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Topic: Building a landslide simulation windows Application using Analytical methods.

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2021/2022

To :

- *My very dear parents.*
- *To my wife and my children.*
- *To my brothers and sisters.*
- *To all of my friends.*

ABSTRACT

A significant revolution with computers' usage in civil engineering business and construction process has been performed. Computers reduce all the extensive work specifically through the introduction of programs and software.

Limit Equilibrium method "method of slices" have gone through a series of changes as the computer has provided increased ability to solve complex and nonlinear formulations. The objective of this work is to provide the geotechnical engineer with information that allows, the assessment of newly proposed methods for determining the factor of safety of soil, and to illustrate the procedures used in the Simplified Bishop method of slope stability analysis and provides guidance for checking and verifying the results of slope stability analyses.

Key Words: Landslide, method of slices, Bishop Method, slope stability, safety factor of soil, Analytical method, calculation program of landslide.

ملخص

حدثت ثورة كبيرة في مجال استخدام أجهزة الكمبيوتر في أعمال الهندسة المدنية وعملية البناء. حيث تقلل أجهزة الكمبيوتر من العمل المكثف على وجه التحديد من خلال إدخال البرامج وتطويرها.

طريقة التوازن الحدي "طرق الشرائح" قد مرت بسلسلة من التغييرات حيث قدم الكمبيوتر قدرة متزايدة على حل الصيغ المعقدة وغير الخطية ، والهدف من هذا العمل هو تزويد المهندس الجيوتقني بالمعلومات التي تسمح بتقييم الأساليب المقترحة حديثًا لتحديد عامل سلامة التربة ، ولتوضيح الإجراءات المستخدمة في طريقة Simplified Bishop لتحليل ثبات المنحدر وتقديم إرشادات للتحقق من نتائج تحليلات ثبات المنحدرات.

الكلمات المفتاحية : انزلاق التربة، طريقة الشرائح، طريقة بيشوب، توازن المنحدرات، عامل سلامة التربة، الطرق التحليلية، برامج حساب انزلاق التربة.

Résumé

Une révolution significative est apparue avec l'utilisation des ordinateurs dans le domaine de génie civil. Les ordinateurs réduisent tout les difficultés du travail et du calcul, notamment grâce à l'introduction de programmes et de logiciels. La méthode à l’équilibre limite « la méthode des tranches » a subi une série de changements à mesure que l'ordinateur a fourni une capacité accrue à résoudre des formulations complexes et non linéaires. L'objectif de ce travail est de fournir à l'ingénieur géotechnicien des informations permettant l'évaluation des méthodes nouvellement proposées, pour déterminer le facteur de sécurité du sol, et pour illustrer les procédures utilisées dans la méthode simplifiée de Bishop d'analyse de la stabilité des pentes et fournir des conseils pour vérifier les résultats des analyses de stabilité des pentes.

Mots clés : Glissement du terrain, méthode des tranches, Méthode de Bishop, stabilité des pentes, facteur de sécurité du sol, méthodes analytiques, programme du calcul des glissements.

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General Introduction

GENERAL INTRODUCTION

The analysis for the stability of slopes was one of the first analytical tool developed in soil mechanics. In recent years there has been numerous changes proposed on how best to analyze slopes for the assessment of stability. “Limit Equilibrium” methods of slices have gone through a series of changes as the computer has provided increased ability to solve complex and nonlinear formulations. In recent years numerous new methods have been proposed for the analysis of slopes. These methods have provided new methodologies for the calculation of the normal forces along any proposed slip surface as well as new search routines that attempt to directly determine the shape and location of the most critical slip surface. Each new method of analysis has needed to be tested against a history of experience and previous methods of analysis.

Slope stability studies have constituted an important part of geotechnical engineering practice. The ability to analyze a soil or rock mass and calculate a factor of safety has lent considerable credibility to the engineering profession. This analytical ability has also been profitable for geotechnical engineers. Changes in methodologies for the analysis of slopes have been considerable over a matter of a few decades and this has given rise to concerns over what is the best methodology to use in practice. Some slope stability methods emerged in the early years of soil mechanics. More recently new analytical forms of analysis have emerged. This often leaves the practicing geotechnical engineer with questions regarding the significance of the new methodologies. The advent of the computer has proven to be a valuable tool for analysis purposes. At the same time the computer has birthed other more complex computational tools.

A significant revolution with computers’ usage in civil engineering business and construction process has been presented. Computers reduce all the extensive work specifically through the introduction of programs and software. Lately, software development has effectively contributed in various civil engineering disciplines, as it provides engineers with the ability to perform variety of complex calculations, modeling, drafting, designing practice and several analysis processes for civil engineering infrastructure.

The application of civil engineering software can be applied for much essential work like designing huge structure for example, (facilities, highway systems, bridges highway).

Accuracy: The accuracy of the computer in civil engineering is something that allows the processes to be done as well as possible without any mistakes. Computers can ensure that everything is going to be measured as well as possible and that you know exactly what you need to do and how to do it.

Software: The software developed and improved in the field of civil engineering over the years has been designed to ensure that the engineering can take place without there being any problems. They also the speed and accuracy to be successfully and ensure that everything is going to work as smoothly as possible so there are not going to be any mistakes or problems along the way.

You will find that without a computer, and without civil engineer software, the field of civil engineering would be a lot more difficult and it would take longer for certain processes to be made and to be made as properly as possible. The computer allows us to do things as quickly as possible and to the highest standard that we can achieve and meet, without the use of computers within this profession, we would not be able to have everything done as quickly as we expect within today's society.

You can find the exact programs and systems which are used to designs and information processing when you look on a civil engineering website. You can be sure that there is going to be all of the information there for you and that you are going to be able to use it to your advantage when you need to and when you are researching the subject.

The work undertaken by software engineers is generally of a highly complex and technical nature and involves the application of computer science and mathematics in an environment which is constantly evolving as a result of technological advances.

If we considerate all these advantages noted above, for the work of research and development of software in the field of civil engineering, we can appreciate the importance of this work, for civil engineers, and how much the development software facilitates designing work, and the results obtained through software, became very precise results, very easy work.

This is why our end-of-study project subject was at the same time a very important subject for geotechnical engineers because it deals with a very delicate subject, that of **'a landslide'**, A landslide is a problem Very widespread, it affects all types of projects, whether building construction, or road projects, dams, dikes, bridges or projects in the field of environmental protection, and on the other hand, a brave step to develop a software that analyzes and calculates a landslide using the Bishop Simplified method. So our title of our project is “**Building a landslide simulation windows Application by using Analytical method**”.
The objective of this end-of-study project is:

> To provide the practicing geotechnical engineer with information that allows the assessment of newly proposed methods for determining the factor of safety of soil.

Provide our students and our civil engineers with a very simple and very detailed manual, well illustrated, in order to fully understand the method of slices, it is the most used method in terms of analysis of landslides.

Draw the attention of future civil engineers to the importance of software development in the field of civil engineering.

Chapter I: Definition and typology of soil movements.

Chapter I: **Definition and typology of soil movements.**

1- Introduction: Geologists, engineers, and other professionals often rely on unique and slightly differing definitions of landslides. This diversity in definitions reflects the complex nature of the many disciplines associated with studying landslide phenomena. For our purposes, landslide is a general term used to describe the down slope movement of soil, rock, and organic materials under the effects of gravity and also the landform that results from such movement, Varying classifications of landslides are associated with specific mechanics of slope failure and the properties and characteristics of failure types; these will be discussed briefly herein. There are a number of other phrases/terms that are used interchangeably with the term "***landslide***" including ***"mass movement"***, ***"slope failure"***, and so on. One commonly hears such terms applied to all types and sizes of landslides. Regardless of the exact definition used or the type of landslide under discussion, understanding the basic parts of a typical landslide is helpful. Figure I-1 shows the position and the most common terms used to describe the unique parts of a landslide.

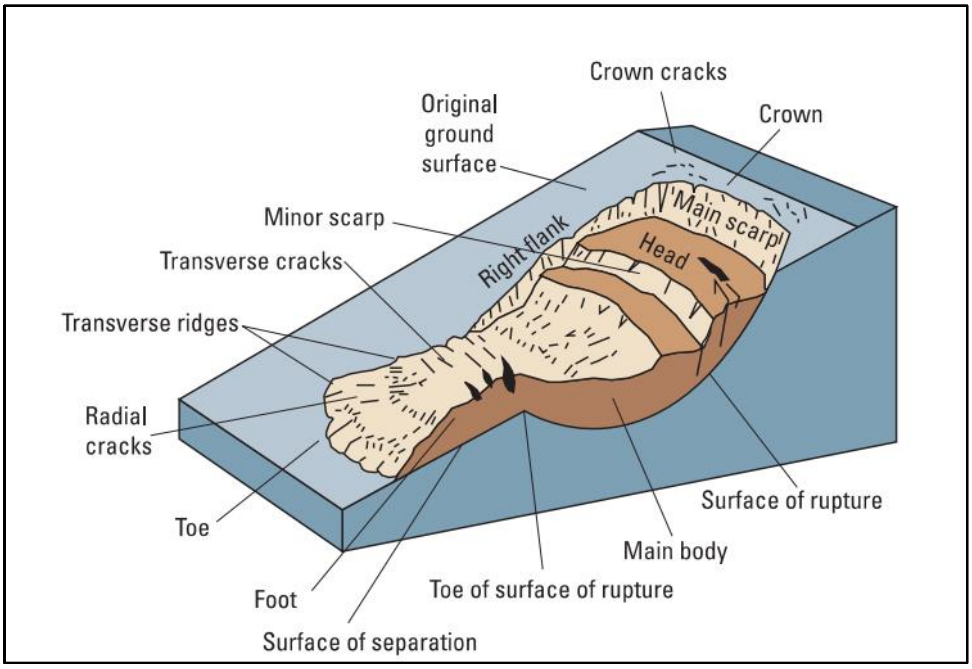


Figure I-1. A simple illustration of a rotational landslide that has evolved into an earth flow.[1]

2- What is a landslide and what causes one?

2-1 Definition of a landslide: is defined as the movement of a mass of rock, debris, or earth down a slope. Landslides are a type of "mass wasting," which denotes any down-slope movement of soil and rock under the direct influence of gravity. The term "landslide" encompasses five modes of slope movement: falls, topples, slides, spreads, and flows. These are further subdivided by the type of geologic material (bedrock, debris, or earth). Debris flows (commonly referred to as mudflows or mudslides) and rock falls are examples of common landslide types.

Almost every landslide has multiple causes. Slope movement occurs when forces acting down-slope (mainly due to gravity) exceed the strength of the earth materials that compose the slope. Causes include factors that increase the effects of down-slope forces and factors that contribute to low or reduced strength. Landslides can be initiated in slopes already on the verge of movement by rainfall, snowmelt, changes in water level, stream erosion, changes in ground water, earthquakes, volcanic activity, disturbance by human activities, or any combination of these factors. Earthquake shaking and other factors can also induce landslides underwater. These landslides are called submarine landslides. Submarine landslides sometimes cause tsunamis that damage coastal areas.

2-2 Origins and Consequences of Slope Failures [2]**:** Gravitational forces are always acting on a mass of soil or rock beneath slope. As long as the strength of the mass is equal to or greater than the gravitational forces, the forces are in balance, the mass is in equilibrium, and movement does not occur. An imbalance of forces results in slope failure and movement in the forms of creep, falls, slides, avalanches, or flows. Slope failures can range from being a temporary nuisance by partially closing a road-way, to destroying structures, to being catastrophic and even burying cities.

2-3 Causes of Landslides [1]**:** There are two primary categories of causes of landslides: natural and human- caused. Sometimes, landslides are caused, or made worse, by a combination of the two factors.

a Natural Occurrences [1]**:** This category has three major triggering mechanisms that can occur either singly or in combination (1) water,(2).seismic activity, and (3)volcanic activity .Effects of all of these causes vary widely and depend on factors such as steepness of slope, morphology or, shape of terrain, soil type, under lying geology, and whether there are people or structures on the affected areas.

a-1 Landslides and Water[1]**:** Slope saturation by water is a primary cause of landslides. Saturation can occur in the form of intense rainfall, snowmelt, changes in ground-water levels, and surface- water level changes along coastlines, earth dams, and in the banks of lakes, reservoirs, canals, and rivers. Landslides and flooding are closely associated because both are related to precipitation, run off, and the saturation of ground by water. Flooding may cause landslides by undercutting banks of streams and rivers and by saturation of slopes by surface water (overland flow). In addition, debris flows and mudflows usually occur in small, steep stream channels and commonly are mistaken for floods. In fact, these two events often occur simultaneously in the same area. Conversely, landslides also can cause flooding when sliding rock and debris block stream channels and other waterways, allowing large volumes of water to back up behind such dams. This causes backwater flooding and, if the dam fails, subsequent downstream flooding. Moreover, solid landslide debris can “bulk” or add volume and density to otherwise normal stream low or cause channel blockages and diversions, creating flood conditions or localized erosion. Landslides also can cause tsunamis (seiches), overtopping of reservoirs, and (or) reduced capacity of reservoirs to store water. Steep wildfire-burned slopes often are landslide-prone due to a combination of the burning and resultant denudation of vegetation on slopes, a change in soil chemistry due to burning, and a subsequent saturation of slopes by water from various sources, such as rainfall. Debris f1ows are the most common type of landslide on burned slopes. Wildfires, of course, may be the result of natural or human causes. **Figure I-2** shows a devastating landslide caused by rainfall, and possibly made worse by a leaking water pipe, which added even more water to the soil.

Figure I-2:The Mameyes, Puerto Rico, landslide, 1985. [1]

a-2 Landslides and Seismic Activity[1]: Many mountainous areas that are vulnerable to landslides have also experienced at least moderate rates of earthquake activity in recorded times. Earthquakes in steep landslide-prone areas greatly increase the likelihood that landslides will occur, due to ground shaking alone, liquefaction of susceptible sediments, or shaking-caused dilation of soil materials, which allows rapid infiltration of water. For instance, the 1964 Great Alaska earthquake in the United States caused widespread land sliding and other ground failure, which led to most of the monetary loss attributed to the earthquake. Other areas in North America, such as the State of California, the Puget Sound region in Washington, and the St. Lawrence lowlands of eastern Canada, have experienced landslides, lateral spreading, and other types of ground failure classified as landslides, due to moderate to large earthquakes. Rockfalls and rock topples can also be caused by loosening of rocks or rocky formations as a result of earthquake ground shaking. Figure I-3 shows damage from a landslide that was triggered by an earthquake. There is also a great danger of landslide dams forming in streams and rivers below steep slopes, a result of rock and earth being shaken down by the earthquake. These landslide dams often completely or partially block the flow of water, causing water to back up behind the landslide dam, flooding areas upriver. As these dams are often unstable, they may erode either quickly or over a period of time and fail catastrophically, unleashing the backed up water as a rapid deluge below the dam. This deluge is capable of causing a great deal of damage downriver.

Figure I.3. Earthquake-induced landslide damage to a house built on artificial fill, after the 2004 Niigata Prefecture earthquake in Japan. [1]

a-3 Landslides and Volcanic Activity[1]: Landslides due to volcanic activity represent some of the most devastating types of failures. Volcanic lava may melt snow rapidly, which can form a deluge of rock, soil, ash, and water that accelerates rapidly on the steep slopes of volcanoes, devastating anything in its path. These volcanic debris Flows (also known as lahars, an Indonesian term) can reach great distances after they leave the flanks of the volcano and can damage structures in that areas surrounding the volcanoes.

Volcanic edifices are young, unconsolidated, and geologically weak structures that in many cases can collapse and cause rockslides, landslides, and debris avalanches. Many islands of volcanic origin experience periodic failure of their perimeter areas (due to the weak volcanic surface deposits), and masses of soil and rock slide into the ocean or other water bodies, such as inlets. Such collapses may create massive sub-marine landslides that may also rapidly displace water, subsequently creating deadly tsunamis that can travel and do damage at great distances, as well as locally. **Figure I-4** shows a collapse of the side of a volcano and the resulting devastation.

Figure I-4. The side of Casita Volcano in Nicaragua, Central America, collapsed on October 30, 1998, [1]

b Human Activities [1]:
Populations expanding onto new land and creating neighborhoods, towns, and cities are the primary means by which humans contribute to the occurrence of landslides. Disturbing or changing drainage patterns, destabilizing slopes, and removing vegetation are common human-induced factors that may initiate landslides. Other examples include over steepening of slopes by undercutting the bottom and loading the top of a slope to exceed the bearing strength of the soil or other component material. However, landslides may also occur in once-stable areas due to other human activities such as irrigation, lawn watering, draining of reservoirs (or creating them), leaking pipes, and improper excavating or grading on slopes. New construction on landslide-prone land can be improved through proper engineering (for example, grading, excavating) by first identifying the site's susceptibility to slope failures and by creating appropriate landslide zoning.

2-4 Elements of Slope Stability[2]**:** Dependent Variables : Stated simply, slope failures are the result of gravitational forces acting on a mass which can creep slowly, fall freely, slide along some failure surface, or flow as a slurry. Stability can depend on a number of complex variables, which can be placed into four general categories as follows:

1. Topography — in terms of slope inclination and height
2. Geology — in terms of material structure and strength
3. Weather — in terms of seepage forces and run-off quantity and velocity
4. Seismic activity — as it affects inertial and seepage forces

2-5 Classification of Slope Failures: A classification of slope failures is given in **Table I-1**.The most important classes are fall, slides, avalanches, and flows.

Table I-1: A Classification of Slope Failures		
Type	**Form**	**Definition**
1- Falls	Free fall	Sudden dislodgment of single or multiple blocks of soil or rock which fall in free descent
	Topple	Overturning of a rock block about a pivot point located below its center of gravity
2- Slides	Rotational or slump	Relatively slow movement of an essentially coherent block (or blocks) of soil, rock, or soil—rock mixtures along some well—defined arc—shaped failure surface
	Planar or translational	Slow to rapid movement of an essentially coherent block (or blocks) of soil or rock along some well-defined planar failure surface.
Subclasses	Block Slide	A single block moving along a planar surface.
	Wedges	Block or blocks moving along intersecting planar surfaces
	Lateral Spreding	A number of intact blocks moving as separate units with differing displacements
	Debris slide	Soil-rock mixtures moving along a planar rock surface
3-Avalanches	Rock Or Debris	Rapid to very rapid movement of an incoherent mass of rock or soil-rock debris wherein the original structure of the formation is no longer discernible, occurring along an ill-defined surface.
4- Flows	Debris of Sand or Silt or Mud or soil	Soil or soil-rock debris moving as a viscous fluid or slurry, usually terminating at distances far beyond the failure zone; resulting from excessive pore pressures (sub classed according to material type)
5- Creep	/	Slow, imperceptible down slope movement of soil or soil-rock mixtures.
6- Solifluction (particular case of creep)	/	Shallow portions of the regolith moving down slope at moderate to slow rates in Arctic to sub-Arctic climates during periods of thaw over a surface usually consisting of frozen ground
7- Complex	/	Involves combinations of the above, usually occurring as a change from one form to another during failure with one form predominant

2-5 -1 Major factors of classification [2]**:**

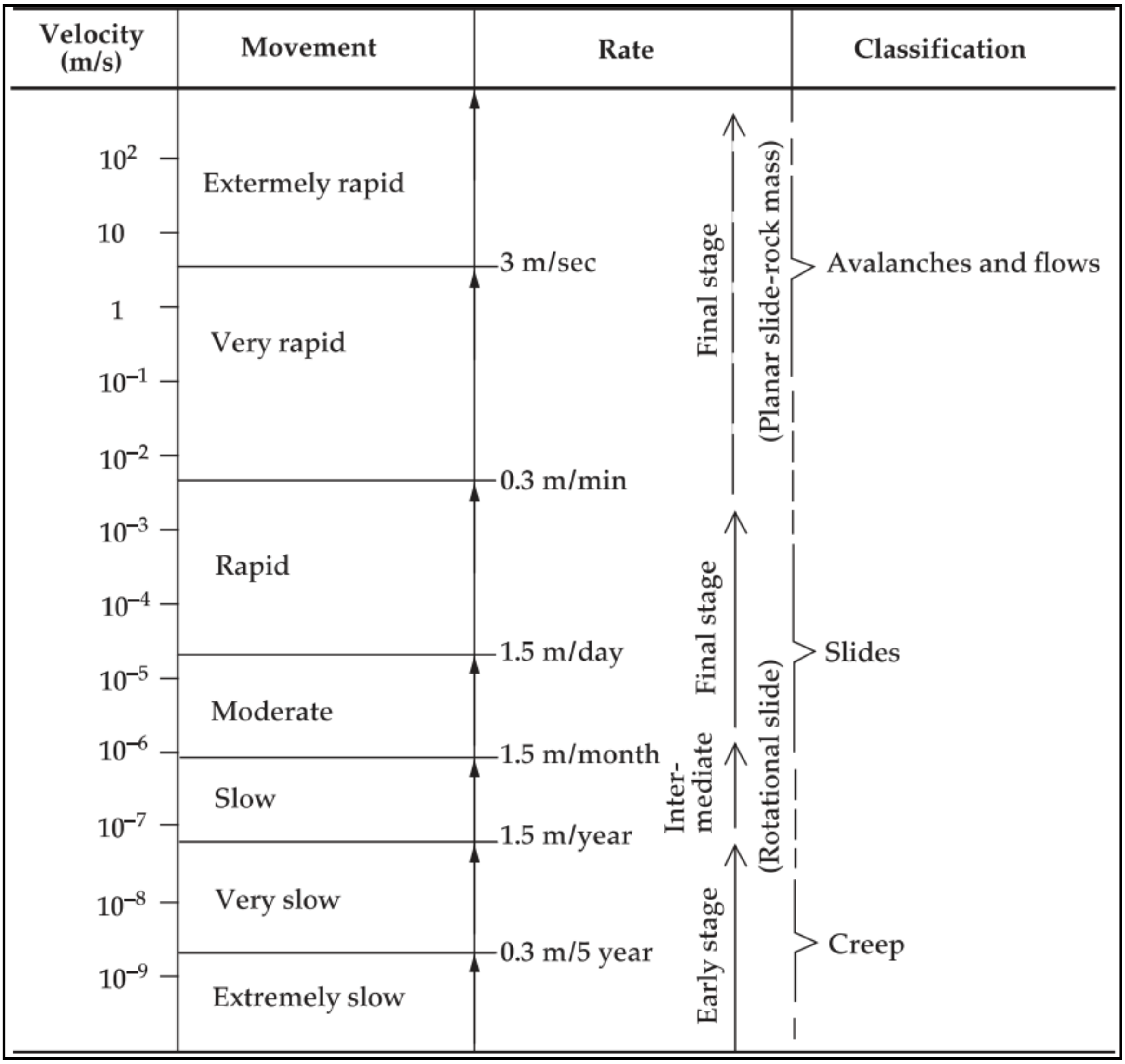
- *Movement form:* Fall, slide, slide flow (avalanche),flow
- *failure surface form:* Arc-shaped, planar, irregular, ill-defined
- fuss *coherency:* Coherent, with the original structure essentially intact although dislocated, or incoherent, with the original structure totally destroyed
- *Constitution:* Single or multiple blocks, or a heterogeneous mass without blocks, or a slurry
- *Failure cause:*Tensile strength or shear strength exceeded along a failure surface, or hydraulic excavation, or excessive seepage forces.

