

# A methodology based on GIS for 3D Slope Stability Analysis

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**Abstract**— In this paper, we present an analysis of slope stability using Geographic Information Systems (GIS). The methodology is based on the calculation of the safety factor in 2D and 3D using GIS. Hovland's Method in 3D and 2D have been used in the stability analysis of the slope located at the 34 kilometer point (KP.34) on the highway in the North of Morocco connecting Tangier to Ksar Sghir. Isohypse and the digital elevation model (DEM) of the studied site have been built from topographical surveys. Results shows that the safety factors (FS) obtained in 3D analysis are about 11 % higher than those obtained in 2D analysis and the slope becomes unstable when the water table level is below 1m.

**Keyword**-Slope stability, GIS, Hovland Method

## I. INTRODUCTION

Slope stability problems are frequently encountered in the construction of roads, canals, dikes and dams. Moreover, some natural slopes are or may become unstable. Slope failure can be catastrophic and cause loss of life and considerable damage. The study of a slope includes, besides the recognition of the site and the choice of the mechanical characteristics of the soil, a stability calculation to determine firstly failure curve along which the slip risk is highest, secondly the corresponding value of the safety factor.

Slope stability analysis is applied by two-dimensional 2D and three-dimensional 3D analyses. In slope stability analysis, it is clear that a three-dimensional situation may become important in cases where the geometry of the slope and slip surface varies significantly in the lateral direction, the material properties are highly anisotropic, or the slope is locally loaded [1].

There are several methods of slope stability analysis in 2D and 3D: Limit equilibrium methods (LEM) and Finite Element Methods (FEM). Limit equilibrium methods have been the primary method used in estimating the stability of slope for decades ([2]-[3]). The basic principle of all these methods is to cut the volume of soil studied in a number of slices and apply different forces. The procedures are based on finding a Factor of Safety (FS) for the slope. It is useful to know exactly what percentage the 3D safety factor is higher than the 2D analysis.

Since the middle of 70s, many 3D methods of slope stability analysis have been proposed; these methods are traditionally based on an extension of 2D Limit equilibrium methods analysis. The slicing method in 2D analysis has been extended into 3D analysis with columns by various authors due to the popularity of 2D LEM slicing methods. Hovland [4] analyzed a three dimensional slope stability using the method of columns. A new 3D slices method has been proposed by Ugai [5], to analyze 3D slope stability by extending the Fellenius method. Hungr [6] and Huang and Tsai [7] have proposed a three dimensional slope stability analysis method based on an extension of Bishop's simplified 2D method of slices. The 2D general limit equilibrium formulation (Fredlund and Krahn [8]) has been extended by Lam and Fredlund [9] to analyze a 3D slope stability problem using the column method.

A geographical information system (GIS) is a relatively new software tool for geotechnical engineers ([10]). At the same time, using GIS can easily and effectively analyze the problem of 3D slope stability. If a GIS based geotechnical analysis model can be used, all related data are transformed into GIS Raster data and can be stored, retrieved, and analysed to calculate a safety factor. Some researchers have incorporated GIS in the slope stability analysis ([11]-[12]-[13] and [14]).

This paper presents a methodology based on the calculation of the safety factor in 2D and 3D using GIS.

## II. DATA AND METHODOLOGY

### A. Data

The studied slope is located at the 34 kilometer point (KP.34) on the highway in the North of Morocco connecting Tangier to Ksar Sghir ( Fig. 1).



Fig. 1. Location of the study area

Digital elevation model (DEM) has been built from topographical survey, and then the slope and aspect have been determined for each pixel of the studied slope (Fig. 2).

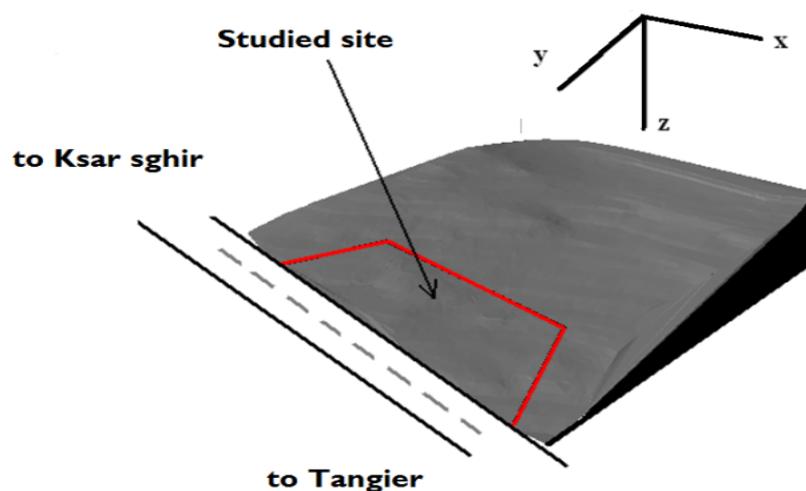


Fig. 2. Studied Slope

### B. Methodology

There are various methods of 2D stability analysis available in practice. Hovland proposed an approach for the 3D slope stability analysis. Hovland's method is an extension of the assumptions used in the two-dimensional ordinary method of slices, but columns were used instead of slices. Hovland's method neglects all the inter-column forces acting on the sides of the columns. The shear and normal forces acting on the base of each column are derived as components of the weight of the column.

