Stratified slopes, numerical and empirical stability analysis

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Abstract

Urbanisation means that many natural slopes in and around cities are often subjected to cuts resulting in dramatic changes in the geometry of slope faces mostly by increasing slope angle which could lead to failures with catastrophic consequences. As most natural slopes are of non-homogeneous layered nature, understanding the stability behaviour of such slopes will be of utmost importance. The current practice in analysing slopes of complicated nature, geometrically and materially, is mostly to apply simplifications sacrificing accuracy leading to use of large factors of safety, which could undermine analytical and economic feasibility of projects. In this research limit-equilibrium and finite element methods are used, respectively by OASYS Slope and PLAXIS 2D, to empirically and numerically model and analyse geometrically non-homogeneous stratified slopes with the aim of understanding the effects of non-homogeneity of geometry and materials on stability under various inclination angles of slope face. The analysis included determination of factors of safety as well as a sensitivity analysis looking into the combined effects of contributing parameters.

Keywords:

Computational mechanics; Geotechnical engineering; Slopes - stabilisation

List of notation

LEM	Limit Equilibrium Method
FEM	Finite Element Method
c'	Effective cohesion
φ'	Effective internal friction angle
C	Slope crest
m	Top of the slip circle (LEM analysis)
n	Bottom of the slip circle (LEM analysis)
FoS	Factor of Safety
β	Slope angle
E	Elastic modulus

1. Introduction

Slope failures are a major problem everywhere in the world because of their human, financial and environmental consequences, causing thousands of deaths due to landslides each year (Kawamoto et al., 2000; USGS, 2016). Therefore, engineers must understand how slopes behave but also how their failures can be prevented. With the expansion of cities and growth in infrastructure construction leading to cuts through natural slopes, engineers ought to deal with slope stability scenarios very often (Bromhead Edward, 2015). This could include road works, dam constructions, bridges or development projects in outskirts of metropolitan cities surrounded by highlands. This outlines the importance of ground investigations to acquire soil stratification to perform stability analysis which can become very expensive and lead to an incomplete or more scattered set of borehole data (Sun, Zhao, Shang, & Zhong, 2013). Ground conditions can be variable even for a small-scale study. Other main variables are water and rainfall intensity (Kawamoto et al., 2000; P. Orense, Shimoma, Maeda, & Towhata, 2004) as well as the geometry of the slope and its material properties (Zhou, Deng, & Xu, 2012). In the past researches, little attention was given to the actual arrangement and orientation of the soil layers and the impact this has on the overall stability of a soil slope. In the research, OASYS analysis is based on the Limit Equilibrium Method (LEM) (Smith, 1981) and the method of slices (Bishop, 1955) while PLAXIS 2D is a finite element method (FEM) based software based on the Shear Strength Reduction Technique (Hammouri, Malkawi, & Yamin, 2008).

Since its development and with the assumptions that a cylindrical slip surface will occur, Bishop's (1955) method of slices has been widely used. This method worked based on the assumption that the inter-slice forces are horizontal which satisfies the equilibrium of moments but not the forces in the soil mass. In this research the later method of slices with parallel inclined inter-slice forces (Spencer, 1967), which is a modification to the original method of slices suggested by Bishop (1955), was used. The advantages of the modified Bishop method suggested by Spencer was that it could avoid interlocking problems in the slices. This method enables each slice to remain in equilibrium both horizontally and vertically by calculating the inter-slice forces and satisfies equilibrium of both forces and moments.

In this research, the Bishop's method of slices with the advanced parallel inclined method for the inter-slices was used utilising OASYS Slope software. The Factor of Safety against failure for the given probable slip surfaces was calculated using (Bishop, 1955):

$$FoS = \frac{\Sigma \text{ Resisting Forces}}{\Sigma \text{ Driving Forces}} \quad 1.$$

So long as the ratio of the Resisting to Driving Forces is greater than 1, failure will not occur. If the ratio reaches 1, the slope fails.

With the finite element method, slices and therefore interslice forces are not needed in the process of creating the model and the analysis, and the shape of the slip surface could follow the weakest surface in the soil mass based on the analysis conducted considering the implemented constitutive soil model. According to Griffiths (1999), it is known that finite element lets the failure occur progressively on the model and allows monitoring of the displacements until overall shear failure occurs. Finite element does not use slices as mentioned as opposed to the limit equilibrium methods providing less limitations on the location and shape of the failure surface (Griffiths & Lane, 1999).

The shear strength reduction technique is a method which reduces the strength parameters ("c" and "phi" in Mohr-Coulomb soil model) until failure occurs. Using the finite element method for geotechnical analysis creates potential advantages over conventional / empirical methods. The FEM satisfies the input boundary conditions, equilibrium of the model, the constitutive model behaviour and compatibility (physical and mathematical – i.e. no gaps or overlapping occurs within the FE model) (Potts, 1999). The shear strength parameters at failure are then used to calculate the factor of safety of the slope – i.e. the ratio of the initial strength parameters to the ones at failure (Fu & Liao, 2010).

PLAXIS 2D (2016.1) uses the shear strength reduction technique (reducing cohesion c and angle of frictional resistance φ until failure occurs) to assess the slope stability (Wu, Cheng, Liang, & Cao, 2014) when undertaking the "Safety Calculation". The software works on the

basis that reducing the shear strength of soil mass in a slope gradually increases the shear strains propagating from the toe upwards leading to general failure of slope (Matsui & San, 1992).

While PLAXIS 2D Safety Calculation reduces the shear strength parameters until failure occurs, it is up to the user to define how many calculation steps to undertake – i.e. the user must check that failure has or has not fully occurred before reading the final Safety Factor. If the failure has happened, the Factor of Safety calculated last, will be considered as the required output. However, if failure has not yet occurred, the user must specify additional calculation steps to allow for more strain to develop and for the failure to occur (Vermeer, 1993).

2. Model development process

In order to appreciate the effects that stratification has on the stability of slopes before and after being subject to a cut, two models were developed and named Cases 1 and 2 as will be referred to in the rest of this document. Both models were analysed using the Limit Equilibrium and the Finite Element methods before and after the cut.

Case 1: The geometry follows the one obtained from the case study presented below (Guo & He, 2011). In this case, the slope layers are laid approximately horizontal (Figure 1)

Case 2: Geometry is changed from Case 1 by rotating the orientation of the layers by almost 90 degrees leading to a stratified slope made of near vertical layers of geo-materials (Figure 2).

