

Stability analysis of geometrically non-homogeneous stratified slopes

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ABSTRACT

Due to ongoing construction of cities and development of new buildings and infrastructures, many natural slopes in and around urban areas are often subjected to cuts. These excavations result in dramatic changes in the geometry of slope faces mostly by the slope angle to the ground level increasing which could potentially develop levels of risks of slope failures with catastrophic consequences. As most natural slopes are of non-homogeneous layered nature it will be of utmost importance to understand the stability behaviour of such slopes. The current practice in analysing slopes of complicated nature, geometrically and materially, is mostly to apply simplifications which could sacrifice accuracy resulting in application of large factors of safety which could question analytical and also economic feasibility of projects. In this research limit equilibrium and finite element methods are implemented by employing commercial software in order to empirically and numerically model and analyse stratified slopes with the aim of understanding effects of non-homogeneity of geometry and materials on stability. The analysis included determination of factors of safety as well as a sensitivity analysis looking into the combined effects of contributing parameters such as slope angle and non-homogeneity in stability analysis.

Keywords: natural slopes, non-homogeneity, numerical modelling, stability analysis

1. Introduction

Slope failures are a major problem everywhere in the world because of their hazardous and costly consequences which cause thousands of deaths every year [4][9]. Most slopes are natural and engineers must often cut through them in order to construct new transportation routes, buildings and infrastructures [1]. Therefore, the slope stratification must be known to obtain the factor of safety of the slope for the desired face angle using data from ground investigations[8].

Natural ground is extremely variable from one location to another, even on a same relatively small area which is why knowing the ground conditions is highly important before starting any design and construction. Some factors such as the presence of water [6], the rainfall intensity [4], the soil properties and the overall geometry of the slope [10] have an impact on slope behaviour when subjected to additional loads. However little attention was given to the direction of the layers within the slope itself which is what this research focuses on. Nowadays, computers and softwares are used to obtain quicker results: OASYS Slope uses the Limit Equilibrium Method [7] and PLAXIS 2D uses the Finite Element Method [3] to analyse slopes considering the appropriate input parameters [5]. In this research, the aim is to observe the effect of the soil layers' direction on the general stability of a slope before and after cut using and comparing limit equilibrium and finite element methods.

2. Modelling process

Guo and He [2] used a stratified slope model in their research which is used again here with Limit Equilibrium and Finite Element methods as it is a good representation of a natural slope. To observe the impact the stratification of the ground has on the stability of the slope, the original model was modified by changing the inclination of the main layers within the slope keeping approximate equivalent layer thicknesses (Figure 1 (a) and (b)). With the main focuses being the slope geometry

and stratification effects, the water table was placed very deep and its effects are not considered. Initially, the slope face rests at an angle of 18 degrees, then 56 degrees after the cut (Figure 1 (a) and (b)) to observe any change in behaviour of the slope when increasing the steepness.

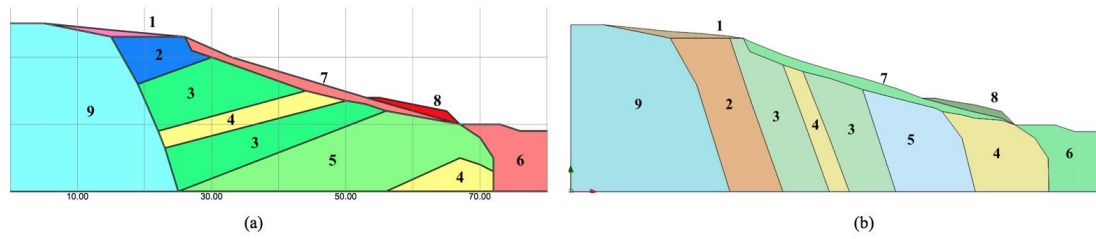


Figure 1: Presentation of the models: Case 1 (original) (a) and Case 2 (b)*

* C: crest location of the slope; Numbering corresponds to a material type as presented in Table 1.

