

Deterministic landslide hazard zonation

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Summary

In this exercise a simple slope stability model (the *infinite slope* model) is used to calculate safety factor maps for different conditions. The effect of groundwater depth and seismic acceleration is evaluated using input maps of these factors for different return periods of rainfall (related to the groundwater level) and earthquakes (related to the seismic acceleration). The model is generated as an ILWIS function. The different scenarios are calculated by changing the variables of the function. The model is applied to a data set of the city of Manizales, in central Colombia.

Getting started

The data for this case study are stored on the ILWIS 2.1 CD-ROM in the directory d:\appguide\chap06. If you have already installed the data on your hard-disk, you should start up ILWIS and change to the subdirectory where the data files for this chapter are stored, c:\ilwis21\data\appguide\chap06. If you did not install the data for this case study yet, please run the ILWIS installation program (see ILWIS Installation Guide).



- Double-click the ILWIS program icon in the ILWIS program group.
- Change the working drive and the working directory until you are in the directory c:\ilwis21\data\appguide\chap06.

Now you are ready to start the exercises of this case study.

6.1 Introduction

The final aim of large scale landslide hazard analysis (scales larger than 1:10,000) is to create quantitative hazard maps. The hazard degree can be expressed by the *Safety Factor*, which is the ratio between the forces that make the slope fail and those that prevent the slope from failing. F-values larger than 1 indicate stable conditions, and F-values smaller than 1 unstable. At F=1 the slope is at the point of failure. Many different models exist for the calculation of Safety Factors. Here we will use one of the simplest models, the so-called *infinite slope model*. This two dimensional model describes the slope stability of slopes with an infinitely large failure plane. It can be used in a GIS, as the calculation can be done on a pixel basis. The pixels in the parameter maps can be considered as homogeneous units. The effect of the neighboring pixels is not considered, and the model can be used to calculate the stability of each individual pixel, resulting in a hazard map of safety factors. The safety factor is calculated according the following formula (Brunsden and Prior, 1979) :

$$F = \frac{c' + (\gamma - m\gamma_w) z \cos^2\beta \tan\phi'}{\gamma z \sin\beta \cos\beta} \quad [6.1]$$

in which:

- c' = effective cohesion (Pa= N/m²).
- γ = unit weight of soil (N/m³).
- m = z_w/z (dimensionless).
- γ_w = unit weight of water (N/m³).
- z = depth of failure surface below the surface (m).
- z_w = height of watertable above failure surface (m).
- β = slope surface inclination (°).
- φ' = effective angle of shearing resistance (°).

The infinite slope model can be used either on profiles as well as on pixels, as shown in figure 6.1. The entire analysis requires first the preparation of the data base. This will be shown in chapter 7. The parts on groundwater modelling and the modelling of seismic acceleration are not shown here. For more information see Van Westen (1993). In this exercise only part 3b1 will be demonstrated: the calculation of average safety factors for different scenarios. These average safety factor maps could be used in the creation of failure probability maps.