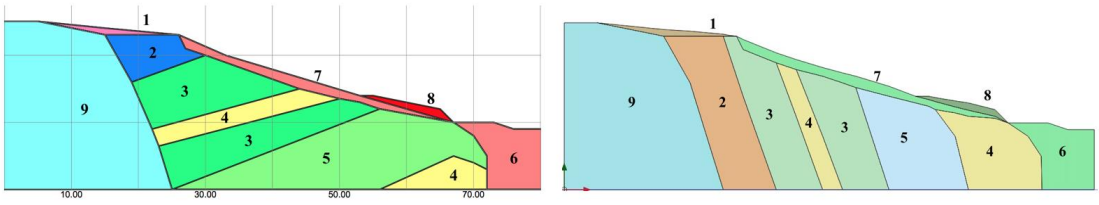
Thicknesses of the layers in Cases 1 and 2 were similar as well as the soil type (see Figure 1 and Table 1). The slope face angle (β) in both Cases were 18° before cut (Figure 1) and 56° after cut (Figure 2).The aim of the geometrical modifications made to Case 1 was to observe the effects of the soil layers orientation on the general stability of a stratified slope before and after cut using both limit equilibrium and finite element analysis methods by adopting the Mohr-Coulomb criteria as the governing constitutive model.

In all cases studied in this work water table levels were assumed to be sufficiently below the failure surface for the pore water pressure not to be included in the analyses. However, if water table levels were high enough to be included in the model area then the global water table levels and appropriate pore pressure boundary conditions must have been included and activated in the PLAXIS model in appropriate analysis stages according to the site conditions and Terzaghi's

principle of effective stress (effective stress = total stress - pore water pressure) would be implemented for the safety analysis. The models were created and analysed using the Limit Equilibrium method (LEM) with OASYS Slope and the Finite Element Method (FEM) with PLAXIS 2D software.

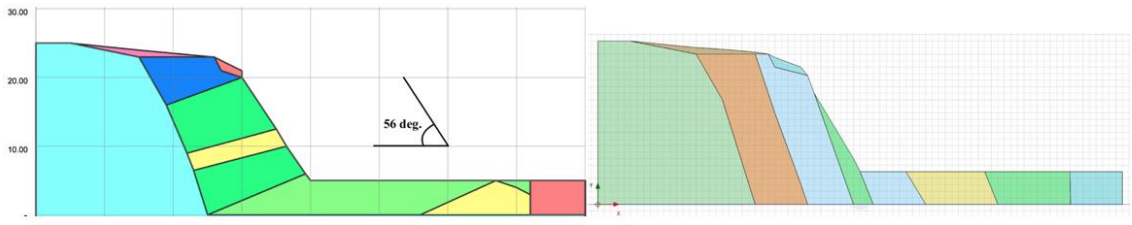
The Limit Equilibrium method uses user-defined grids to be used as centre point for the hypothetical circular slip surfaces to be developed and analysed to locate the slip surface on which the factor of safety of the slope is the lowest (the most probable slip surface) (Xiao, Yan, & Cheng, 2011). The Bishop analysis method (Bishop, 1955) was used in these Cases to find the Factor of Safety on the shear strength in the OASYS analysis using LEM.

The Finite Element Method was used using the phi-c reduction technique by PLAXIS 2D software. In this method the shear strength of the soil mass is reduced in as the analysis progresses in a step-by-step basis until failure occurs and the calculations are repeated until the stability factor of safety for the slope is obtained. 15-node triangular isoparametric elements were used in the analysis and the meshing criteria was set to “very fine” to achieve higher accuracy (Brinkgreve et al., 2011) in the outputs. Two phases were defined for the analysis with the Initial Stress Conditions phase being followed by the Factor of Safety calculations.



(a) (b)

Figure 1. Presentation of the models: (a) Case 1 (original); (b) Case 2 (amended layer orientations) (Numbering corresponds material properties as presented in Table 1)



(a) (b)

Figure 2. Models representing post-cut geometries: (a) Case 1 (b) Case 2 (amended layer orientations)

Figure 2 shows the slope after-cut conditions. It must be noted that drained safety analysis was conducted in this research (no water involved in the models) so the excavation was created in one instantaneous step. The first model created (Figure 2a) had a relatively thin layer of cobblestone at the top (Layer 7 in Figure 1) which was replaced later in the analysis by a fill material (soil number 6 in Table 1) due to leading the analysis towards very unusually localised failure of the cobblestones and a very low factor of safety (nearly 0) calculated by the LEM which was out of the scope of this study (Figure 3). Changing the Cobblestone layer to fill material was only done after ensuring that the thickness and positioning of the cobblestone layer was responsible for the very low overall factor of safety for the slope by conducting a trial analysis completed by assuming higher hypothetical shear strength properties for the cobblestone layer (c' and φ') which led to the overall output factor of safety of 1.8 for the slope. The cobblestone layer replacement by fill material enabled the study of the overall stability behaviour of the slope.

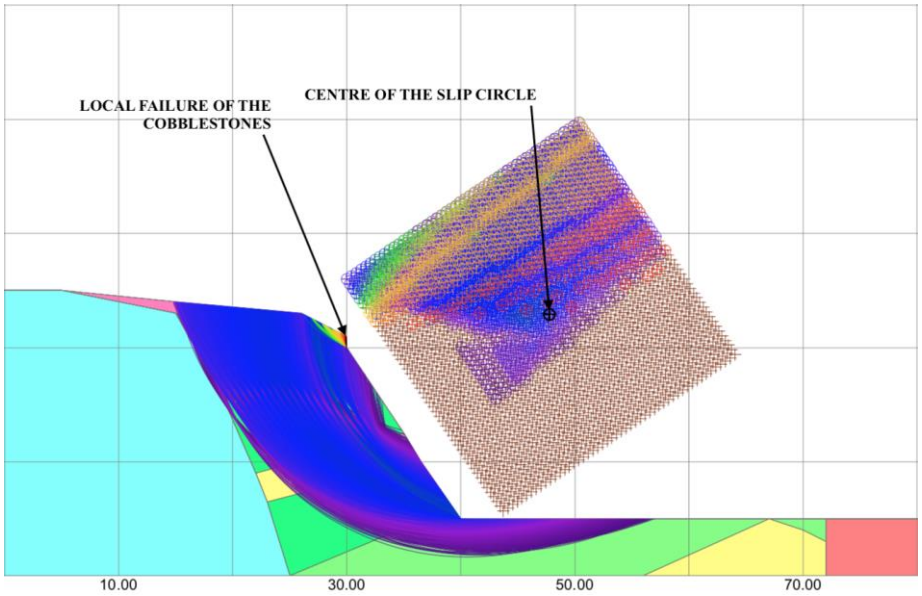


Figure 3. Case 1 after cutting - local failure (the small part of Cobblestones is collapsed) issue at the crest due to presence of loose material (cobblestone layer) (OASYS slope model).

Table 1. Slope material properties used in the LEM and FEM analyses (Guo & He, 2011)

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

*Numbers inside brackets represent material ID numbers as presented in Figure 1 and Figure 15.

