Available online www.jsaer.com

Journal of Scientific and Engineering Research, 2019, 6(6):80-92

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

3D Side Resistance in the Analyses of Translational Landslides

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Abstract Currently available commercial software for 3D Limit Equilibrium (LE)slope analysis do not take into account the resistance provided by the near end vertical sides of a translational slope during failure. Shear resistance provided by the end sides is significant in translational landslides because of greater area due to gentler slope inclination, and therefore, such slopes exhibit the most pronounced difference between 3D and 2D factor of safety. As a consequence, 3D factor of safety is underestimated and back calculated shear strength of the soil is overestimated.Different researchers proposed different methods to incorporate 3D side resistance in LE analysis. Using the side inclination method presented by Akhtar and Stark [1], a parametric study is carried for different slope inclinations and width to height ratios using limit equilibrium, finite element and finite difference analyses, expanding upon the existing work of Akhtar and Stark [1].

It is concluded that the difference between 3D and 2D factor of safety increases as the width to height ratio of slope decreases. Flatter slopes require a slight side inclination, while steeper slopes require a greater inclination to provide enough side resistance. A quadratic relation is presented by which appropriate side inclination can be found for any given slope inclination. Lastly, 3D/2D FS plots developed using the side inclination method are used to find the factor of safety of past translational failures and it is concluded that this method provides accurate solution within the acceptable error limits.

Keywords 3D Slope Stability, 3D Side Resistance, Side Inclination, translational Landslides

Introduction

Stability of a slope is the degree to which it can withstand its own movement. Stability is determined by the balance of stress in soil and its shear strength. Landslides occur when stress exceeds strength of soil. Most slope stability analyses are performed using 2D limit equilibrium methods which assume plane strain conditions for solution and it is assumed that the failure surface is infinitely wide due to which end effects are negligible. A 2D analysis is better for design of slopes as it yields conservative results [2], but for back-analysis of failed slopes, 2D analysis overestimates the shear strength of soil and the difference can be as high as 30% [3]. Selecting a critical cross-section for 2D analysis also becomes difficult when dealing with complex slope geometry, ground topography, and pore-water conditions. Therefore, 3D analysis is recommended for the design and back-analysis of slopes so that the true factor of safety (FS) and back-analysed shear strength is calculated by taking into account the 3D effects as well during analysis.

During a typical slope failure the shear resistance of the slope mass is mobilized along its back scarp, the lateral end sides and base of the failure surface. Translational landslides have a large difference in the mobilized shear strength on the end vertical sides and back scarp as compared to the base of the failure surface [3]. Translational slopes occur in gentler slopes, usually have an almost horizontal failure surface and near vertical end sides. Due to greater area of the end vertical sides such slopes are influenced greatly by the side resistance mobilized along the end vertical sides and can produce a huge difference in 2D and 3D FS.

Current available 3D slope stability limit equilibrium (LE) software do not take into account the shear strength mobilized along the end sides of the slope and therefore the calculated 3D FS is almost identical to the average 2D FS of a translational landslide while in reality, considering shear resistance coming from the end sides, the difference between 2D and 3D FS can be as much as 30% [3, 4]. In order to make 3D analysis more realistic, different researchers have proposed different methods for incorporating 3D end effects in the analysis of translational landslides.

This paper expands upon the parametric study carried out by Akhtar and Stark [1] to investigate the side inclination method of incorporating 3D side resistance in translational landslides and provide a comparison of 2D and 3D analyses with side resistance for various slope inclinations and width to height ratios. Results of the parametric study show that assigning a slight inclination (with respect to the vertical axis) to the end sides of the slope in a 3D LE program, provides a reasonable estimate of the side shear resistance. The resulting 3D/2D FS ratios are in agreement with finite element (FE) and finite difference (FD) analyses. Previous research from Akhtar and Stark [1] and the present work has been combined to develop an equation to find side inclination, to be used in stability program, by using inclination of slope in the equation. Lastly, the 3D/2D FS plots developed with this method are used to find the 3D FS for previous translational landslide case histories and the results from side inclination method are compared with the original results.

Past Research

Chen and Chameau [5-6] and Leshchinsky et al [7] indicated that the flatter the slope, the greater the difference between 2D and 3D factors of safety. Therefore, in translational failures, which can occur in relatively flat slopes because of the presence of underlying weak material(s), the difference between 3D FS and 2D FS is much greater. They concluded that the three-dimensional effects are more significant at smaller widths of the failure mass. Skempton [8] suggested the application of 3 factors to 2D back calculated shear strength,

1/ (1+ (KB/D))

Where K = Coefficient of earth pressure mobilized at failure

D = Average depth of failure mass

B = Average width of failure mass

He reported that the above correction factor can produce an average of 5% increase in the back-calculated shear strength which can be used to simplify the above equation to:

Su (3D) = 1.05 x Su (2D)

Stark and Eid [3] reported that translational landslides exhibit the most pronounced difference between 2D and 3D factors of safety. They considered an imaginary layer at sides of slide mass. This layer had no effect on base and back scarp of slope. Vertical sides were considered at inclination < 5^0. This imaginary layer was friction less and had cohesion equal to:

$c'_{imaginary} = Ko x σ'v x \tan ϕ'_{upper}$

Where,

$=1-\sin ϕ'_{upper}$.

