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ORIGINAL ARTICLE

Cut soil slope stability analysis along National Highway at Wozeka–Gidole Road, Ethiopia

Kedir Mohammed Bushira[1] · Yoseph Birru Gebregiorgis[2] · Ramish Kumar Verma[2] · Zhuping Sheng[3]

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Abstract
The Wozeka–Gidole road in Ethiopia experiences frequent slope failure and triggered during road construction. This study identified the actually failed slope to verify numerical results of both limit equilibrium method (LEM) and finite element method (FEM) with the actually failed slope. Modeling of the actually failed slope with the FEM-based PLAXIS software and LEM-based SLOPE/W software had been used to calculate the factor of safety (FOS). The comparative study of the LE methods shows that The Bishop, Janbu, Morgenstern-Price, GLE and Spencer methods yield in most cases identical FOS for circular slip surface. However, the ordinary method may underestimate the FOS. All LE methods, except the Ordinary methods, estimate higher FOS than FE analysis in PLAXIS. Numerical results of both FEM and LEM verify instability of the slope. In general, the model provides the possible major causes of slope instability and their possible remedial measures in the study area.

Keywords Wozeka–Gidole Road · Slope-stability analysis · Factor of safety · LEM · FEM · PLAXIS · SLOPE/W

Introduction

Slope instability has been identified as one of the most frequent natural disasters that can lead to enormous monetary loss and human life in danger. It is a geodynamic process that destroys the existing earth surface geomorphology. Generally, a slope failure initiates from one or more combination of factors like slope geometry, slope material strength, geohydrological condition, structural discontinuity, weathering, development of weak zones, lithological disturbance and heavy rainfall (Singh and Singh 1992). Soil slope failure is one of the most significant geological hazards along highway cut slopes but relatively fewer studies have been carried out to investigate these critical zones. Landslides are the result of two interacting sets of forces; the precondition factors, naturally induced which govern the stability conditions of slopes, and the preparatory and triggering factors, induced either by natural factors or by human intervention (Mandal and Mandal 2016). A single landslide event can cause enormous detrimental effects on the social, economic and environmental aspects of any country and its population especially for developing countries where early warning systems and mitigation measures are minimal. Countries along the equatorial and temporal regions are more vulnerable (Michael and Samanta 2016). Assessment and safety of road cut soil slopes along national highway is an important and challenging aspect for geotechnical engineers. In recent years, it has been seen an increasing number of projects in which slope remediation was the main solution to stabilize highway embankments and failing earth masses. However, due to the high cost associated with such projects, better engineering analysis tools should be used. Slope stability methods vary in their theoretical background and approach and hence the analysis results vary depending on the theory

✉ Kedir Mohammed Bushira
kedir.mohammed@uabc.edu.mx

Yoseph Birru Gebregiorgis
yosbirru@gmail.com

Ramish Kumar Verma
rkverma42@gmail.com

Zhuping Sheng
zsheng@ag.tamu.edu

1 Universidad Autonoma de Baja California, Mexicali 21280, Baja California, Mexico

2 Department of Civil Engineering, Arbaminch Institute of Technology, Arba Minch University, P.O. Box 21, Arba Minch, Ethiopia

3 Texas A&M AgriLife Research Center, 1380 A&M Circle, El Paso, TX 79927, USA

used. In addition, simplified assumptions in 2D slope stability methods have led to factors of safety that differ from the more rigorous 3D slope stability analysis methods. In practice, 3D analysis of slope stability is not performed unless the geometry and material properties of the slope are very complicated or the failure mechanism is complex.

At the present time, no single analysis method is preferred over the other by agencies and therefore, the reliability of any remedial solution to any slope failure is completely left to the engineer in charge. Most practitioners prefer one method over the other based on their familiarity with the method rather than on the conditions of the failing slope. As a result, the remediation methods are either under designed or overdesigned. In reality, the mechanism of the failing slope should be studied in detail by gathering enough field data and observations in order to choose the most appropriate analysis method (Duncan 1996).

Finite element method is a very powerful computational tool in engineering. It gains its power from the ability to simulate physical behaviors using computational tools without the need to simplify the problem. Indeed, complex engineering problems need finite element methods to obtain more reliable and accurate results. Nowadays, newly proposed analysis methods, in engineering, can be verified using finite element method as a benchmark (Duncan 1996; Stark et al. 2005).

Slope stability analysis using finite element uses a similar failure defined as the limit equilibrium method for the soil mass and does not need simplifying assumptions.

Limit equilibrium methods first define a proposed slip surface (SS) then the slip surface is examined to obtain the factor of safety, which is defined as the ratio between the available resisting moments and the driving moments along the surface. Many methods for slope stability analysis using finite elements have been proposed during the last two decades.

Among those methods, gravity increase method (Swan and Seo 1999) and strength reduction method (Matsui and San 1992) is considered the most widely used methods. In the gravity increase method, gravity forces are increased gradually until the slope fails (gf) then the factor of safety is defined as the ratio between the gravitational acceleration at failure (gf) and the actual gravitational acceleration (g). In the strength reduction method, soil strength parameters are reduced until the slope becomes unstable, therefore, the factor of safety is defined as the ratio between the initial strength parameter and the critical strength parameter. Therefore, strength reduction method has exactly the same definition as the limit equilibrium methods (Griffiths and Lane 1999).