3. Model analysis results

3.1. OASYS model - LEM analysis

3.1.1. Case 1

The slope was modelled to observe its stability and failure mechanisms prior and following a cut. In its natural environment, the slope (Case 1 shown in Figure 1a) had a factor of safety of 2.2 (Figure 4a), which was observed to drop significantly after the removal of the slope material after the cut down to 0.8 (Figure 4c). On the most probable slip surface before the cut (Figure 4a), the high point ‘m’ (x=19m,y=23m; Figure 4a) was located 7m away from the crest of the slope to the left, and the lower point of the slip surface ‘n’ (x=67m,y=13m; Figure 4a) is placed above the toe of the slope. After the cut (Figure 4c), point ‘m’ (x=22m,y=23m; Figure 4c) of the slip surface was placed at a point 6m to the left of point C (closer to the crest compared to pre-cut conditions Figure 4a) and reaches the very bottom of the slope where slope and horizontal ground meet (point ‘n’, in after-cut conditions; x=40m,y=5m; Figure 4c) suggesting that the whole slope will slip down.

Before the cut, the slip surface goes as deep as 10m, but recovers to a shallower location after the cut getting to the depth of 6m (Figure 4a and 4c).

3.1.2. Case 2

Prior to any excavation, the stratified slope had a factor of safety of 2.1 (Figure 4b) suggesting that the slope was stable, however the value dropped to 0.6 (unstable slope) after the removal of the slope material (Figure 4d). In the case of the most probable slip surface before the cut, the high point 'm' was located 2m away from the crest 'C' to the left (x=24m,y=23m; Figure 4b) and point 'n' (lower point) was located half way down the slope (x=47m,y=16m; Figure 4b). Following the cut (Figure 4d), the most probable slip surface at the top starting point (m; x=24m,y=22m; Figure 4d) followed the interface of the dirty sandstone and mudstone layers (similar to the pre-cut scenario) and similar to the after-cut conditions in Case 1 (Figure 4c), the slip surface reached the bottom of the slope at the bottom (n; x=40m,y=5m; Figure 4d). The failure plane in the case of vertically stratified soil slope was shallower compared to horizontal stratification and the deepest point was recorded at the depth of 5m below the slope surface (Figure 4b).

Before the cut, the slip surface is located at 5m below the surface (at the deepest part) as well as after the cut (Figure 4b and d). The difference in depth for the slip surface between Case 1 and Case 2 post-cut (Figure 4c and d) is not significant compared to the two Cases in pre-cut conditions (Figure 4a and b).

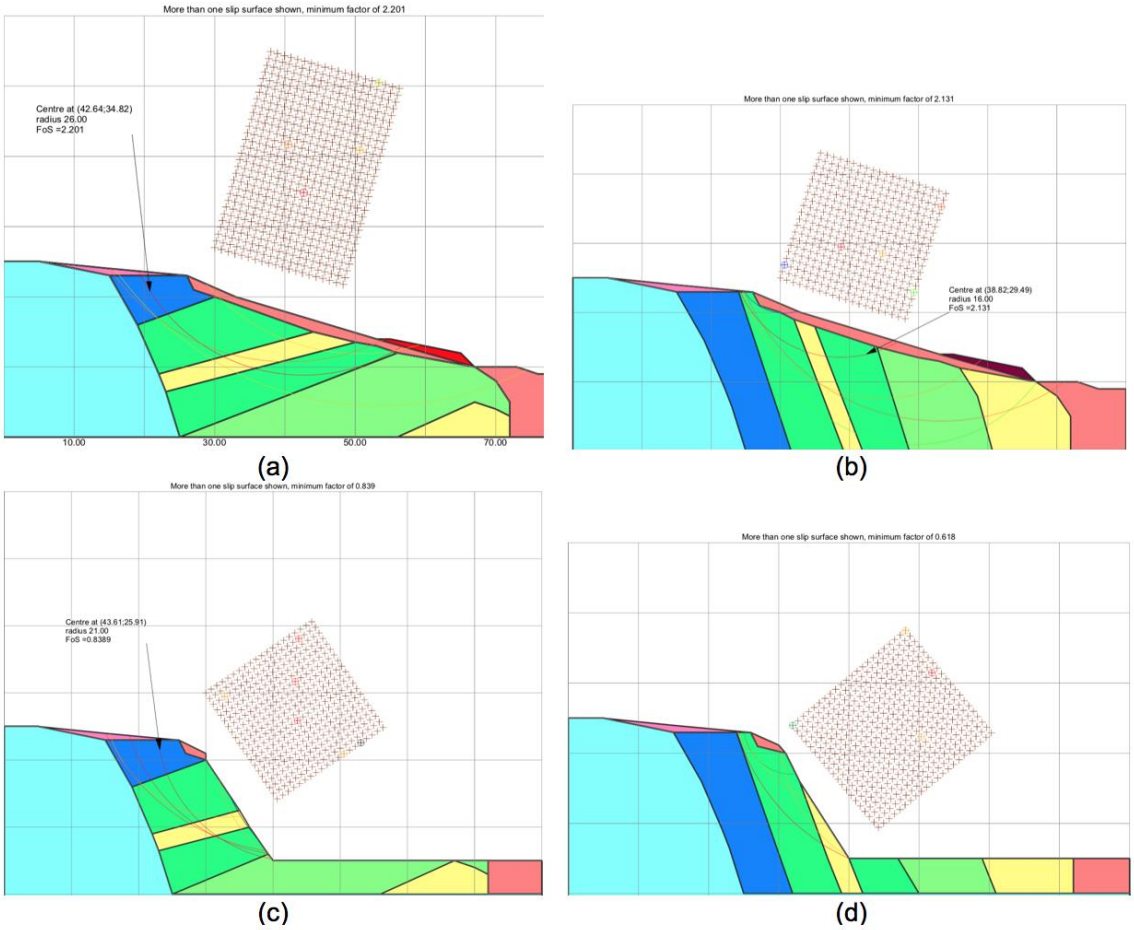


Figure 4. OASYS Slope LEM; (a) Case 1 Pre-cut, (b) Case 2 Pre-cut, (c) Case 1 post cut and (d) Case 2 post cut. (Each Distance between consecutive gridlines represents 10m)

3.2. PLAXIS model FEM analysis

Very fine mesh choice for all slope models simulated and analysed using the FEM contributed to the accuracy of the results. FE results do not rely on a given circular slip surface and give a more realistic non-circular (when it is the case) slip surface as the slope behaviour affects every node and elements and the effects they have on each other.