For Hovland's three-dimensional method, the safety factor is acquired by dividing the soil mass above the failure surface into a number of equal sized vertical soil columns assuming the x and y-coordinates are perpendicular and in the horizontal plane. The z coordinate is vertical and the y-coordinate is to be set to the direction of the down slope movement of the failure block. The area of the soil column within the xy plan is defined by  $\Delta X$  and  $\Delta Y$ . By assuming both the  $\Delta X$  and  $\Delta Y$  values are constant for all columns.

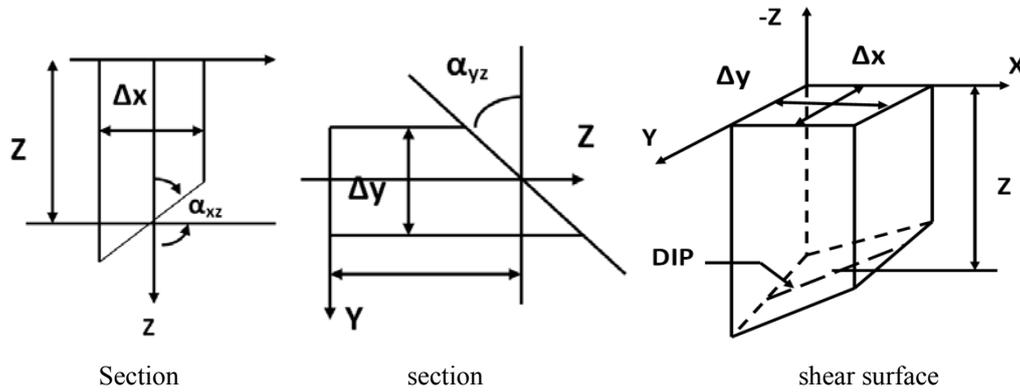


Fig. 3. Section, and Three-Dimensional Views of one Soil Column [4]

Hovland defines the three-dimensional safety factor as the ratio of total available resistance along the failure surface over the total mobilized stress along it, the three dimensional safety factor for Hovland's method is as follows:

$$FS_{3D} = \frac{\sum_x \sum_y [c' A + (WJ - U) \tan \phi']}{\sum_x \sum_y W \sin \alpha_{yz}} \quad (*)$$

$\alpha_{yz}$  and  $\alpha_{xz}$  :Inclinations of the base of the column with respect to the  $x_{-}$  and  $y_{-}$  axes(Fig. 3).

Where:

$$J = \cos(DIP) = \frac{1}{\sqrt{1 + \tan^2 \alpha_{xz} + \tan^2 \alpha_{yz}}}$$

$W = \gamma \Delta x \Delta y$  : Weight of the column

$$A = \Delta x \Delta y \left( \frac{\sqrt{1 - \sin^2 \alpha_{xz} \sin^2 \alpha_{yz}}}{\cos \alpha_{xz} \cos \alpha_{yz}} \right) : \text{Area of soil column, with } \sin \theta = \sqrt{1 - \sin^2 \alpha_{xz} \sin^2 \alpha_{yz}}$$

$$U = \gamma_w h_w \frac{\sin \theta}{\cos \alpha_{xz} \cos \alpha_{yz}} : \text{Pore water pressure}$$

Hovland's formula (\*) can be explained below by:

$$FS_{3D} = \frac{\sum_x \sum_y \left[ \frac{c' \Delta x \Delta y \sin \theta}{\cos \alpha_{xz} \cos \alpha_{yz}} + \left( \gamma \Delta x \Delta y \cos(DIP) - \gamma_w h_w \frac{\Delta x \Delta y \sin \theta}{\cos \alpha_{xz} \cos \alpha_{yz}} \right) \tan \phi' \right]}{\sum_x \sum_y \gamma \Delta x \Delta y \sin \alpha_{yz}}$$

For  $\alpha_{xz} = 0$  , the safety factor in 2D can be expressed by:

$$FS_{2D} = \frac{\sum_y \left[ \frac{c' \Delta y \sin \theta}{\cos \alpha_{yz}} + \left( \gamma \Delta y \cos(DIP) - \gamma_w h_w \frac{\Delta y \sin \theta}{\cos \alpha_{yz}} \right) \tan \phi' \right]}{\sum_y \gamma \Delta y \sin \alpha_{yz}}$$

Where :  $\theta = \frac{\pi}{2}$

Raster Calculator tool of ArcGIS 9.3 that is a part of the Spatial Analyst function was used to calculate the 3D and 2D safety factor for each pixel using Hovland method. Fig. 4 shows the procedures of the safety factor calculation (in 2D and 3D) using ArcGIS9.3.