The gravity increase method is used to study the stability of embankments during construction since it gives more reliable results while the strength reduction method is used to study the stability of existing slopes (Albataineh 2006).

In order to compare results of limit equilibrium methods with finite element analysis results, strength reduction method was selected in this study since it resembles the limit equilibrium approach more than the gravity increase method.

In finite element slope stability analysis, the use of the strength reduction method with advanced soil models leads to a behavior similar to the Mohr–Coulomb model since stress-dependent stiffness behavior and hardening effects are excluded. In advanced constitutive soil models, stiffness modulus is stress-dependent and changes based on step-size computation increments. When strength reduction method is used stiffness modulus from the previous step is used as a constant stiffness modulus during computations, and as a result, the advanced soil model behaves like the Mohr–Coulomb model where a constant stiffness modulus is used, as well (Brinkgreve et al. 2013).

The Mohr–Coulomb model needs six parameters as input; Ø friction angle, C cohesion, Ψ dilation angle, E deformation modulus (Young's modulus), v Poisson's ratio, and γ unit weight. For slope stability analysis, $\Psi = 0$ was adopted assuming a non-associated flow rule, based on the results by Griffiths and Lane (1999). Young's modulus and Poisson's ratio are of insignificant importance in slope stability analysis using strength reduction method, due to the nature and mathematical formulation of the method (Matsui and San 1992).

Wozeka–Gidole road project passes through the western escarpment of the southern segment of the Ethiopian central rift. Construction practices on both sides of the rift escarpments show stability problems despite variations in magnitude. According to Ethiopians Road Authority (ERA) preliminary landslide investigation report, landslides are initiated during the road construction following the heavy precipitation received from October to December 2009.

The ultimate aim of this research is to verify numerical results of both limit equilibrium method (LEM) and finite element method (FEM) with the actually failed slope and to identify the cause of failure together with putting possible remedial measures.

In order to be able to model the cut slope, this research uses the FEM method based PLAXIS (Brinkgreve et al. 2013) and LEM based SLOPE/W (GEO-SLOPE International Ltd. 2012) software.

Description of the study area

Wozeka–Gidole road is extended between 5°33′33.88″N 37°24′58.21″E to 5°39′0.89″N 37°21′59.79″E, which connects the town Wozeka and Gidole (Fig. 1).