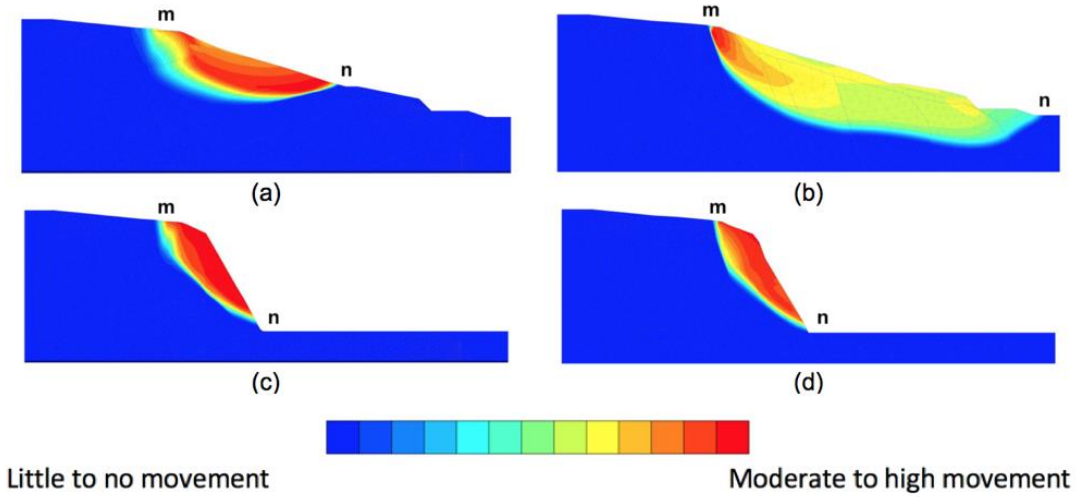


Figure 5. PLAXIS 2D (FEM analysis): (a) Case 1 Pre-cut; (b) Case 2 Pre-cut; (c) Case 2 post-cut; (d) Case 2 post-cut.

For the finite element models created by PLAXIS 2D, a “very fine” mesh was assigned and the numbers of elements / nodes for the cases before and after excavation were 1097 / 9027 and 766 / 6377 respectively.

The FE analysis resulted in different outcomes compared to the LEM. Different factors of safety, slope failure locations and as well as different shapes of the failure surface were obtained. In Case 1 (Figure 1a), the factor of safety was 1.8 (stable slope) before the cut but the value dropped to 0.5 after the cut (Figure 5a and 5c). These values are lower than the values obtained using the LEM analysis (Figure 4a and 4c).

Additionally, in the case of the FEM before the cut (Figure 5a), analysis an abnormality was observed on the mostly circular slip surface at the location where the dirty sandstone was placed (Figure 1a) and the slip surface depth was even shallower (Figure 5a). This be explained by the shear strength parameter values of the material at that point (c=100 kPa; phi=30°) which is considerably higher than the average soil strength parameters as observed in Table 1. The higher shear strength parameter values interrupted the circular slip surface by creating a dent and nearly dividing the slip surface to two sections. The effect of this was also reflected in the factor of safety values where the value changed from 2.2 (LEM) to 1.8 (FEM) (other parameters based on the methods themselves also affect the changes). This abnormality can also be observed in the displacements measured in the x (horizontal) and y (vertical) directions.

In Figures 6, 7, 9-14, there are no values for positive and negative maxima represented by the ends of the coloured scales (+/-). Plus sign (+) reflects left-to-right or upwards movements whilst minus sign (-) shows right-to-left or downwards movements. Extreme strain values occur closer the maxima (+ and -).

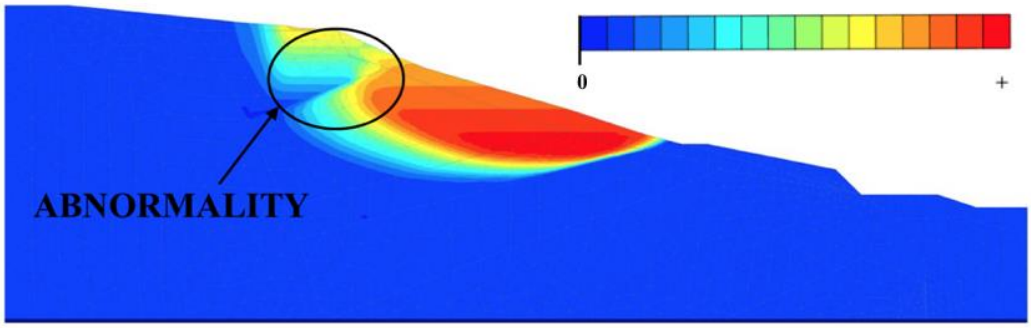


Figure 6. Case 1 before cut - displacement in the horizontal direction, (Plus sign shows displacements happening in the left-to-right direction).

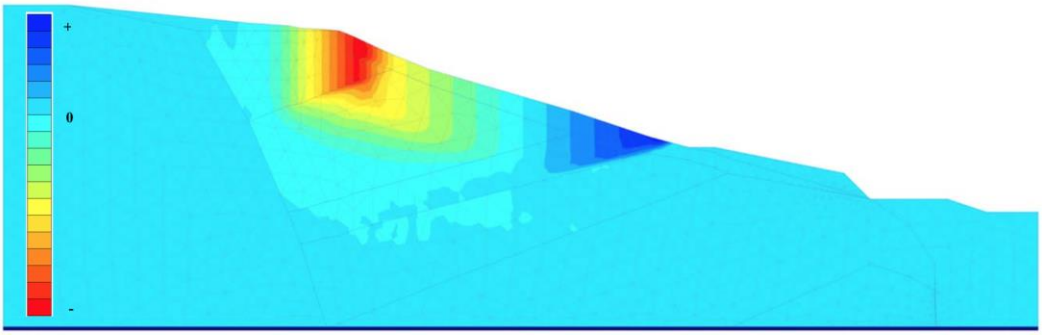


Figure 7. Case 1 before cut y-direction displacement, (Plus sign shows displacements happening in the upwards direction).

As it can be seen in Figure 6 and Figure 7 when the lowest factor of safety was achieved, the top of the most probable slip surface moved downwards while the rest of the slope tended to move in the horizontal direction to the right. This behaviour was expected as was observed before by Jiang and Murakami (2012). It can also be seen from Figure 7 that at the lower boundary of the moving soil mass (blue shaded area in Figure 7), located at the interface between two layers, only the layer on top was subjected to the upward displacement which was induced by the left-to-right sliding of the soil mass on the inclined interface of the Mudstone over the Carbonaceous Mudstone as illustrated in Figure 8.

Before the cut, the slip surface is located at 6m below the surface (at the deepest point); however, this depth becomes greater after cut and reaches to 9m (Figure 5a and 5c).

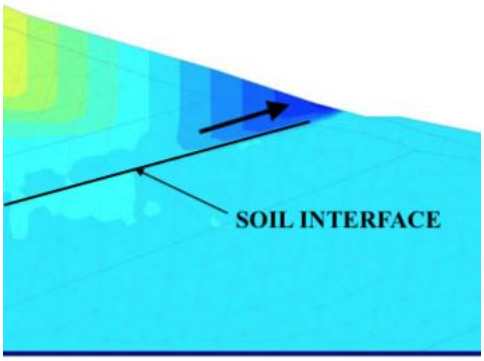


Figure 8. Inclined displacement of the Brown Coal strata upon the Mudstone strata due to sliding on sloping surface (Figure 1a and Figure 7).

After the cut (Figure 5c) and compared to the LEM analysis, it was observed that in the FEM analysis the bottom end of the slip surface (point “n”; x=39m y=8m, Figure 5c) was not located at the toe of the slope but at approximately 3m above the toe. Displacements also were obtained in both horizontal (x) and vertical (y) directions (Figure 9 and Figure 10).