Arellano and Stark [4] proposed the application of external horizontal and vertical forces (Sx and Sy) equal to the shear resistance due to at-rest earth pressure (k_o) acting at the centroid of the two end sides. The at-rest earth pressure acting on the vertical side of the slide mass, σ'x, was determined by:

σ'x = σ'v x Ko

The coefficient of earth pressure at rest was calculated as:

$Ko = 1-\sin(ϕ'_{upper})$

Shear resistance due to at-rest pressure acting on the end vertical sides of the slide mass, S', was assumed to act parallel to base of the failure surface and estimated by:

$S' = σx \times \tan(ϕ'_{upper})$

Only upper layer was considered for centroid calculation while area below and between upper and lower material was not considered. Arellano and Stark [4] reached the conclusion that lower width to height ratio slopes had higher 3D/2D FS by at least 20% which meant the effect of side resistance increases with decrease in width of slope similar to Chen and Chameau [5], while for the same W/H ratio, a decrease in slope inclination increases 3D/2D FS due to greater area of end sides.

Eid at el. [9] carried out a similar parametric study and developed 2D and 3D stability charts for slopes susceptible to translational failure. Horizontal and vertical forces 'S_y' and 'S_z' were applied on the centroids of the end sides which were components of shear resisting force 'S'. The procedure of incorporating 3D side resistance in the analysis was different than that of Arellano and Stark [4] as in this method the earth pressure forces and pore water pressure forces were calculated separately and applied at the centroid.

Akhtar and Stark [1] suggested slightlyinclining the end sidesof the sliding mass with the vertical which modeled the shear strength along the sides of the slope in the software. This method is much easier to model and the results were in accordance with the finite element and finite difference solutions.

Research Methodology

The main objective of this study is the extension of the research carried out by Akhtar and Stark [1] by carrying out analyses for different slope inclinations and checks the accuracy of the side inclination method by applying the current 3D/2D FS plots to previous case studies related to translational failures. Table 1 outline the material properties used for the current parametric study to develop the 3D/2D FS plots. Akhtar and Stark [1] carried out research for slopes with inclinations of 1H: 1V, 3H: 1V, 5H: 1V and height of the slope was kept constant at 10 meters. In the present research the slope inclinations are varied as 1.25H: 1V, 1.75H: 1V, 2.5H: 1V and 4H: 1V. Combining both research works presents a more holistic picture of this method's applicability. For each slope inclination the following parameters are varied:

- Side Inclination: 3 Degrees ~ 8 Degrees.
- Width-Height Ratio: 1, 1.5, 2, 4, 5, 6, 8, 10, 12.

The ground water table was placed at the height of H/2 as measured at a distance of L from toe of slope and decreases linearly to zero at the toe. The head scarp is assumed to be inclined at 45°+ $\phi_{up}/2$ from the horizontal to stimulate active earth pressure condition where "ϕ_{up}" is friction angle of upper material [4]. This inclination would result in minimum lateral earth pressure conditions and minimum shear resistance along the back scarp at time of failure. The bottom of failure surface exceeds 0.2m in the lower material and parallel to the upper surface of lower material until it daylights at toe of slope. This is done to ensure that the failure surface passes from the weaker material [4]

Table 1: Properties of Parametric Model

Parameter	Unit	Upper Material	Lower Material	Bottom Block	End Blocks[2]	Interface[3]
Unit Weight[1], ʹY	(kN/m^3)	17	18	18	25	-
Cohesion, c'	(kPa)	0	0	0	0	0.05
Friction Angle, ϕ'	(^{o})	30	8	40	45	30
Dilation Angle, Si, Ψ	(^{o})	0	0	0	0	-
Young's Modulus	(kN/m^2)	3x10^4	3 x10^3	3 x10^5	3 x10$^{6`}$	-
Poisson's Ratio, ϑ	-	0.35	0.35	0.35	0.35	-
Bulk Modulus	(kN/m^2)	3x10^4	3 x10^3	3 x10^5	3 x10$^{6`}$	-
Shear Modulus	(kN/m^2)	1x10^4	1 x10^3	1 x10^5	1 x10$^{6`}$	-
Normal Stiffness	(kN/m^2)	-	-	-	-	1 x10^4
Shear Stiffness	(kN/m^2)	-	-	-	-	1 x10^3

[1]Density rough (kg/m^3) = Unit weight x (1000/9.81)

[2]End blocks in PLAXIS analysis use same properties as slope.

[3]Only used in FLAC analysis.

Composite general/wedge surface is used for the analysis in CLARA-W. Software is instructed to use single trial surface for analysis. The software first builds column analogy as per input provided. Then all the cross sections are added and software makes a 3D model and the failure surface is defined by the input cross sections. The software uses orthogonal interpolation to convert all 2D cross sections into a 3D model. The analysis is done by Janbu's method for the current analysis because it provides a quick and accurate solution for non-circular failure surfaces and it does not have convergence problems as other rigorous methods like Spencer [10] and Morgenstern and Price [11] have. After that, the software computes the factor of safety and gives in the form of slide surface.

Parametric Model

The parametric model used in this study is modeled with the help of case studies that had undergone translational failure. It is the same parametric model used by Arellano and Stark [4] and Akhtar and Stark [1] as shown in figures 1-4.