2-5 -2 Other factors to consider [2]**:**

- Fuss *displacement:* Amount of displacement from the failure zone, which can vary from slight to small, to very large. Blocks can move together with similar displacements, or separately with varying displacements.

- Material type: Rock blocks or slabs, soil-rock mixtures (debris), sands, silts, blocks of over consolidated clays, or mud (weak cohesive soils).
- Rate of movement during failure varies from extremely slow and barely perceptible to extremely rapid as given in **Table I.2.**

Table I-2: Velocity of movement for slope failure forms [2]**.**

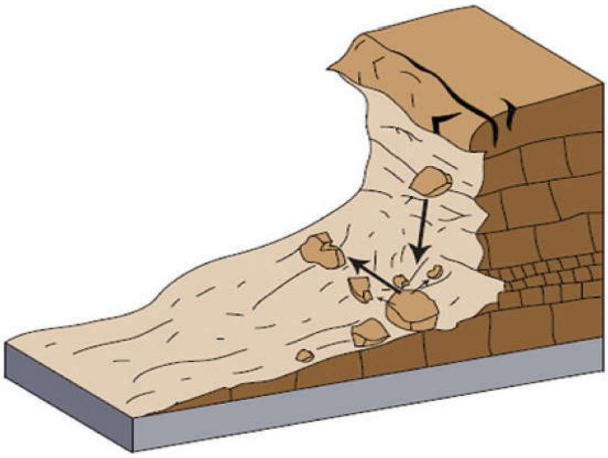


2-5-3 Basic Landslide Types [1]**:** Landslides can be classified into different types on the basis of the type of movement and the type of material involved. In brief, material in a landslide mass is either rock or soil (or both); the latter is described as earth if mainly composed of sand-sized or finer particles and debris if composed of coarser fragments. We treat "type of movement" as synonymous with "landslide type."

1 Falls [1]**:** A fall begins with the detachment of soil or rock, or both, from a steep slope along a surface on which little or no shear displacement has occurred. The material subsequently descends mainly by falling, bouncing, or rolling.

1-a- Rock fall [1]**:** Falls are abrupt, downward movements of rock or earth, or both, that detach from steep slopes or cliffs. The falling material usually strikes the lower slope at angles less than the angle of fall, causing bouncing. The falling mass may break on impact, may begin rolling on steeper slopes, and may continue until the terrain flattens.

1) **Occurrence and relative size/range:** Common worldwide on steep or vertical slopes—also in coastal areas, and along rocky banks of rivers and streams. The volume of material in a fall can vary substantially, from individual rocks or clumps of soil to massive blocks thousands of cubic meters in size.
2) **Velocity of travel:** Very rapid to extremely rapid, free-fall; bouncing and rolling of detached soil, rock, and boulders. The rolling velocity depends on slope steepness.
3) **Triggering mechanism:** Undercutting of slope by natural processes such as, streams and rivers or differential weathering (such as the freeze/thaw cycle), human activities such as excavation during road building and (or) maintenance, and earth quake shaking or other intense vibration.
4) **Effects (direct/indirect):** Falling material can be life-threatening. Falls can damage property beneath the fall-line of large rocks. Boulders can bounce or roll great distances and damage structures or kill people. Damage to roads and railroads is particularly high: rock falls can cause deaths in vehicles hit by rocks and can block highways and railroads.
5) **Corrective measures/mitigation :** Rock curtains or other slope covers, protective covers over roadways, retaining walls to prevent rolling or bouncing, explosive blasting of hazardous target areas to remove the source, removal of rocks or other materials from highways and railroads can be used. Rock bolts or other similar types of anchoring used to stabilize cliffs, as well as scaling, can lessen the hazard. Warning signs are recommended in hazardous areas for awareness. Stopping or parking under hazardous cliffs should be warned against.
6) **Predictability:** Mapping or hazardous rock fall areas has been completed in a few areas around the world. Rock-bounce calculations and estimation methods for delineating the perimeter of rock fall zones have also been determined and the information widely published. Indicators of imminent rock fall include terrain with overhanging rock or fractured or jointed rock along steep slopes, particularly in areas subject to frequent freeze-thaw cycles. Also, cut faces in gravel pits may be particularly subject to falls. Figures I-5 and I-6. Show a schematic and an image of rock fall.



FigureI-5: Schematic of a rock fall. [1]

Figure I-6: A rockfall/slide that occurred in Clear Creek Canyon, Colorado, USA, 2005, [1]

1-b Topple [1]**:** Topple is recognized as the forward *rotation* out of a slope of soil mass or rock around a point or *axis* below the *center of gravity* of the displaced mass. Toppling is sometimes driven by gravity exerted by the weight of material upslope from the displaced mass. Sometimes toppling is due to water or ice in cracks in the mass. Topples can consist of rock, debris (coarse material) or earth materials (fine- grained material). Topple can be complex and composite.

1) **Occurrence:** Known to occur globally, often prevalent in columnar-jointed volcanic terrain, as well as along stream and river courses where the banks are steep.
2) **Velocity of travel:** Extremely slow to extremely rapid, sometimes accelerating throughout the movement depending on distance of travel.
3) **Triggering mechanism:** Sometimes driven by gravity exerted by material located upslope from the displaced mass and sometimes by water or ice occurring in cracks within the mass; also, vibration, undercutting, differential weathering, excavation, or stream erosion.
4) **Effects (direct/indirect):** Can be extremely destructive, especially when failure is sudden and (or) the velocity is rapid.
5) **Corrective measures/mitigation:** In rock there are many options for the stabilization of topple-prone areas. Some examples for reinforcement of these slopes include rock bolts and mechanical and other types of anchors. Seepage is also a contributing factor to rock instability, and drainage should be considered and addressed as a corrective means.
6) **Predictability:** Not generally mapped for susceptibility; some inventory of occurrence exists for certain areas. Monitoring of topple prone areas is useful; for example, the use of tiltmeters.

Tiltmeters are used to record changes in slope inclination near cracks and areas of greatest vertical movements. Warning systems based on movement measured by tiltmeters could be effective. Figures I-7 and I-8 show a schematic and an image of topple.

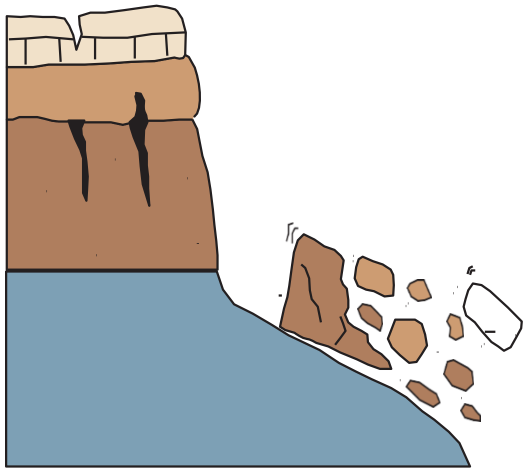


Figure I-7: Schematic of a topple. [1]

Figure I-8: Photography of block toppling at Fort St. John, British Columbia, Canada. [1]

2 Slides[1]**:** A slide is a down slope movement of a soil or rock mass occurring on surfaces of rupture or on relatively thin zones of intense shear strain. Movement does not initially occur simultaneously over the whole of what eventually becomes the surface of rupture; the volume of displacing material enlarges from an area of local failure.

a- Rotational landslide or slump: A landslide on which the surface of rupture is curved upward (spoon-shaped) and the slide movement is more or less rotational about an axis that is parallel to the contour of the slope. The displaced mass may, under certain circumstances, move as a relatively coherent mass along the rupture surface with little internal deformation. The head of the displaced material may move almost vertically downward, and the upper surface of the displaced material may tilt backwards toward the scarp. If the slide is rotational and has several parallel curved planes of movement, it is called a slump.

1) **Occurrence:** Because rotational slides occur most frequently in homogeneous materials, they are the most common landslide occurring in “fill” materials.
2) **Relative size/range:** Associated with slopes ranging from about 20 to 40 degrees. In soils, the surface of rupture generally has a depth-to-length ratio between 0.3 to 0.1.
3) **Velocity of travel (rate of movement):** Extremely slow (less than 0.3 meter or 1 foot every 5 years) to moderately fast (1.5 meters or 5 feet per month) to rapid.
4) **Triggering mechanism:** Intense and (or) sustained rainfall or rapid snowmelt can lead to the

saturation of slopes and increased groundwater levels within the mass rapid drops in river level following floods, ground-water levels rising as a result of filling reservoirs, or the rise in level of streams, lakes, and rivers, which cause erosion at the base of slopes. These types of slides can also be earthquake-induced.

5) **Effects (direct/indirect):** Can be extremely damaging to structures, roads, and lifelines but are not usually life-threatening if movement is slow. Structures situated on the moving mass also can be severely damaged as the mass tilts and deforms. The large volume of material that is displaced is difficult to permanently stabilize. Such failures can dam rivers, causing flooding.
6) **Mitigation measures:** Instrumental monitoring to detect movement and the rate of movement can be implemented. Disrupted drainage pathways should be restored or reengineered to prevent future water buildup in the slide mass. Proper grading and engineering of slopes, where possible, will reduce the hazard considerably. Construction of retaining walls at the toe may be effective to slow or deflect the moving soil; however, the slide may over- top such retaining structures despite good construction.
7) **Predictability:** Historical slides can be reactivated; cracks at tops (heads) of slopes are good indicators of the initiation of failure. Figures I-9 and I-10 show a schematic and an image of a rotational landslide.

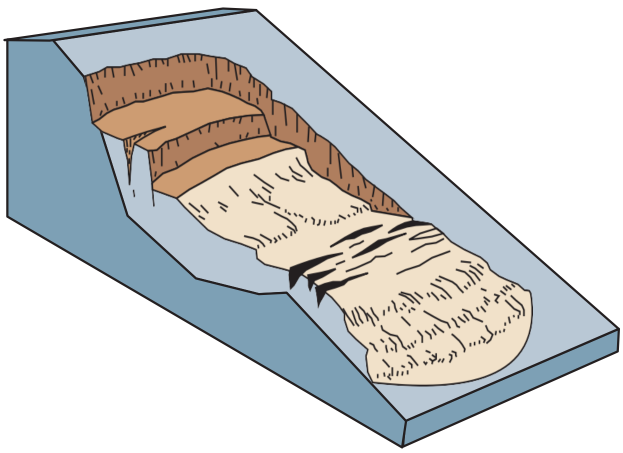


Figure I-9: Schematic of a rotational landslide. [1]

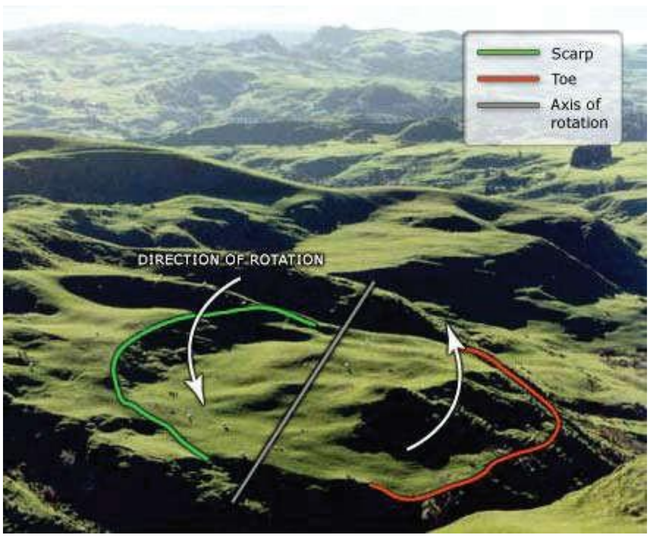


Figure I-10: Photography of a rotational landslide which occurred in New Zealand. [1]

b- Translational Landslide or planar [1]**:**

The mass in a translational landslide moves out, or down and outward, along a relatively planar surface with little rotational movement or backward tilting. This type of slide may progress over considerable distances if the surface of rupture is sufficiently inclined, in contrast to rotational slides, which tend to restore the slide equilibrium. The material in the slide may range from loose, unconsolidated soils to extensive slabs of rock, or both. Translational slides commonly fail along geologic discontinuities such as faults, joints, bedding surfaces, or the contact between rock and soil. In northern environments the slide may also move along the permafrost layer.

1) **Occurrence:** One of the most common types of landslides, worldwide. They are found globally in all types of environments and conditions.
2) **Relative size/range:** Generally shallower than rotational slides. The surface of rupture has a distance-to-length ratio of less than 0.1 and can range from small (residential low size) failures to very large, regional landslides that are kilometers wide.
3) **Velocity of travel:** Movement may initially be slow (5 feet per month or 1.5 meters per month) but many are moderate in velocity (5 feet per day or 1.5 meters per day) to extremely rapid. With increased velocity, the landslide mass of translational failures may disintegrate and develop into a debris flow.

4) **Triggering mechanism:** Primarily intense rainfall, rise in ground water within the slide due to rainfall, snowmelt, flooding, or other inundation of water resulting from irrigation, or leakage from pipes or human-related disturbances such as undercutting. These types of landslides can be earthquake-induced.
5) **Effects (direct/indirect):** Translational slides may initially be slow, damaging property and (or) lifelines; in some cases they can gain speed and become life-threatening. They also can dam rivers, causing flooding.

6) **Mitigation measures:** Adequate drainage is necessary to prevent sliding or, in the case of an existing failure, to prevent a reactivation of the movement. Common corrective measures include leveling, proper grading and drainage, and retaining walls. More sophisticated remedies in rock include anchors, bolts, and dowels, which in all situations are best implemented by professionals. Translational slides on moderate to steep slopes are very difficult to stabilize permanently.
7) **Predictability**: High probability at occurring repetitively in areas where they have occurred in the past, including areas subject to frequent strong earth quakes. Widening cracks at the head or toe bulge may be an indicator of imminent failure. Figures I-11 and I-12 show a schematic and an image of a translational landslide.

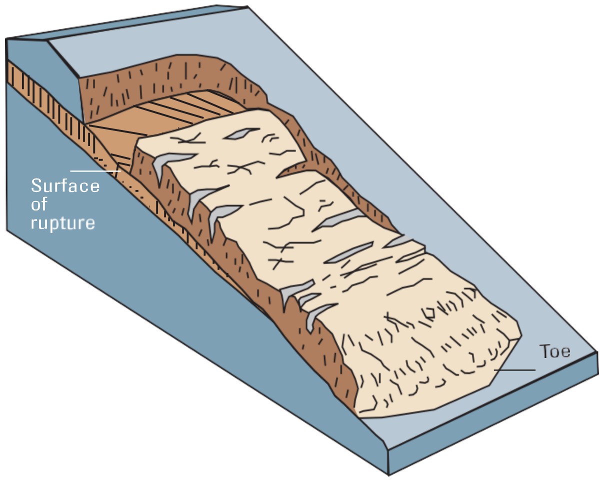


Figure I-11: Schematic of a translational landslide. [1]	**Figure I-12: A translational landslide that occurred in 2001 in the Beatton River Valley, British Columbia, Canada. [1]**

c- Spreads [1]**:** An extension of a cohesive soil or rock mass combined with the general subsidence of the fractured mass of cohesive material into softer underlying material. Spreads may result from liquefaction or flow (and extrusion) of the softer underlying material. Types of spreads include block spreads, liquefaction spreads, and lateral spreads.

Lateral Spreads: Lateral spreads usually occur on very gentle. slopes or essentially Hat terrain, especially where a stronger upper layer of rock or soil undergoes extension and moves above an underlying softer, weaker layer. Such failures commonly are accompanied by some general subsidence into the weaker underlying unit. In rock spreads, solid ground extends and fractures, pulling away slowly from stable ground and moving over the weaker layer without necessarily forming a recognizable surface of rupture. The softer, weaker unit may, under certain conditions, squeeze upward into fractures that divide the extending layer into blocks. In earth spreads, the upper stable layer extends along a weaker underlying unit that has flowed following liquefaction or plastic deformation. If the weaker unit is relatively thick, the overriding fractured blocks may subside into it, translate, rotate, disintegrate, liquefy, or even flow.

1) **Occurrence:** Worldwide and known to occur where there are liquefiable soils. Common, but not restricted, to areas of seismic activity.
2) **Relative size/range:** The area affected may start small in size and have a few cracks that may spread quickly, affecting areas of hundreds of meters in width.
3) **Velocity of travel:** May be slow to moderate and sometimes rapid after certain triggering mechanisms, such as an earthquake. Ground may then slowly spread over time from a few millimeters per day to tens of square meters per day.

4) **Triggering mechanism:** Triggers that destabilize the weak layer include:

- ✓ Liquefaction of lower weak layer by earthquake shaking
- ✓ Natural or anthropogenic over loading of the ground above an unstable slope
- ✓ Saturation of underlying weaker layer due to precipitation, snowmelt, and (or) groundwater changes
- ✓ Liquefaction of underlying sensitive marine clay following an erosional disturbance at base of a riverbank/slope
- ✓ Plastic deformation or unstable material at depth (for example, salt).

5) Effects (direct/indirect): Can cause extensive property damage to buildings, roads, railroads, and lifelines. Can spread slowly or quickly, depending on the extent of water saturation of the various soil layers. Lateral spreads may be a precursor to earth flows.

6) **Mitigation measures:** Liquefaction potential maps exist for some places but are not widely available. Areas with potentially liquefiable soils can be avoided as construction, sites, particularly in regions that are known to experience frequent earthquakes. If high ground-water levels are involved, sites can be drained or other water-diversion efforts can be added.