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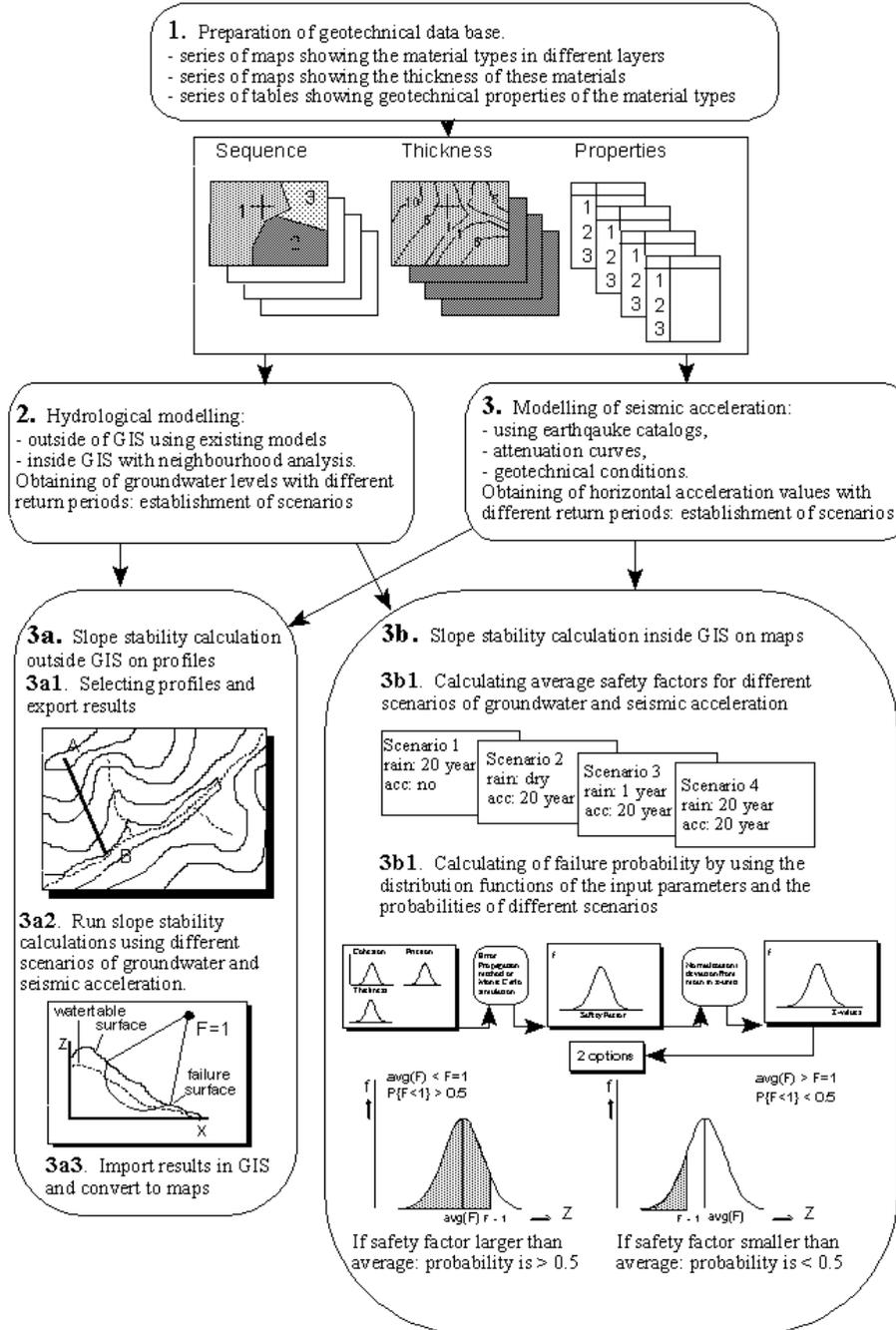


Figure 6.1: Flowchart for deterministic landslide hazard analysis

6.2 Visualization of the input data

In this exercise the slope stability analysis is made by using only two parameter maps: `Asht` (thickness of volcanic ashes) and `Slope` (slope angles in degrees).



- Double-click the map `Asht`. Click **OK** in the **Display Options** dialog box. The map is displayed.
- Move through the map and press the left mouse button to see the information. As you can see the area outside of the study area reveals a ? when you press the left mouse button. These pixels are called *undefined*. This means that no information is stored for them.
- Also display the map `slope`. This map contains slope angles in degrees.

Practically the entire study area of Manizales is covered by a mantle of volcanic ashes. In this exercise you will calculate the stability of the volcanic ash cover. This means that the depth of the possible failure plane is taken at the contact of the volcanic ashes and the underlying material. The consequence of that is that safety factors will not be calculated for the entire area, but only for the areas where there is volcanic ash at the surface.