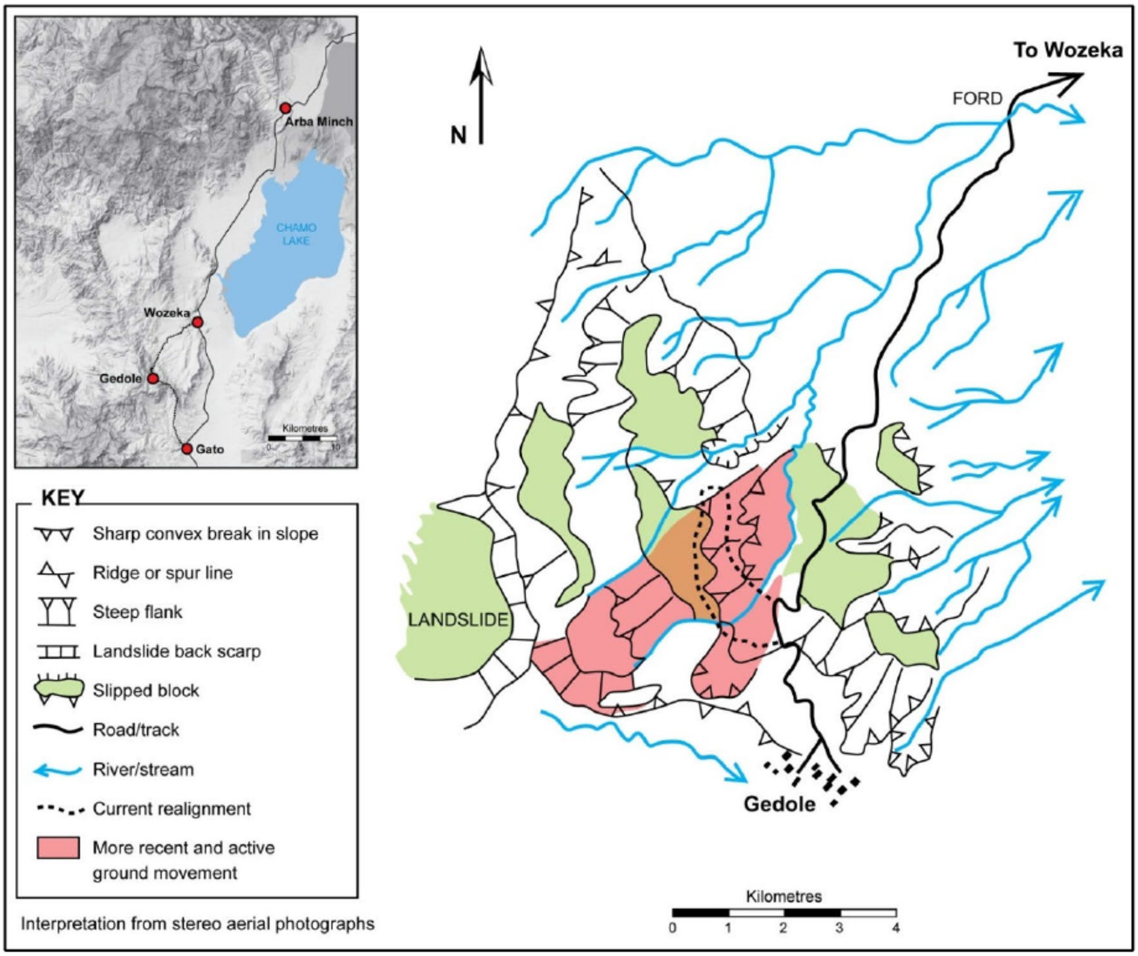

Fig. 1 Location map and Geomorphological Interpretation of the Wozeka–Gedole Area

The Wozeka–Gidole road is part of the Arbaminch–Jinka surface treatment road which is located on western escarpment of the central rift southern segment where the two of the rift valley lakes, namely Abaya and Chamo is found. According to the explanatory note to geological map of Ethiopia (1:2,000,000), the southern segment comprises the Abaya–Chamo rift, the Amaro horst, the Gelana-Garben and several other features. The Abaya–Chamo is filled with young lacustrine sediments and represents the youngest part of the Ethiopian Rift. Wozeka–Gidole road project crosses a sharply faulted escarpment of Gidole Mountain.

According to Ethiopian Road Authority (ERA) preliminary landslide investigation report on the Wozeka–Gidole road, colluvium derived from trachyte–rhyolite rocks are the dominant formations encountered along the routing stretch. Highly jointed and fractured dark basalt has formed the Gidole ridge which overlies the completely weathered trachyte–rhyolite. The cut sections portray layers of reddish brown clayey silty gravel between which is intercalated grayish to very dark grayish clay showing shale like structure. In addition to the intercalated continuous thin layers of grayish to very dark grayish clay (black cotton), there are pockets of black cotton soil within reddish brown clayey silty gravel layers. This may be due to the chemical as well as mechanical weathering of the basalt boulders embedded within those layers.

Regional geology

There is presently no large-scale geological map of the area and therefore a tentative geological interpretation has been made based on the 1:2,000,000 scale Geological Map of Ethiopia and satellite imagery (Fig. 2). The section of road where problems have occurred appears to be within the late Eocene Jimma Basalts stratigraphical unit (Pjb). These rocks were subjected to at least.

20 million years of humid tropical weathering prior to the commencement of rifting in the middle Miocene. Most of the lineaments identified in Fig. 2 are probably

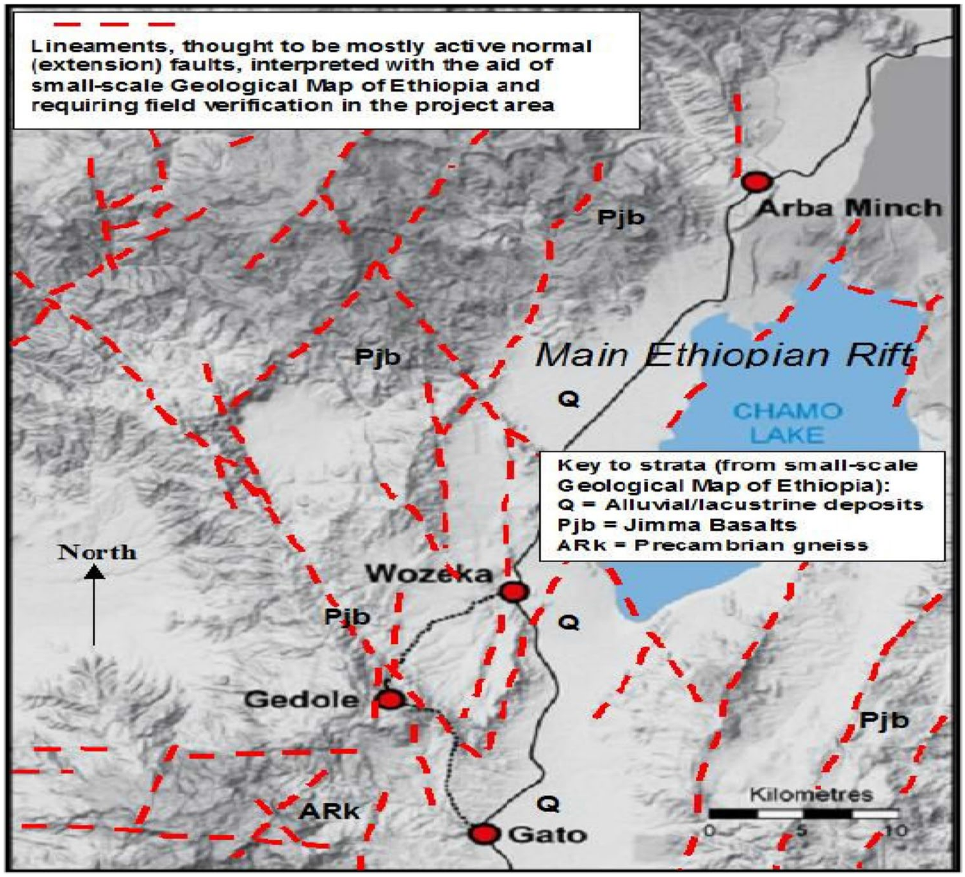

Fig. 2 Geology of the Arba Minch–Wozeka–Gedole Area. (Source: Ethiopian road authority change control design manual)