7) **Predictability:** High probability of recurring in areas that have experienced previous problems. Most prevalent in areas that have an extreme earthquake hazard as well as liquefiable soils. Lateral spreads are also associated with susceptible marine clays and are a common problem throughout the St. Lawrence Lowlands of eastern Canada. Figures I-13 and I-14 show a schematic and an image of a lateral spread.

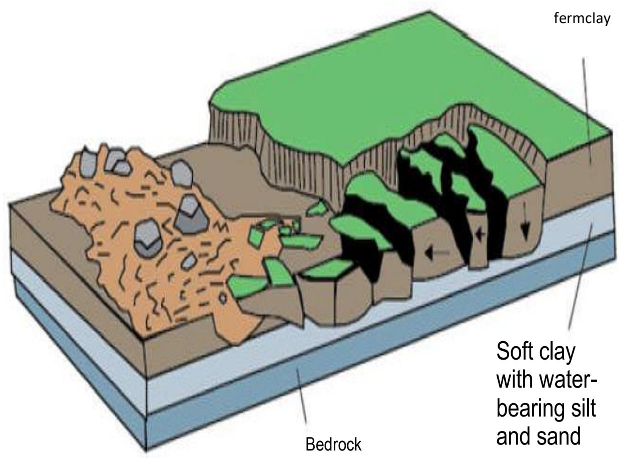


Figure I-13: Schematic of a lateral spread. A liquefiable layer underlies the surface layer. [1]

Figure I-14: Photography of lateral spread damage to a roadway as a result of the 1989 Lorna Prieta, California, USA, earthquake. [1]

3 Flows [1]**:** A flow is a spatially continuous movement in which the surfaces of shear are short-lived, closely spaced, and usually not preserved. The component velocities in the displacing mass of a flow resemble those in a viscous liquid. Often, there is a gradation of change from slides to flows, depending on the water content, mobility, and evolution of the movement.

a- Debris Flows: A form of rapid mass movement in which loose soil, rock and sometimes organic matter combine with water to form a slurry that flows down slope. They have been informally and inappropriately called “mudslides” due to the large quantity of fine material that may be present in the flow. Occasionally, as a rotational or translational slide gains velocity and the internal mass loses cohesion or gains water, it may evolve into debris how. Dry flows can sometimes occur in cohesionless sand (sand flows). Debris flows can be deadly as they can be extremely rapid and may occur without any warning.

1) **Occurrence:** Debris flows occur around the world and are prevalent in steep gullies and canyons; they can be intensified when occurring on slopes or in gullies that have been denuded of vegetation due to wildfires or forest logging. They are common in volcanic areas with weak soil.
2) **Relative size/range:** These types of flows can be thin and watery or thick with sediment and debris and are usually confined to the dimensions of the steep gullies that facilitate their downward movement. Generally the movement is relatively, shallow and the run out is both long and narrow, sometimes extending for kilometers in steep terrain. The debris and mud usually terminate at the base of the slopes and create fanlike, triangular deposits called debris fans, which may also be unstable.
3) **Velocity of travel:** Can be rapid to extremely rapid (35 miles per hour or 56 km per hour) depending on consistency and slope angle.
4) **Triggering mechanisms:** Debris flows are commonly caused by intense surface-water flow, due to heavy precipitation or rapid snowmelt that erodes and mobilizes loose soil or rock on steep slopes. Debris flows also commonly mobilize from other types of landslides that occur on steep slopes, are nearly saturated, and consist of a large proportion of silt and sand sized material.
5) **Effects (direct/indirect):** Debris flows can be lethal because of their rapid onset, high speed of movement, and the fact that they can incorporate large boulders and other pieces of debris. They can move objects as large as houses in their down slope flow or can fill structures with a rapid accumulation of sediment and organic matter. They can affect the quality of water by depositing large amounts of silt and debris.
6) **Mitigation measures:** Flows usually cannot be prevented thus, homes should not be built in steep-walled gullies that have a history of debris flows or are otherwise susceptible due to wildfires, soil type, or other related factors. New flows can be directed away from structures by means of deflection, debris-flow bassins can be built to contain how, and warning systems can be

put in place in areas where it is known at what rainfall thresholds debris f1ows are triggered. Evacuation, avoidance, and (or) relocation are the best methods to prevent injury and life loss.

7) **Predictability:** Maps of potential debris flow hazards exist for some areas. Debris flows can be frequent in any area of steep slopes and heavy rainfall, either seasonally or intermittently, and especially in areas that have been recently burned or the vegetation removed by other means. Figures I-15 and I-16 show a schematic and an image of a debris flow.

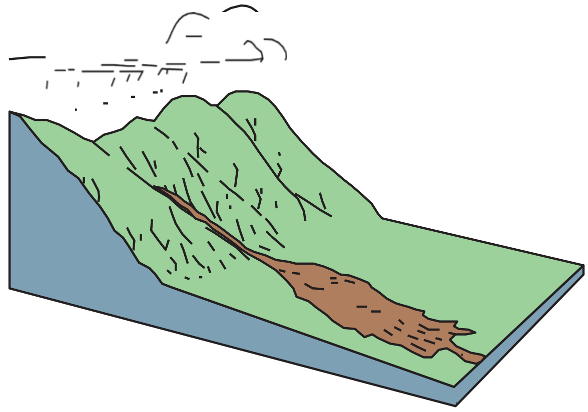


Figure I-15: Schematic of a debris flow.[1]

Figure I-16: Debris-flow damage to the city of Caraballeda, located at the base of the Cordillera de la Costan, on the north coast of Venezuela. In December1999. [1]

b- Earth flow [1]**:** Earth flows can occur on gentle to moderate slopes, generally in fine-grained soil, commonly clay or silt, but also in very weathered, clay-bearing bedrock. The mass in an earth flow moves as a plastic or viscous flow with strong internal deformation. Susceptible marine clay (quick clay) when disturbed is very vulnerable and may lose all shear strength with a change in its natural moisture content and suddenly liquefy, potentially destroying large areas and flowing for several kilometers. Size commonly increases through head scarp retrogression. Slides or lateral spreads may also evolve down slope into earth flows. Earth flows can range from very slow (creep) to rapid and catastrophic. Very slow flows and specialized forms of earth flow restricted to northern permafrost environments are discussed elsewhere.

1) **Occurrence:** Earth flows occur worldwide in regions underlain by fine-grained soil or very weathered bedrock. Catastrophic rapid earth f1ows are common in the susceptible marine clays or the St. Lawrence Lowlands of North America, coastal Alaska and British Columbia, and in Scandinavia.

2) **Relative (size/range):** Flows can range from small events of 100 square meters in size to large events encompassing several square kilometers in area. Earth flows in susceptible marine clays

may run out for several kilometers. Depth of the failure ranges from, shallow to many tens of meters.

3) **Velocity of travel:** Slow to very rapid.
4) **Triggering mechanisms :** Triggers include saturation of soil due to prolonged or intense rainfall or snowmelt, sudden lowering of adjacent water surfaces causing rapid drawdown of the ground-water table, stream erosion at the bottom of a slope, excavation and construction activities, excessive loading on a slope, earthquakes, or human-induced vibration.
5) **Effects (direct/indirect):** Rapid, retrogressive earth flows in susceptible marine clay may devastate large areas of flat land lying above the slope and also may run out for considerable distances, potentially resulting in human fatalities, destruction of buildings and linear infrastructure, and damming of rivers with resultant flooding upstream and water siltation problems downstream. Slower earth flows may damage properties and sever linear infrastructure.
6) **Corrective measures/mitigation:** Improved drainage is an important corrective measure, as is grading of slopes and protecting the base of the slope from erosion or excavation. Shear strength of clay can be measured, and potential pressure can be monitored in suspect slopes. However, the best mitigation is to avoid development activities near such slopes.
7) **Predictability:** Evidence of past earth flows is the best indication of vulnerability. Distribution of clay likely to liquefy can in some cases be mapped and has been mapped in many parts of eastern North America. Cracks opening near the top of the slope may indicate potential failure. Figures I-17 and I-18 show a schematic and an image of an earth flow.

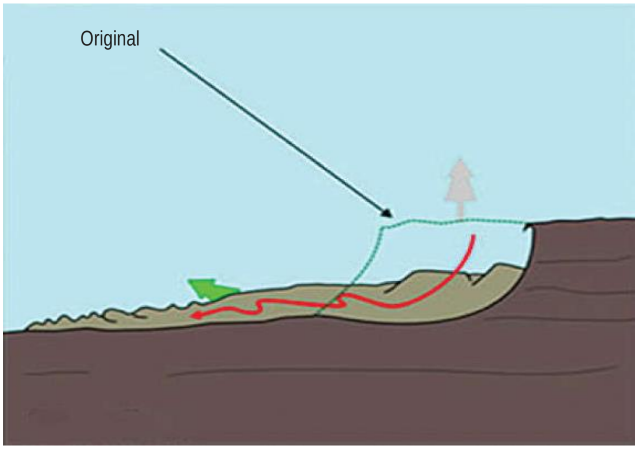


Figure I-17: Schematic of an earth flow. [1]

Figure I-18: The 1993 Lemieux landslide a rapid earth flow in sensitive marine clay near Ottawa, Canada. [1]

c- Lahars [1]**:** The word "lahar" is an Indonesian term. Lahars are also known as volcanic mudflows. These are flows that originate on the slopes of volcanoes and are a type *of* debris flow. A lahar mobilizes the loose accumulations of tephra (the airborne solids erupted from the volcano) and related debris.

1) **Occurrence:** Found in nearly all volcanic areas of the world.
2) **Relative size/range:** Lahars can be hundreds of square kilometers or miles in area and can become larger as they gain speed and accumulate debris as they travel down slope; or, they can be small in volume and affect limited areas of the volcano and then dissipate down slope.
3) **Velocity of travel:** Lahars can be very rapid (more than 35 miles per hour or 50 kilometers per hour) especially if they mix with a source of water such as melting snowfields or glaciers. If they are viscous and thick with debris and less water, the movement will be slow to moderately slow.
4) **Triggering mechanism:** Water is the primary triggering mechanism, and it can originate from crater lakes, condensation of erupted steam on volcano particles, or the melting of snow and ice at the top of high volcanoes. Some of the largest and most deadly lahars have originated from eruptions or volcanic venting which suddenly melts surrounding snow and ice and causes rapid liquefaction and flow down steep volcanic slopes at catastrophic speeds.
5) **Effects (direct/indirect):** Effects can be extremely large and devastating, especially when triggered by a volcanic eruption and consequent rapid melting of any snow and ice the flow can bury human settlements located on the volcano slopes. Some large flows can also dam rivers, causing flooding upstream. Subsequent breaching of these weakly cemented dams can cause catastrophic flooding downstream. This type of landslide often results in large numbers of human casualties.
6) **Mitigation measures:** No corrective measures are known that can be taken to prevent damage from lahars except for avoidance by not building or locating in their paths or on the slopes of volcanoes. Warning systems and subsequent evacuation work in some instances may save lives. However, warning systems require active monitoring, and a reliable evacuation method is essential.
7) **Predictability:** Susceptibility maps based on past occurrences of lahars can be constructed, as well as run out estimations of potential flows. Such maps are not readily available for most hazardous areas. Figures I-19 and I-20 show a schematic and an image of a lahar.

	
Figure I-19: Schematic of a lahar. [1]	**FigureI-20: Photography of a lahar caused by the 1982 eruption of Mount St. Helens in Washington, USA. [1]**

4 Debris Avalanche [1]**:** Debris avalanches are essentially large, extremely rapid, often open, slope flows formed when an unstable slope collapses and the resulting fragmented debris is rapidly transported away from the slope. In some cases, snow and ice will contribute to the movement if sufficient water is present, and the flow may become a debris flow and (or) a lahar.

1) **Occurrence:** Occur worldwide in steep terrain environments. Also common on very steep volcanoes where they may follow drainage courses.
2) **Relative size/range:** Some large avalanches have been known to transport material blocks as large as 3 kilometers in size, several kilometers from their source.
3) **Velocity of travel:** Rapid to extremely rapid; such debris ava1anches can travel close to 100 meters/sec.
4) **Triggering mechanism:** In general, the two types of debris avalanches are those that are "cold" and those that are "hot." A cold debris avalanche usually results from a slope becoming unstable, such as during collapse of weathered slopes in steep terrain or through the disintegration of bedrock during a slide-type landslide as it moves down, slope at high velocity. At that point, the mass can then transform into a debris avalanche. A hot debris avalanche is one that results from volcanic activity including volcanic earthquakes or the injection of magma, which causes slope instability.
5) **Effects (direct/indirect):** Debris avalanches may travel several kilometers before stopping, or they may transform into more water-rich lahars or debris flows that travel many tens of kilometers farther downstream. Such failures may inundate towns and villages and impair stream quality.

They move very fast and thus may prove deadly because there is little chance for warning and response.

6) **Corrective measures/mitigation:** Avoidance of construction in valleys on volcanoes or steep mountain slopes and real-time warning systems may lessen damages. However, warning systems may prove difficult due to the speed at which debris avalanches occur there may not be enough time after the initiation of the event for people to evacuate. Debris avalanches cannot be stopped or prevented by engineering means because the associated triggering mechanisms are not preventable.

7) **Predictability:** If evidence of prior debris avalanches exists in an area, and if such evidence can be dated, a probabilistic recurrence period might be established. During volcanic eruptions, chances are greater for a debris avalanche to occur, so appropriate cautionary actions could be adopted. Figures I-21 and I-22 show a schematic and an image of a debris avalanche.

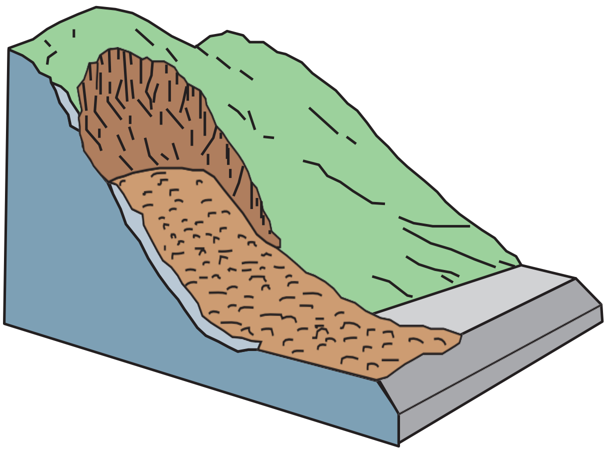


Figure I-21: Schematic of a debris avalanche. [1]	**Figure I-22: A debris avalanche that buried the village of Guinsaugon, Southern Leyte, Philippines, in February 2006. [1]**

5. Slow Earth flow (Creep) [1]**:** Creep is the informal name for a slow earth flow and consists of the imperceptibly slow, steady downward movement of slope-forming soil or rock. Movement is caused by internal shear stress sufficient to cause deformation but insufficient to cause failure. Generally, the three types of creep are: (1) seasonal, where movement is within the depth of soil affected by seasonal changes in soil moisture and temperature; (2) continuous, where shear stress continuously exceeds the strength of the material; and (3) progressive, where slopes are reaching the point of failure for other types of mass movements.

1) **Occurrence:** Creep is widespread around the world and is probably the most common type of landslide, often preceding more rapid and damaging types of landslides. Solifluction. A

specialized form of creep common to permafrost environments occurs in the upper layer of ice-rich, fine-grained soils during the annual thaw of this layer.

2) **Relative size/range:** Creep can be very regional in nature (tens of square kilometers) or simply confined to small areas. It is difficult to discern the boundaries of creep since the event itself is so slow and surface features representing perceptible deformation may be lacking.
3) **Velocity of travel:** Very slow to extremely slow. Usually less than1meter (0.3foot) per decade.
4) **Triggering mechanism:** For seasonal creep, rainfall and snowmelt are typical triggers, whereas for other types of creep there could be numerous causes, such as chemical or physical weathering, leaking pipes, poor drainage, destabilizing types of construction, and so on.
5) **Effects:** It is hard to detect in some places because of the slowness of movement, creep is sometimes not recognized when assessing the suitability of a building site. Creep can slowly pull apart pipelines, buildings, highways, fences, and so forth, and can lead to more drastic ground failures that are more destructive and faster moving.
6) **Corrective measures/mitigation:** The most common mitigation for creep is to ensure proper drainage of water, especially for the seasonal type of creep. Slope modification such as flattening or removing all or part of the landslide mass, can be attempted, as well as the construction of retaining walls.
7) **Predictability:** Indicated by curved tree trunks, bent fences and (or) retaining walls, tilted poles or fences, and small soil ripples or ridges on the surface. Rates of creep can be measured by inclinometers installed in boreholes or by detailed surface measurements. Figures I-23 and I-24 show a schematic and an image of creep.

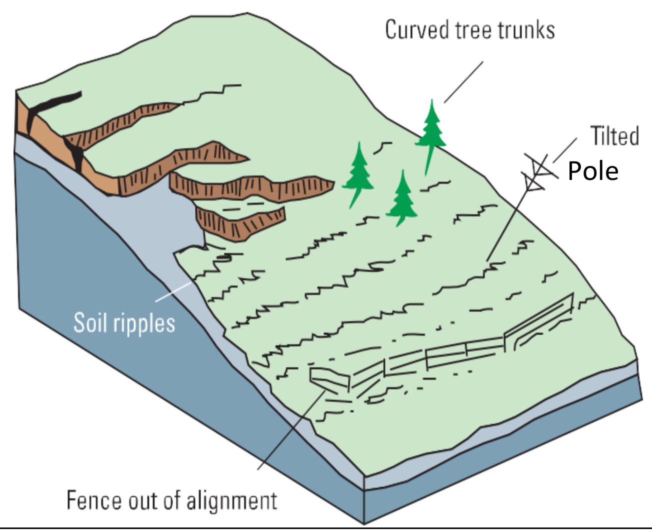


Figure I-23: Schematic of a slow earthflow, often called creep. [1]

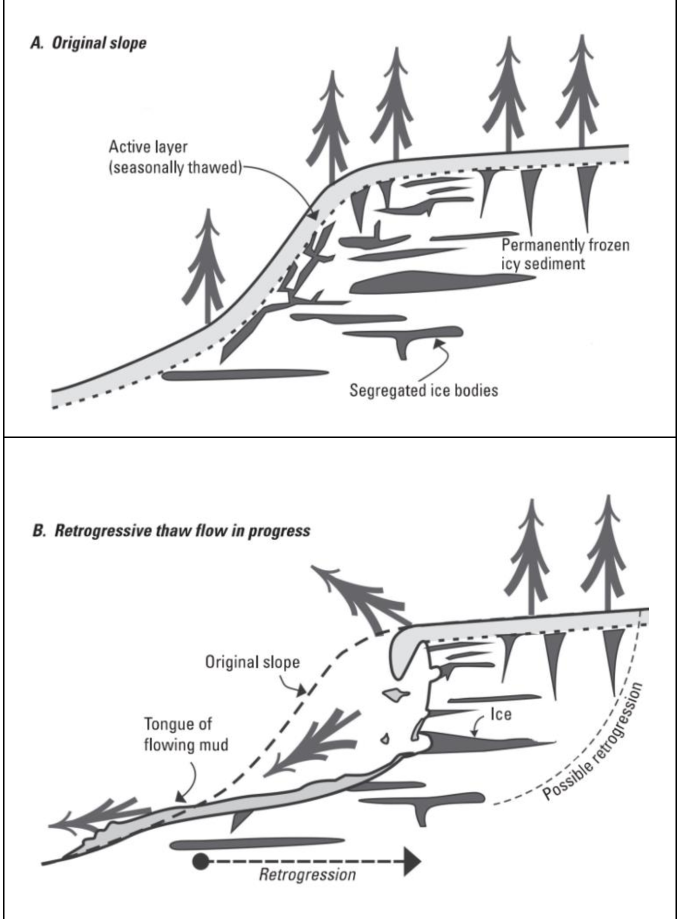
Figure I-24: This photography shows the effects of creep, in an area near East Sussex, United Kingdom. [1]

6 Flows in Permafrost [1]**:** Failures in permafrost conditions involve the movement of line-grained, previously ice-rich soil and can occur on gentle slopes. Seasonal thaw of the upper meter of frozen ground melts ground ice and results in oversaturation of the soil, which in turn loses shear, strength and initiates flows. Solifluction a form of cold environment creep, involves very slow deformation of the surface and forms shallow lobes elongated down slope. Active layer detachments, also known as skin flows, involve rapid flow of a shallow layer of saturated soil and vegetation, forming long, narrow flows moving on the surface but over the underlying permanently frozen soil. This type of movement may expose buried ice lenses, which when thawed may develop into retrogressive thaw flows or possibly debris flows. Retrogressive thaw flows are larger features with a bimodal shape of a steep headwall and low-angle tongue of saturated soil. This type of feature will continue to expand through heads carp retrogression until displaced vegetation buries and insulates the ice-rich scarp.