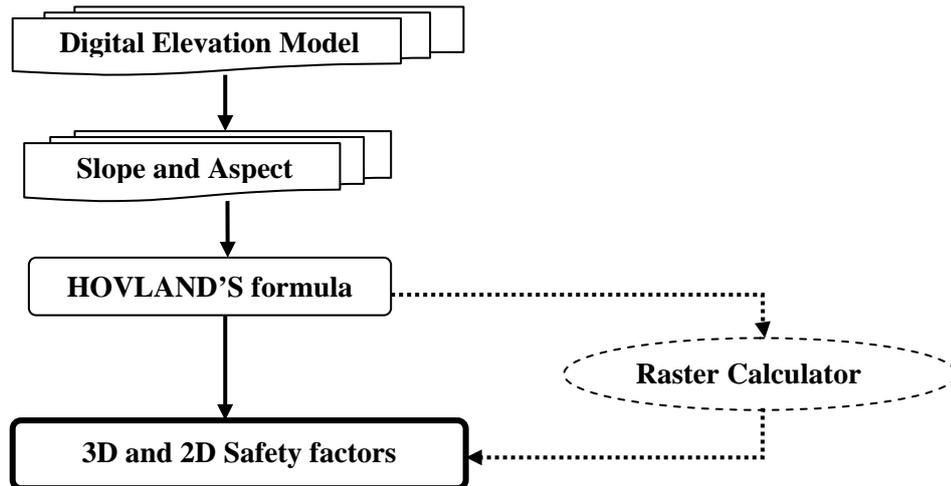


Fig. 4. Computing steps of safety factors

### III.RESULTS ANS DISCUSSION

Results show that the safety factors in 2D and 3D vary linearly with the increase of the effective cohesion and the effective friction angle. 2D and 3D safety factors increase with the increase of effective cohesion and effective friction angle, which shows the effect of these two parameters on the slope stability analysis. We found also that 3D FS are always higher than 2D FS and the gap between the safety factors in 2D and 3D is approximately constant, and it is of the order of 0.17 (Fig. 5).

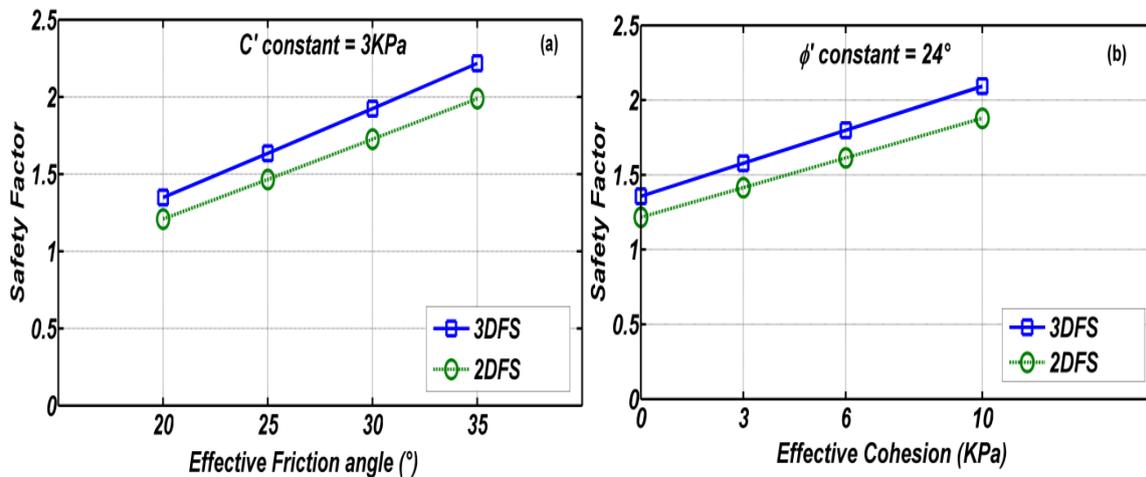


Fig. 5. Influence of the effective friction angle (a) and the effective cohesion (b) on the safety factor

The piezometric measurements revealed that the water table level varies from 0.5m to 4m. In the case of high water tables, (Hw=0.5m and HW= 1m), the safety factors in 2D and 3D are below 1 (Fig. 6), which indicates that the studied slope is unstable in the case of a rise of the water table at these depths. This being due probably to the effect of the pore water pressure U, which plays an important role in reducing the shear strength of the soil, which reduces the safety factor and therefore increases the risk of instability.