extensional faults that have been active within the last 10,000 years, i.e. during the Holocene. They generally trend either NNW–SSE, reflecting the orientation of the main Ethiopian rift (MER) and its border faults, or NNE–SSW, possibly guided by ancient fractures in the underlying Precambrian basement. There are also N–S and E–W lineaments representing a change in the tectonic regime at the southern end of the MER. Gedole is in the highest seismic risk area (zone 4) and five shallow (10 km) earthquakes of magnitude 4.1–5.2 have been recorded over the last 25 years.

Material and methodology

A detailed geological field investigation was carried out to measure the input parameters for the numerical simulation of road cut soil slopes. During the field observation of this specific site, it was found necessary to start by visual inspection of the whole stretch of Wozeka–Gidole road. During the initial visit, the whole portion of the road was covered and the failed cut slope sections were identified (Fig. 3) visually and selected for further detailed investigations. In the site, landslides was triggered by construction of the section of road between Wozeka and Gedole.

Fig. 3 Landslides triggered by construction of the section of road between Wozeka and Gedole

In general, the degree of landslide hazard decreases with increasing distance from drainage and settlements etc. (Shit et al. 2016).

Representative soil samples were collected from vulnerable soil slopes. All these collected soil samples were tested in the laboratory as per ASTM standards to determine the

Table 1 Field density of material by using core cutter method

Station (km)	Material description	Bulk density (gm/cc)	Water content (%)	Dry density (gm/cc)
11 + 820	Clayey silty gravel	1.65	25	1.32
11 + 820	Highly plastic clay	1.55	44	1.08

various properties viz. Atterberg limits, unit weight, cohesion, friction angle, tensile strength, Young's modulus, Poisson's ratio etc. An in-situ density measurement was conducted by core cutter methods in each test pit where samples have been recovered for laboratory tests. The determined soil properties and slope geometries were used as input parameters in numerical simulation.

The numerical simulation was performed by PLAXIS and SLOPE; based on a finite element method and (FEM) limit equilibrium method (LEM) respectively.

Results and discussions

The field studies were carried out to identify vulnerable soil slopes followed by in-situ tests to determine field density and a collection of representative samples for laboratory tests. The geo-engineering properties like Atterberg limits, unit weight, cohesion friction angle, tensile strength; Young's modulus and Poisson's ratio were calculated by laboratory tests to understand the behavior of geo-materials from the first two layers (Table 1). The slope with unique slope geometries was analyzed by numerical simulation methods viz. Limit equilibrium (LEM) and finite element method (FEM). The soil behavior and numerical analysis of slope are discussed below.

Identified soil properties

The soil classification was performed by using ASTM Standard Practice for Classification of Soils.

According to the Unified Soil Classification System, the soil in layer 1 (0–31 m) was grouped under highly plastic clay (CH) and the soil in the second portion (31–40 m) can be classified as clayey silty gravel (GC–GM). An in-situ density measurement was conducted by core cutter methods in each test pit where samples have been recovered for laboratory tests. The bulk density was computed upon completion of each test. The field dry densities were later computed based on the results of the natural moisture content determined in the laboratory (Table 1).

Soil classification according to plasticity index (ASTM D4318), indicates that soil at first layer of the slope face

Table 2 Basic and geotechnical properties of the slope forming geomaterials

Soil	Clayey-silty gravel	Highly-plastic clay
Plastic limit (%)	52.76	54.78
Liquid limit (%)	59.62	85.20
Plasticity index (%)	6.88	30.42
Unit weight (kN/m^3)	16.18	15.2
Cohesion (kPa)	18.34	15
Friction angle (kPa)	40.20	17.6
Young's modulus (kPa)	1×10^6	1×10^6
Poison's ratio	0.3	0.3

was highly plastic (PI > 17) and low plastic (PI < 7) at the second layer of the slope face.The Direct shear test and unconfined compression test for cohesive soils were performed to determine the strength and deformation properties (ASTM 3080) (Table 2).

Numerical results

Numerical results of LEM and FEM were compared using the calculated factor of safety (FOS). The comparison was made by analyzing modeling results from GEO-SLOPE 2007 (LEM based) and PLAXIS (FEM based) software.

Shear parameters obtained after saturation which was the worst-case scenario and shear parameters obtained by using field moisture content during sampling was used for comparisons. The sloping geometry used is shown in Fig. 4a, with the complete set of input parameters given in Tables 2 and 3.

PLAXIS and GEO-SLOPE modeling results (Tables 4, 5) show that the slope falls during the rainy season where the soil is in full saturated condition (worst case scenario).

The results of FOS also indicate that the slope is likely to fail with produced slip surface (Figs. 4, 5) even without reaching to the fully saturated condition. From the two results, it can be concluded that with the prevailing condition the cut slope is unstable which actually witnessed the site situation.

