Slope Stability Analysis Under External Static Surcharge

Soumia Merat, Lynda Djerbal(✉), and Ramdane Bahar

LEEGO, University of Science and Technology Houari Boumediene, 32 El Alia, 16111, BP Algiers, Algeria
ldjerbal@yahoo.fr

Abstract. In the assessment of slopes, factor of safety values still remain the primary indexes for determining how close or far slopes are from failure. Limit equilibrium and finite elements methods are among the most popular methods of slope analysis. Both methods were used to analyze homogeneous and inhomogeneous slopes. However, Limit equilibrium methods are relatively simple and suffer from many assumptions compared with finite element analysis. Recently, as computational techniques advance, more and more attention has been paid to the slope stability evaluations using finite element methods (FEM). This article demonstrates a finite element approach to analyze the response of homogeneous and layered slopes. A detailed parametric analysis is presented to study the effect of surcharge (it can be an imposition of building load….etc.) on the stability of the slope. In regard with these results it is seen that the factor of safety increases with increase in soil properties, groundwater depth, slope length, distance from the crest of slope. However, it decreases with increase in surcharge intensity, increase of weak soil layer thickness and increase of slope angle and slope height.

Keywords: Slope stability · Surcharge · Finite element method
Factor of safety · Layered slope

1 Introduction

Slope stability analysis is one of the most important areas of interest in geotechnical engineering. The embankment slope can be failure due to its geotechnical properties, geological structure conditions, other internal factors and the various external conditions such as depth of water, seismic loads, surcharge, etc. The evaluation of stability of the natural slopes becomes very essential for the safe design, especially when the slopes are situated close to residential areas or when structures are built on these slopes. The objective of our work is the study of the stability of the slope the under static loads combining with various parameters using the software Plaxis^{2D} 2015 for finite element analysis.

Many slope stability analysis methods and tools have also been developed over the last 50 years. The main interest of slope stability analysis is typically to determine a factor of safety (FS) against slope failure (Wei et al. 2010). Each stability analysis method differs from the others in some of the basic assumptions, but most of these

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methods will give similar factors of safety/slip surfaces for normal cases, which are sufficient for normal engineering uses (Cheng and Lau 2008).

Recently, as computational techniques advance, more and more attention has been paid to the slope stability evaluations using finite element methods (FEM) which has become popular for the analysis of slopes and has been successfully implemented to calculate Factor of Safety for more than a decade (Dawson et al. 1999; Griffiths and Lane 1999; Hammah et al. 2004).

The paper deals with the assessment of slope stability under static load taking into account a number of influencing parameters such as: ground water level (GWL), slope geometry, soil properties, distance to crest…etc. The effect of each factor is discussed in this paper. Consequently, the objectives of the present study are: **(i)** to investigate the effect of slope geometry on the factor of safety, **(ii)** to show the effect of ground water position and surcharge intensity, **(iii)** to evaluate the influence of homogeneous and a layered soil (in term of mechanical properties) on the stability of slope, **(iv)** to assess the effect of the position of surcharge on the factor of safety.

2 Slope Stability Analyses by FEM and Boundary Conditions

FEM is a powerful numerical tool for solving many engineering problems and mathematical physics. Due to rapid development of computer technology, FEM has gained increasing popularity over the traditional methods in geotechnical engineering (Moni and Sazzad 2015).

The geometric model (Fig. 1) is incorporated in the Plaxis^{2D}. After incorporating the model, the properties of soil is assigned for the specified interface and the material model is set to be the Mohr–Coulomb model. The two lateral boundaries were allowed to move only in the vertical directions (roller type: restrained against horizontal movement) whereas the bottom boundary was completely restrained and fully blocked from movement (Closed: restrained in both horizontal and vertical direction).