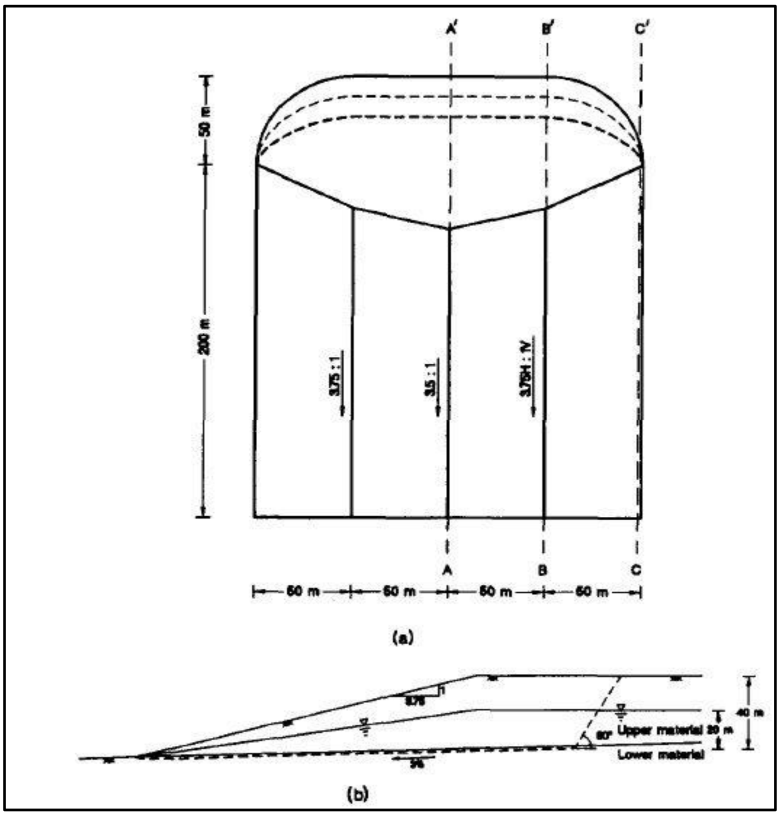

Figure 1: Plan view and cross section of slope model

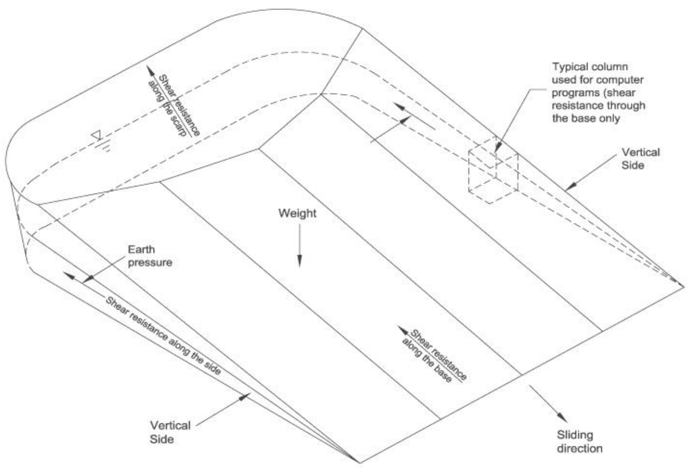

Figure 2: 3D View of the model

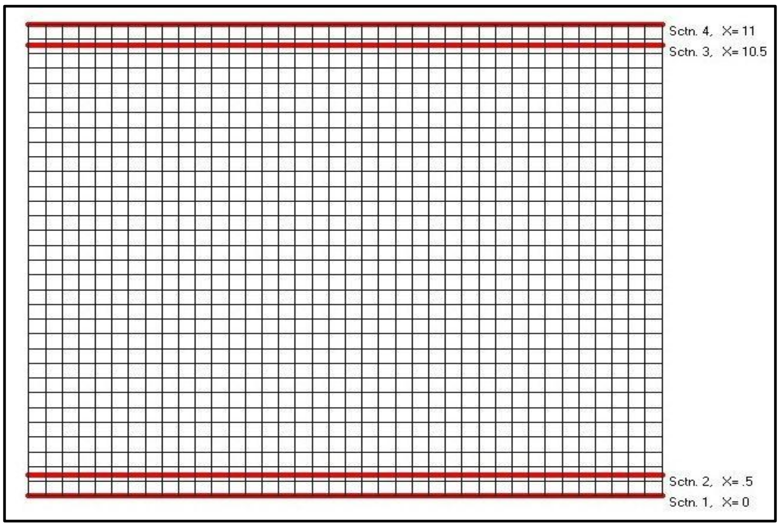

Figure 3: Location of cross-section in modified model (CLARA-W)

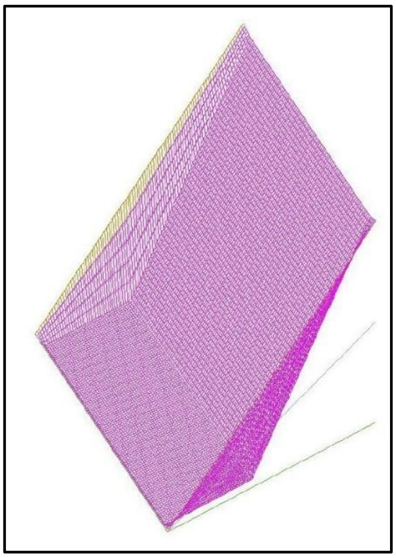

Figure 4: Slide geometry of modified model with Side Inclinations (CLARA-W)

The 3D analysis software used for this study is CLARA-Was it is more user-friendly and also satisfies more conditions of equilibrium compared to other commercial 3D software. Also CLARA-W has capability of representing piezo-metric surface and external loads. Thus CLARA-W is used in this study for 2D and 3D analysis. All the 3D slope stability softwares involve motion in one direction only and that is also assumed here for this study. CLARA-W utilizes the 3D extension of Bishop's simplified method and Janbu's simplified method for solution [12]. The assumptions to make analysis problem determinate are same as for 2D methods [13-14].