A comparison of modeling results shows that the factor of safety in 2D limit equilibrium was highly dependent on the analysis method. Bishop's method failed to satisfy horizontal force equilibrium and Janbu's method didn't satisfy moment equilibrium. The calculated FOS values differ by up to 13% upon comparison based on results presented in Table 5.

Possible remedial measures

Modeling results of PLAXIS and GEO-SLOPE software confirm the slope failure. On the basis of field observation and the results obtained, reducing the slope angle and

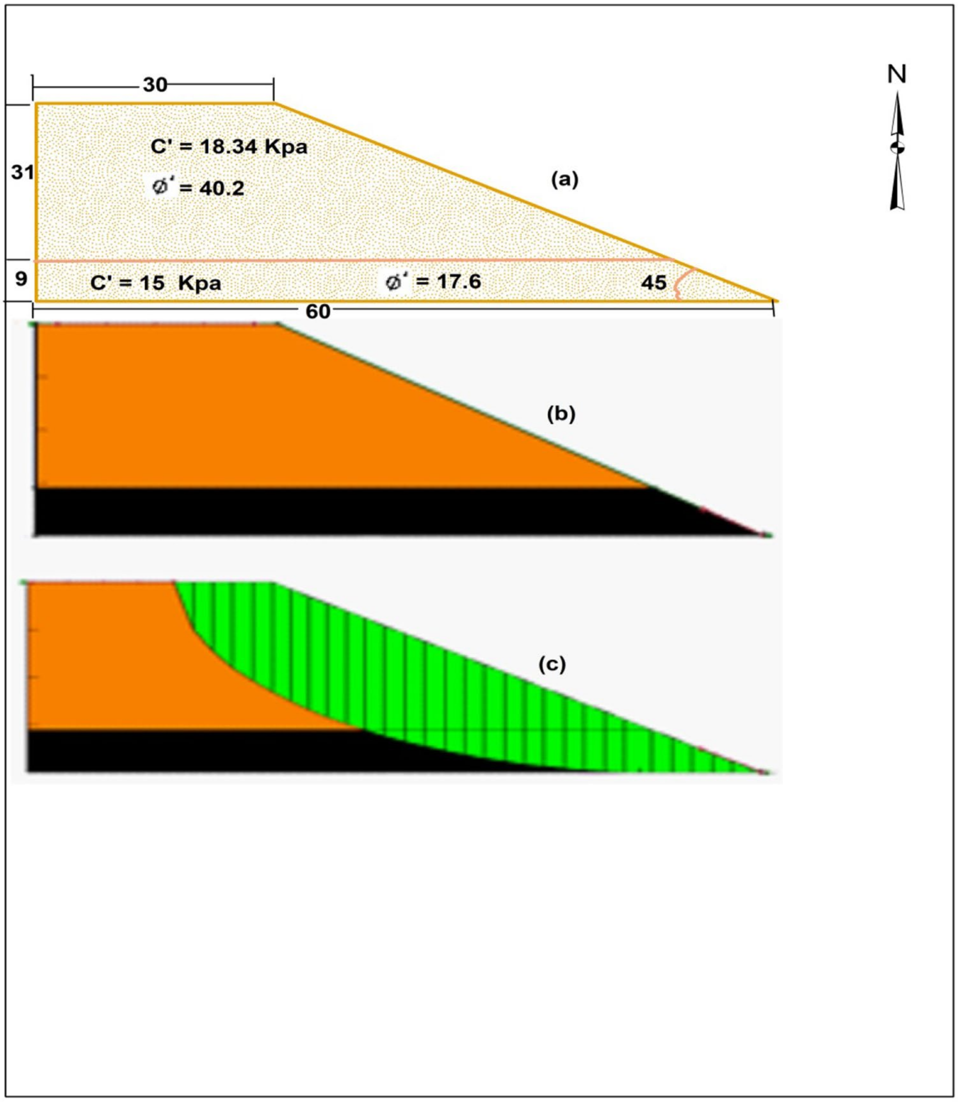

Fig. 4 **a** Geometry of the slope with slope height and angle and 2D GEO-SLOPE limit equilibrium result, **b** slope geometry, **c** slip surfaces

Table 3 Shear parameters used for calculation of factor of safety

Soil layer	C′, after saturation	Ø′, after saturation	C′	Ø′	γ	γsat
Clayey silty gravel	9.56	40	18.34	40.2	16.18	16.22
Highly plastic clay	6.03	16.5	15	17.6	15.21	16.80

Table 4 FOS obtained after PLAXIS program

Scenarios	FOS
Using shear parameters after full saturation	Fully collapse
Using shear parameters using field moisture cont	0.799

managing surface and groundwater conditions were identified and checked as stability remedial measures. Hence, the effect of reducing the slope angle and surface and groundwater conditions were incorporated in this model and found in the following section.