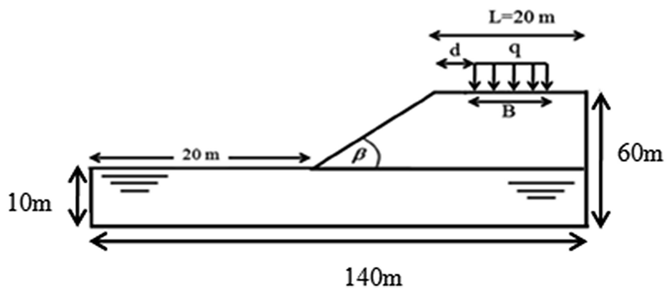


Fig. 1. Geometry of the numerical model of slope considered in the present study

In this paper for Finite Element Method analysis, meshes are generated and set to be medium with 167 elements and 1435 nodes. After generating the meshes, and assigning related properties, the stability analysis is performed then a surcharge is added on the terrain of slope (Griffiths and Lane 1999).

3 Geometry and Soil Parameters

In this study, a slope with an inclination angle of 26.56° (2/1) to the horizontal plane and a height of 50 m is considered (Fig. 1). The groundwater table is assumed to be at the ground surface. The soil type was specified as «Marl» of Azazga. The soil properties related to the unsaturated soil were taken as given by van Genuchten (1980) (Sun et al. 2015).

The surface soil layer behavior was modeled as linear, elastic-perfectly plastic the material by using Mohr–Coulomb model and analyzed using soil parameters giving by undrained tests. The FEM analysis using Mohr-Coulomb material model requires parameters such as modulus of elasticity, poison's ratio, angle of internal friction and cohesion.

The properties of soil used in the present study are presented in Table 1. Two types of soils are considered. Soil-1 (Marl) is used in the analysis of a slope of homogeneous soil. Whereas soil-2 (clayey loam) is used for thin layer of slope of layered soil. Both Soil-1 and Soil-2 are used in the analysis of a slope of layered soil.

Table 1. Summary of soils parameters of Azazga soil layer used in the FEM

Soil layer	Soil model	γunsat (kN/m^3)	γsat (kN/m^3)	ν	C (kpa)	φ (°)	K (m/min)	E′ (Kpa)
Soil 1 (Marl)	Mohr-Coulomb	18	19	0.33	165	14	$Kx = 10^{-5}$ $Ky = 10^{-5}$	$4 * 10^6$
Soil 2 Clayey loam	Mohr-Coulomb	15.8	17.8	0.33	55	15	$Kx = 10^{-3}$ $Ky = 10^{-3}$	$4.038 * 10^5$

ν: Poisson ratio, C: Cohesion, φ': Friction angle, K_x and K_y: Horizontal and vertical hydraulic conductivity respectively, E′: Young modulus.

4 Parametric Analysis

A parametric study is carried out to analysis the effect of distributed surcharge (***q***) on the stability of the slope in terms of the factor of safety. The distribution of weight along slope and loading the top of a slope may have great influence on stability (Noroozi and Hajiannia 2015).

There are many factors affect the stability of the slope. Usually a slope fails by the change in location of surcharge, magnitude of surcharge, variation of sloping angle, etc. and this paper focuses on the level water table, geometry of the slope (length, height, slope angle…etc.), variation of mechanical properties (cohesion and friction angle), surcharge range, surcharge distribution width, distance to crest (Fig. 2).

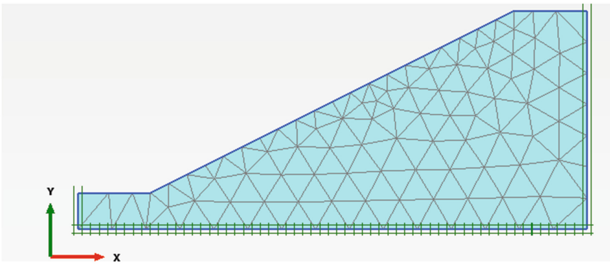


Fig. 2. Model slope with triangular medium mesh

4.1 Effect of Ground Water Depth

Before applying a surcharge to the model, we tried to understand the effect of ground water level on the slope stability; we had decreased the ground water level by a step of 5 m. The preliminary model indicated, as obvious, that the stability of the slope is found to increase if the water table is located at deeper locations: for a depth close to the soil surface, the factor of safety seems to be smaller (at 5 m depth, FS took a value **1.56**). However, it increases when the ground water level is located at a deeper layer (ex: at 50 m depth, it equals to **2.08**) and it's linearly proportional as shown in Fig. 3.