1) **Occurrence:** Flows are common in ice-rich permafrost soils in northern latitudes and high altitudes (cold environments).
2) **Relative size/range:** Flows are generally small but can increase in size through head scarp retrogression. They may evolve into a larger debris flow.
3) **Velocity of travel:** Very slow (solifluction), slow (retrogressive thaw flow), rapid (active layer detachment).
4) **Triggering mechanisms:** Above-average, summer temperatures, frost wedges, wildfire, and anthropogenic disturbances to insulating peat layer. Such landslides are particularly likely in warming climates.
5) **Effects (direct/indirect):** Damage to pipelines and roads and other structures can be severe.

6) **Corrective measures/mitigation:** Infrastructure designs that have minimal effect on the surface peat layer or temperature of the active layer and avoidance, when possible, of ice- rich soils when planning roads and other infrastructure, can reduce risk. Ice content of the upper soil can be readily tested.

7) **Predictability:** If ice-rich soil thaws, it will flow. In some areas, ice content has been mapped; in other areas, ice content can be estimated on the basis of specific mapped units shown on surficial geology maps. Figures I-25 and I-26 show a schematic and an image of permafrost-related flow.



FigureI-25: Schematic of a retrogressive thaw flow slide. [1]

FigureI-26: Photography of a retrogressive thaw flow in the North west Territories, Canada. [1]

Conclusion:

- ✓ There are a number of other phrases/terms that are used interchangeably with the term "***landslide***" including ***"mass movement"***, ***"slope failure".***
- ✓ Complex landslides are landslides that feature components of two or more of the basic types at landslides and can occur either simultaneously or at different times during the onset of slope failure.

Movements and landslides cause major accidents magnitudes of which the material damage is often considerable and can cause losses in human lives. However, it is necessary to clearly identify the danger that can be caused by landslides either by treatment of the land or by total evacuation of the places the prevention against the risk of some type of landslide seems impossible given the complexity and the sudden change in the behavior of some type of soil, however, the following criteria is required to determine the degree of risk

- ✓ *Prediction:* Some failures can be predicted, others cannot, although most hazardous conditions are recognizable.
- ✓ *Occurrence:* Some forms occur without warning; many other forms give warning, most commonly in the form of early surface cracks.
- ✓ *Movement velocities:* Some move slowly, others progressively or retrogressively, others at great velocities.
- ✓ *Movement distances:* Some move short distances; others can move for many miles.
- ✓ *Movement volume:* Some involve small blocks; others involve temendous volumes.
- ✓ *Failure forms:* Some geologic formations have characteristic failure forms; others can fail in a variety of forms, often complex.
- ✓ *Mathematical* analysis: Some conditions can be analyzed mathematically, many cannot.
- ✓ *Treatments:* Some conditions cannot be treated to make them stable; they should be avoided.

Chapter II: Overview of literature approach used for computing a landslide.

Chapter II: Overview of literature approach used for computing a landslide.

1 Introduction

This chapter provides guidance for analyzing the static stability of slopes of earth, slopes of other types of embankments, excavated slopes, and natural slopes in soil and soft rock. Criteria are presented for strength tests, analysis conditions, and factors of safety. The criteria in this chapter are to be used with methods of stability analysis that satisfy all conditions of equilibrium. Methods that do not satisfy all conditions of equilibrium may involve significant inaccuracies and should be used only under the restricted conditions described herein. This procedure is intended to guide design and construction engineers, rather than to specify rigid procedures to be followed in connection with a particular project.

2 History of limit equilibrium analysis [3]:

The earliest application of statics to a sliding mass considered a planar sliding surface because of its ease of analysis. The movement of a large earth mass into the Goteborg harbor in Sweden showed the characteristics of a circular shape (Petterson, 1915). The entire sliding mass was considered as a single unit and the tending overturning moment was used to estimate the shear resistance of the soft sediments (Figure II-1). Further landslides in the same harbor almost 20 years later resulted in a revisitation of possible stability analysis that could be performed. Fellenius (1936) subdivided the sliding mass into vertical slices, consequently, the name "method of slices". Assumptions were made regarding the inter-slice shear and inter-slice normal forces existing between each of the slices as shown in (Figure II-2). The assumption was to simply ignore all inter-slice forces. The analysis was considerably simpler to perform but later would become the focus of concerns related to the accuracy of the analysis.

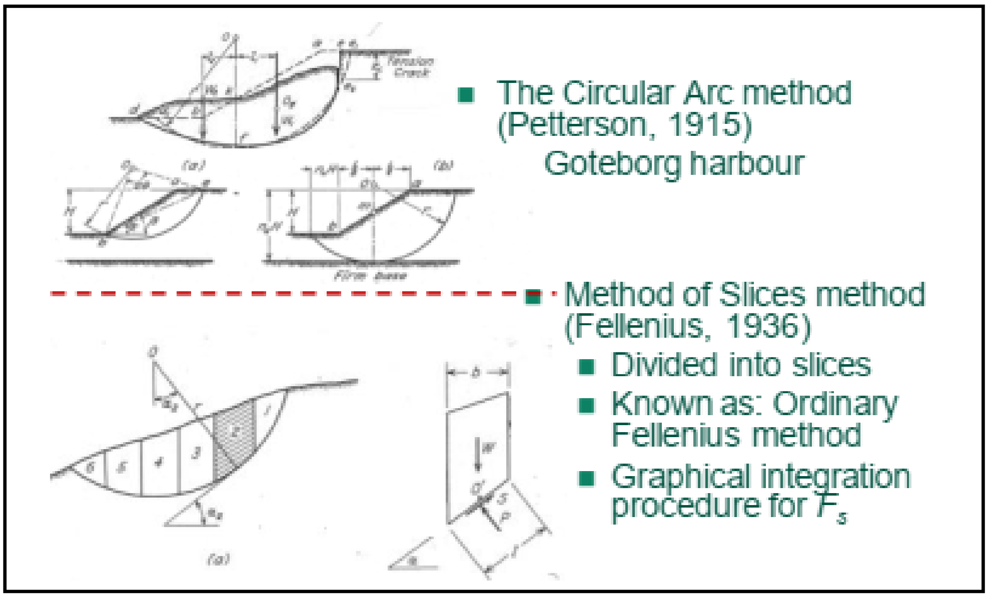


Figure II-1: Early history of slope stability analysis by Petterson (1915) and Fellenius (1936) [3].

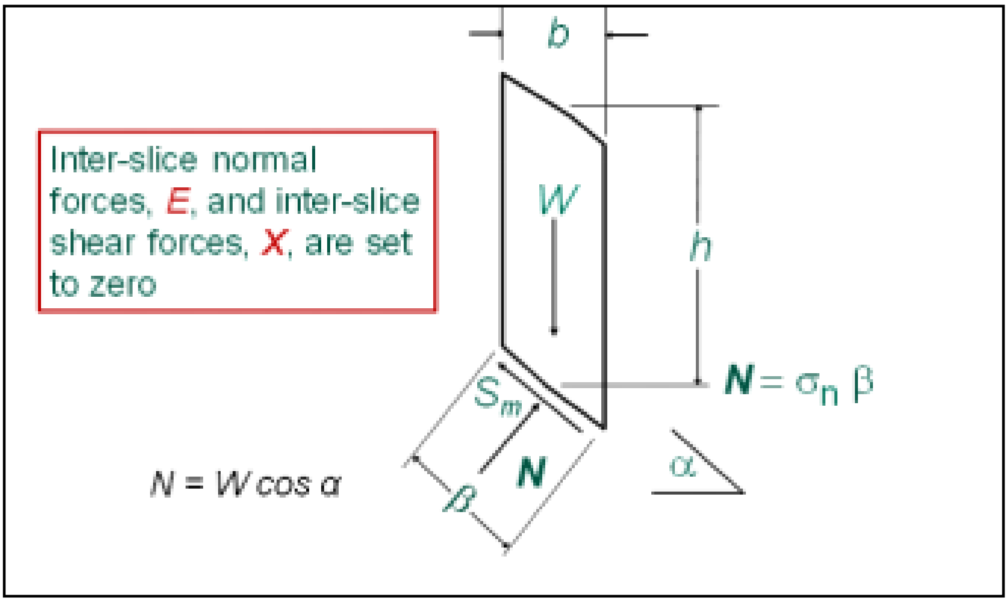


Figure II-2: Free-body diagram for Fellenius method [3].

Little additional research was undertaken to improve the method of slices until the 1950. In 1955 Bishop (Imperial College, London) published the results of his PhD thesis. (Figure II-3) shows the free-body diagram of one slice for a sliding mass with a circular shaped slip surface. All inter-slice forces were shown along with a separation of the pore-water force and the force associated with the effective stresses (i.e., an effective stress analysis). Also indicated was the force related to partial submergence of the slope.

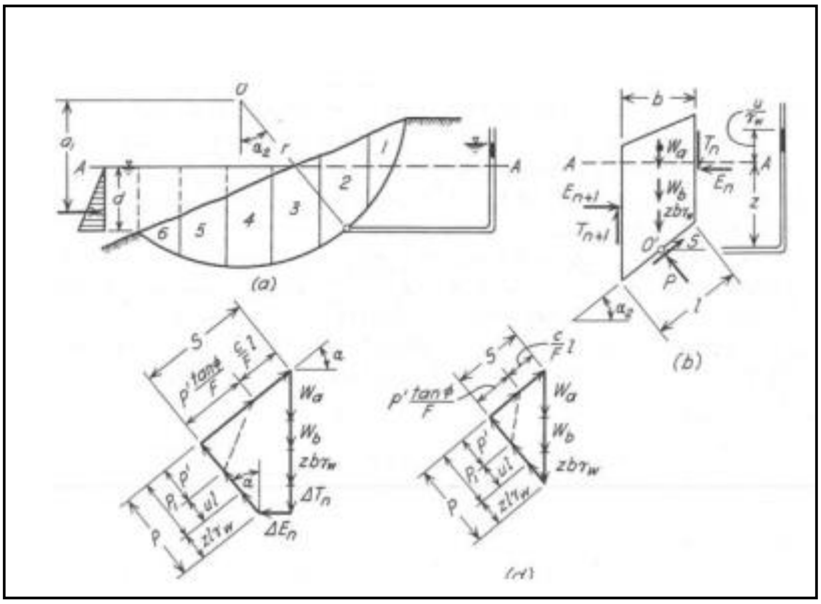


Figure II-3. Bishop’s Simlified method of slices (Bishop, 1955) [3].

Bishop (1955) derived three main equations; namely, 1) a moment equilibrium equation for the overall mass with respect to the center of rotation, 2) a force equilibrium equation for the overall mass in the horizontal direction, and 3) a vertical force equilibrium equation for each slice comprising the sliding mass. While the equations associated with complete equilibrium of the sliding mass were derived, it was not possible to simultaneously satisfy both the horizontal equilibrium and moment equilibrium equations using longhand calculations. Consequently, it was suggested that the overall horizontal force equilibrium be ignored along with the inter-slice shear forces, for the calculation of the factor of safety, giving rise to the Bishop Simplified method of slices (Figure II-4).

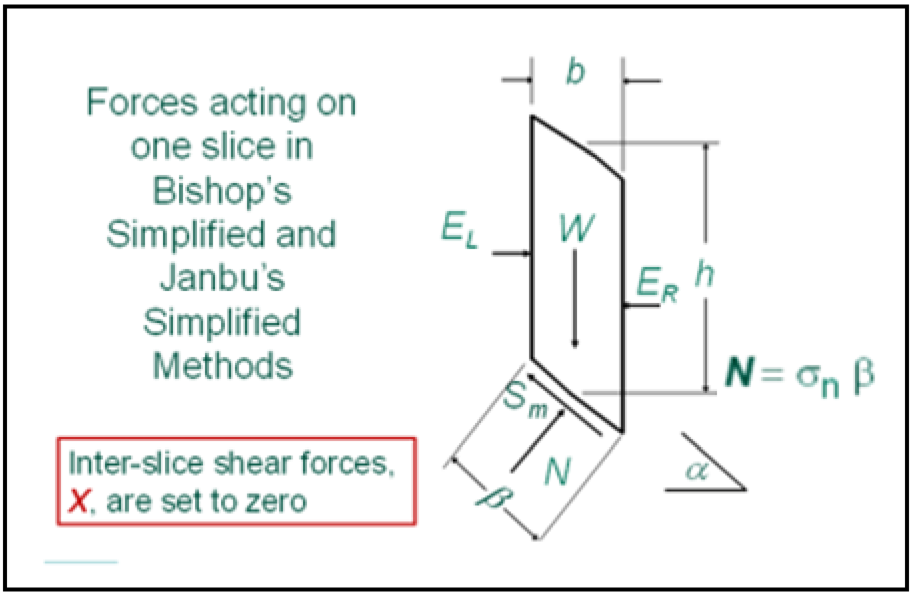


Figure II-4. Free-body of a slice for Bishop's Simplified and Janbu's Simplified methods [3].

In 1954, Janbu had suggested using the overall force equilibrium equation along with an omission of the inter-slice shear forces and moment equilibrium during the calculation of the factor of safety of a slope. This gave rise to the Janbu Simplified method of slices.

Janbu also suggested a more elaborate analysis referred to as the Janbu Generalized method. This method made used of a moment equilibrium for each slice to generate a "line of thrust" to define the point of application of the inter-slice forces.

Mainframe digital computers came on the scene in the mid 1960s and with them came additional computing power. Morgenstern and Price (1965) were some of the first to take advantage of the increased computational ability. Most importantly it became possible to obtain a factor of safety solution that satisfied both moment and force equilibrium conditions if one additional variable, referred to as Lambda, λ, was introduced into the formulation (Morgenstern and Price, 1965). It was also suggested that the inter-slice shear and inter-slice normal forces be related through use of an arbitrary but reasonable mathematical function.

Morgenstern and Price (1965) noted that the slope stability analysis was indeterminate because of a lack of physical understanding of the internal stress state along the sides of each slice. It was also suggested that it might be possible to introduce additional elements of physics into the analysis to render the analysis determinate (Figure II-5). While the use of an additional stress analysis might be possible, it was not done until 1983 by Wilson and Fredlund.

In 1967 Spencer published a method of slices analysis for calculating the factor of safety of a soil mass. The method satisfied both force and moment equilibrium conditions and assumed that the slope of the inter-slice resultant be maintained at a constant slope. Consequently, the formulation was a special case of the Morgenstern-Price (1965) method.

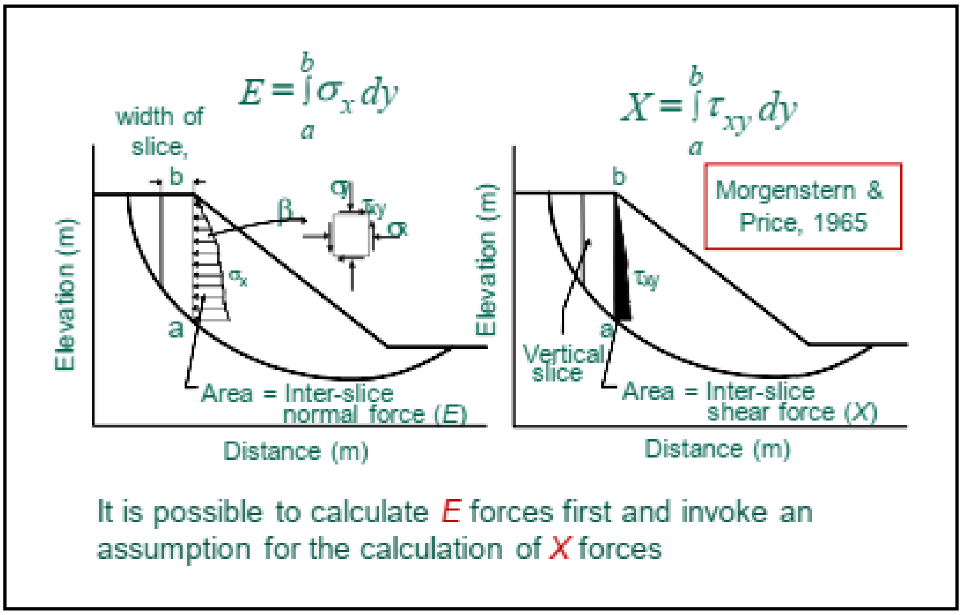


Figure II-5. Morgenstern-Price (1965) method of analysis [3].

In 1977, Fredlund and Krahn published a general set of force and moment equilibrium equations based on the basic assumptions associated with a limit equilibrium analysis.

This did not result in a new method of slope stability analysis; however, it showed the inter-relationship and the limitations associated with each of the methods of analysis that had previously been published.

The summary of limit equilibrium analytical methods could be visualized through a common set of Newtonian equilibrium equations and a shear strength criterion.

Other suggested limit equilibrium methods of slices were also shown to be related to the common set equilibrium equations (Fredlund et al., 1981).

3. Basic Design Considerations

a. Conventional analysis procedures (limit equilibrium) [4]:

The conventional limit equilibrium methods of slope stability analysis used in geotechnical practice investigate the equilibrium of a soil mass tending to move down slope under the influence of gravity. A comparison is made between forces, moments, or stresses tending to cause instability of the mass, and those that resist instability. Two-dimensional (2-D) sections are analyzed and plane strain conditions are assumed. These methods assume that the shear strengths of the materials along the potential failure surface are governed by linear (Mohr-Coulomb) or non linear relationships between shear strength and the normal stress on the failure surface.

A free body of the soil mass bounded below by an assumed or known surface of sliding (potential slip surface), and above by the surface of the slope, is considered in these analyses. The requirements for static equilibrium of the soil mass are used to compute a factor of safety with respect to shear strength. The factor of safety is defined as the ratio of the available shear resistance (the capacity) to that required for equilibrium (the demand). Limit equilibrium analyses assume the factor of safety is the same along the entire slip surface. A value of factor of safety greater than 1.0 indicates that capacity exceeds demand and that the slope will be stable with respect to sliding along the assumed particular slip surface analyzed. A value of factor of safety less than 1.0 indicates that the slope will be unstable.

The most common methods for limit equilibrium analyses are methods of slices. In these methods, the soil mass above the assumed slip surface is divided into vertical slices for purposes of convenience in analysis. Several different methods of slices have been developed. These methods may result in different values of factor of safety because: (a) the various methods employ different assumptions to make the problem statically determinate, and (b) some of the methods do not satisfy all conditions of equilibrium.

b. Special analysis procedures (finite element, three-dimensional (3-D), and probabilistic methods) [4]:

(1) The finite element method can be used to compute stresses and displacements in earth structures. The method is particularly useful for soil-structure interaction problems, in which structural members interact with a soil mass. The stability of a slope cannot be determined directly from finite element analyses, but the computed stresses in a slope can be used to compute a factor of safety. Use of the finite element method for stability problems is a complex and time-consuming process.

(2) Three-dimensional limit equilibrium analysis methods consider the 3D shapes of slip surfaces. These methods, like 2D methods, require assumptions to achieve a statically determinate definition of the problem. Most do not satisfy all conditions of static equilibrium in three dimensions and lack general methodologies for locating the most critical 3D slip surface. The errors associated with these limitations may be of the same magnitude as the 3D effects that are being modeled. These methods may be useful for estimating potential 3D effects for a particular slip surface. However, 3-D methods are not recommended for general use in design because of their limitations. The factors of safety presented in our project are based on 2D analyses.

(3) Probabilistic approaches to analysis and design of slopes consider the magnitudes of uncertainties

regarding shear strengths and the other parameters involved in computing factors of safety. In the traditional (deterministic) approach to slope stability analysis and design, the shear strength, slope geometry, external loads, and pore water pressures are assigned specific unvarying values. The value of the calculated factor of safety depends on the judgments made in selecting the values of the various design parameters. In probabilistic methods, the possibility that values of shear strength and other parameters may vary is considered, providing a means of evaluating the degree of uncertainty associated with the computed factor of safety. Although probabilistic techniques are not required for slope analysis or design, these methods allow the designer to address issues beyond those that can be addressed by deterministic methods, and their use is encouraged. Probabilistic methods can be used to supplement conventional deterministic analyses with little additional effort.