For Bishop's simplified method, inter-column shear forces were assumed to be negligible. The individual vertical force equilibrium of columns and overall moment equilibrium condition were sufficient for determining all unknowns. Horizontal force equilibrium was neglected in both longitudinal and transverse direction. Factor of safety was calculated for a common horizontal axis parallel to x-direction. Janbu's simplified method assumes that vertical and horizontal force equilibrium is sufficient to find all unknowns and therefore moment equilibrium is not satisfied. Factor of safety is obtained from horizontal force equilibrium.

PLAXIS 3D Tunnel V.2 [15] was used for 2D and 3D FE analyses, while 2D and 3D FD analyses were performed using FLAC [16] and FLAC3D [17], respectively.

Analysis and Results

Table 2-5 show the 3D/2D factors of safety using Limit Equilibrium analyses for different slope inclinations.

For each inclination the W/H ratio is varied from 1 to 12 and side inclination from 3-8 degrees.

Table 2: Ratio of 3D/2D Factor of safety ratios of slope 1.25H: 1V

Slope Inclination	Width W (m)	Height H (m)	W/H -	Length L (m)	3D/2D FS Janbu 3°	4°	5°	6°	7°	8°
1.25H:1V	10	10	1	12.99	1.18	1.21	1.26	1.32	1.32	1.26
	15	10	1.5	12.99	1.13	1.16	1.18	1.21	1.21	1.21
	20	10	2	12.99	1.11	1.13	1.13	1.18	1.16	1.16
	40	10	4	12.99	1.05	1.08	1.08	1.11	1.08	1.08
	50	10	5	12.99	1.05	1.05	1.05	1.08	1.08	1.08
	60	10	6	12.99	1.05	1.05	1.05	1.05	1.05	1.05
	80	10	8	12.99	1.03	1.05	1.05	1.05	1.05	1.05
	100	10	10	12.99	1.03	1.03	1.03	1.05	1.05	1.05
	120	10	12	12.99	1.03	1.03	1.03	1.03	1.03	1.03

Table 3: Ratio of 3D/2D Factor of safety ratios of slope 1.75H: 1V

Slope Inclination	Width W (m)	Height H (m)	W/H -	Length L (m)	3D/2D FS Janbu 3°	4°	5°	6°	7°	8°
1.75H:1V	10	10	1	27.03	1.30	1.48	1.43	1.54	1.52	1.54
	15	10	1.5	27.03	1.22	1.33	1.3	1.37	1.35	1.37
	20	10	2	27.03	1.15	1.26	1.22	1.28	1.26	1.28
	40	10	4	27.03	1.09	1.13	1.11	1.15	1.13	1.15
	50	10	5	27.03	1.07	1.11	1.09	1.13	1.11	1.13
	60	10	6	27.03	1.07	1.09	1.09	1.11	1.09	1.11
	80	10	8	27.03	1.04	1.07	1.07	1.09	1.07	1.09
	100	10	10	27.03	1.04	1.07	1.04	1.07	1.07	1.07
	120	10	12	27.03	1.04	1.04	1.04	1.07	1.04	1.07

Table 4: 3D/2D Factor of safety ratios of slope 2.5H: 1V

Slope Inclination	Width W (m)	Height H (m)	W/H -	Length L (m)	3D/2D FS Janbu 3°	4°	5°	6°	7°	8°
2.5H:1V	10	10	1	27.03	1.43	1.72	1.66	1.79	1.74	1.81
	15	10	1.5	27.03	1.31	1.48	1.43	1.53	1.50	1.55
	20	10	2	27.03	1.22	1.36	1.33	1.40	1.41	1.41
	40	10	4	27.03	1.10	1.19	1.16	1.21	1.19	1.21
	50	10	5	27.03	1.09	1.14	1.12	1.16	1.16	1.17
	60	10	6	27.03	1.07	1.12	1.10	1.14	1.12	1.14
	80	10	8	27.03	1.05	1.09	1.07	1.10	1.10	1.10
	100	10	10	27.03	1.05	1.07	1.07	1.09	1.07	1.09
	120	10	12	27.03	1.03	1.05	1.05	1.07	1.07	1.07

Table 5: 3D/2D Factor of safety ratios of slope 4H: 1V

Slope Inclination	Width W (m)	Height H (m)	W/H -	Length L (m)	3D/2D FS Janbu 3°	4°	5°	6°	7°	8°
4H:1V	10	10	1	45.45	1.63	2.10	1.99	2.15	2.09	2.15
	15	10	1.5	45.45	1.47	1.74	1.65	1.78	1.74	1.81
	20	10	2	45.45	1.32	1.56	1.49	1.59	1.56	1.62
	40	10	4	45.45	1.15	1.28	1.24	12.95	1.28	1.31
	50	10	5	45.45	1.13	1.22	1.19	1.23	1.23	1.26
	60	10	6	45.45	1.10	1.18	1.17	1.19	1.19	1.21
	80	10	8	45.45	1.08	1.14	1.12	1.17	1.14	1.15
	100	10	10	45.45	1.06	1.10	1.09	1.12	1.12	1.13
	120	10	12	45.45	1.05	1.09	1.08	1.09	1.09	1.1

From the analysis tables, it can be seen that for the same W/H ratio, FS increases as side inclination increases which implies that more columns are included in the analysis on the end sides, at the bases of which shear strength is mobilized and models higher shear strength for the slope, resulting in the increase of3D FS. For the same side inclination, increase of W/H ratio decreases the 3D/2D FS ratio. This is in accordance with previous research of Lafebvre et al. [18], Arellano and Stark [4] and Chen and Chemeau [5-6], that for narrow slopes, 3D end effects greatly influence the factor of safety (FS). Conversely, for wider slopes where the conditions approach plane strain conditions, difference between 2D and 3D analysis becomes less and the 3D/2D FS ratio is almost reaches unity.