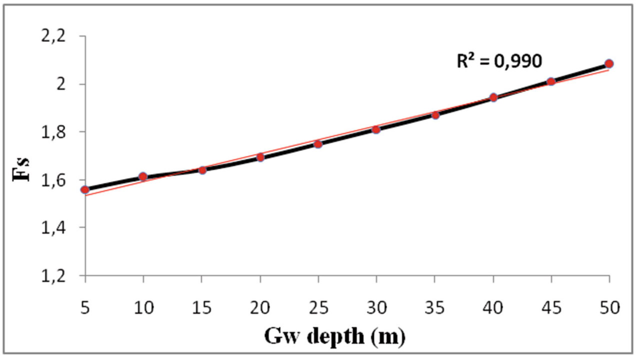


Fig. 3. Variation of factor of safety (FS) for different values of ground water depth

4.2 Effect of Ground Water Level and Surcharge

A combined study used to show the effect of ground water level and surcharge on the slope stability. It is noted that the factor of safety appears to be proportional with ground water depth (polynomial second order) for the different applied surcharges where the safety factor is higher for lower surcharge values and deeper ground water locations, and it will be smaller if the case is the opposite (unfavorable) as shown in Fig. 4. For q = 100 KN/m^2 and ground water table located at 50 m depth, FS is equal to 1.9, while it took the value 1.01 if q = 700 KN/m^2 and the ground water table is found at 5 m depth.

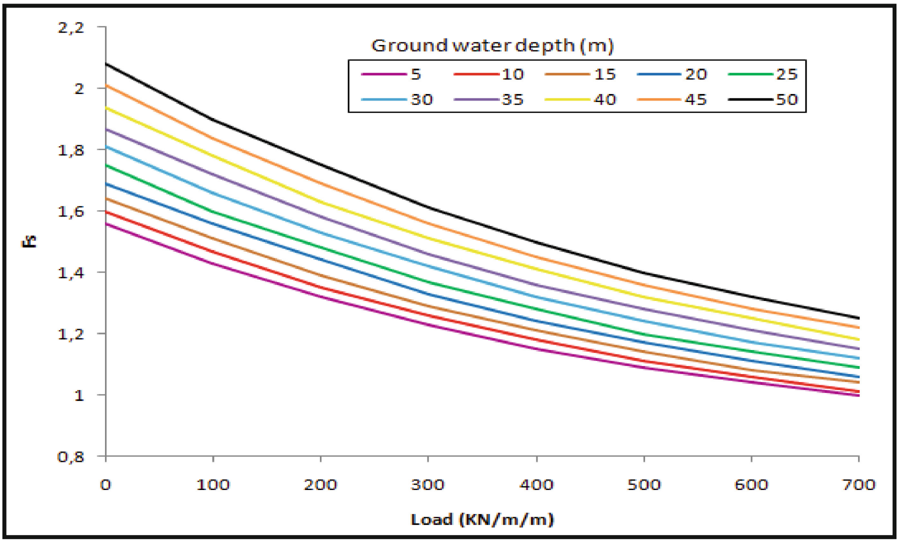


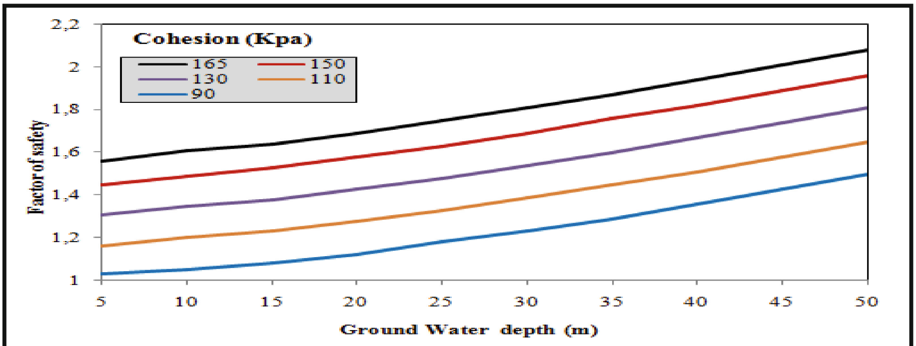
Fig. 4. Variation of factor of safety (FS) with surcharge (q) for different ground water depth