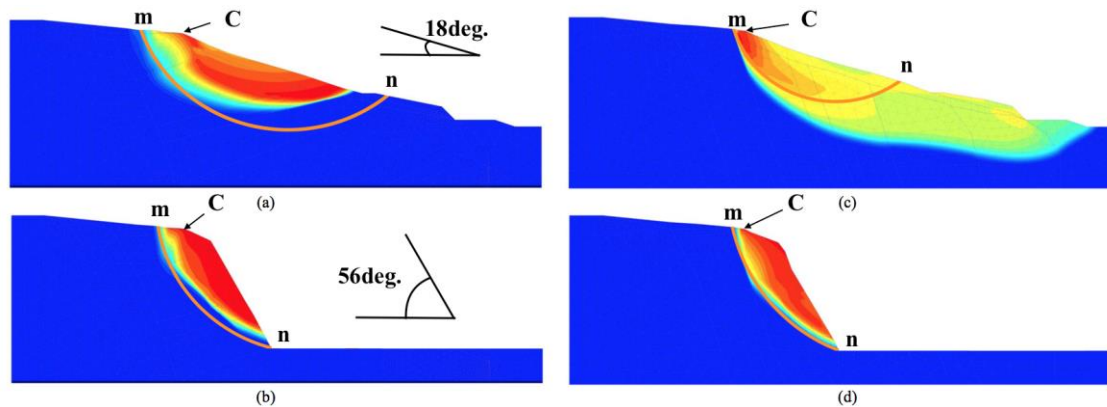


Figure 2: Slip surface results with Limit Equilibrium (orange curved line) and Finite Element (colour shading): Case 1 (a) before and (b) after cut and case 2 (c) before and (d) after cut

Table 1: Slope soil parameters

Soil Type	Elastic Modulus (MPa)	Poisson's ratio	Unit Weight (kN/m ³)	Cohesion (kPa)	Friction angle (°)
Filling Soil (6)**	15.1	0.3	18.1	18	20.3
Brown Coal (4)	23.1	0.27	23	16	12
Carbonaceous Mudstone (5)	16.3	0.28	22.5	30	23.2
Mudstone (3)	12.7	0.29	21.2	16.9	16.6
Ophitic (9)	200	0.21	26.2	200	28.35
Dirty Sandstone (2)	120	0.22	27.3	100	33
Soil (1)	80.6	0.26	19.3	18	10.2
Cobble-stones (7)	2000	0.21	21.5	0	24
Clay (8)	40	0.29	19.4	18.3	16

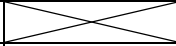
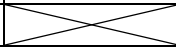
** (1): Material ID number linked to Figure 1 and Figure 2.

3. Observation of the results

Initially, the case study used in this research had a layer of cobblestones (Layer 7 in Figure 1) which was replaced in the analysis by a different material because (i) while running the limit equilibrium analysis a factor of safety of 0.064 was found (very low factor of safety) for the “after cut” case (Figure 2 (b) and (d)) and (ii) it was also observed that this failure was local in the cobblestones at the very top of the slope rather than a general failure. The OASYS Slope software conveniently allows the user to select which failure surface to be shown. Using PLAXIS 2D, the local failure of the cobble-stones was a much greater problem as the software calculates the overall lowest factor of

safety (generally in the slope). Cobble-stones is a cohesionless material ($c=0$ kPa) and increasing the c value led to a converging factor of safety of 1.865 when $c=10$ ($FoS=1.527$ when $c=2$ kPa) which proved that this material was the source of misleading results. With a factor of safety being close to 0 a good representation of the general factor of safety could not be obtained using this model. As the aim of this paper is focused on general failures linked to the geometry of the slope, cobblestones layer was replaced by filling material to address the issue.

Table 2: Factors of Safety for cases 1 and 2 and comparison ratios

Condition		LE	FE	LE/FE ratio
Case 1	Before Cut	2.201	1.877	1.17
	After Cut	0.839	0.533	1.57
<i>Before/After ratio</i>		2.62	3.52	
Case 2	Before Cut	2.131	2.003	1.64
	After Cut	0.618	0.545	1.14
<i>Before/After ratio</i>		3.45	3.68	

a. Limit Equilibrium Method

The slope was modelled to observe its stability and failure mechanisms prior and following a cut. In its natural environment, the slope (case 1; Figure 1) had a factor of safety of 2.201 (stable; Figure 2 (a)), which was observed to drop significantly after the removal of the soil down to 0.839 (unstable; Figure 2 (b)). Regarding the slip surface before the cut (Figure 2 (a)), the high point 'm' was located at 7m away from the crest to the left and the lower point of the failure surface 'n' at $\frac{3}{4}$ down the slope with a maximum normal depth to the slope surface of 10m. After the cut (Figure 2 (b)), the slip surface was 6m to the left of point C (point 'm', closer than previously) and reaches the very bottom of the slope where slope and horizontal ground meet (point 'n') showing a full slope failure. The failure plane was shallower at a depth of 7m.