The 3D/2D factors of safety from LE analyses (Clara-W) are computed and compared with that of FD(FLAC-3D) and FE (PLAXIS-3D) analyses for comparison. For all results the ratios of 3D/2D obtained from FD analysis are higher than ratios of FE and serve as upper bound and lower bound solutions. Figures 5-11 show the trend of 3D/2D ratio of safety factor for each slope inclination, as it decreases with the increase in W/H ratio. The 3D/2D FS plots from Akhtar and Stark [1] are also presented to fill the gap between results of different slope inclinations.

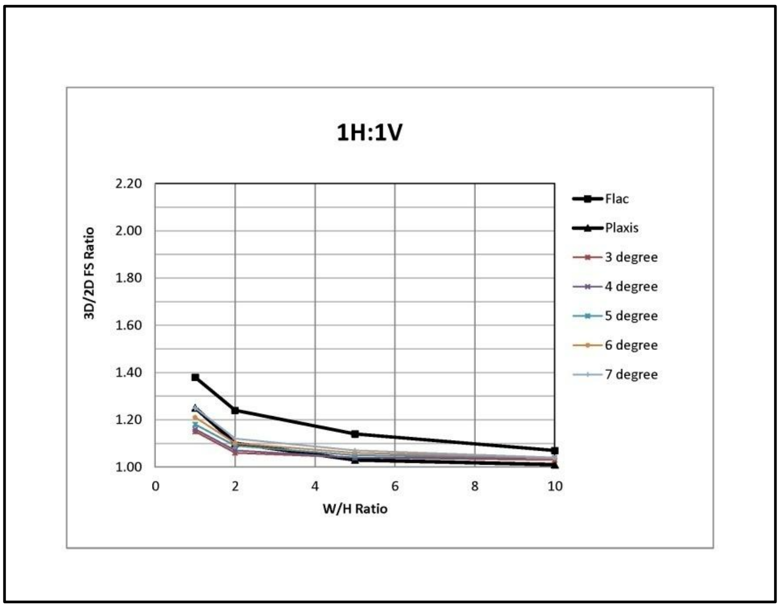

Figure 5: 3D/2D FS Ratios for Slope 1H: 1V [1]