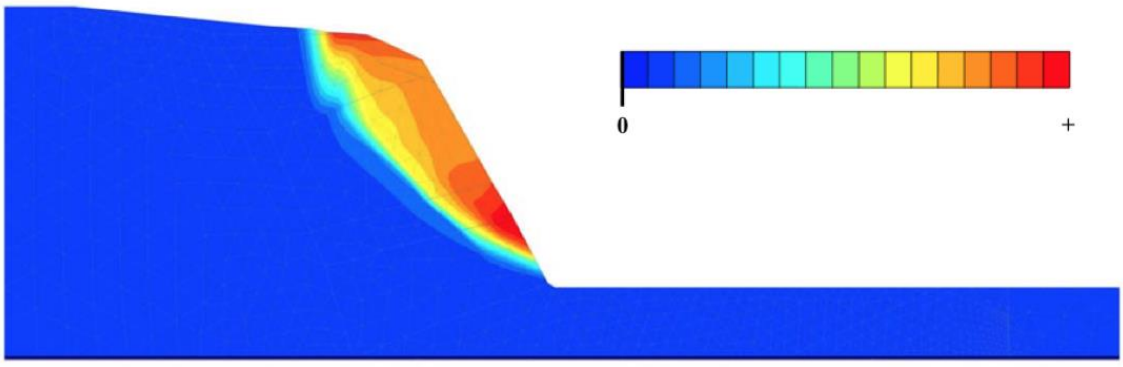


Figure 9. Case 1 - after cut x-direction displacement (Plus sign shows displacements happening in the left-to-right direction**).**

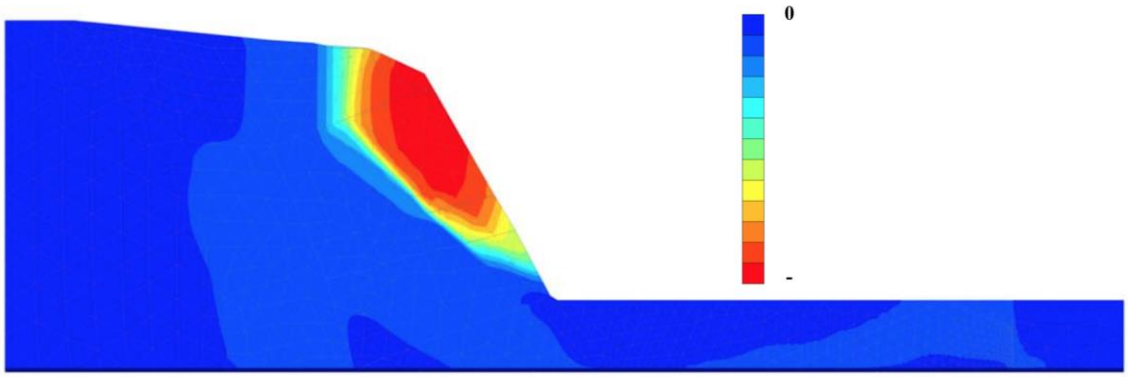


Figure 10. Case 1 after cut y-direction displacement (Minus sign shows displacements happening in the downwards direction**).**

In case 2, a factor of safety of 2.0 (stable slope - however lower value compared to the LEM analysis Figure 4b) was obtained before the slope was cut (Figure 5b). Compared to Case 1, the top of the most probable slip surface (m) was located 2m to the left of point C (same as LEM analysis results for Case 2 – see Figure 15c) but the bottom end of the slip surface was located at the very bottom of the slope (n, x=77m, y=8m). After the removal of the materials during the cutting process, the factor of safety was calculated to be 0.5 (unstable slope) - Figure 5d; this is a lower value compared the LEM analysis results -see Figure 4d).

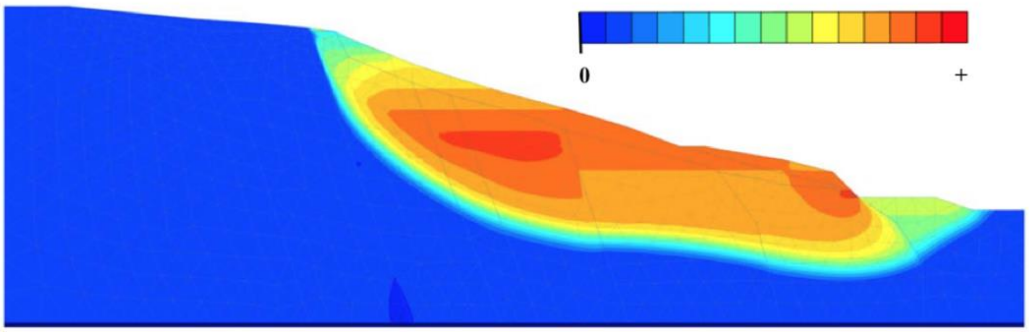


Figure 11. Case 2 before cut x-direction displacement (Plus sign shows displacements happening in the left-to-right direction**).**

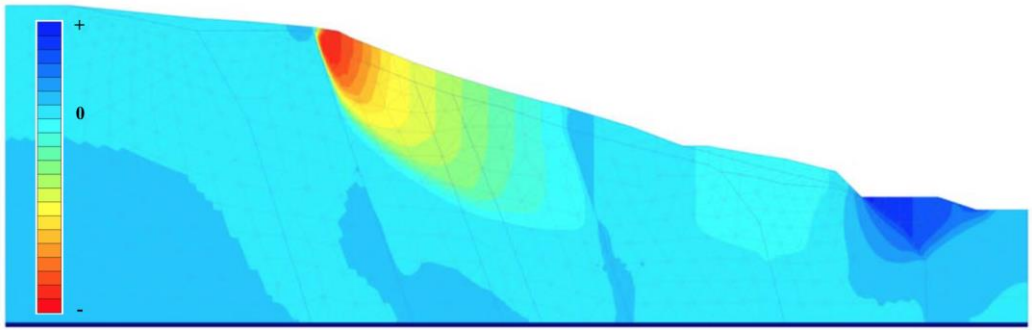


Figure 12. Case 2 before cut y-direction displacement (Plus sign shows displacements happening in the upwards direction**).**

Before the cut in Case 2, most of the slip surface analysed using the FE method moves horizontally to the right side of the slope (Figure 11) and only the very top left part of the slope surface, as shown in Figure 12, has a significant downward movement along the interface of Dirty Sandstone layer and the Mudstone layer (Figure 1b). Also, as presented in Figure 12, the toe of the slope displays some upwards movement (toe heave) due to the horizontal push observed in the Brown Coal over the Filling Soil (Figure 1b) part of the slope as can be seen in Figure 12.