Besides of the thickness of the ashes, which is the depth of the failure surface, and the slope of the terrain, we also need to know the other parameters of formula 6.1. From laboratory analysis the following average values are known:

c'	= effective cohesion (Pa= N/m ²)	= 10000 Pa
γ_w	= unit weight of water (N/m ³)	= 10000 N/m ³
z	= depth of failure surface below the surface (m)	= map <code>ASHT</code>
β	= slope surface inclination (°)	= map <code>slope</code>
ϕ'	= effective angle of shearing resistance (°)	= 30 °
$\tan(\phi')$	= tangent of the effective angle of shearing resistance	= 0.58

The only unknown parameter yet is the depth of the water table. In formula 6.1 this is expressed as the value m , which is the relation between the depth of the watertable and the depth of the failure surface.

6.3 Preparation of the data

Before you can start with the analysis, you need to reorganize the map `Slope`. In the calculation we need three parameters that are derived from the slope:

$\sin(\text{slope}) =$ the sine of the slope
 $\cos(\text{slope}) =$ the cosine of the slope
 $\cos^2(\text{slope}) = \cos(\text{slope}) * \cos(\text{slope})$

The ILWIS functions for sine and cosine only work with input values in radians, while our map `Slope` is in degrees. Therefore we need to convert to slope map from degrees to radians first. ILWIS has the function `Degrad` for that:

`Degrad(Slope)` degrees to radians function: $\text{slope} * \frac{\pi}{180}$



- Type the following formula on the command line:
`Slrad:=degrad(Slope)↵`
Accept the default minimum, maximum and precision.
- Open the result map and compare the values of the map `Slrad` with those of the map `Slope`. Calculate it with the ILWIS pocket line calculator or the Windows calculator for some pixels, using the formula given above.

Now you have the slope in radians, and you can calculate the sine and cosine. You will calculate individual maps for these so that the Safety factor formula (formula 6.1) can be calculated easier.



- Type the following formula on the command line:
`Si:=sin(Slrad)↵`
(with this formula you calculate the sine of the slope).
Accept the default minimum (-1), maximum (+1) and give a precision of 0.001.
- Open the result map and compare the values of the map `Si` with those of the map `Slrad`. Calculate it with the pocket line calculator or the Windows calculator for some pixels, using the formula given above.
- Type the following formula on the command line:
`Co:=cos(Slrad)↵`
(with this formula you calculate the cosine of the slope).

Accept the default minimum (-1), maximum (+1) and give a precision of 0.001.

- Open the result map and compare the values of the map C_0 with those of the map S_{rad} . Check it for some pixels, using the formula given above.

- Type the following formula on the command line:

$C_0^2 = sq(C_0)$

(with this formula you calculate the square of the cosine, using the ILWIS function $Sq()$).

Accept the default minimum, maximum and precision

- Check your results again.

Now all necessary parameters for the formula 6.1 are known, except for the parameter m related to the groundwater depth.

6.4 Creating a function for the infinite slope formula

In the following sections you will use formula 6.1 extensively for different scenarios, and different input data. To avoid that you have to retype the formula each time, it is better to create a user-defined function for it.

Besides many internal pre-programmed functions, ILWIS gives the user an opportunity to create new functions. Especially when you need to execute certain calculations which require a lot of typing work several times, user-defined functions may be time saving. A user-defined function is an expression which may contain any combination of operators, functions, maps and table columns.



- Double-click **New Function** in the operations list. The **Create function** dialog box is opened.

- Type for the **Function Name**: F_s

Type for the expression:

$$\frac{(Cohesion + (\Gamma - M * \Gamma_{max}) * Z * C_0^2 * \tan \phi)}{(\Gamma * Z * S_i * C_0)}$$

Type the **Description**: *Safety factor*.

- Click **OK**. The **Edit Function** dialog box is opened. Click **OK**.

In this dialog box you can edit the expression of the function. Now the expression is:

```
Function fs(Value Cohesion,Value Gamma,Value M,Value  
gammaw,Value Z,Value Co2,Value Tanphi,Value Si,Value Co)  
: Value  
Begin  
Return (Cohesion +(Gamma-M*Gammaw)*Z*Co2*Tanphi)  
/(Gamma*Z*Si*Co)  
End;
```

As you can see the function contains the following variables (listed in the first line):

- Value Cohesion: the value for the effective cohesion.
- Value gamma: the value for the unit weight of soil.
- Value m: the value for the relation z_w/w .
- Value gammaw: the value for the unit weight of water.
- Value z: the value for the depth of failure surface below the surface.
- Value co2: the value for the square of the cosine of the slope.
- Value tanphi: the value for the tangent of the effective angle of shearing resistance.
- Value si: the value for the sine of the slope.
- Value co: the value for the cosine of the slope.