4.3 Effect of Soil Properties (Cohesion and Friction Angle)

In addition to the effect of ground water level, the mechanical properties of soil layer have an important influence on slope stability, i.e., a soil with high mechanical properties (ex: cohesion, friction angle) represents more stable case (with a high safety factor). In other words, the greatest factor of safety values are a combination of more favorable parameters of cohesion and friction angle (Chaudhary et al. 2016). The initial factor of safety for soil-1 (2.08) is greater than safety factor of soil-2 (1.29) for initial values of cohesion and friction angle because the soil-1 had stronger mechanical properties (C′ and φ') than soil-2.

As an example, when the soil 2 took the initial values both of cohesion and friction angle (C′ = 55 kPa; $\varphi' = 15°$), FS is found to be 1.189. If the cohesion value is doubled and tripled to take the following values (2C′ = 110 kPa; 3C′ = 165 kPa), FS is found to be 1.617 and 2.045 respectively. As expected, greater the cohesion, greater is the safety factor. It can be seen from the figure that there is significant increase in the safety factor with increase in cohesion (Fig. 5). If the friction angle is doubled and tripled to take the following values ($2\varphi' = 30°$; $3\varphi' = 45°$), FS is found to be 1.93 and 2.827 respectively. The soil friction angle has higher influence on the factor of safety than cohesion.

For different values of cohesion and friction angle, a comparison between a model without load and a loaded one reveals that the surcharge decreases the stability of the slope as shown in Figs. 6 and 7. It is also observed that the slope stability also varies linearly both with cohesion and friction angle (Fig. 8).



Cohesion	90	110	130	150	165
R^2	0.977	0.986	0.988	0.99	0.99

Fig. 5. Variation of factor of safety (Fs) for different values of Cohesion and ground water depth

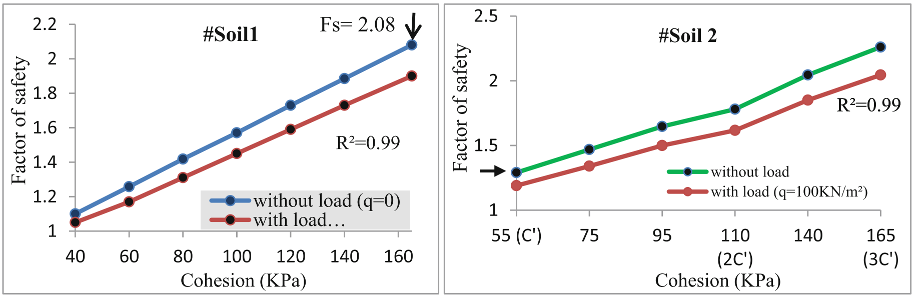


Fig. 6. Variation of factor of safety (FS) with and without surcharge (q) for different values of Cohesion

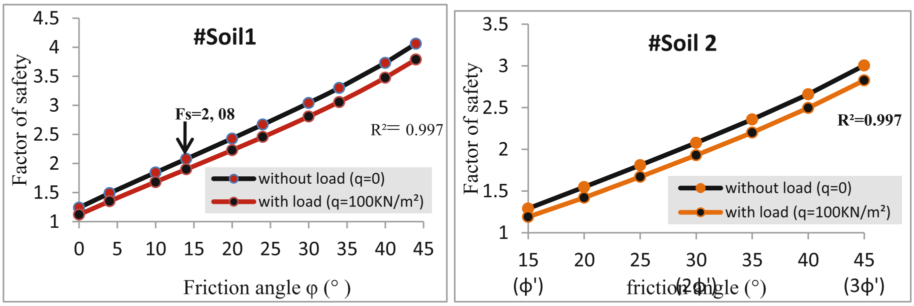


Fig. 7. Variation of factor of safety (FS) with and without surcharge (q) for different values of friction angle