Table 5 FOS values after GEOSLOPE program

Limit equilibrium methods	Factor of safety
Using shear parameters obtained after full saturation	
Spencer	0.248
Bishop	0.233
Ordinary	0.104
Janbu	0.205
GLE	0.211
M-P	0.218/0.228
Using shear parameters obtained for a sample directly from the site	
Spencer	0.927
Bishop	0.941
Ordinary	0.690
Janbu	0.898
GLE	0.925
M-P	0.926/0.921

Flattening the slope (reducing the slope angle)

The steep slope has a tendency for downward movement of slope material by the gravitational acceleration and increases its sliding speed (Biswas et al. 2017).

The calculated factor of safety was interpreted using a standard that, typical minimum acceptable values of a factor of safety in the slope stability analysis are; 1.3 for the end of construction and multistage loading, 1.5 for normal long-term loading conditions and 1.0–1.2 for rapid drawdown (Duncan 1996).

The slope angle was changed from (1H: 1V) to (2H: 1V) and (2.5H: 1V), by keeping the height constant; A different slip surface was produced by both software's (Fig. 6). Comparisons of modeling results after reducing the slope angle shows that the cut slope is likely stabilized with 26.5° cut slope rather than 45°.

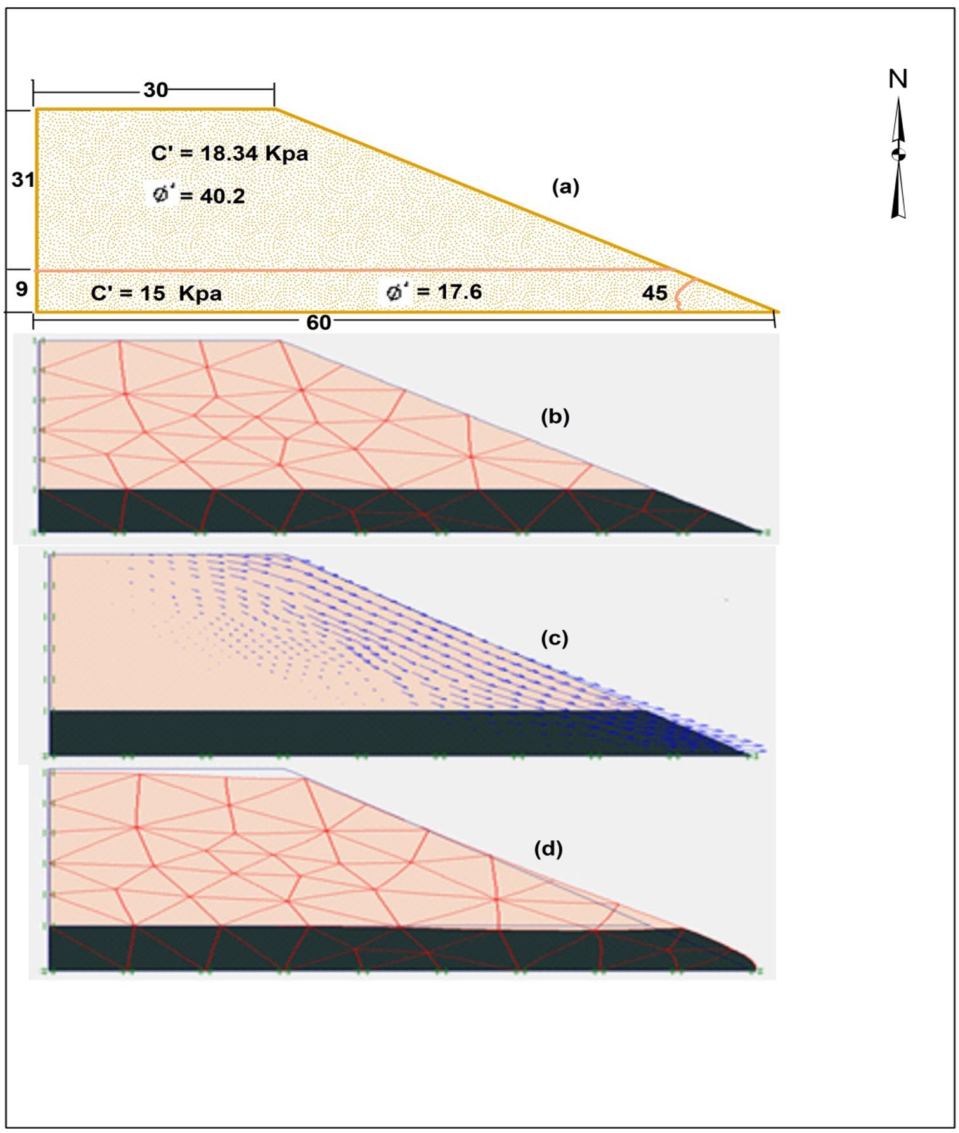

Fig. 5 **a** Geometry of the slope with slope height and angle 2D PLAXIS finite element result, **b** mesh generation for the slope, **c** total incremental displacement, **d** deformed mesh