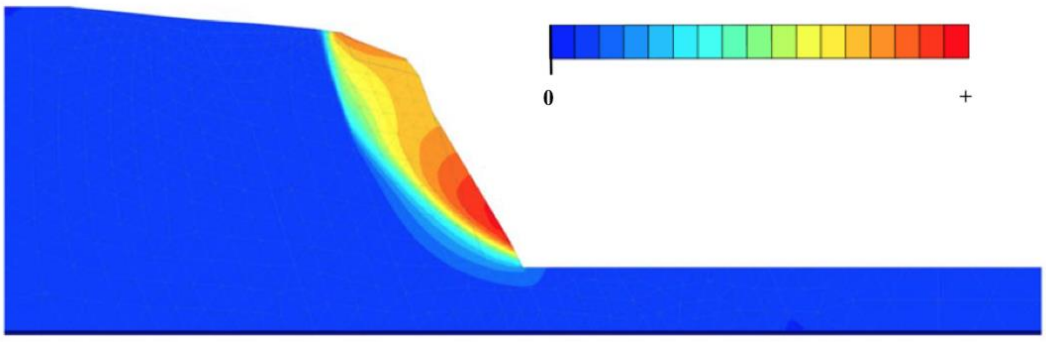


Figure 13. Case 2 after cut x-direction displacement (Plus sign shows displacements happening in the left-to-right direction**).**

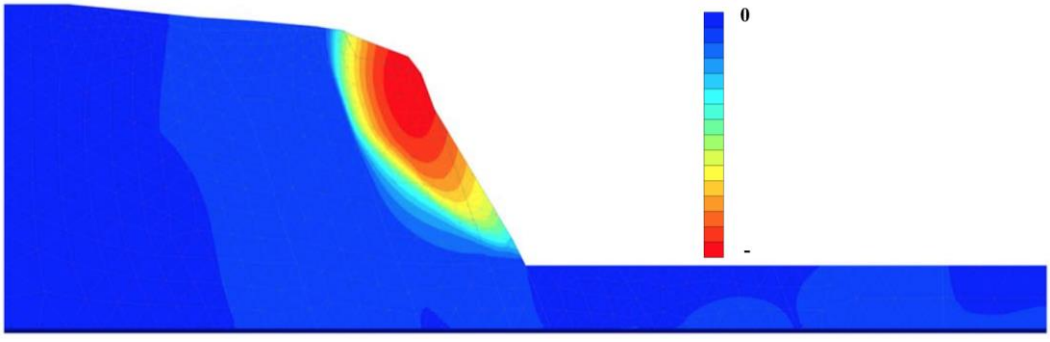


Figure 14. Case 2 after cut y-direction displacement (Minus sign shows displacements happening in the downwards direction**).**

After the cut in Case 2, while the bottom of the failing mass slides to the right as shown in Figure 13, all the soil mass located on the upper section of the collapsing body falls with a downward movement (Figure 14). As observed in Case 2 with LEM analysis as well, the most probable slip surface falls even more dramatically in the interface of the dirty sandstone and mudstone layers (Figure 5d). This phenomenon more strongly signifies the impact the verticality of the layers on the location of the slip surface and consequently on the values of the factor of safety. Factor of safety from FEM for this surface was 0.5 compared to 0.6 from LEM analysis further emphasizing the effect of orientation of layers. The top of the slip surface (point “m”) in the case of FEM analysis of Case 2 had the same location as in the LEM analysis whereas the bottom end, point “n” (x=39m, y=7m), was located 2m above the toe. This presents the same difference as between LEM and FEM analysis for Case 1 as shown above (Figure 5c).
Before the cut, the slip surface goes as deep as 10m (at the deepest point) but then recovers to a shallower location after the cut at 6m (Figure 5a and c). It can be observed here that in both cases, the depth at which the slip surface locate itself is more variable depending on the case and even with the two post-cut scenarios with one at 10m (Figure 5c) and the other at 6m (Figure 5d).

3.3. Results comparison

In order to observe the differences between LEM and FEM analyses, the results were superimposed and presented in Figure 15.

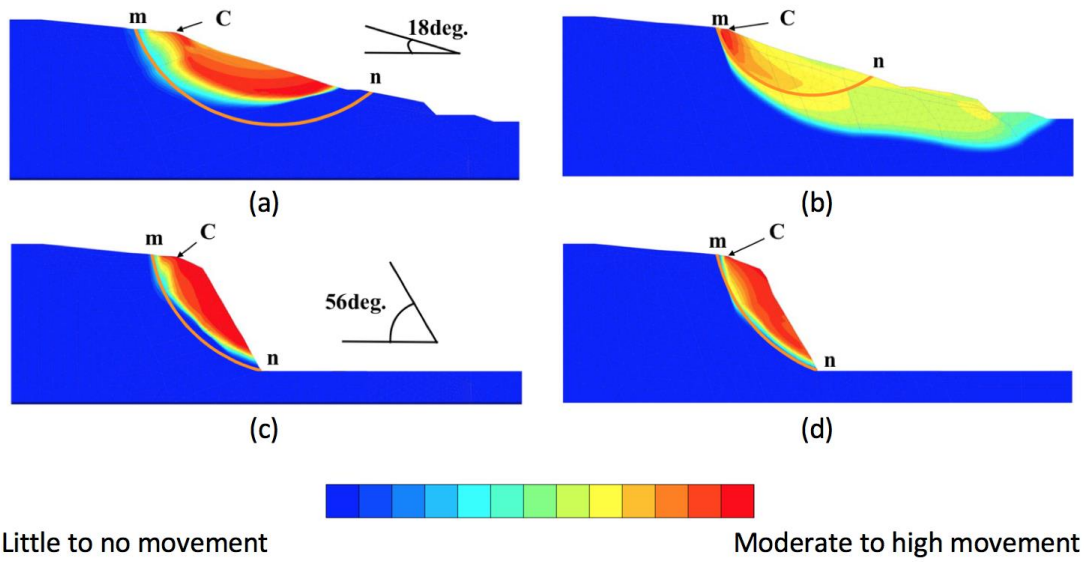


Figure 15. LEM (bold curves) and FEM analysis results (contours), (a) Case 1 before cutting the slope; (b) Case 2 before cutting the slope; (c) Case 1 after slope cut; (d) Case 2 after slope cut

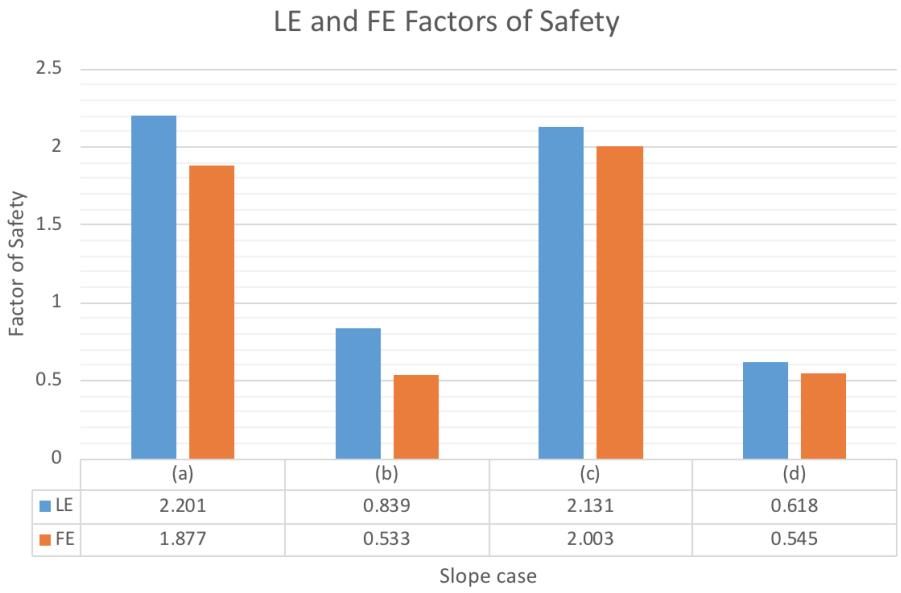


Figure 16. Combined Factor of Safety results for LE and FE: (a) Case 1 before cutting the slope; (b) Case 1 after slope cut; (c) Case 2 before cutting the slope; (d) Case 2 after slope cut.