Then, case 2 (Figure 1 (b)) was modelled and analysed. Prior any excavation, the stratified slope had a factor of safety of 2.131 (stable; Figure 2 (c)), then 0.618 after the removal of the soil (unstable; Figure 2 (d)). Regarding the slip surface before the cut (Figure 2 (c)), the high point 'm' was located at 2m away from the crest 'C' to the left to half way down the slope with a maximum normal depth to the slope surface of 5m. Following the cut (Figure 2 (d)), the slip surface at 'm' followed the interface of the dirty sandstone and mudstone layers (approximately the same as before the cut) and like in case 1, it reached the bottom of the slope 'n'. The failure plane was shallower at a depth of 5m.

b. Finite Element Method

The FE method resulted in differences in the factor of safety, the location and shape of the failure line. In case 1, the factor of safety was 1.877 (stable; Figure 2 (a)) before the cut then 0.533 (unstable; Figure 2 (b)): lower than LE (Table 2). Before the excavation (Figure 2 (a)), the slip surface was located at a lower depth than using LE (6.5m-7m) and a non-circular abnormality was observed at the location of the dirty sandstone where the slip surface depth was even lower which can be explained by the shear strength parameters of the soil type ($c=100$ kPa; $\phi=30^\circ$) which were higher than the average layer. After the cut (Figure 2 (b)), (compared to LE), it was observed that the bottom end of the slip surface was not located at the toe of the slope but at approximately 2.5m above this location.

In case 2, a factor of safety of 2.003 (stable; lower than LE, Table 2) was obtained before the slope cut (Figure 2 (c)). Compared to case 1, the top of the slip surface was located 2m to the left of point C (same as LE in case 2) but the bottom end of the slip was located at the very bottom of the slope with a slip located at 10m depth. After the removal of the soil, the factor of safety was 0.545 (unstable; Figure 2 (d); lower than LE, Table 2). As observed in case 2 with LE, an even more significant meeting line between the slip surface and the interface of the dirty sandstone and mudstone layers was observed demonstrating the impact the verticality of the layers has on the location of the slip surface.

The top of the slip had the same location as in LE but the bottom end was located at 2m above the horizontal ground (same difference as in case 1 between LE and FE methods).

c. Combined Observations

Before the cut, the bottom of the slip surface in case 1 was located at the interface of two layers at a given depth whereas in a vertically stratified slope, the slip surface depths through each layer was depending on their respective shear strength (the higher 'c' and 'phi', the shallower). This first same phenomenon was observed after the cut in case 2 where a part of the slip surface followed the vertical interface of two layers. It appeared that after the cut, the arrangement of the layers had some effects on the factor of safety and that the shear failure in vertically stratified slopes followed a circular pattern (Figure 2 (d)) against a linear pattern in the horizontal case (Figure 2 (b)). When a stratified slope problem is modelled before construction, simplifications regarding the stratification should be avoided to use a good representation of the reality. Indeed, if any stratified slope (most natural slopes) was simplified into a homogeneous slope (with adequate soil properties), the impact that the layer orientation and interface would have on the stability would be ignored to some extent, which would lead to misleading results especially when observing the location of the slip surface at failure.

4. Conclusions

Limit Equilibrium and Finite Element Methods were used to assess the factor of safety and location of the failure of two stratified slopes and enable the assessment for the need of slope reinforcement or other slope stabilisation methods to avoid landslides. It was observed that in fact, the orientation of the soil layers show a higher factor of safety when layers are as original compared to rotated. The factors of safety using the FE method are lower than the ones from the LE method. This makes the use of the FE method safer for designs of structures or excavations of stratified slopes. Indeed, FE method looks at elements within the generated mesh which provides a better accuracy. If the certainty about the slope behaviour is increased, the applied factor of safety within a design could be reduced leading to more economically viable designs. Attention must be paid to local failures when using the FE Methods as these may not be always of high concern.

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