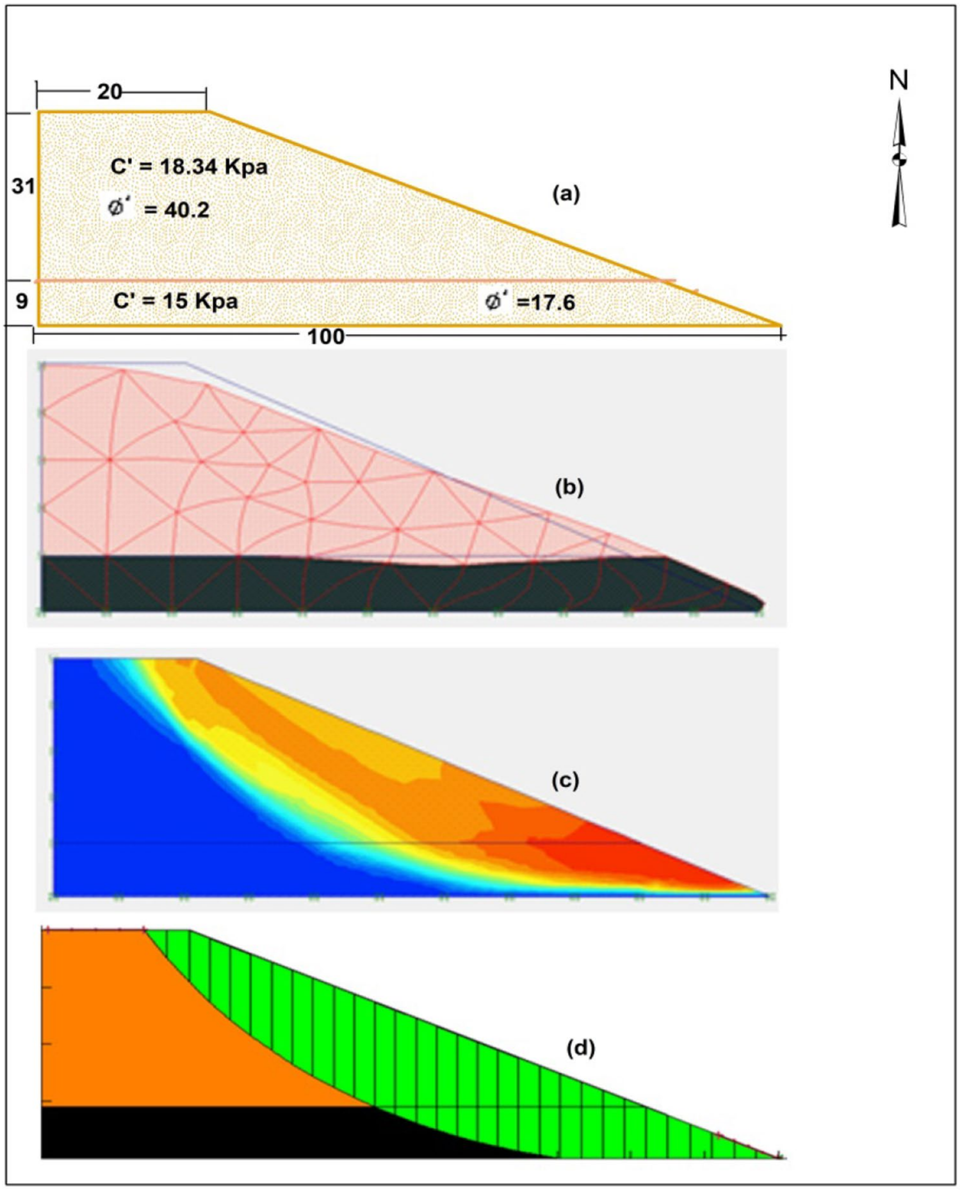

Fig. 6 **a** Cross section of the slope model after flattening to (2H: 1V), **b** deformed mesh and **c** slip circle for the flattened slope by using PLAXIS and **d** slip circle obtained after flattening by using the GEO-SLOPE program

Table 6 FOS values for slope angle of (1H: 1V), (2H: 1V) and (2.5H: 1V) obtained using shear parameters after saturation

Obtained			
LEM	FOS (1H: 1V)	FOS (2H: 1V)	FOS (2.5H: 1V)
Spencer	0.248	0.389/0.396	0.570/0.573
Bishop	0.233	0.400	0.582
Ordinary	0.104	0.100	0.193
Janbu	0.205	0.365	0.513
GLE	0.211	0.388	0.576
M-P	0.218/0.228	0.382/0.391	0.574/0.579

Table 7 FOS values for slope angle of (1H: 1V), (2H: 1V) and (2.5H: 1V) obtained using shear parameters before saturation

Using shear parameters			
LEM	FOS (1H: 1V)	FOS (2H: 1V)	FOS (2.5H: 1V)
Spencer	0.927	1.439/1.440	1.612/1.613
Bishop	0.941	1.454	1.624
Ordinary	0.890	1.283	1.436
Janbu	0.898	1.348	1.525
GLE	0.925	1.441	1.622
M-P	0.926/0.921	1.442/1.443	1.622/1.623

The calculated FOS after PLAXIS software program was compared for both reducing slope angle and lowering water content. FOS of 1.285 and 1.510 for an unsaturated sample with flattening of (2H: 1V), (2.5H: 1V) respectively and FOS of 0.362 and 0.501 for the fully saturated condition after flattening of (2H: 1V), (2.5H: 1V) respectively were obtained.