Note: *finite element, and three-dimensional (3-D), and probabilistic methods).*
these three methods will not be the subject of our end-of-study project because they are very complicated methods, they require a lot of technicality in terms of applying them in programs and software, which is why we prefer the slice method is very simple to handle in a computer program.

b. Strain softening and progressive failure [4]:

"Progressive failure" occurs under conditions where shearing resistance first increases and then decreases with increasing strain, and, as a result, the peak shear strengths of the materials at all points along a slip surface cannot be mobilized simultaneously. When progressive failure occurs, a critical assumption of limit equilibrium methods that peak strength can be mobilized at all points along the shear surface is not valid. "Strain softening" is the term used to describe stress-strain response in which shear resistance falls from its peak value to a lower value with increasing shear strain. There are several fundamental causes and forms of strain softening behavior, including:

(1) Undrained strength loss caused by contraction-induced increase in pore water pressure. Liquefaction of cohesion less soils is an extreme example of undrained strength loss as the result of contraction-induced pore pressure, but cohesive soils are also subject to undrained strength loss from the same cause.

(2) Drained strength loss occurring as a result of dilatancy. As dense soil is sheared, it may expand, becoming less dense and therefore weaker.

(3) Under either drained or undrained conditions, platy clay particles may be reoriented by shear deformation into a parallel arrangement termed "slickensides," with greatly reduced shear resistance. If materials are subject to strain softening, it cannot be assumed that a factor of safety greater than one based on peak shear strength implies stability, because deformations can cause local loss of strength, requiring mobilization of additional strength at other points along the slip surface. This, in

turn, can cause additional movement, leading to further strain softening. Thus, a slope in strain softening materials is at risk of progressive failure if the peak strength is mobilized anywhere along the failure surface. Possible remedies are to design so that the factor of safety is higher, or to use shear strengths that are less than peak strengths. In certain soils, it may even be necessary to use residual shear strengths.

4. Aspects applicable to all load Conditions [4]:

Some aspects of slope stability computations are generally applicable, independent of the design condition analyzed. These are discussed in the following paragraphs.

a. Shear strength:

Correct evaluation of shear strength is essential for meaningful analysis of slope stability. Shear strengths used in slope stability analyses should be selected with due consideration of factors such as sample disturbance, variability in borrow materials, possible variations in compaction water content and density of fill materials, anisotropy, loading rate, creep effects, and possibly partial drainage. The responsibility for selecting design strengths lies with the designer, not with the laboratory.

(1) Drained and undrained conditions: A prime consideration in characterizing shear strengths is determining whether the soil will be drained or undrained for each design condition. For drained conditions, analyses are performed using drained strengths related to effective stresses. For undrained conditions, analyses are performed using undrained strengths related to total stresses.

(2) Laboratory strength tests: Laboratory strength tests can be used to evaluate the shear strengths of some types of soils.

(3) Linear and non linear strength envelopes: Strength envelopes used to characterize the variation of shear strength with normal stress can be linear or nonlinear, as shown in Figure II-6.

Linear strength envelopes correspond to the Mohr-Coulomb failure criterion. For total stresses, this is expressed as:

$$s = c + \sigma \tan \varphi \tag{II-1}$$

where

s : maximum possible value of shear stress = shear strength

c : cohesion intercept

σ : normal stress

φ : total stress friction angle.

(b) For effective stresses, the Mohr-Coulomb failure criterion is expressed as:

$$s = c' + \sigma' \tan \varphi' \tag{II-2}$$

Table II-1 Shear Strengths and Pore water Pressures for Static Design Conditions [4]**.**

Design Condition	**Shear Strength**	**Pore Water Pressure**
During Construction and End-of Construction	Free draining soils – use drained shear strengths related to effective stresses (1).	Free draining soils Pore water pressures can be estimated using analytical techniques such as hydrostatic pressure computations if there is no flow, or using steady seepage analysis techniques (flow nets or finite element analyses)
	Low-permeability soils – use undrained strengths related to total stresses (2).	Low-permeability soils – Total stresses are used pore water pressures are set to zero in the slope stability computations.
Steady-State Seepage Conditions	Use drained shear strengths related to effective stresses.	Pore water pressures from field measurements, hydrostatic pressure computations for no-flow conditions, or steady seepage analysis techniques (flow nets, finite element analyses, or finite difference analyses)
Sudden Drawdown Conditions	Free draining soils – use drained shear strengths related to effective stresses.	Free draining soils – First-stage computations (before drawdown) – steady seepage pore pressures as for steady seepage condition. Second- and third-stage computations (after drawdown) – pore water pressures estimated using same techniques as for steady seepage, except with lowered water level.
	Low-permeability soils – Three-stage computations: First stage--use drained shear strength related to effective stresses; second stage-use undrained shear strengths related to consolidation pressures from the first stage; third stage-use drained strengths related to effective stresses, or undrained strengths related to consolidation pressures from the first stage, depending on which strength is lower – this will vary along the assumed shear surface	Low-permeability soils – First-stage computations--steady-state seepage pore pressures as described for steady seepage condition. Second-stage computations – total stresses are used pore water pressures are set to zero. Third-stage computations - same pore pressures as free draining soils if drained strengths are used; pore water pressures are set to zero where undrained strengths are used.

(1) Effective stress shear strength parameters can be obtained from consolidated-drained (CD, S) tests (direct shear or triaxial) or consolidated-undrained (CU, R) triaxial tests on saturated specimens with pore water pressure measurements. Repeated direct shear or Bromhead ring shear tests should be used to measure residual strengths. Undrained strengths can be obtained from unconsolidated-undrained (UU, Q) tests. Undrained shear strengths can also be estimated using consolidated-undrained (CU, R) tests on specimens consolidated to appropriate stress conditions representative of field conditions; however, the "R" or "total stress" envelope and associated c and φ, from CU, R tests should not be used.

(2) For saturated soils use $\varphi = 0$. Total stress envelopes with $\varphi > 0$ are only applicable to partially saturated soils.

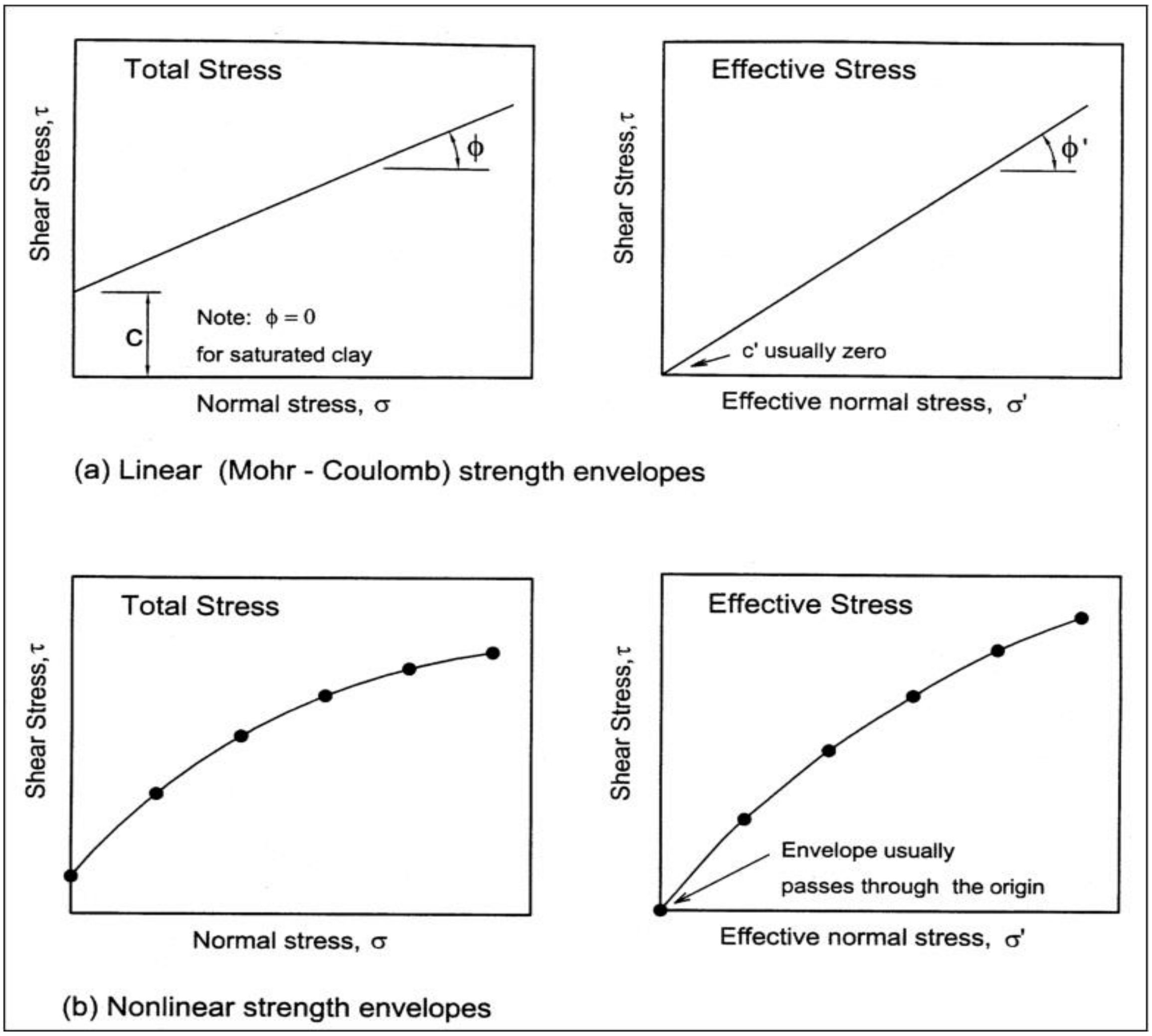


Figure II-6. Strength envelopes for soils [4].

where

s : maximum possible value of shear stress = shear strength

c' : effective stress cohesion intercept

σ' : effective normal stress

ϕ' : effective stress friction angle.

(c) Nonlinear strength envelopes are represented by pairs of values of s and σ or s and σ'.

b. Pore water pressures: For effective stress analyses, pore water pressures must be known and their values must be specified. For total stress analyses using computer software, hand computations, or slope stability charts, pore water pressures are specified as zero although, in fact, the pore pressures are not zero. This is necessary because all computer software programs for slope stability analyses subtract pore pressure from the total normal stress at the base of the slice:

Normal stress on base of slice: $\sigma - u$ (II-3)

The quantity σ in this equation is the total normal stress, and u is pore water pressure.

(1) For total stress analyses, the normal stress should be the total normal stress. To achieve this, the pore water pressure should be set to zero. Setting the pore water pressure to zero ensures that the total normal stress is used in the calculations, as is appropriate.

(2) For effective stress analyses, appropriate values of pore water pressure should be used. In this case, using the actual pore pressure ensures that the effective normal stress ($\sigma' = \sigma - u$) on the base of the slice is calculated correctly.

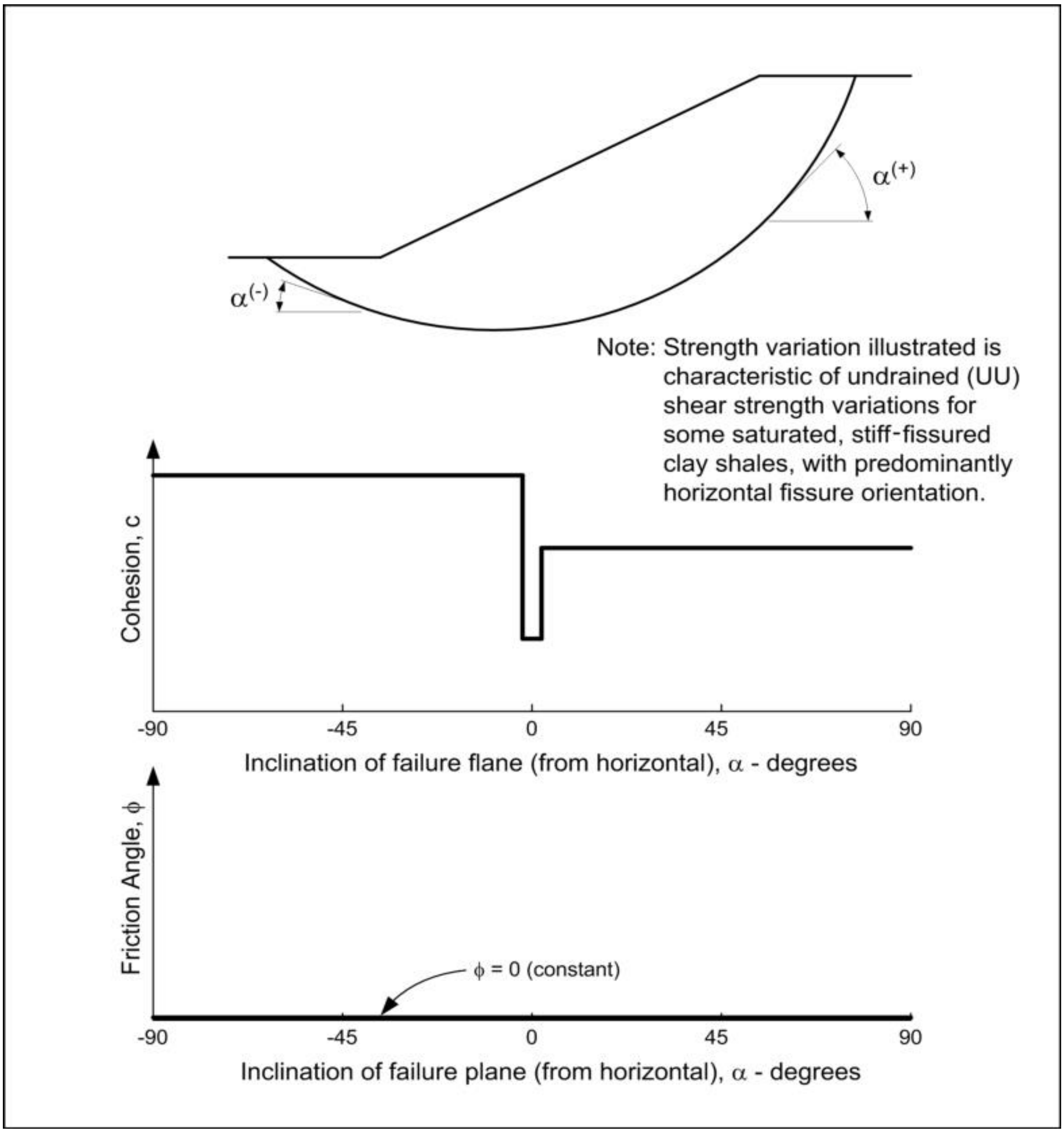


Figure II-7 Representation of shear strength parameters for anisotropic soil [4].

c. Unit weights: The methods of analysis described in this chapter use total unit weights for both total stress analyses and effective stress analyses. This applies for soils regardless of whether they are above or below water. Use of buoyant unit weights is not recommended, because experience has shown that confusion often arises as to when buoyant unit weights can be used and when they cannot. When computations are performed with computer software, there is no computational advantage in the use of buoyant unit weights. Therefore, to avoid possible confusion and computational errors, total unit weights should be used for all soils in all conditions. Total unit weights are used for all formulations.

d. External loads: All external loads imposed on the slope or ground surface should be represented in slope stability analyses, including loads imposed by water pressures, structures, surcharge loads, anchor forces, hawser forces, or other causes. Slope stability analyses must satisfy equilibrium in terms of total stresses and forces, regardless of whether total or effective stresses are used to specify the shear strength.

e. Tensile stresses: Use of Mohr-Coulomb failure envelopes with an intercept, c or c', implies that the soil has some tensile strength (Figure II-8). Although a cohesion intercept is convenient for representing the best-fit linear failure envelope over a range of positive normal stresses, the implied tensile strength is usually not reasonable. Unless tension tests are actually performed, which is rarely done, the implied tensile strength should be neglected. In most cases actual tensile strengths are very small and contribute little to slope stability.

(1) One exception, where the tensile strengths should be considered, is in back-analyses of slope failures to estimate the shear strength of natural deposits. In many cases, the existence of steep natural slopes can only be explained by tensile strength of the natural deposits. The near vertical slopes found in loess deposits are an example. It may be necessary to include significant tensile strength in back-analyses of such slopes to obtain realistic strength parameters. If strengths are back-calculated assuming no tensile strength, the shear strength parameters may be significantly overestimated.

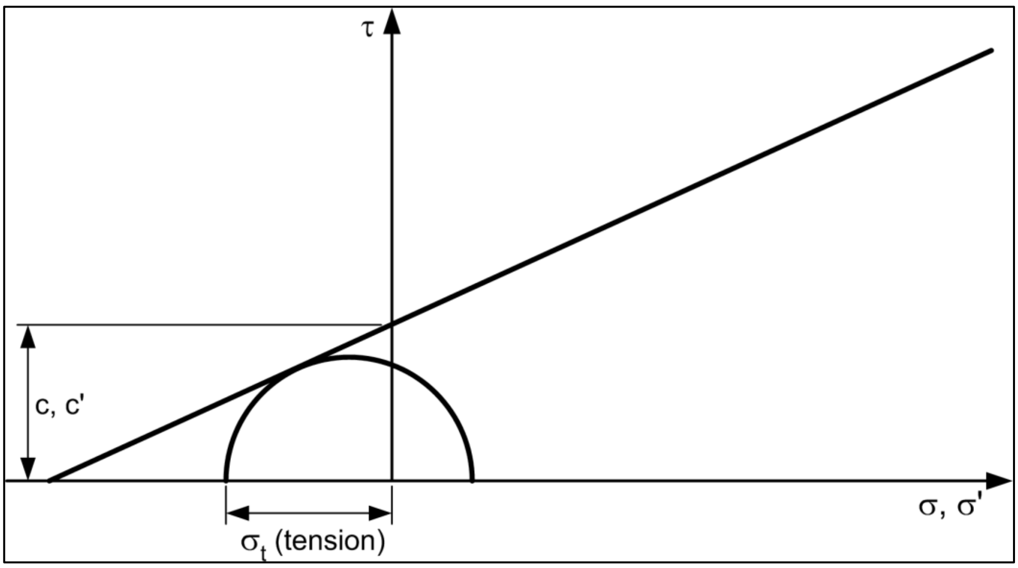


Figure II-8. Tensile stresses resulting from a Mohr-Coulomb failure envelope with a cohesion intercept [4].

5. Analyses of Stability during Construction and at the End of Construction [4]**:**

***a. General*.** Computations of stability during construction and at the end of construction are performed using drained strengths in free-draining materials and undrained strengths in materials that drain slowly.

Consolidation analyses can be used to determine what degree of drainage may develop during the construction period. As a rough guideline, materials with values of permeability greater than 10^{-4} cm/sec, usually will be fully drained throughout construction. Materials with values of permeability less than 10^{-7} cm/sec usually will be essentially undrained at the end of construction. In cases where appreciable but incomplete drainage is expected during construction, stability should be analyzed assuming fully drained and completely undrained conditions, and the less stable of these conditions should be used as the basis for design.

For undrained conditions, pore pressures are governed by several factors, most importantly the degree of saturation of the soil, the density of the soil, and the loads imposed on it. It is conceivable that pore pressures for undrained conditions could be estimated using results of laboratory tests or various empirical rules, but in most cases pore pressures for undrained conditions cannot be estimated accurately. For this reason, undrained conditions are usually analyzed using total stress procedures rather than effective stress procedures.

b. Shear strength properties [4]: During construction and at end of construction, stability is analyzed using drained strengths expressed in terms of effective stresses for free-draining materials and undrained strengths expressed in terms of total stresses for materials that drain slowly.

Staged construction may be necessary for embankments built on soft clay foundations. Consolidated undrained triaxial tests can be used to determine strengths for partial consolidation during staged construction.

c. Pore water pressure [4]: For free-draining materials with strengths expressed in terms of effective stresses, pore water pressures must be determined for analysis of stability during and at the end of construction. These pore water pressures are determined by the water levels within and adjacent to the slope.

Pore pressures can be estimated using the following analytical techniques:

(1) Hydrostatic pressure computations for conditions of no flow.

(2) Steady-state seepage analysis techniques such as flow nets or finite element analyses for non hydrostatic conditions. For low-permeability soils with strengths expressed in of total stresses, pore water pressures are set to zero for purposes of analysis.