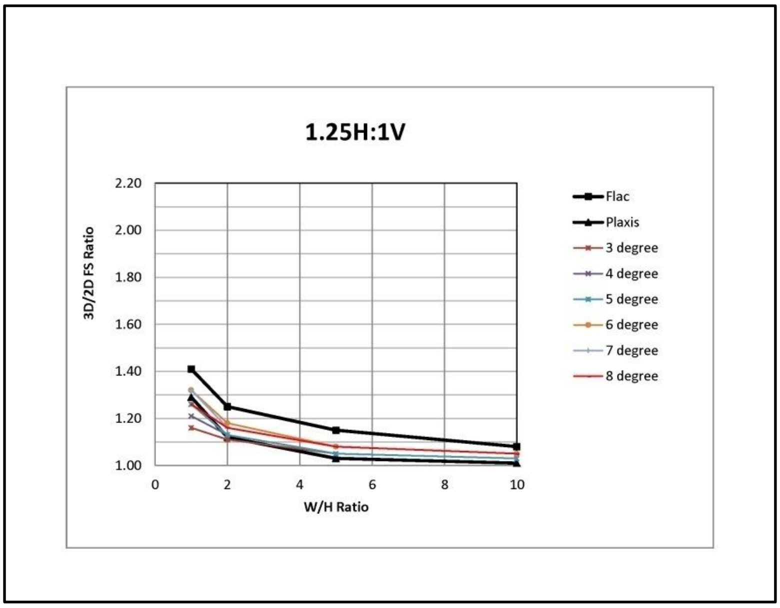

Figure 6: 3D/2D FS Ratios for Slope 1.25H: 1V

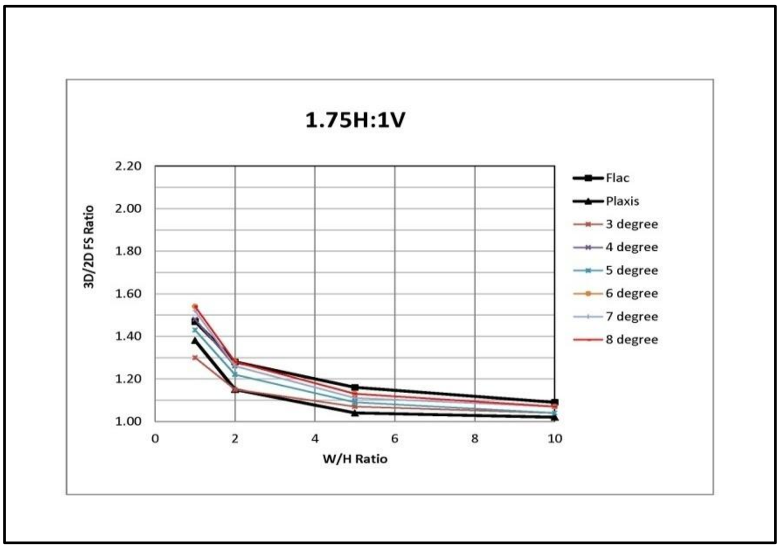

Figure 7: 3D/2D FS Ratios for Slope 1.75H: 1V

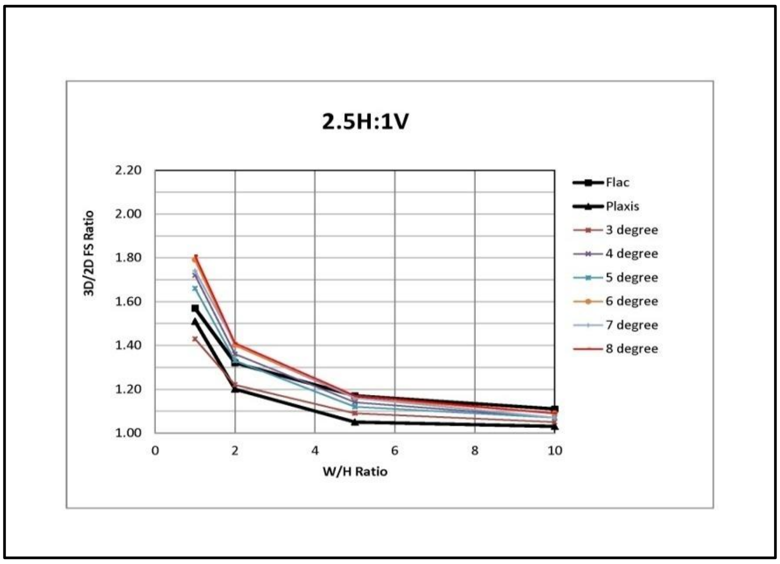

Figure 8: 3D/2D FS Ratios for Slope 2.5H: 1V

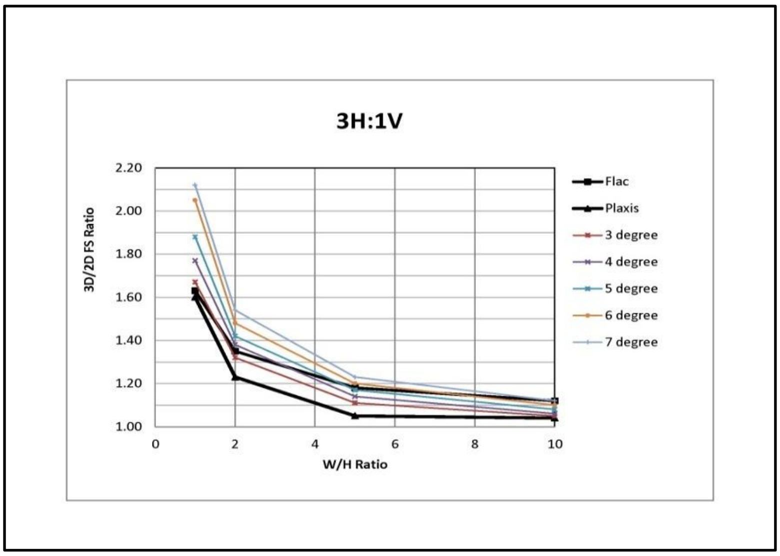

Figure 9: 3D/2D FS Ratios for Slope 3H: 1V [1]

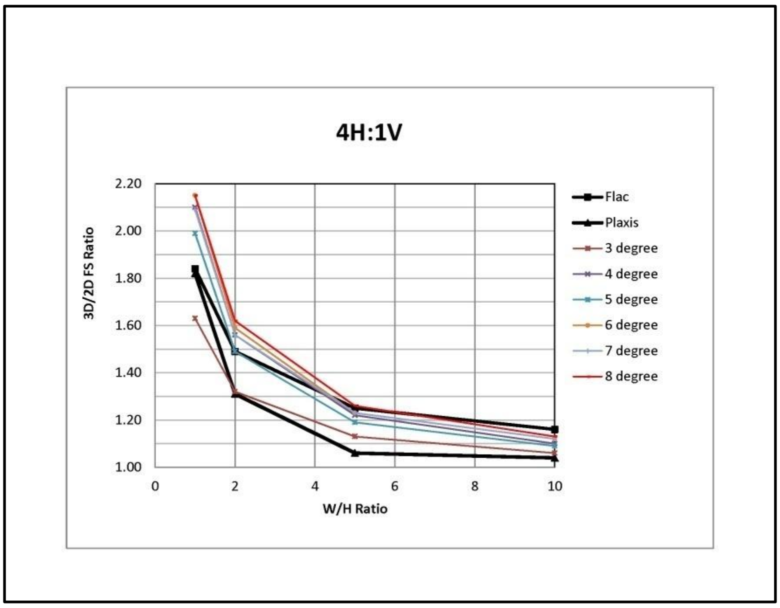

Figure 10: 3D/2D FS Ratios for Slope 4H: 1V

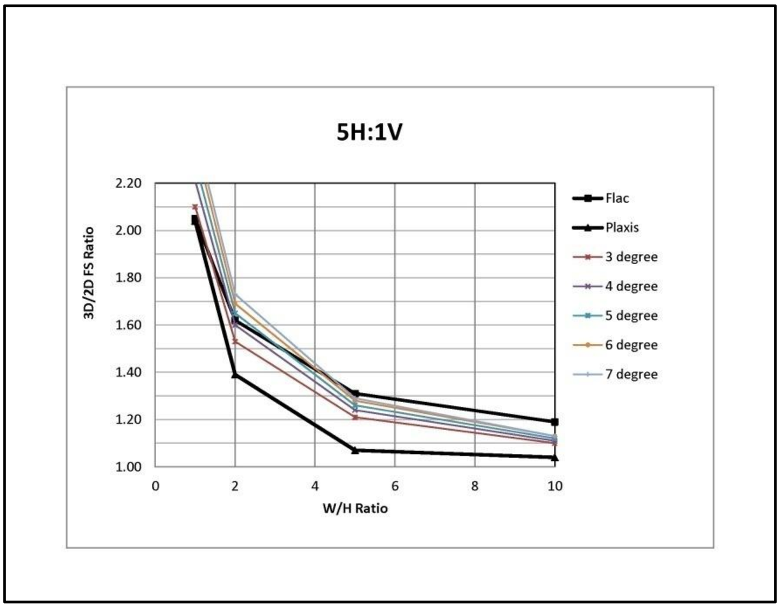

Figure 11: 3D/2D FS Ratios for Slope 5H: 1V [1]