GEO-SLOPE result confirms that, flattening the slope to (2H: 1V) and (2.5H: 1V) with lowering the groundwater table stabilize the cut slope (Tables 6, 7). FOS results after PLAXIS software shows the same.

Based on the results obtained it can be concluded that flattening the slope angle to 2.5H: 1V and above with lowering of the water table would be one of the techniques to stabilize the slope. The other possible remedial measures are:

Removing unstable or potentially unstable materials

Pockets of black cotton soil which are found within the reddish brown clayey silty gravel soils were expected to be one of the causes for instability of the slope especially when they are in contact with water during rainy seasons. Therefore, removing of such soils will stabilize the slope, even if it is a difficult task to remove all of them because they are distributed and also found at a great depth.

Incorporating benches in the slope

The purpose of benching in the slope is to transform the behavior of one high slope into several lower ones. For this reason, the benches should be sufficiently wide. For the slope with cohesive and frictional strengths, the chief objective is to flatten the slope (Abramson et al. 1996).The benching of the slope is also used to control erosion and to establish vegetation. The vertical heights of benches are typically about 25–30 ft. Each bench should have drainage to convey runoff to a suitable drainage outlet (Abramson et al. 1996).

Drainage control and lowering water table

It has been noticed during the field studies and the simulation result obtained, most of the slope failures become active during the rainy season on Wozeka–Gidole road. It clearly indicates the contribution of surface runoff and infiltration to aggravate the slope instability phenomenon (Table 6). It has been inferred that efforts should be made to control the surface drainage and percolation of water into problematic slopes for their stabilization.

The surface drainage control should be planned to involve; (1) Reshaping the surface of the slope area to control flow and surface runoff, (2) impermeabilizing the slope crest to prevent excessive water infiltration, (3) providing a flow line to divert undesirable surface flow into non-problem area, (4) minimizing the removal of vegetation and establishing new vegetation growth and (5) construction of toe drains to intercept the discharge and materials swept down by the flow.

The surface drains designed in the light of above-mentioned aspect will take care of the runoff before it reaches the area immediately behind the crest of the slope. The diversion of the drainage channels in the slope area should be made with great care to avoid the chance of feeding water into the slope if incorrectly sited and improperly sealed.

Vegetation

Vegetation cover is one of the most sensitive indicators of soil loss. The existence of vegetation cover has decreasing effects on soil erosion susceptibility because it protects the soil from raindrop impact and splash, reduces the erosive action of surface runoff and allows excess surface water to infiltrate (Conforti et al. 2014) reported in Sharma and Singh (2017).

It is probably the best slope protection, particularly against the erosion of soil slopes. A grass mat covering the slope will not only bind the surface material together, but it will also tend to inhibit the entry of water to the slope. Tree plantation may seem contradictory with other solutions proposed for the slope stability. This is attributed to the function of trees in facilitating infiltration of the flood water during intense rainfall. However, from experience bare lands are prone than vegetated lands to slope instability. The interwoven of plant roots will help in stabilizing the soil where they are grown from and have a tremendous contribution to slope stability as well. This program will not only help to alleviate the problem related to the performance of the road under construction but also enhance environmental protections.

Increasing public awareness

A rough estimation during the site visit indicates that most of the areas near the project are cultivated despite my failure to support it with concrete statistical data. Some of the facts narrated previously i.e. cutting of trees, overgrazing, making terrace for houses and intensive agricultural practices, small path and improper drainage need to be emphasized and the locals to be educated about the seriousness of the slope failure and their causes and impacts on the road as well as on their day to day activities.

Conclusions

A conceptual model of the actual Failed Cut slope on Wozeka–Gidole road was identified with two layers to investigate numerical results of limit equilibrium and finite element methods. Limit equilibrium based SLOPE/W and finite element based PLAXIS software's was used. From the modeling result, the causes of failure were identified and possible remedial measures were indicated. The main conclusions drawn from the model are:

- PLAXIS and GEO-SLOPE modeling result show that the Wozeka–Gidole road cut slope falls during the rainy season where the soil is in full saturated condition (worst case scenario). The results of FOS also indicate that the slope is likely to fail even without reaching to the fully saturated condition which confirms the actual conditions.
- GEO-SLOPE and PLAXIS modeling results confirm that, flattening the slope to (2H: 1V) and (2.5H: 1V) with lowering the groundwater table stabilize the cut slope.
- A comparison of modeling results shows, The Bishop, Janbu, Morgenstern-Price, GLE and Spencer methods yield in most cases identical FOS for circular SS. However, the ordinary method may underestimate the FOS from 5 to 6% for the circular SS obtained by this method. All LE methods, except the Ordinary methods, estimate higher FOS than FEM analysis in PLAXIS. The Ordinary method may underestimate FOS up to 7% compared to FEM.
- Results of FEM, as well as LEM solutions, show that none of the slope stabilizing techniques presented above alone can't stabilize the failed slope of Wozeka–Gidole road, unless and otherwise drainage condition was applied properly. Since lowering of the GWT was found providing a substantial improvement on FOS, such installations are strongly recommended to keep the slopes stable in critical conditions.
- Plantation of vegetation will not only control surface erosion and reduce rainwater infiltration, but also maintain suction in the unsaturated part of the slopes during the rainy season.

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