6. Analyses of Steady-State Seepage Conditions [4]**:**

a. General. Long-term stability computations are performed for conditions that will exist a sufficient length of time after construction for steady-state seepage or hydrostatic conditions to develop. (Hydrostatic conditions are a special case of steady-state seepage, in which there is no flow) Stability computations are performed using shear strengths expressed in terms of effective stresses, with pore pressures appropriate for the long-term condition.

b. Shear strength properties [4]: By definition, all soils are fully drained in the long-term condition, regardless of their permeability. Long-term conditions are analyzed using drained strengths expressed in terms of effective stress parameters (c' and ϕ').

c. Pore water pressures [4]: The pore pressures used in the analyses should represent the field conditions of water pressure and steady-state seepage in the long-term condition. Pore pressures for use in the analyses can be estimated from:

(1) Field measurements of pore pressures in existing slopes.

(2) Past experience and judgement.

(3) Hydrostatic pressure computations for conditions of no flow.

(4) Steady-state seepage analyses using such techniques as flow nets or finite element analyses.

7. Factor of safety guidance [4]**:** factors of safety are required to ensure adequate performance of slopes throughout their design lives. Two of the most important considerations that determine appropriate magnitudes for factor of safety are uncertainties in the conditions being analyzed, including shear strengths and consequences of failure or unacceptable performance.

(1) What is considered an acceptable factor of safety should reflect the differences between new slopes, where stability must be forecast, and existing slopes, where information regarding past slope performance is available. A history free of signs of slope movements provides firm evidence that a slope has been stable under the conditions it has experienced. Conversely, signs of significant movement indicate marginally stable or unstable conditions. In either case, the degree of uncertainty regarding shear strength and piezometric levels can be reduced through back analysis. Therefore, values of factors of safety that are lower than those required for new slopes can often be justified for existing slopes.

(2) Historically, geotechnical engineers have relied upon judgment, precedent, experience, and regulations to select suitable factors of safety for slopes. Reliability analyses can provide important insight into the effects of uncertainties on the results of stability analyses and appropriate factors of safety. However, for design and construction of earth and rock-fill dams, required factors of safety continue to be based on experience. Factors of safety for various types of slopes and analysis conditions

are summarized in Table II-2. These are minimum required factors of safety for new embankment dams. They are advisory for existing dams and other types of slopes.

Table II-2 Minimum Required Factors of Safety: New Earth and Rock-Fill Dams[4].

Analysis Condition(1)	**Required Minimum Factor of Safety**	**Slope**
(1) End-of-Construction (including staged construction)	1.3	Upstream and Downstream
Long-term (Steady seepage, maximum storage pool, spillway crest or top of gates).	1.5	Downstream
(2) Maximum surcharge pool	1.4	Downstream
(3) Rapid drawdown	1.1 - 1.3	Upstream

1 For embankments over 15 m high on soft foundations and for embankments that will be subjected to pool loading during construction, a higher minimum end-of-construction factor of safety may be appropriate.
2 Pool thrust from maximum surcharge level. Pore pressures are usually taken as those developed under steady-state seepage at maximum storage pool. However, for pervious foundations with no positive cutoff steady-state seepage may develop under maximum surcharge pool.
3 FS = 1.1 applies to drawdown from maximum surcharge pool; FS = 1.3 applies to drawdown from maximum storage pool.
For dams used in pump storage schemes or similar applications where rapid drawdown is a routine operating condition, higher factors of safety, e.g., 1.4-1.5, are appropriate. If consequences of an upstream failure are great, such as blockage of the outlet works resulting in a potential catastrophic failure, higher factors of safety should be considered.

8. Fundamentals of Slope Stability Analysis [4].

a. Conventional approach. Conventional slope stability analyses investigate the equilibrium of a mass of soil bounded below by an assumed potential slip surface and above by the surface of the slope. Forces and moments tending to cause instability of the mass are compared to those tending to resist instability. Most procedures assume a two-dimensional (2D) cross section and plane strain conditions for analysis. Successive assumptions are made regarding the potential slip surface until the most critical surface (lowest factor of safety) is found. Figure II-9 shows a potential slide mass defined by a candidate slip surface. If the shear resistance of the soil along the slip surface exceeds that necessary to provide equilibrium, the mass is stable. If the shear resistance is insufficient, the mass is unstable. The stability or instability of the mass depends on its weight, the external forces acting on it (such as surcharges or accelerations caused by dynamic loads), the shear strengths and porewater pressures along the slip surface, and the strength of any internal reinforcement crossing potential slip surfaces.

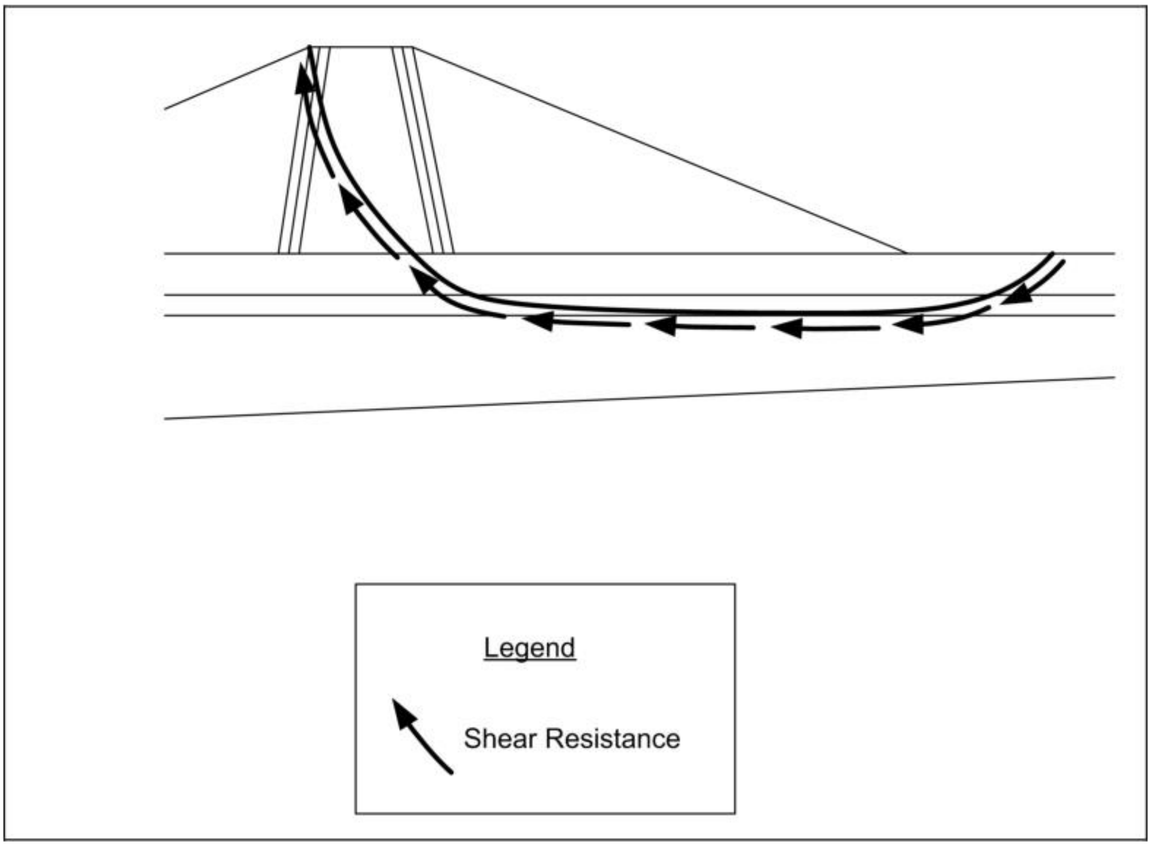


Figure II-9. Slope and potential slip surface [4].

b. The factor of safety. Conventional analysis procedures characterize the stability of a slope by calculating a factor of safety. The factor of safety is defined with respect to the shear strength of the soil as the ratio of the available shear strength (s) to the shear strength required for equilibrium (τ), that is:

$$F = \frac{\text{Available shear strength}}{\text{Equilibrium shear stress}} = \frac{s}{\tau} \qquad \text{(E II-4)}$$

(1) Shear strength is discussed below. If the shear strength is defined in terms of effective stresses, the factor of safety is expressed as:

$$F = \frac{c' + (\sigma - u)\tan\emptyset'}{\tau} \qquad \text{(E II-5)}$$

Where:

c' and $\emptyset'$: Mohr-Coulomb cohesion and friction angle, respectively, expressed in terms of effective stresses

σ= total normal stress on the failure plane.

u = pore water pressure; (σ– u) is the effective normal stress on the failure plane.

If the failure envelope is curved, the factor safety can be expressed as:

$$F = \frac{s(\sigma')}{\tau} \qquad \text{(E II-6)}$$

Where: $s(\sigma')$ represents the shear strength determined from the effective stress failure envelope for the particular effective normal stress, σ'.

Equation E II-5 can also still be used with a curved failure envelope by letting c' and $\emptyset'$ represent the intercept and slope of an equivalent linear Mohr-Coulomb envelope that is tangent to the curved failure envelope at the appropriate value of normal stress, σ'.

(2) For total stresses, the factor of safety is expressed using the shear strength parameters in terms of total stresses, i.e:

$$F = \frac{c + \sigma \tan \emptyset}{\tau} \qquad \text{(E II-7)}$$

Where: c and ∅ are the Mohr-Coulomb cohesion and friction angle, respectively, expressed in terms of total stresses. Curved failure envelopes are handled for total stresses in much the same way they are handled for effective stresses: The strength is determined from the curved failure envelope using the particular value of total normal stress, σ, the effective stress form of the equation for the factor of safety (Equation E II-5) will be used. Any of the equations presented in terms of effective stress can be converted to their equivalent total stress form by using c and ∅ rather than c' and ∅' and by setting pore water pressure, u, equal to zero.

c. Limit equilibrium methods – General assumptions [4]:

The methods presented in our project is "limit equilibrium" methods. In these methods, the factor of safety is calculated using one or more of the equations of static equilibrium applied to the soil mass bounded by an assumed, potential slip surface and the surface of the slope. In some methods, such as the Infinite Slope method, the shear and normal stresses (σ and τ) can be calculated directly from the equations of static equilibrium and then used with Equation E II-5 or E II-7 to compute the factor of safety. In most other cases, including the Simplified Bishop, the Corps of Engineers' Modified Swedish Method, and Spencer's Method, a more complex procedure is required to calculate the factor of safety. First, the shear stress along the shear surface is related to the shear strength and the factor of safety using Equation E II-5 or E II-7. In the case of effective stresses, the shear stress according to Equation E II-5 is expressed as:

$$\tau = \frac{c' + (\sigma - u) \tan \emptyset'}{F} \qquad \text{(E II-8)}$$

The factor of safety is computed by repeatedly assuming values for F and calculating the corresponding shear stress from Equation E II-8 until equilibrium is achieved. In effect, the strength is reduced by the factor of safety, F, until a just-stable, or limiting, equilibrium condition is achieved. Equation E II-8 can be expanded and written as:

$$\tau = \frac{c'}{F} + \frac{(\sigma - u)\tan\emptyset'}{F} \qquad \text{(E II-9)}$$

The first term represents the contribution of "cohesion" to shear resistance; the second term represents the contribution of "friction." The "developed" cohesion and friction are defined as follows:

$$c_D' = \frac{c'}{F} \qquad \text{(E II-10)}$$

And

$$tan\emptyset_D' = \frac{\tan\emptyset'}{F} \qquad \text{(E II-11)}$$

Where:

c_D' = developed cohesion

$\emptyset_D'$ = developed friction angle

d. Assumptions in methods of slices:

Many of the limit equilibrium methods (Ordinary Method of Slices (OMS), Simplified Bishop, Corps of Engineers' Modified Swedish, Spencer) address static equilibrium by dividing the soil mass above the assumed slip surface into a finite number of vertical slices. The forces acting on an individual slice are illustrated in Figure II-10. The forces include:

W - slice weight

E - horizontal (normal) forces on the sides of the slice.

X - vertical (shear) forces between slices.

N - normal force on the bottom of the slice.

S - shear force on the bottom of the slice.

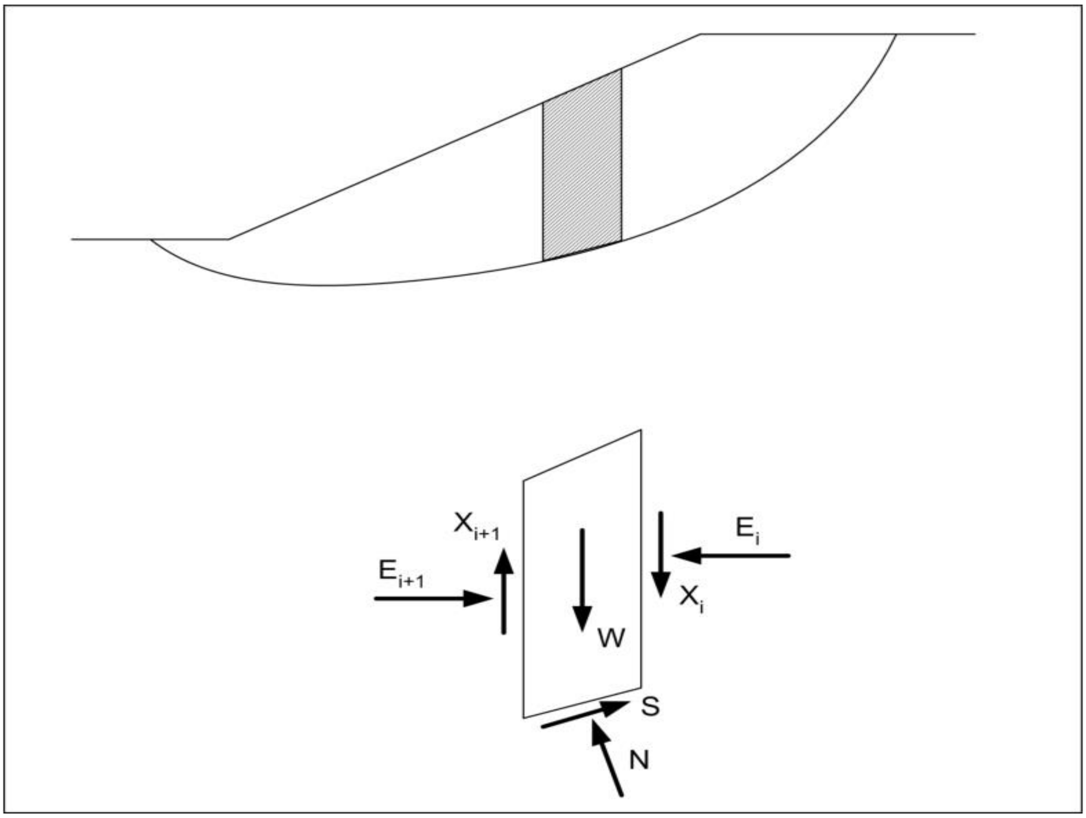


Figure II-10: Typical slice and forces for method of slices [4].

Except for the weight of the slice, all of these forces are unknown and must be calculated in a way that satisfies static equilibrium.

(1) For the current discussion, the shear force (S) on the bottom of the slice is not considered directly as an unknown in the equilibrium equations that are solved. Instead, the shear force is expressed in terms of other known and unknown quantities, as follows: S on the base of a slice is equal to the shear stress, τ, multiplied by the length of the base of the slice, $\Delta\ell$, i.e,

$$s = \tau.\Delta\ell \qquad \text{(E II-12)}$$

or, by introducing Equation E II-8, which is based on the definition of the factor of safety,

$$S = \frac{c'\Delta\ell}{F} + \frac{(\sigma - u)\Delta\ell \tan\phi'}{F} \qquad \text{(E II-13)}$$

Finally, noting that the normal force N is equal to the product of the normal stress (σ) and the length of the bottom of the slice ($\Delta\ell$), i.e., N = $\sigma.\Delta\ell$, Equation E II-12 can be written as:

$$S = \frac{c'\Delta\ell}{F} + \frac{(N - u\Delta\ell)\tan\phi'}{F} \qquad \text{(E II-14)}$$

(2) Equation E II-14 relates the shear force, S, to the normal force on the bottom of the slice and the factor of safety. Thus, if the normal force and factor of safety can be calculated from the equations of static equilibrium, the shear force can be calculated (is known) from Equation E II-14. Equation E II-14 is derived from the Mohr-Coulomb equation and the definition of the factor of safety, independently of the conditions of static equilibrium. The forces and other unknowns that must be calculated from the equilibrium equations are summarized in Table II-3. As discussed above, the shear force, S, is not included in Table II-3, because it can be calculated from the unknowns listed and the Mohr-Coulomb equation (E II-14), independently of static equilibrium equations.

Table II-3 **Unknowns and Equations for Limit Equilibrium Methods** [4].

Unknowns	**Number of Unknowns for n Slices**
Factor of safety (F)	1
Normal forces on bottom of slices (N)	n
Interslice normal forces, E	n-1
Interslice shear forces, X	n-1
Location of normal forces on base of slice	n
Location of interslice normal forces	n-1
TOTAL NUMBER OF UNKNOWNS	5n-2
Equations	**Number of Equations for n Slices**
Equilibrium of forces in the horizontal direction, $\sum Fx = 0$	n
Equilibrium of forces in the vertical direction, $\sum Fy = 0$	n
Equilibrium of moments	n
TOTAL NUMBER OF EQUILIBRIUM	3n

3) In order to achieve a statically determinate solution, there must be a balance between the number of unknowns and the number of equilibrium equations. The number of equilibrium equations is shown in the lower part of Table II-3. The number of unknowns (5n – 2) exceeds the number of equilibrium equations (3n) if n is greater than one. Therefore, some assumptions must be made to achieve a statically determinate solution.

(4) The various limit equilibrium methods use different assumptions to make the number of equations equal to the number of unknowns. They also differ with regard to which equilibrium equations are satisfied. For example, the Ordinary Method of Slices, the Simplified Bishop Method, and the U.S. Army Corps of Engineers' Modified Swedish Methods do not satisfy all the conditions of static equilibrium. Methods such as the Morgenstern and Price's and Spencer's do satisfy all static equilibrium conditions. Methods that satisfy static equilibrium fully are referred to as "complete" equilibrium methods.

e. Limitations of limit equilibrium methods [4]:

Complete equilibrium methods have generally been more accurate than those procedures which do not satisfy complete static equilibrium and are therefore preferable to "incomplete" methods. However, the "incomplete" methods are often sufficiently accurate and useful for many practical applications, including hand checks and preliminary analyses. In all of the procedures described in this document, the factor of safety is applied to both cohesion and friction, as shown by Equation E II-9.

(1) The factor of safety is also assumed to be constant along the shear surface. Although the factor of safety may not in fact be the same at all points on the slip surface, the average value computed by assuming that F is constant provides a valid measure of stability for slopes in ductile (non brittle) soils. For slopes in brittle soils, the factor of safety computed assuming F is the same at all points on the slip surface may be higher than the actual factor of safety.

(2). Limitations of limit equilibrium procedures are summarized in Table II-4.

f. Shape of the slip surface [4]:

All of the limit equilibrium methods require that a potential slip surface be assumed in order to calculate the factor of safety. Calculations are repeated for a sufficient number of trial slip surfaces to ensure that the minimum factor of safety has been calculated. For computational simplicity the candidate slip surface is often assumed to be circular or composed of a few straight lines (Figure II-11). However, the slip surface will need to have a more complicated shape in complex stratigraphy. The assumed shape is dependent on the problem geometry and stratigraphy, material characteristics (especially anisotropy), and the capabilities of the analysis procedure used. Commonly assumed shapes are discussed below.

Table II-4 Limitations of Limit-Equilibrium Methods[4].
1. The factor of safety is assumed to be constant along the potential slip surface. 2. Load-deformation (stress-strain) characteristics are not explicitly accounted for. 3. The initial stress distribution within the slope is not explicitly accounted for. 4. Unreasonably large and or negative normal forces may be calculated along the base of slices under certain conditions. 5. Iterative, trial and error, solutions may not converge in certain cases.

(1) Circular. Observed failures in relatively homogeneous materials often occur along curved failure surfaces. A circular slip surface, like that shown in Figure II-11a, is often used because it is convenient to sum moments about the center of the circle, and because using a circle simplifies the calculations. A circular slip surface must be used in the Ordinary Method of Slices and Simplified Bishop Method. Circular slip surfaces are almost always useful for starting an analysis. Also, circular slip surfaces

are generally sufficient for analyzing relatively homogeneous embankments or slopes and embankments on foundations with relatively thick soil layers.