The same side inclination angle for all four slope inclinations, does not yield 3D/2D FS ratio that is within the upper and lower bound values set by FE and FD analyses. As an example, for 1.25H: 1V slope, a side inclination of 6° is required where as a side inclination of 3° may be required for 4H: 1V slope. Flatter slopes i.e., 4H: 1V have higher 3D/2D FS values than for steeper slopes which is because of larger area of the sides in flatter slopes.

The analyses carried out by Akhtar and Stark [1], involved slope inclinations of 1H: 1V, 3H: 1V, 5H: 1V and the appropriate side inclination angles were evaluated for each slope inclination by LE analyses compared to FE and FD analyses. This study extends the previous work of Akhtar and Stark [1] and provides analyses for slope inclinations of 1.25H: 1V, 1.75H: 1V, 2.5H: 1V, 4H: 1V and completes the gap in the previous work by Akhtar and Stark [1]. Table 6 and figure 9 illustrate the data of Akhtar and Stark [1] and the present research, and shows that both studies support each other.

Table 6: Combined result of Akhtar and Stark [1] and current research

Sr. No.	Slope inclination (xH:1V)	Slope inclination (degree)	Side inclination (degree)
1	1	45.00	7
2	1.25	38.66	6
3	1.75	29.74	5
4	2.5	21.80	3
5	3	18.43	3
6	4	14.04	3
7	5	11.31	3

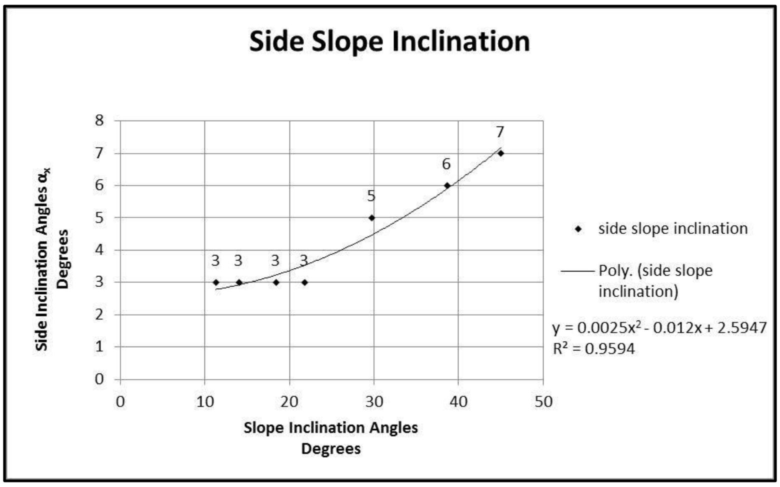

Figure 12: Combined result of Akhtar and Stark [1] and current research

Regression analysis was carried to find the relation between slope inclination and side inclination. A second degree polynomial curve was found to be best suited for this bilinear data with an R^2 value of 0.9594 as shown figure 12. By using the following equation, one can conveniently find the appropriate side inclination needed for a translational slope based upon its average slope inclination.

$$Y = 0.0025X^2 - 0.012X + 2.5947 \quad (1)$$

Where

Y= side inclination angle (degrees)

X= average slope inclination angle (degrees)

Case Studies

Three case studies, Kettleman Hills Waste Landfill [6], San Diego Landslide [3] and Mokra Gora Landslide [20] are analysed with the 3D/2D FS plots developed by using the side inclination method in the current study, and previous study of Akhtar and Stark [1], and compared with the original results of the case studies to check the authenticity of this method.

The methodology of the analysis is to find the suitable side inclination, with the help of equation 1, which must be assigned to the end sides of the slope for incorporating side resistance. The average slope inclination and width-to-height (W/H) ratio for the slope under consideration is assessed. 3D/2D factor of safety for the slope is then interpolated from figures 5-11 and finally 3D factor of safety is calculated by using the average 2D factor of safety for that slope.

Kettleman Hills Landslide [19]

Landfill Unit B-19, covering an area of about 36 acres, formed part of a Class I hazardous-waste treatment-and-storage facility at Kettleman City, California. The waste repository essentially consisted of a very large oval shaped bowl excavated in the ground to a depth of about 100 feet, into which the waste fill was placed. The "bowl" had a nearly horizontal base (2% slope), and side slopes of 1:2 or 1:3 (vertical: horizontal). To prevent the escape of hazardous materials into the underlying and surrounding ground, the base and sides of the excavation were lined with a multilayer system of impervious geomembranes, clay layers and drainage layers. The system included geotextile filter fabric, granular leachate-collection layers, plastic geonet-drainage layers, HDPE (high-density polyethylene) geomembrane liners, and compacted clay layers.