Factors of safety obtained from the LEM analysis were higher compared to the ones obtained from the finite element method in all cases.

As a general observation of the results and as expected, the factors of safety from both cases 1 and 2 before the cut were higher compared to the values obtained from the models simulating after-cut situations. As shown in Figure 16, the factors of safety after the cut were at least 50% smaller compared to the values relating to before-cut. This might be due to the fact that after a cut in slope, the slope angle (β) increases dramatically resulting in sharp falls in the stability factors of safety. Comparing LEM and FEM analysis results reveal that drop in the factor of safety values is consistent considering both methods; however, values obtained post-cut from the FEM analysis are much lower (especially in Case 1) compared to the LEM results (Figure 16b). This outcome suggests that implementing the finite element analysis will provide factor of safety values that will result in safer designs. Indeed, if only LEM analysis was used to calculate the factor of safety against failure, based on the findings in this research, failure could be underestimated. This is because obtained value for the factor of safety from FEM analysis (if conducted) would be smaller making the FEM analysis not only the more accurate but also the more conservative approach.

Table 2. Depth of the most probable slip surface for each Case (as illustrated in Figure 1) using LEM and FEM (depth defined as the length of a hypothetical line perpendicular to the slope surface connecting the slope surface to the most probable slip surface)

Cases (Figure 1)	LEM	FEM
a	10m	6m
b	5m	10m
c	6m	9m
d	5m	6m

Table 2 compiles the data for the depth at which the slip surface is located in both cases (Figure 1), pre- and post-cut using both LEM (Figure 4) and FEM (Figure 5).

3.4. Layers material strength effect

Before the cut, the bottom of the slip surface in Case 1 was located at the interface of two layers at a given depth. The same phenomenon was observed after the cut in Case 2 where a part of the slip surface followed the vertical interface of two layers. In a vertically stratified slope, the slip surface depths through each layer is changing. These variations are due to the differences

in the shear strength parameters of slope materials in different layers (the higher the shear strength - c' and φ' values, the shallower the slip surface).

After the cut, the circular pattern generated by the LEM shown in Figure 4c and Figure 4d was similar in both Cases 1 and 2. Important details can also be observed from the FEM analysis. Arrangement of the layers had some effects on the factor of safety and the shear failure in vertically stratified slopes which followed a circular pattern (Figure 15d) as opposed to the linear pattern seen in the horizontally stratified layers case in FEM analysis (Figure 15c).

As observed in the finite element results section, the relative shear strength of different slope materials involved in the analysis and present on the most probable slip surface or in its closest vicinity affects the slip surface location greatly. This shows how a high strength soil (e.g. the dirty sandstone in the examples used in this research - Figure 1a) can have the ability to improve the overall stability factor of safety. Lower layers of soils with higher shear strength contribute significantly towards the relocation of the most probable slip surface to a much shallower position in the slope mass leading also to a smaller failure mass (Figure 5a and Figure 6). This outcome highlights the effect of shear strength of slope material on the actual shape of the failure surface which is not taken into consideration in convention methods of slices due to pre-assumptions made on the shape of the slip surface.

3.5. Layers interface effects

Although failure generally happens in the weakest soil, in these cases (i) the slip surface tends to be located at the interfaces rather than within the soil media itself (especially in the case of analysis using the LEM) – i.e. in the cases where the slip surface is at the interface of the Mudstone with the Carbonaceous Mudstone layers (Figure 4a and also pointed at in Figure 17), and (ii) with the FEM, the slip surface linearly followed the interface lines of the two layers - i.e. in the case where the vertically downwards soil mass movement is restrained between the Dirty Sandstone and Mudstone (Figure 5b).

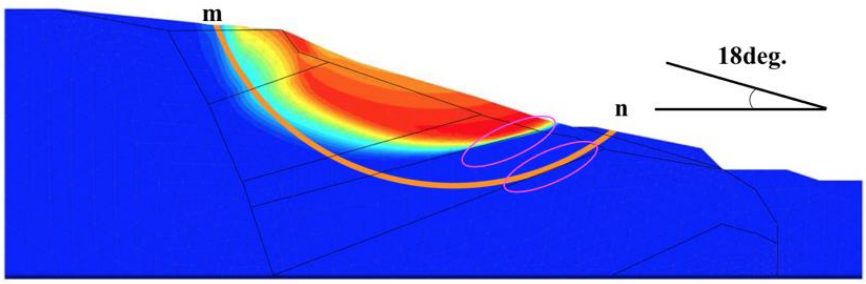


Figure 17. Case 1 before cut – showing slip surface - layer interface interaction. The soils interface where slip occurs is encircled; orange curve corresponds to LE result; colour shading corresponds to FE result (see legend in Figure 15).

The two encircled zones in Figure 17 show the location of the most probable slip surface in relation to the layer interface and how they interact. The soil mass involved in the failure (moving soil mass) restrained by the layer interface the results from LEM and FEM suggest that if the slope failure is to occur, it is very likely to happen at the interface of two different soils (Figure 15a,b and d).

Observation (ii) can be obtained from the encircled zones - FEM analysis of the probable circular failure slope surfaces (Figure 17); however, a better example for this observation will probably be from Case 2 after-cut conditions (Figure 18).

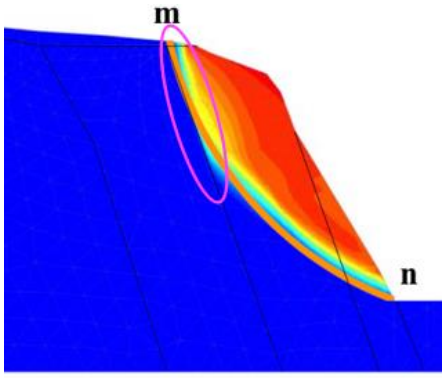


Figure 18. Case 2 after cut slip/interface interaction. The soil interface where slip occurs is encircled; bold curve corresponds to LE result; shading/contour corresponds to FE result (see legend in Figure 15).