(2) Wedge. “Wedge” failure mechanisms are defined by three straight line segments defining an active wedge, central block, and passive wedge (Figure II-11b). This type of slip surface may be appropriate for slopes where the critical potential slip surface includes a relatively long linear segment through a weak material bounded by stronger material. A common example is a relatively strong levee embankment founded on weaker, stratified alluvial soils.

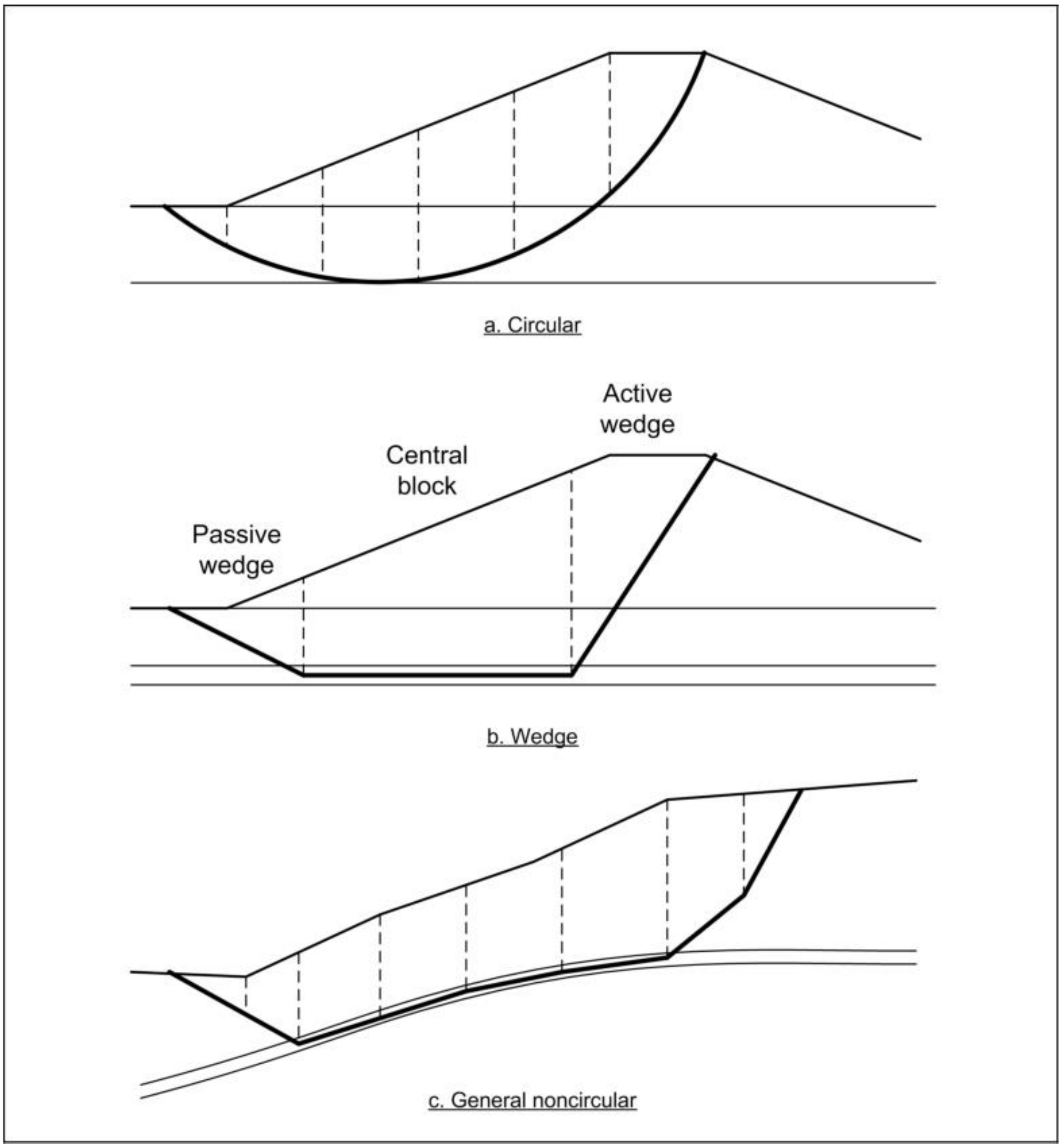


Figure II-11. Shapes for potential slip surfaces [4].

(3) Two circular segments with a linear midsection. This is a combination of the two shapes (circular and wedge) discussed above that is used by some computer programs.

(4) General, noncircular shape. Slope failure may occur by sliding along surfaces that do not correspond to either the wedge or circular shapes. The term general slip surface refers to a slip surface composed of a number of linear segments which may each be of any length and inclined at any angle. The term "noncircular" is also used in reference to such general-shaped slip surfaces. Prior to about 1990, slip surfaces of a general shape, other than simple wedges, were seldom analyzed, largely because of the difficulty in systematically searching for the critical slip surface. However, in recent years improved search techniques and computer software have increased the capability to analyze such slip surfaces. Stability analyses based on general slip surfaces are now much more common and are useful as a design check of critical slip surfaces of traditional shapes (circular, wedge) and where complicated geometry and material conditions exist. It is especially important to investigate stability with non circular slip surfaces when soil shear strengths are anisotropic.

(a) Inappropriate selection of the shape for the slip surface can cause computational difficulties and erroneous solutions.

(b) A common problem occurs near the toe of the slope when the slip surface exits too steeply through materials with large values of ϕ or ϕ'.

g. Location of the critical slip surface [4]**:**

The critical slip surface is defined as the surface with the lowest factor of safety. Because different analysis procedures employ different assumptions, the location of the critical slip surface can vary somewhat among different methods of analysis. The critical slip surface for a given problem analyzed by a given method is found by a systematic procedure of generating trial slip surfaces until the one with the minimum factor of safety is found. Searching schemes vary with the assumed shape of the slip surface and the computer program used. Common schemes are discussed below.

(1) Circular slip surfaces. Search schemes for circular arc slip surfaces are illustrated in Figures II-12, II-13, and II-14. A circular surface is defined by the position of the circle center and either (a) the radius, (b) a point through which the circle must pass, or (c) a plane to which the slip surface must be tangent. In case (b), the toe of the slope is often specified as the point through which the circle must pass. Searches are usually accomplished by changing one of these variables and varying a second variable until a minimum factor of safety is found. For example, the location of the center point may be varied while the plane of tangency is fixed, or the radius may be varied while the center point is fixed. The first search variable is then fixed at a new value and the second variable is again varied.

This process is repeated until the minimum factor of safety corresponding to both search variables is found. For a homogeneous slope in cohesionless soil ($c = 0$, $c' = 0$), a critical circle will degenerate to a plane parallel to the slope and the factor of safety will be identical to the one for an infinite slope. Theoretically, the critical "circle" will be one having a center point located an infinite distance away from the slope on a line perpendicular to the midpoint of the slope. The circle will have an infinite radius as well. When attempts are made to search for a critical circle in a homogeneous slope of cohesionless soil with most computer programs, the search will appear to “run-away” from the slope. The search will probably be stopped eventually as a result of either numerical errors or round off or some constraint imposed by the software being used. In such cases the Infinite Slope analysis procedure, should be used.

(2) Wedge-shaped slip surfaces. Wedge-shaped slip surfaces require searching for the critical location of the central block and for the critical inclination of the bases of the active and passive wedges. Searching for the critical location of the central block is illustrated in Figure II-15a and involves systematically varying the horizontal and vertical coordinates of the two ends of the base of the central block, until the central block corresponding to the minimum factor of safety is found. For each trial position of the central block, the base inclinations of the active and passive wedge segments must be set based on simple rules or by searching to locate critical inclinations. A simple and common assumption is to make the inclination of each active wedge segment (measured from the horizontal) 45 + $\emptyset_D'/2$ degrees, and of each passive wedge segment 45 - $\emptyset_D'/2$ degrees. The quantity $\emptyset_D'$ represents the developed friction angle (tan $\emptyset_D'$= tan $\emptyset'$/F) and should be consistent with the computed factor of safety.

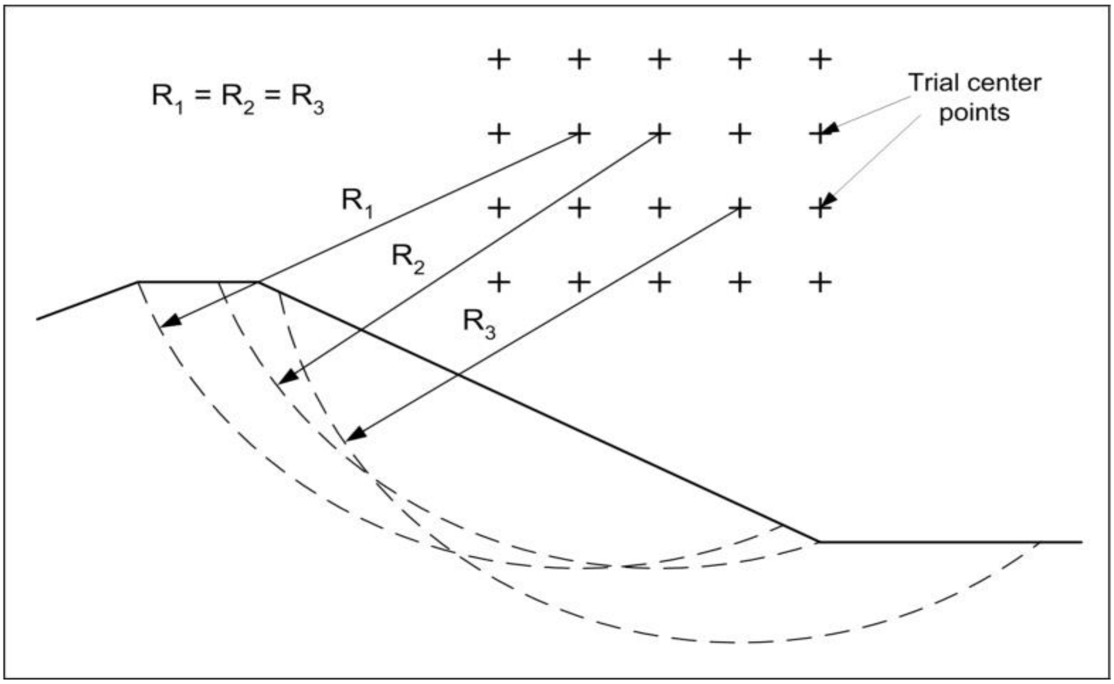


Figure II-12. Search with constant radius [4].

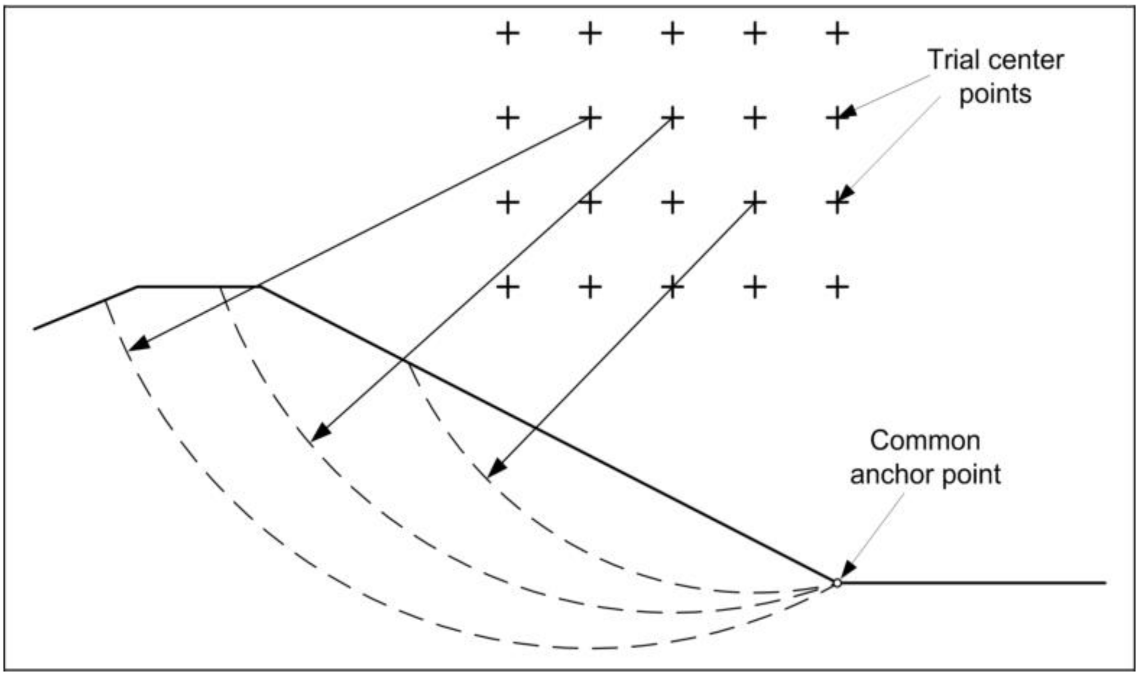


Figure II-13. Search with circles through a common point [4].

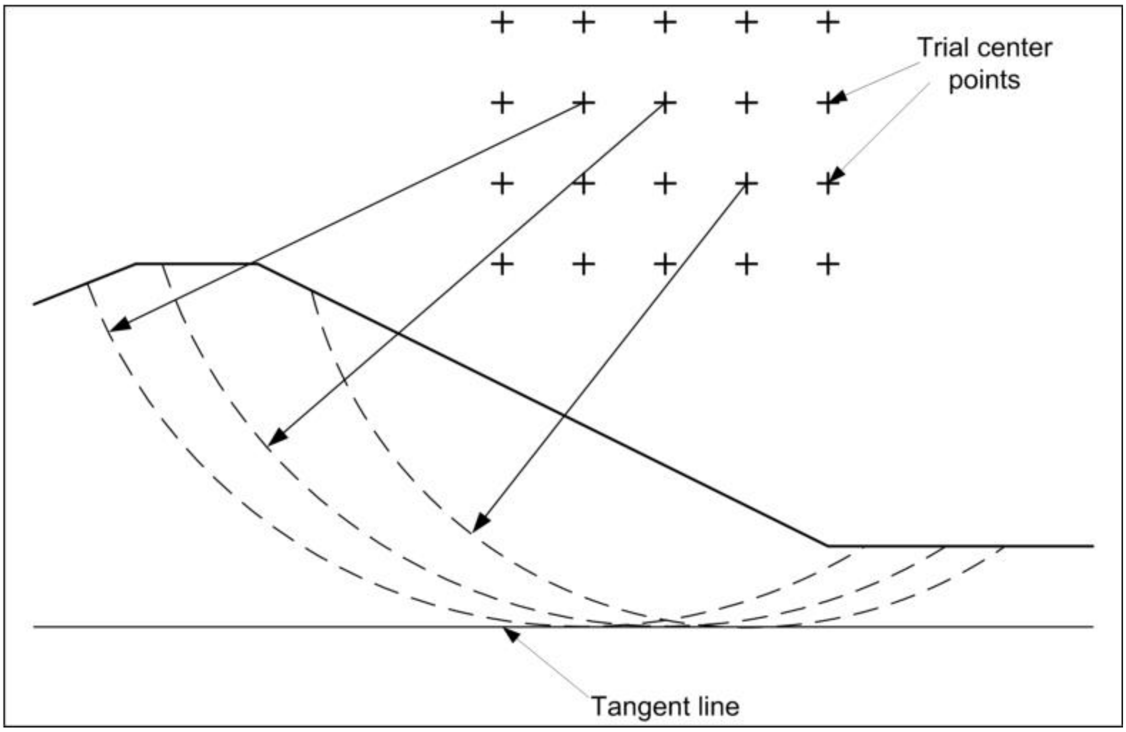


Figure II-14. Search with circles tangent to a prescribed tangent line [4].

This assumption for the inclination of the active and passive wedges is only appropriate where the top surfaces of the active and passive wedges are horizontal but provides reasonable results for gently inclined slopes. Common methods for searching for the inclination of the base of the wedges are shown in Figure II-15b. One technique, used where soil properties and inclinations of the base of each wedge vary in the zone of the active and passive wedges, is to assume that the bottoms of the wedges are inclined at $\alpha = \theta \pm \emptyset'_D/2$. The value of θ is then varied until the maximum interslice force is found for the active wedge and minimum inter slice force is found for the passive wedge. A second search technique, where the bases of the active and passive wedges are considered to be single planes, is to vary the value of α until a maximum inter slice force is obtained for the entire group of active wedge segments and the minimum is found for the entire group of passive wedge segments.

(3) General shapes. A number of techniques have been proposed and used to locate the most critical general-shaped slip surface. One of the most robust and useful procedures is the one developed by Celestino and Duncan (1981). The method is illustrated in Figure II-16. In this method, an initial slip surface is assumed and represented by a series of points that are connected by straight lines. The factor of safety is first calculated for the assumed slip surface. Next, all points except one are held fixed, and the "floating" point is shifted a small distance in two directions. The directions might be vertically up and down, horizontally left and right, or above and below the slip surface in some assumed direction. The factor of safety is calculated for the slip surface with each point shifted as described. This process is repeated for each point on the slip surface. As any one point is shifted, all other points are left at their original location. Once all points have been shifted in both directions and the factor of safety has been computed for each shift, a new location is estimated for the slip surface based on the computed factors of safety. The slip surface is then moved to the estimated location and the process of shifting points is repeated. This process is continued until no further reduction in factor of safety is noted and the distance that the shear surface is moved on successive approximations becomes minimal.

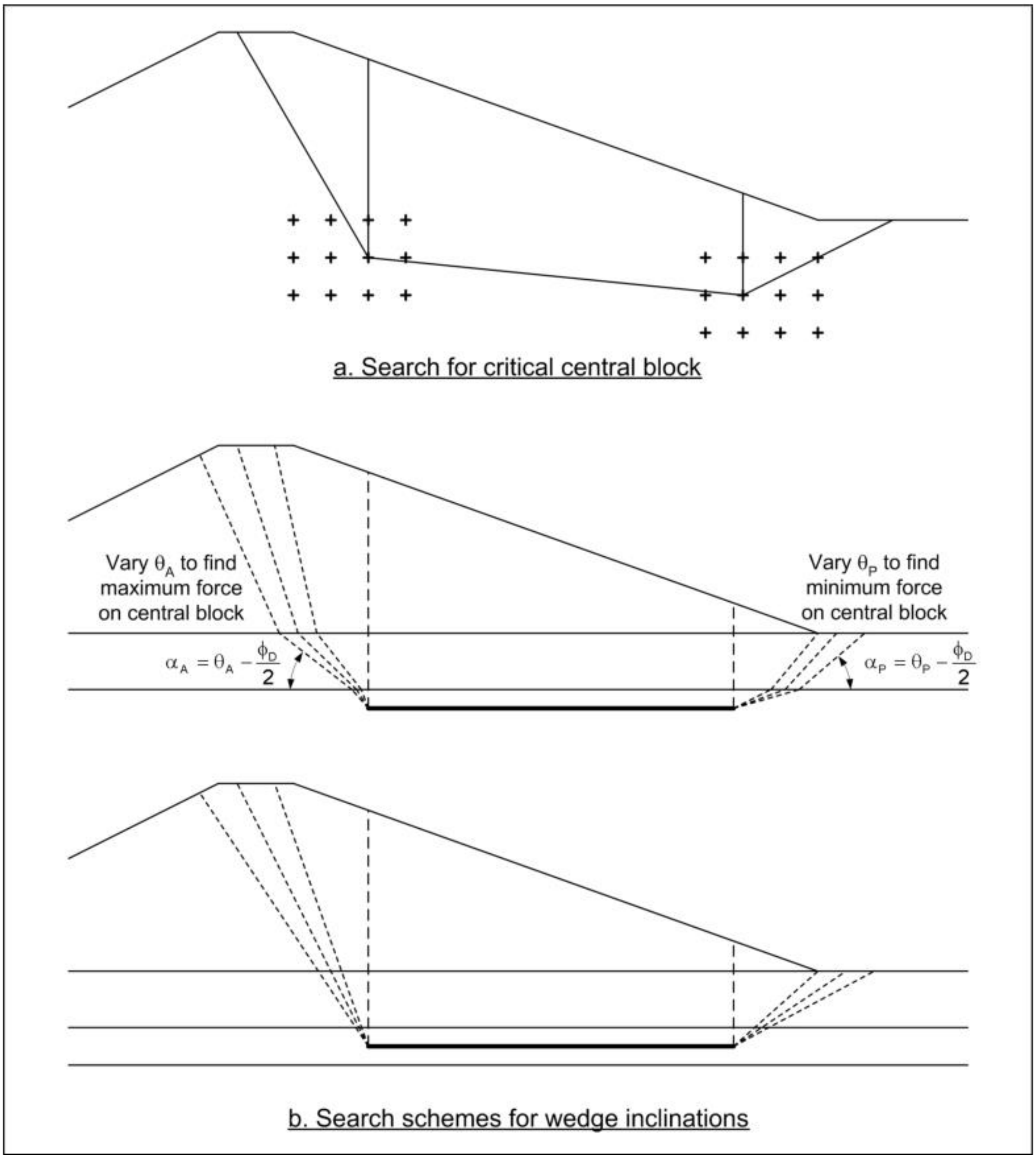


Figure II-15. Search schemes for wedges [4].