A slope-stability failure occurred that resulted in lateral displacements of the surface of the waste fill of up to 35 ft. and vertical settlements of the surface of the fill of up to 14 ft. The slope had a height of 90 ft, width of 560 ft and average inclination of 18° as evident from the sections in figure 10.The author reported that the average 2D factor of safety of the overall fill mass from ten representative sectionswas estimated to be F.S~1.1, while a 3D analysis using Multi-Block Analysis method resulted in a factor of safety of 1.06.

Using equation 1, for a slope inclination of 18°, the side inclination is calculated as 3° while the W/H ratio of the slope is 6.22. Using3D/2D FS plots from the current research, the 3D/2D FS comes out to be 1.095 for this slope. Using the average 2D FS of 1.1, 3D FS is calculated as 1.122 which has an error of 5.5%, from the original 3D FS within the acceptable error limit of 6% [21].

San Diego Landslide [3]

The landslide area composed of claystone and sandstone with an almost horizontal failure slip surface, measured with inclinometers and ground water levels measured with piezometers. In the 3D slope stability analysis, sides of the sliding mass were taken to be vertical, while the back scarp was assumed inclined 60° from the horizontal to stimulate an active earth pressure condition.The average 2D factor of safety was 0.92 for 44 different cross sections, however when the slope was re-analysed by including resistance of vertical sidesusing the “imaginary layer” method it yielded a 3D FS of 1.02, an increase of almost 9% in the 3D factor of safety.

Similar to the previous example, equation 1 is used to find the appropriate side inclination of 3°needed for San Diego Landslide which had an inclination of 15.95° and a W/H ratio of 6.5. Using the 3D/2D FS plots and interpolating we get the 3D/2D FS value of 1.097. Using 2D FS of 0.92, we get a 3D FS value of 1.01 which is almost equal to the value reported by Stark and Eid [3] using the “imaginary layer” method as well as Arellano and Stark [4] reported the same value by using their method of side forces.

Mokra Gora Landslide [20]

Sliding occurred along the contact of different lithological layers. In the frontal and partly in the central parts of the landslide, sliding occurred along the contact of diluvial debris and surface weathered zone of flysch sediments, while the surface weathered zone was affected by sliding in the foot part of the landslide. The maximum length of landslide was 135m, the width was between 40m and 65m and maximum height was about 5.5.

For the critical cross section of the slope, 2D factor of safety using Janbu’s method was determined to be 1.0, while 3D analysis, using equivalent sliding body method and considering lateral confinement, gave a factor of safety of 1.06.

Using equation 1, we find the suitable side inclination for this slope geometry to be 3° for a slope inclination of 19°. An average width of 55m is used to find the W/H ratio of 10. From the 3D/2D plots, a 3D/2D FS of 1.049 is calculated. 2D FS was 1.0, therefore 3D FS comes out to be 1.05 by side inclination plots from the current research which is close to the author’s reported value of 1.06.

Summary of Work

The above examples from previous case studies demonstrate that the side inclination method is accurate enough to be used as a method of 3D slope stability for translational landslides and also validates the importance of performing a 3D analysis especially for translational slopes. The highest error is found in the result of Kettleman Hills landfill of 5.5%. This could be due to the 3D method of solution used by Seed et al [19], at the time of which 3D analysis was not very common and this method might have errors of its own.

It should be noted that the above examples are solved only for demonstration purpose and it is imperative to develop slope specific 3D/2D FS plots by side inclination method considering site specific geometry, pore-water conditions and material properties for proper solution.

Conclusions

Commercially available software for 3D slope analysis does not take into account the resistance provided by the ends of the slope during a slope failure. The downside of this is that 3D analysis effectively becomes 2D analysis and the 3D FS is underestimated while back-calculated shear strength is underestimated. Different researchers like Stark and Eid [3], Arellano and Stark [4] etc., tried to incorporate end effects in 3D slope modelling as easily as possible and make the 3D analysis effective in practical application.

The current research is a step further in making 3D slope analysis of translational landslides more accessible and accurate as well as expands upon previous study by Akhtar and Stark [1] and validates the side inclination method by comparing it with past case studies. The following conclusions are drawn from this research:

- The side inclination method by Akhtar and Stark [1] is applicable to failure of slopes in translational failure mode and gives reasonably accurate solutions compared to FE and FD analyses and past case histories.
- 3D/2D factors of safety for FD analysis are higher than FE analysis and these can be used as upper and lower limits for 3D/2D FS obtained from LE analyses.
- The 3D/2D FS ratio is greater for higher side inclination angles (i.e., 8°) and decrease with the decrease of side inclination angles. This advocates that the inclination added to the sides provide 3D side resistance.
- For flatter slopes, a small tilt of sides is enough to provide the necessary resistance while for steeper slopes greater inclination of sides is needed.
- Flatter slopes have higher 3D/2D FS values than for steeper slopes, keeping height of slope constant. This is because of larger area of the end sides in flatter slopes.
- The 3D/2D FS ratio is greater for narrow slopes and decrease inversely with the increase in W/H ratio; hence 3D end effects are significant for narrow slopes.
- For wide slopes of W/H >10, the 3D/2D FS ratio is closer to unity, which implies that 3D end effects become less significant in slopes of larger widths i.e., analysis is approximating towards plane strain conditions.
- A quadratic relation between side inclination and slope inclination is presented which can be used to find side inclinations for any given slope inclination.
- Compared with solutions from past slope failures, side inclination method gives 3D factor of safety within the acceptable error limit of 6%.
- This method should be adopted in the solution of to real world translational slope problems to further authenticate its accuracy.
- A comparative study might be carried out between all the methods of incorporating end side resistance to develop and establish a single solid method to be used in the limit equilibrium analyses of translational landslides.

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