However, a number of these variables are fixed. You will use them for all calculations: The fixed variables are: Value Cohesion (10000 Pa), Value Gammaw (10000 N/m³), Value Z (raster map Asht), Value Co2 (raster map Co2), Value Tanphi (0.58), Value Si (raster map Si), and Value Co (raster map Co).

So you can simplify the function considerably, so that it looks like:

```
Function fs(Value Gamma,Value M) : Value  
Begin  
Return(10000+((Gamma-m*10000)*Asht*Co2*0.58))  
/(Gamma*Asht*Si*Co)  
End;
```

As you can see there are only two variables: Value Gamma and Value M.



- Edit the Function until it is the same as above. Click OK.

6.5 Calculating Safety Factors for groundwater scenarios

Now that the function is created, you can start to calculate safety factor maps for different scenarios. In the first part you will calculate the safety factors for different scenarios where only rainfall is the triggering factor. You will not yet look to the influence of an earthquake.

Dry condition

You will first calculate the safety factor for the volcanic ashes under the assumption that the soil is completely dry. In that case the parameter m is equal to zero.

Remember the other parameter that were given on the previous page:

c' =	Effective cohesion (Pa= N/m ²)	= 10000 Pa
γ =	Unit weight of soil (N/m ³)	= 11000 N/m ³
γ_w =	Unit weight of water (N/m ³)	= 10000 N/m ³
z =	Depth of failure surface below the surface (m)	= map Asht
m =	Relation z_w/z (dimensionless)	= 0
β =	Slope surface inclination (°)	= map Slope
ϕ' =	Effective angle of shearing resistance (°)	= 30 °
$\tan(\phi')$ =	Tangent of the effective angle of shearing resistance	= 0.58
$\sin(\beta)$ =	Sine of slope angle	= map Si
$\cos(\beta)$ =	Cosine of slope angle	= map Co
$\cos^2(\beta)$ =	Square of the cosine of slope angle	= map Co2

Now you can start with the actual calculation of the average safety factor map representing the situation under dry conditions. The two variables for the function f_s are 11000 (Value Gamma) and 0 (Value M).



- Type the following formula on the command line:

```
Fdry:=fs(11000,0)↵
```

- Use a minimum of 0, a maximum of 100, and a precision of 0.1. Use the georeference Manizal.
- Open the result map and compare the values of the map Fdry with those of the input maps. Calculate the safety factor manually for some pixels with the Pocket line calculator or the Windows calculator, using formula 6.1.

As you can imagine a situation with a completely dry situation does not occur in a tropical region such as Manizales, which receives quite a lot of rainfall each year. In any case the map F_{dry} gives the most stable situation. Let us see how much percent of the area is unstable under these conditions. In order to know that we will first classify the map F_{dry} into three classes:

- Unstable = safety factor lower than 1
- Critical = safety factor between 1 and 1.5
- Stable = safety factor above 1.5

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- Create a new domain $Stabil$ (type class, group) with the following three classes:

Boundary	Name
1	Unstable
1.5	Critical
100	Stable

- Use the **Slicing** operation to classify the map F_{dry} with the domain $Stabil$ into the map F_{dryc} .
- Calculate a histogram of the map F_{dryc} and write down the percentages of the three classes in a table on a sheet of paper with the column name Dry . Later we will calculate the values for other situations.

The percentage of the pixels classified as unstable gives you an indication of the error, since the occurrence of unstable pixels under fully dry conditions is not possible.

Completely saturated condition

The next scenario that you will evaluate is a condition in which the slopes are completely saturated. This is also not a very realistic situation, but it will give us the most pessimistic estimation of slope stability, with only one triggering factor involved (rainfall leading to high watertables).