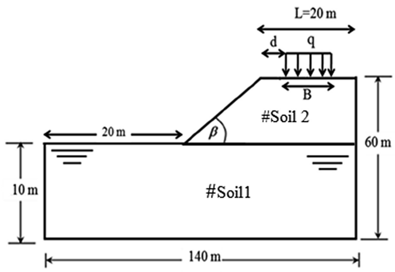


Fig. 8. Layered slope considered in the present study

4.4 Effect of Layered Slope

From the Table 1, it is noted that the soil-1 represents high properties in comparison with soil-2, for that, the slope failure (critical stability) is reached first if the layer takes the soil-2 properties during the application of a surcharge (FS equals to 1 when applying 400 kPa as a load), i.e. counting from this threshold the slope will be unstable and the failure may occur. The slopes that are quite stable can become unsafe, with FS < 1 when the surcharge exceeds a threshold value. In other words, limiting the surcharge can improve the safety of the slope significantly. However, with the same loading condition but with Soil-1, FS is found to increase (1.5) because of the higher soil properties (see Fig. 9) which means that the surcharge threshold is different.

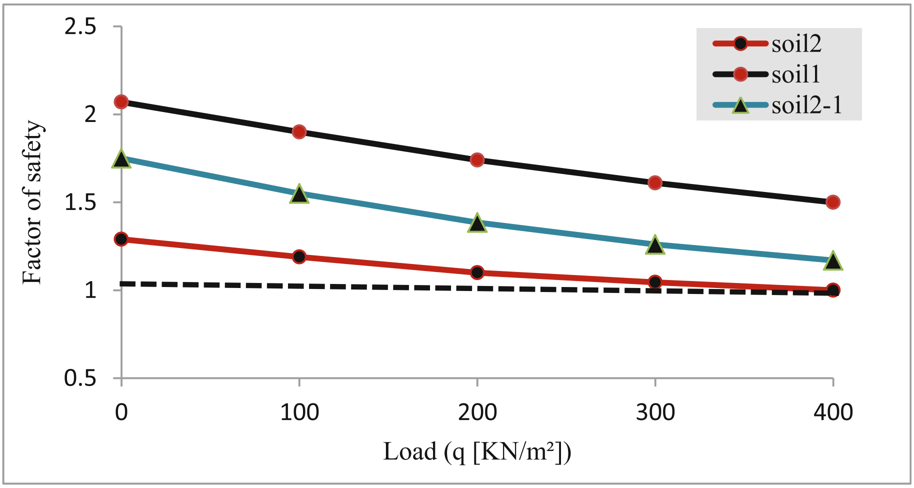


Fig. 9. Variation of factor of safety for the different soil cases

A layered slope as shown in Fig. 9 gave a higher degree of stability (in comparison with a slope only with layer of soil-2. It means that the additional layer with soil-1 properties played a role as a support for strengthening the slope stability.

Because the clayey loam layer (soil-2) is a weak soil layer, the increase in the layer thickness in a layered slope decreases the stability of the slope as shown in Fig. 10. Under a surcharge q = 100 KN/m^2 and for a weak layer height H = 20 m, FS is found to be 1.86. When the height is doubled (H = 40 m), the FS decreases from 1.86 to 1.406.