Two observations can be made from Figure 18 concerning the effects of layers in the location of the slip surface (case 2):

- In LEM analysis, the beginning of the most probable slip surface (point ‘m’ in Figure 18) is located at the beginning of the vertical interface line between soil layers 2 and 3 (Figure 1b and Figure 4b).
- In FEM analysis, not only the starting point of the slip is located at the interface of the layers, but the slip surface continues to follow the interface line with depth until the failure surface reaches the point at which it joins the slope toe (Figure 18).

The second observation from the FEM (mentioned above) is also valid about Case 2 before-cut conditions where at the similar location as for the post-cut (Figure 18) a linear slip surface can be seen (Figure 19).

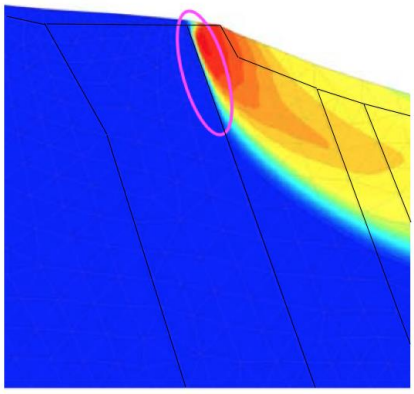


Figure 19. Case 2 before cut slip/interface interaction. The soils interface where slip occurs where encircled; shading/contour corresponds to FE result (see legend in Figure 15).

It is clear in Case 2 before-cut conditions (Figure 19) that the location of the slip surface is constrained by the presence of a layer interface. The encircled area in Figure 19 points out the linear portion of the slip surface from FEM analysis results and the slip surface follows the interface for 6.5m (Figure 19) before starting to curve to join the bottom of the slope (point “n” in Figure 5b), proving the impact the interfaces have on the restriction of the location of the slip surface.

3.6. Combined observations from LEM and FEM analysis of Case 1 and Case 2

Before the cut: *(i)* the bottom of the most probable slip surface in Case 1 (horizontally stratified layers) was located at the interface of two layers (Figure 4a and Figure 5a), *(ii)* whereas in a vertically stratified slope (Case 2), the slip surface depth in each layer depended on the

396 respective and also relative shear strength of the materials involved in the layers (the higher c'
397 and φ' in each soil layer respectively, the shallower the location of the slip surface). The first
398 case *(i)* was observed in the analysis for the after-cut conditions in Case 2 where a part of the
399 slip surface followed the vertical interface of the two adjacent layers in the vicinity of the slip
400 surface and the second *(ii)* was observed in Case 2 before the cut where the slip surface depth
401 is changing along depending on the respective layers' shear strength. After the cut in both
402 cases using FEM, arrangement of layers affected the factor of safety and the shear failure in
403 vertically stratified slopes followed a circular pattern (Figure 15d) as opposed to a more linear
404 pattern in the horizontally stratifies slope case (Figure 15c). It can be stated that based on the
405 findings of this study, when a stratified slope problem is modelled before construction,
406 simplifications regarding the stratification should be avoided as much as possible. No matter if
407 LEM of FEM analysis is implemented, detailed modelling must be considered to obtain a more
408 realistic understanding of the stability conditions of the slope in terms of the factor of safety as
409 well as the failure pattern of the slope. Indeed, if any stratified slope (most natural slopes) was
410 simplified into a homogeneous slope (even if adequately accurate properties for the equivalent
411 slope material are implemented into the analysis), the impact that the layer orientation and
412 interface would have on the stability will be inevitably ignored leading to inaccurate results
413 especially regarding the failure geometry of the slope and the locations of the most probable slip
414 surface which can significantly affect the design and lead to possible slope failures.
415
416 **4. Conclusions**
417 Limit Equilibrium and Finite Element Methods were used to analyse the stability of horizontally
418 and vertically stratified slopes with the aim of assessing their factor of safety and location and
419 shape of the most probable failure slip surface. Based on the analyses results it can be
420 concluded that in the cases studied in this paper, horizontally stratified slopes (in the settings
421 that implemented in the case studies used to conduct this research) were safer and the analysis
422 resulted in higher factor of safety values in comparison to vertically stratified slopes. However,
423 this outcome cannot be fully generalised to all geometrically non-homogeneous stratified slope
424 cases. Considering similar input and geometry parameter values the Finite Element method
425 could provide more realistic results in terms of the slip surface shape and factor of safety values

compared to conventional slope stability analysis methods as it eliminates some simplifications and predetermined failure shape assumptions. The accuracy could further improve by using finer mesh settings. Based on the study outcomes FEM analysis has led to lower factor of safety values compared to the Limit Equilibrium method; however, LEM offers a simpler and quicker way of assessing stability of slope. This makes the use of the finite element method safer for design of structures or excavations in stratified slopes. In addition, outcomes that are more accurate increase the certainty levels leading to lowered design factors of safety (although guidance in Eurocode 7 must be followed) and finally resulting in more economically feasible design. This research focuses on global failures; however, attention must be paid to local failures when using the FE Methods as these may not be always of high concern for global analysis however, they could be misleading and could easily be misinterpreted as global factors of safety.

Based on the cases studied in this research, while undertaking a stability analysis of stratified slopes, simplifications regarding the stratification (using an equivalent layer of material with equivalent strength and mechanical properties) must be avoided as much as possible to obtain more realistic representation of the behaviour of slopes; otherwise, whilst the factor of safety values against failure obtained from the analysis could be reasonably close to the reality, the real geometry of the failure of the most probable slip surface could be significantly affected meaning that horizontal or vertical stratification of the slope material layers could lead to completely different failure shapes which could impact the design work and also the construction costs involved depending on the case conditions being considered. However, if the adjacent layers have strength properties with very small differences the simplification by considering equivalent layers could be used with acceptable levels of accuracy. In cases where two layers are significantly different in terms of strength properties this could immensely affect the failure mechanism and the slip surface shape as well as the factor of safety and equivalent layer simplification can be significantly unrealistic.

The following conclusions can also be drawn from this study:

- This research shows that the slope stratification orientation influences the stability, as the factor of safety of a slope in the vertically stratified geo-material was shown to be significantly lower compared to the factor of safety value for the horizontally stratified

slope (with similar material layer combination as well as mechanical and strength properties).

- The cases studied in this research demonstrated that the layer interface planes are in cases the most vulnerable locations where part or all of the most probable slip surface could pass through due to the relative differences between shear strength parameters in the layers adjacent to the interface plane / slip surface. However, based on the equilibrium, different cases with different layer arrangements and soil strength and geometric properties may behave differently.
- If similar input and geometry parameters were used, based on the outcomes of this research, the finite element method could provide more realistic results in terms of the slip surface shapes and the factor of safety values compared to conventional slope stability analysis methods. This could be due to elimination of some simplifications including predetermined failure shape assumptions in the finite element method. The LEM analysis results obtained in this paper were also limited to circular failures.
- The LEM provides comparably reasonable results and in spite of lacking in accuracy levels slightly compared to the FEM, this method could be much simpler to use in analysing slopes. This could be considered a significant advantage provided that the method is implemented using a reasonably easy to use software with the capability of taking the effect of stratification into account

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