When we have a saturated soil, the m factor from formula 6.1 is equal to 1. This means that the watertable is at the surface. There is also another factor which is different for saturated conditions γ :

- c' = Effective cohesion (Pa= N/m^2) = 10000 Pa
- γ = Unit weight of soil (N/m^3) = 16000 N/m^3
- γ_w = Unit weight of water (N/m^3) = 10000 N/m^3
- z = Depth of failure surface below the surface (m) = map $Asht$

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$m =$	Relation z_w/z (dimensionless)	$= 1$
$\beta =$	Slope surface inclination ($^\circ$)	$= \text{map Slope}$
$\phi =$	Effective angle of shearing resistance ($^\circ$)	$= 30^\circ$
$\tan(\phi) =$	Tangent of the effective angle of shearing resistance	$= 0.58$
$\sin(\beta) =$	Sine of slope angle	$= \text{map Si}$
$\cos(\beta) =$	Cosine of slope angle	$= \text{map Co}$
$\cos^2(\beta) =$	Square of the cosine of slope angle	$= \text{map Co}^2$

The two variables for the function f_s are 16000 (value γ) and 1 (value m).



- Type the following formula on the command line:
`Fsat := fs(16000, 1)`
- Use a minimum of 0, a maximum of 100, and a precision of 0.1. Use the georeference `Manizal`.
- Open the result map and compare the values of the map `Fsat` with the maps `Fdry` and the input map. Calculate the safety factor manually for some pixels with the ILWIS pocket line calculator or the Windows calculator for some pixels, using the formula given above.
- Use the **Slicing** operation (under image procession) to classify the map `Fsat` with the domain `Stabil` into the map `Fsatc`.
- Calculate a histogram of the map `Fsatc` and write down the percentages of the three classes in a table on a sheet of paper with the column name `Sat`. Compare them with the column `Dry`. Later we will calculate the values for other situations.

Other groundwater scenarios

Using these formulae and the input files created in the previous exercises, a number of scenarios can be calculated. We have chosen some scenarios, based on the following combinations:

- Groundwater peaks occurring during 2 months a year: (return period: 0.164 year)

$$m = \text{map M016}, \gamma = 14000$$

- Groundwater peaks occurring once a year (return period: 1 year)

$$m = \text{map M1}, \gamma = 14000$$

- Groundwater peaks occurring once every 20 years (return period: 20 years)
 $m = \text{map } M20, \gamma = 14000$
- Groundwater peaks occurring once every 50 years (return period: 50 years)
 $m = \text{map } M50, \gamma = 14000$

The maps M016, M1, M20 and M50 were calculated with a hydrological model. The explanation on how they were calculated is beyond the scope of this exercise.



- Display the maps M016, M1, M20 and M50.
- Compare the values of these maps in the pixel information window.
- To calculate the safety factor map for the first scenario, type the following formula on the command line:

$$Fm016 := fs(14000, m016) \downarrow$$

with this formula you calculate the safety factor for a situation where there is a groundwater peak that occurs once every two months. For m we now use a map: M016, since the m values are different for different terrain conditions. Compare the formula with formula 6.1 given in the text. Use a minimum of 0, a maximum of 100, and a precision of 0.1. Use the georeference Manizal.
- Use the **Slicing** operation to classify the map Fm016 with the domain *Stabil* into the map Fm016c.
- Calculate a histogram of the map Fm016 and write down the percentages of the three classes in a table on a sheet of paper with the column name 2 months/year. Compare them with the columns *Dry* and *Sat*.
- Then calculate safety factor maps for the other three conditions:
 - (a) Fm1 for the condition of a groundwater table occurring once a year, and using the map M1.
 - (b) Fm20 for the condition of a groundwater table occurring once every 20 years, and using the map M20.
 - (c) Fm50 for the condition of a groundwater table occurring once a year, and using the map M50.
- Classify all maps using the domain *Stabil* and calculate the percentages of the three classes (unstable, critical, stable). Write these values in your table, and compare them.

Now that we have calculated all scenarios, we can compare them. This can be done in a table.