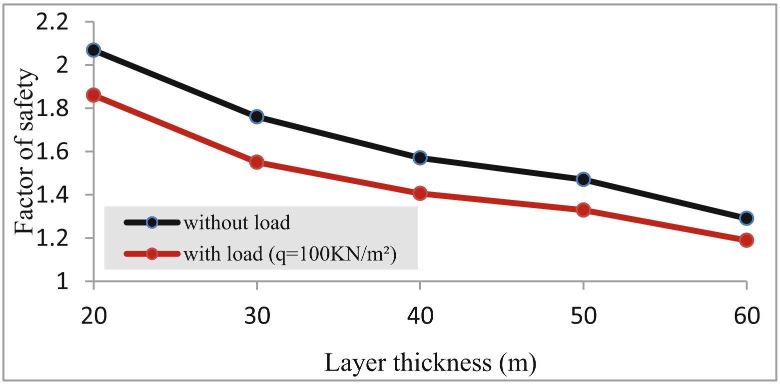
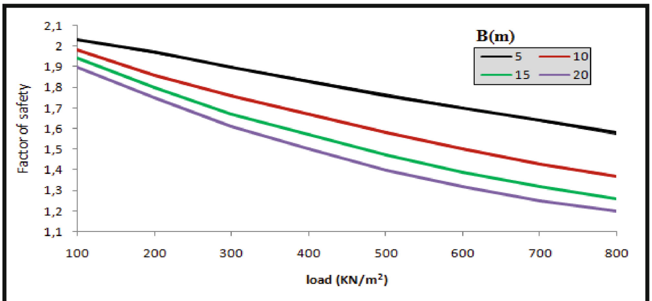


Fig. 10. Variation of factor of safety for the different layer thicknesses

4.5 Effect of Surcharge Width

In order to understand the effect of surcharge width on slope stability, 4 values of the parameter **B** with Increment of 5 m. It is noted that a distributed load on all the slope width **L** represents a delicate and unfavorable case and it's linearly proportional as shown in Fig. 11. As the load width increased, the failure zone extended and propagated towards the toe of the slope (Fig. 12).



B (m)	5	10	15	20
R^2	0.999	0.99	0.98	0.972

Fig. 11. Variation of factor of safety (FS) with surcharge (q) for different surcharge width values

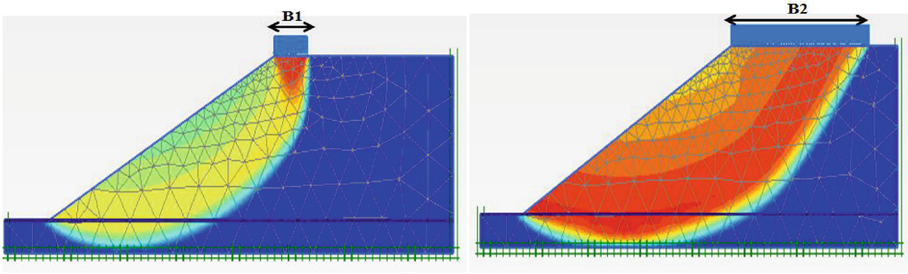


Fig. 12. Propagation and extension of the failure zone (B1 < B2)

4.6 Effect of the Slope Geometry

The geometry of the material has a significant effect in the analysis of the slope. The slope angle and slope height are another important variables (Noroozi and Hajiannia 2015).

4.6.1 Effect of Slope Height

For the same model as shown in Fig. 1 fixing the slope angle (26.56°) and varying the slope height (10 m-20 m-30 m-40 m and 50 m). The results show that the factor of safety decreases gradually when the slope height increases. For a slope with 20 m height, FS is equal to 3.28, However, when the height is doubled to be 40 m, the Factor of Safety decreased to 2.25 (Fig. 13).