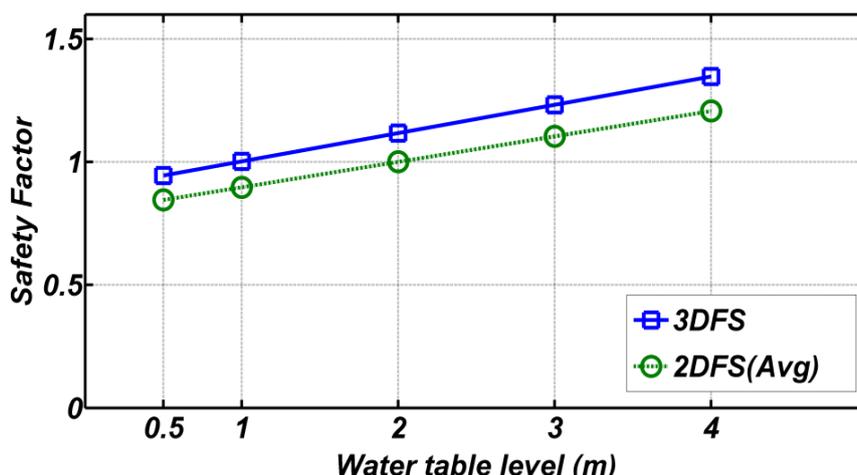


Fig. 6.influence of the water table level on the safety factor

For the water table depths ( $H_w = 2m$ ,  $H_w = 3m$ ) we note that the safety factor (2D and 3D) are greater than 1, so the slope is in theory stable in the case of a considerable lowering of the water table at these depths. For lowest water table level ( $H_w=4$ ), we found that the safety factor values in 2D and 3D are approximately the same that those found for the case of the slope without water table ( $c' = 0$ ,  $\phi' = 24$ ) (Fig. 5(b)). This indicates that the influence of water table on the stability is insignificant at this depth. These results thus show, that the height of the water table and the water pressure distribution play an important role on the shear strength and on the safety factor in 2D and 3D.

TABLE I  
 Calculated safety factor results

| Water table $H_w$ (m) | 3D FS | 2D FS (Avg) | 2D FS (Left) | 2D FS (Mid) | 2D FS (Right) | 2D FS(Avg) / 3D FS |
|-----------------------|-------|-------------|--------------|-------------|---------------|--------------------|
| 0.5                   | 0.944 | 0.845       | 0.868        | 0.798       | 0.874         | 0.895              |
| 1                     | 1.002 | 0.897       | 0.920        | 0.847       | 0.928         | 0.895              |
| 2                     | 1.117 | 1           | 1.026        | 0.946       | 1.034         | 0.895              |
| 3                     | 1.232 | 1.104       | 1.132        | 1.043       | 1.141         | 0.896              |
| 4                     | 1.347 | 1.207       | 1.238        | 1.141       | 1.247         | 0.896              |

2D safety factors have been calculated on three sections of the study area. Results of 2D stability analysis show that the safety factors differ in the three sections (Table1). Also the lower values of the Safety factors are those obtained from the middle section, this is probably due to geotechnical soil characteristics or variation in topography and water table level which indicates that this section is the most critical.

The ratio  $2DFS(Avg) / 3DFS$  is less than 1 at all water table levels, this indicates that 3D safety factors obtained by Hovland's method are higher than those obtained in 2D. However, the variation of the water table level has no influence on the ratio  $2DFS(Avg) / 3DFS$ . Gens has found that the percentage difference between 3D and 2D stability analysis ranges respectively from 3% to 30% with an average of 13.9 % [15], as well as Duncan found that the 3D safety factors are almost 10% higher than those obtained in 2D [16] which shows that these results are similar to those obtained from this study ( $FS_{3D} = 1.11FS_{2D}$ ).

#### IV. CONCLUSION

In this paper we have presented a methodology of slope stability analysis using GIS. We have used several tools in ArcGis 9.3 to calculate the safety Factors in 3D and 2D using Hovland's method. Results indicate that the 3D safety Factors are higher than those in 2D for all water table levels. Also we found that the studied slope become unstable for the highest water table levels (0.5m to 1m). This study revealed also that the Geographic information System can be used effectively for 3D and 2D slope stability analysis.

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