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- Create a table from the domain *Stabil*.
 - Go to **Columns, Join** and select **Table** histogram of *Fdryc*; use the column *Npixpct*. The output column is *Dry*. Accept the default values.
 - Also join the histogram files of the maps *Fm016c*, *Fm1c*, *Fm20c*, *Fm50c* and *Fsatc*. Give them the names *M016*, *M1*, *M20*, *M50* and *Sat*.
 - Select **Options, Show Graph** and display each of these columns as *y* against the *Stabil* value as bar graphs in different colors.
 - Draw conclusions on the effect of the groundwater on the stability of the volcanic ashes in the area.

6.6 Evaluating the effect of seismic acceleration

It is also possible to include the effect of seismic acceleration in the infinite slope model. When the effect of an earthquake acceleration is included, formula 6.1 becomes:

$$F = \frac{c' + (z\gamma \cos^2\beta - z\rho a \cos\beta \sin\beta - \gamma_w z_w \cos^2\beta) \tan\phi'}{z\gamma \sin\beta \cos\beta + z\rho a \cos^2\beta} \quad [6.2]$$

in which:

- c' = Effective cohesion (Pa= N/m²).
- γ = Unit weight of soil (N/m³).
- m = z_w/z (dimensionless).
- γ_w = Unit weight of water (N/m³).
- z = Depth of failure surface below the surface (m).
- z_w = Height of watertable above failure surface (m).
- β = Slope surface inclination (°).
- ϕ' = Effective angle of shearing resistance (°).
- ρ = Bulk density in (kg/m³).
- a = Earthquake acceleration (m/s²).

The bulk density (ρ) is equal to 1100 kg/m³ for dry conditions, 1600 kg/m³ for saturated conditions and 1400 kg/m³ for intermediate conditions.

a is the earthquake acceleration, which depends on the magnitude of an earthquake and the amplification.

Peak acceleration is obtained by multiplying the peak acceleration in hard rock (A_h) with the amplification due to changes in soil properties and groundwater (N).

$$a = A_h * N \quad [6.3]$$

The amplification maps are related to a certain groundwater peak, and the same return periods are used as in the groundwater maps: (N016, N1, N20, N50). The peak acceleration in hard rock is obtained from the formulas:

$$M_s = 8.2 - 2.9 \log(57 / RY) \quad [6.4]$$

and

$$A_h = 1320 e^{0.58M} (R + 25)^{-1.52} \quad [6.5]$$

Some return periods and peak accelerations for magnitudes of 3 to 7 and a hypocentre distance of 112 km (100 km vertically by 50 km horizontally) according to these formulae are given in Table 6.1.

Table 6.1

Magnitude	Return period (years)	Horizontal distance to epicenter (km)	Vertical distance of hypocentre (km)	Distance to hypocentre (km)	Peak acceleration at the rockhead (A_h)	
					cm/s ²	g
3	0.92	50	100	112	4.25	0.0043
4	2.03	50	100	112	7.59	0.0077
5	4.49	50	100	112	13.56	0.0138
6	9.94	50	100	112	24.21	0.0247
7	21.98	50	100	112	43.25	0.0440

Based on this information you can set up a number of scenarios. Six will be presented here, but you can create more with the available data:

1. Dry condition, without earthquake.
2. Groundwater with return period of 20 years, without earthquake.
3. Completely saturated condition, without earthquake.
4. Dry condition, and earthquake of 7 Magnitude.
5. Groundwater with return period of 0.16 years, and earthquake of 7 M.
6. Groundwater with return period of 20 years, and earthquake of 7 M.

For the scenarios that include earthquake acceleration you will have to use a value for the maximum acceleration (A_h) as shown in the table and the amplification maps related to a certain groundwater peak, and the same return periods are used as in the groundwater maps: (N016, N1, N20, N50).



- Create a function F_{snew} based on the formula 6.2.
- List the necessary parameters for each of the six scenarios listed above.
- Calculate the Safety factor for each scenario, using the function F_{snew} .
- Classify the resulting safety factor maps with the domain $Stabil$.
- Calculate the percentages of the three classes and show them in a graph.
- Draw conclusions on the effect of the groundwater and the earthquake acceleration on the stability of the volcanic ashes in the area.

References

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