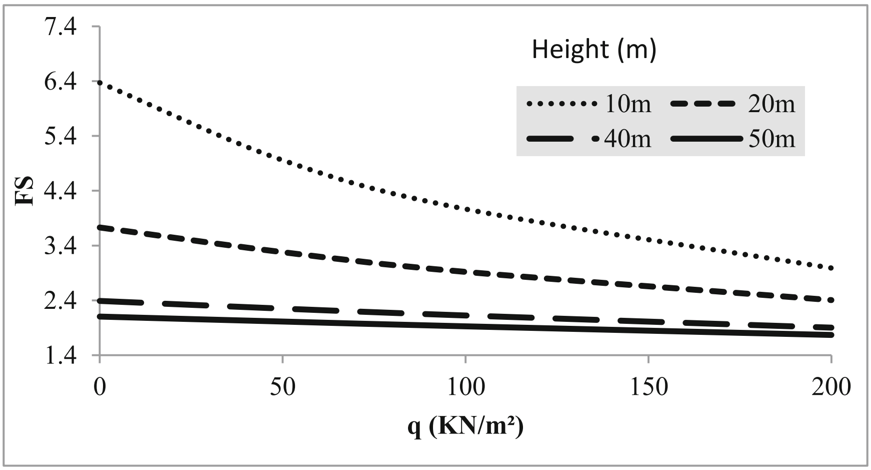


Fig. 13. Variation of factor of safety (FS) with surcharge (q) for different slope heights

4.6.2 Effect of Slope Angle

The slope height is fixed, it took a 50 m as a value and the slope angle is varied (26.56°; 33.69°; 45°). The effect of slope angle on the factor of safety for different values of surcharge is depicted in Fig. 14. It is observed that the factor of safety gradually decreases as the slope angle increases.. Under q = 400 KN/m^2, for a gentle slope (26.56°), FS is equal to 1.67 but for a steep slope (45°), it decreased to 1.36 (Fig. 14).

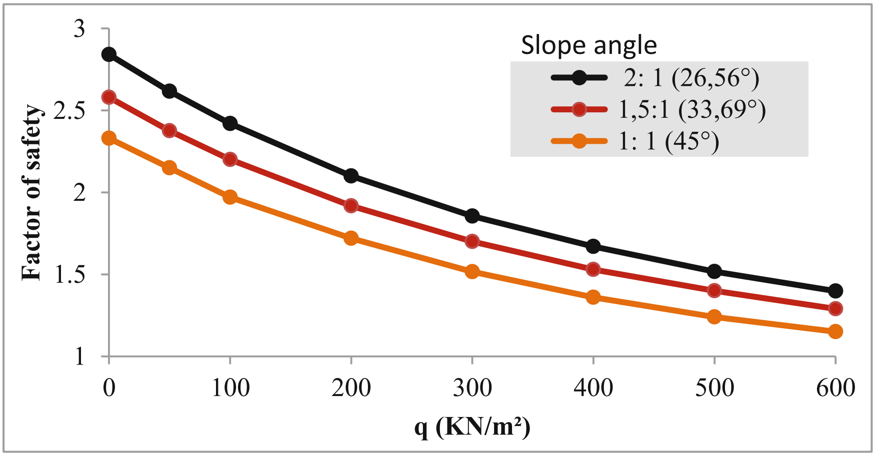


Fig. 14. Variation of factor of safety (FS) with surcharge (q) for different slope angles

It is noted that the factor of safety appears to be proportional with slope angle (polynomial second order) for the different applied surcharges

4.6.3 Effect of Slope Length

In order to know the slope length effect, we had chosen three different cases (case 01, case 02 and case 03) with length of 20 m, 40 m and 80 m respectively while the slope angle and slope height are fixed as shown in Fig. 15.

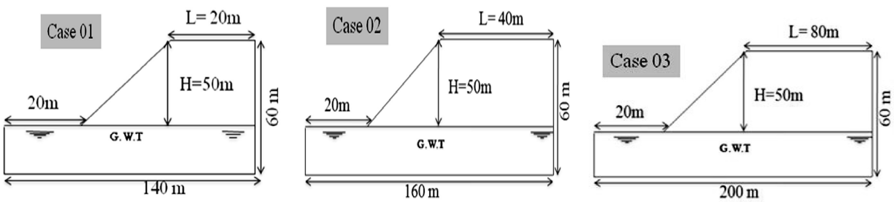


Fig. 15. different model cases used in this study

A surcharge with 20 m width was applied on the 3 profiles and it is observed that the factor of safety increases with increase in slope length. A profile with L = 80 m is more stable during the application of different surcharge values in comparison with the two previous cases. For the case 03, the factor of safety is still constant (2.12) for the surcharge range varying [100–200 kPa], and then it decreases gradually with increase of surcharge (Fig. 16) (Shukla et al. 2009).

