributed to slope failure. During this study, four factors, namely degrading of slope material, water pressure in the cracks on the surface of the slope, road construction and heavy rainfall, were identified as main factors that affected the stability of cut-slope in the study area. Moreover, the laboratory studies have shown that the study areas consist of most clay soil, which is commonly known for the high possibility of sliding and shrinkage characteristic. It was then concluded that the soil properties of the study area also played a major role in the failure of the slopes.

## References

- Abramson, L.W., Thomas, S.L.: Slope Stability and Stabilization Methods, 2nd edn, pp. 1–48. Wiley, New York (2002)
- Duncan J.M., Wright, S.G.: Soil Strength and Slope Stability. Wiley, New Jersey (2005)
- Hadjin, D.J.: New York State Department of Transportation Rock Slope Rating Procedure and Rock-fall Assessment, Transportation Research Record, 1786, Paper number 02-3978 (2002)



- Monroe, J.S.: *The Changing Earth: Exploring Geology and Evolution*, pp. 269–289. West Publishing Company, New York (1994)
- Skinner, B.J., Porter, S.C.: *Physical Geology*, pp. 205–237. Wiley, New York (1987)
- Wills, C.J., Manson, K.D., Brown, C.W., Daveport and Domrose, C.J.: Special report, Landslides in the highway 1 corridor: geology and slope stability along the big sur coast between point lobos and san carposoro creek, monterey and san luis Obispo counties, California, Department of conservation, California geological survey (2008)