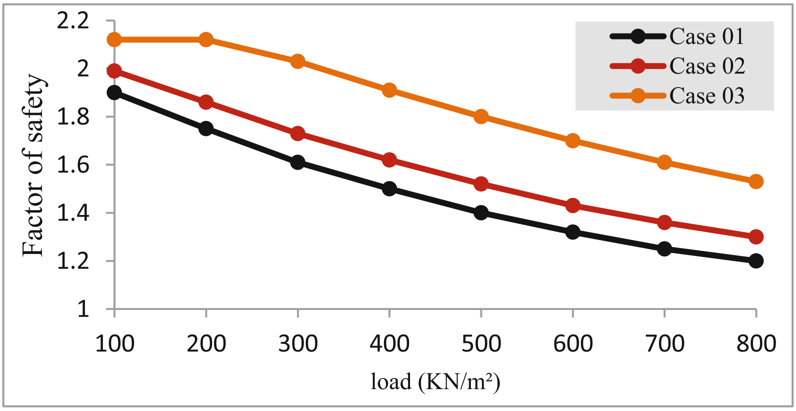


Fig. 16. variation of factor of safety for different slope length values

4.7 Effect of the Position of Surcharge

The case 03 which is mentioned in the previous section was used as a typical model for the analysis of the influence of surcharge position on the factor of safety. The stability increases if the load is applied far from the crest of the slope. The surcharge width B is fixed (B = 15 m). For a distance d = 15 m left from the crest, FS was found 1.47. However, if this distance is tripled to be 45 m, in this case, the stability increased (FS = 1.62).

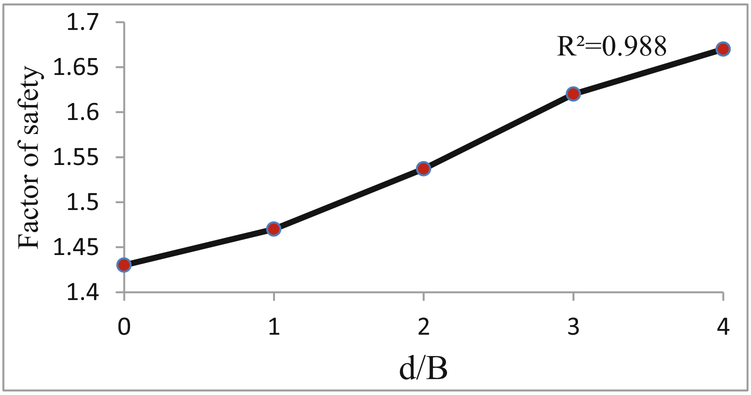


Fig. 17. Variation of factor of safety in function of distance to crest values

As shown in Fig. 17, factor of safety varies linearly with the position of surcharge (with $R^2 = 0.988$). i.e. that the safety factor is a function of the position of surcharge from the crest of slope.

5 Conclusion

A detailed numerical investigation is carried out to study the responses of slopes of homogeneous and layered soil with surcharge. A number of interesting conclusions can be drawn from this parametric study. The analysis of the results allows us to say that the major findings of the study are summarized as follows:

- The factor of safety increases with the increase of soil properties (cohesion, friction angle).
- For the range of parameters considered in the present study, the factor of safety of the slope decreases as a surcharge value increases;
- At any surcharge, the factor of safety decreases with the increase of ground water level;
- It is observed that the slope stability decreases with an increase both in slope angle and slope height. On the other hand, it increases with increase in the slope length;
- The factor of safety of slope of layered soil decreases as the weak layer thickness increases;
- Factor of safety increases with the increase of the distance of surcharge from the crest of the slope;
- As the load width increased, the failure zone extended and propagated towards the toe of the slope.
- All the parameters are correlated with the factor of safety during a loading event, some of them are linear (such as: cohesion, friction angle, surcharge width; surcharge position) while the ground water level, slope angle are polynomial in which the curve varies as a polynomial second order.

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