(4) Limitations and precautions. Any search scheme employed in computer programs is restricted to investigating a finite number of slip surfaces. In addition, most of these schemes are designed to locate one slip surface with a minimum factor of safety. The schemes may not be able to locate more than one local minimum. The results of automatic searches are dependent on the starting location for the search and any constraints that are imposed on how the slip surface is moved. Automatic searches are controlled largely by the data that the user inputs into the software. Regardless of the software used, a

number of separate searches should be conducted to confirm that the lowest factor of safety has been calculated.

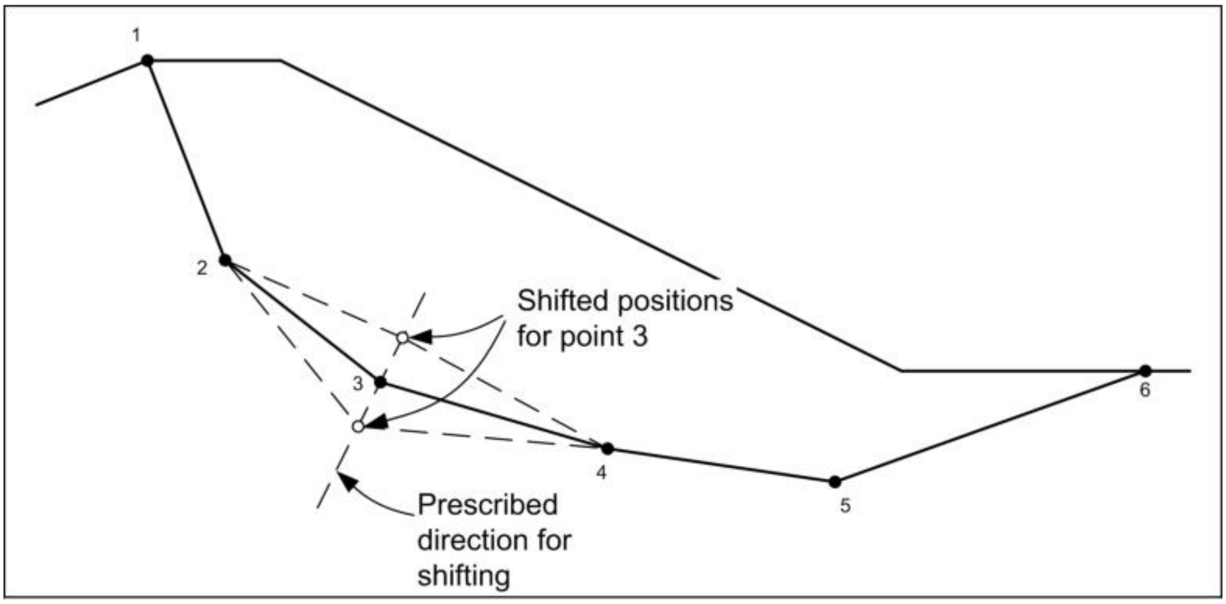


Figure II-16: Search scheme for non circular slip surfaces (after Celistono and Duncan 1981) [4].

(a) In some cases it is appropriate to calculate the factor of safety for selected potential slip surfaces that do not necessarily produce the minimum factor of safety but would be more significant in terms of the consequences of failure. For example, in slopes that contain cohesionless soil at the face of the slope, the lowest factor of safety may be found for very shallow (infinite slope) slip surfaces, yet shallow sloughing is usually much less important than deeper-seated sliding.

(b) Mine tailings, disposal dams, and cohesionless fill slopes on soft clay foundations provide examples where deeper slip surfaces than the one producing the minimum factor of safety are often more important. In such cases, deeper slip surfaces should be investigated in addition to the shallow slip surfaces having the lowest factors of safety.

9. Selection of Method [4]**:**

Some methods of slope stability analysis (e.g., Spencer's) are more rigorous and should be favored for detailed evaluation of final designs. Some methods (e.g., Spencer's, Modified Swedish, and the Wedge) can be used to analyze noncircular slip surfaces. Some methods (e.g., the Ordinary Method of Slices, the Simplified Bishop, the Modified Swedish, and the Wedge) can be used without the aid of a computer and are therefore convenient for independently checking results obtained using computer programs. Also, when these latter methods are implemented in software, they execute extremely fast and are useful where very large numbers of trial slip surfaces are to be analyzed. The various methods are summarized in Table II-5. This table can be helpful in selecting a suitable method for analysis.

Table II-5: Comparison of Features of Limit Equilibrium Methods [4].

Feature	**Ordinary method of slice**	**Simplified Bishop**	**Spencer**	**Modified Swedish**	**Wedge**	**Infinite Slope**
Accuracy		OK	OK			OK
Plane slip surfaces parallel to slope face						OK
Circular slip surfaces	OK	OK	OK	OK		
Wedge failure mechanism			OK			
Non-circular slip surfaces–any shape			OK			
Suitable for hand calculations	OK	OK		OK	OK	OK

Conclusion : According to the table, it can be seen that the best methods for analyzing the stability of slopes are the Bishop's method and the Spencer's method, nevertheless there is a drawback for the Simplified Bishop method, which is that it is not suitable for any form of the line of the rupture but it is very advantageous for the document calculations thus, it is very easy to put a numerical program of the calculation of it, on the other hand the method of Spencer, it is valid for all the shapes of the plane, circular or arbitrary rupture line, but it is difficult for manual calculation, and to put it into a numerical program so for our work we will choose Simplified Bishop method, this method will be presented and explained in detail by chapter III.

This method consider the equilibrium of a mass in an approximate way (division into slices), and are applicable only to circular failure surfaces. However, the general principle of the slice method can be used for other forms of failure surfaces, and errors from the equilibrium approximation can be minimized or eliminated. Slice methods appear to offer the best approach to obtain an accurate solution for any failure surface, whether for laminated or zoned floors.

Chapter III: Bishop's Method.

Chapter III: **Bishop's method.**

1. Introduction: This chapter illustrates the procedures used in the Simplified Bishop method of slope stability analysis and provides guidance for checking and verifying the results of slope stability analyses.

These analyses are performed to check the factors of safety calculated for the critical slip surface, and for other slip surfaces considered significant. The slip surfaces used for the examples studied on page 82 were selected to illustrate the computational procedures.

a. As discussed elsewhere in this chapter, the soil mass above the slip surface is subdivided into vertical slices. Computer programs use more slices than are needed for hand calculations. **Six** to **twelve** slices are sufficient for hand calculations. **Fewer than 6** slices do not provide sufficient accuracy, and **more than12** slices makes the computations unwieldy.

b. In the following examples (see on page 82), computations are performed beginning with the uppermost slice near the top of the slope and proceeding to the toe area, regardless of the direction that the slope faces. Thus, in some cases the computations are performed for slices from left-to-right and in other cases for slices from right-to-left, depending on the direction that the slope faces.

c. All of the computations for the procedures of slices initially summarized in tabular form and then include them in the program.

d. At the end of this chapter and based on the procedures that will be presented in the form of tables for each case, we will build our computer program, a mini software that can perform mathematical calculations and iterative calculations to find the appropriate safety factor value and the appropriate critical slip surface for that safety factor. Our software will initially be based on a purely mathematical calculations so it will be able to define and build a geometric shape, draw a 2D cross section for the project that we are going to study, this model in the form of a drawing is based on a long series of very complex mathematical calculations, which require a lot of skills in the field of programming, after that he start to do the iterative calculations, every time we will select trial slip surfaces and compute factors of safety. The critical slip surface is the one that has the lowest factor of safety.

2. The Ordinary Method of Slices [4]:

a. Assumptions. The Ordinary Method of Slices (OMS) was developed by Fellenius (1936) and is sometimes referred to as "Fellenius' Method." In this method, the forces on the sides of the slice are neglected Figure (III-1). The normal force on the base of the slice is calculated by summing forces in a direction perpendicular to the bottom of the slice. Once the normal force is calculated, moments are summed about the center of the circle to compute the factor of safety. For a slice and the forces shown in Figure (III-1), the factor of safety is computed from the equation,

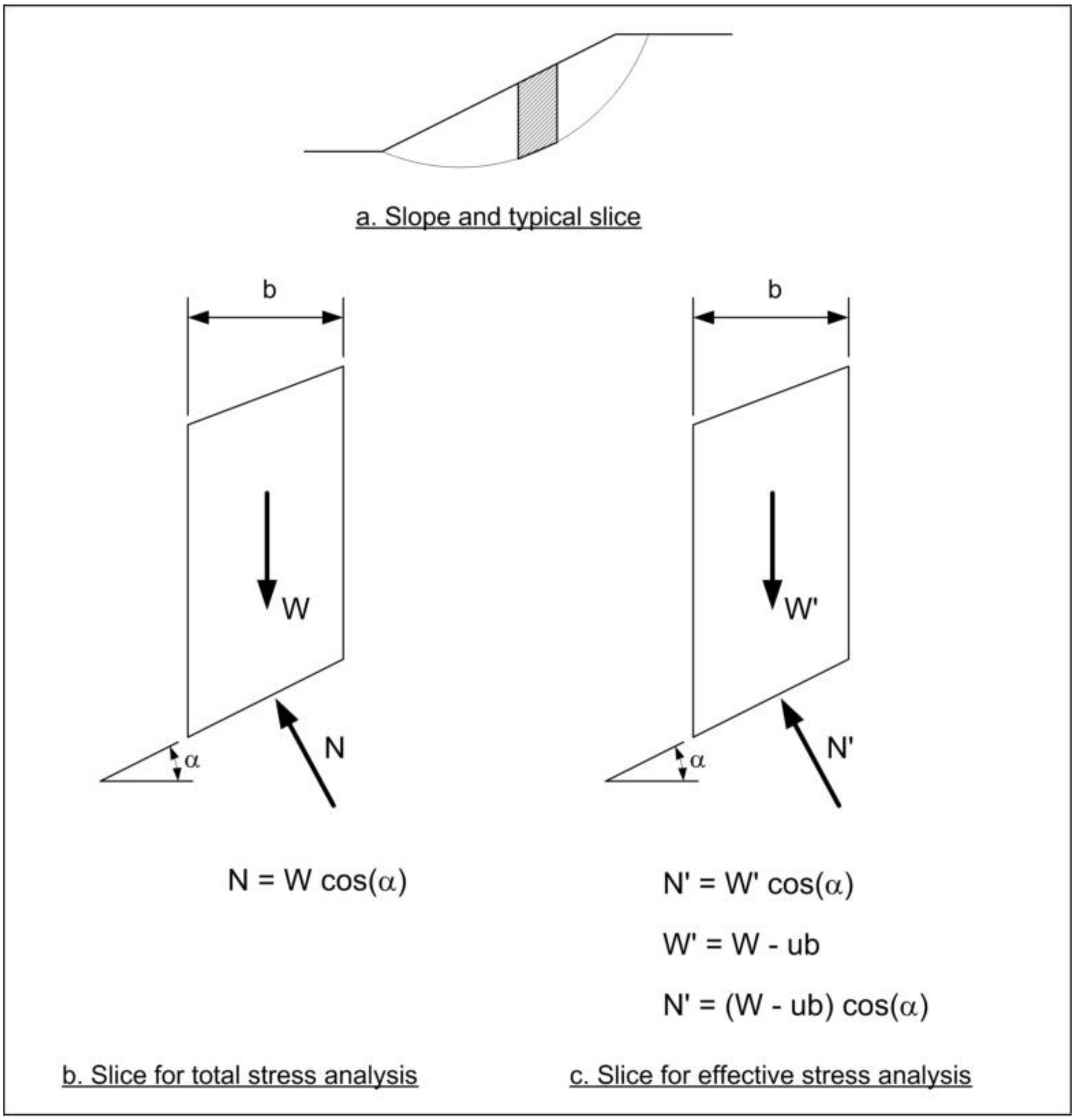


Figure III-1.Typical slice and forces for Ordinary Method of Slices.

$$F = \frac{\sum\left[c'\Delta\ell + (W\cos\alpha - u\,\Delta\ell\cos^2\alpha)\tanh\phi'\right]}{\sum \boldsymbol{W}\sin\boldsymbol{\alpha}} \qquad \text{E (III-1)}$$

Where: c' and ϕ': shear strength parameters for the center of the base of the slice.

W: weight of the slice.

α : inclination of the bottom of the slice.

u : pore water pressure at the center of the base of the slice.

$\Delta\ell$: length of the bottom of the slice.

As shown in Table (III-1), there is only one unknown in the Ordinary Method of Slices (F), and only one equilibrium equation is used (the equation of equilibrium of the entire soil mass around the center of the circle).

Table (III-1): Unknowns and Equations for the Ordinary Method of Slices Procedure [4].

Unknowns	Number of Unknowns for n Slices
Factor of safety (F)	1
TOTAL NUMBER OF UNKNOWNS	1
Equations	Number of Equations for n Slices
Equilibrium of moments of the entire soil mass	1
TOTAL NUMBER OF EQUILIBRIUM EQUATIONS	1

Two different equations have been used to compute the factor of safety by the OMS (**Ordinary Method of Slices)** with effective stresses and pore water pressures. The first equation is shown above as Equation E (III-1). Equation E (III-1) is derived by first calculating an "effective" slice weight, W', by subtracting the uplift force due to pore water pressure from the weight, and then resolving forces in a direction perpendicular to the base of the slice Figure (III-1). The other OMS equation for effective stress analyses is written as:

$$F = \frac{\sum\left[c'\Delta\ell+(W\cos\alpha-u\,\Delta\ell\cos^2\alpha)\tanh\phi'\right]}{\sum \boldsymbol{W}\sin\boldsymbol{\alpha}} \qquad E\,(III\text{-}2)$$

Equation E(III-2) is derived by first resolving the force because of the total slice weight (W) in a direction perpendicular to the base of the slice and then subtracting the force because of pore water pressures. Equation E (III-1) leads to more reasonable results when pore water pressures are used. Equation E (III-1) can lead to unrealistically low or negative stresses on the base of the slice because of pore water pressures and should not be used.

(2) External water on a slope can be treated in either of two ways: The water may simply be represented as soil with c=0 and ϕ=0. In this case, the trial slip surface is assumed to extend through the water and exit at the surface of the water. Some of the slices will then include water and the shear strength for any slices whose base lies in water will be assigned as zero. The second way that water can be treated in an analysis is to treat the water as an external, hydrostatic load on the top of the slices. In this case, the trial slip surface will only pass through soil, and each end will exit at the ground or slope surface Figure (III-2). For the equations presented in this chapter, the water is treated as an external load. Treating the

water as another “soil” involves simply modifying the geometry and properties of the slices.

(3) In the case where water loads act on the top of the slice, the expression for the factor of safety Equation E (III-1) must be modified to the following:

$$F=\frac{\sum\left[c'\Delta\ell+(W\cos\alpha+P\cos\alpha(\alpha-\beta)-u\,\Delta\ell\cos^2\alpha)\tanh\phi'\right]}{\sum W\sin\alpha-\frac{1}{R}\sum Mp} \qquad E\ (III\text{-}3)$$

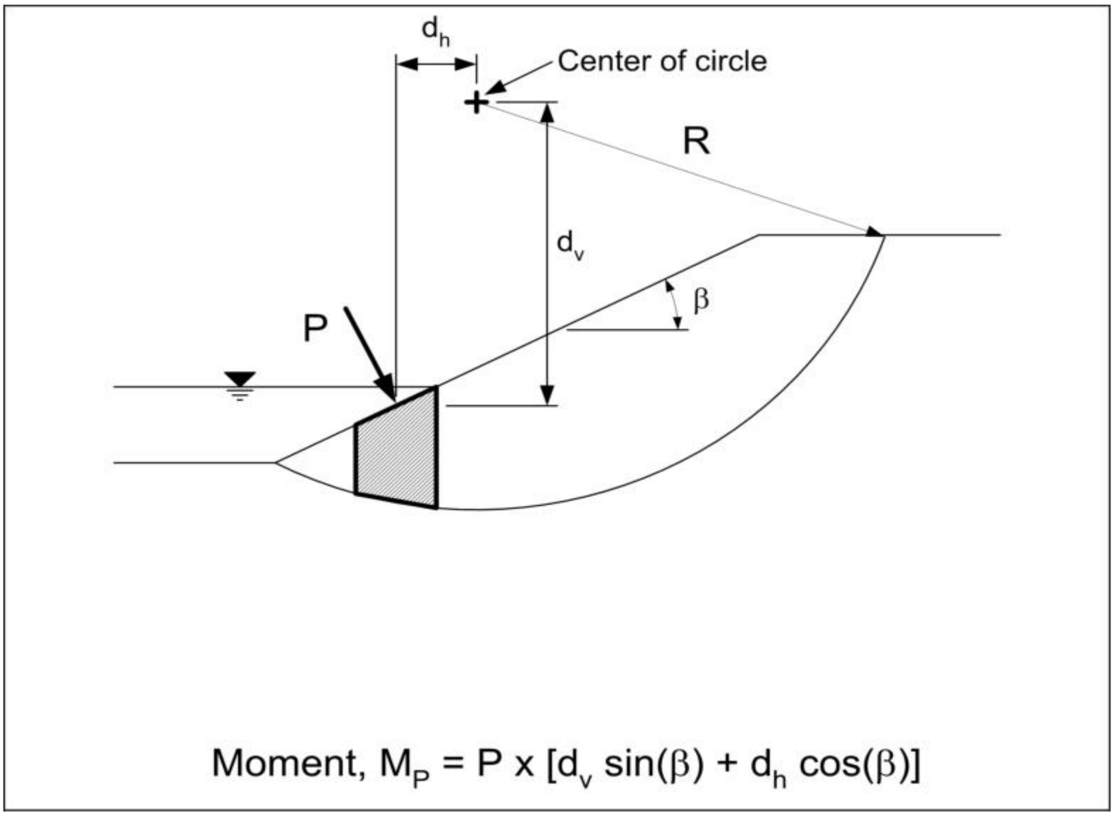


Figure III-2: Slice for Ordinary Method with external water loads [4].

Where: P: resultant water force acting perpendicular to the top of the slice.

β: inclination of the top of the slice.

M_p: moment about the center of the circle produced by the water force acting on the top of the slice.

The moment, M_p, is considered to be positive when it acts in the opposite direction to the moment produced by the weight of the sliding mass.

b. Limitations. The principal limitation of the OMS comes from neglecting the forces on the sides of the slice. The method also does not satisfy equilibrium of forces in either the vertical or horizontal directions. Moment equilibrium is satisfied for the entire soil mass above the slip surface, but not for individual slices.

(1) Factors of safety calculated by the OMS may commonly differ as much as 20 percent from values calculated using rigorous methods (Whitman and Bailey 1967); in extreme cases (such as effective

stress analysis with high pore water pressures), the differences may be even larger. The error is generally on the safe side (calculated factor of safety is too low), but the error may be so large as to yield uneconomical designs. Because of the tendency for errors to be on the "safe side," the OMS is sometimes mistakenly thought always to produce conservative values for the factor of safety. This is not correct. When $\emptyset = 0$, the OMS yields the same factor of safety as more rigorous procedures, which fully satisfy static equilibrium. Thus, the degree to which the OMS is conservative depends on the value of $\emptyset$ and whether the pore pressures are large or small.

(2) Although Equation E (III-1) does not specifically include the radius of the circle, the equation is based on the assumption that the slip surface is circular. The OMS can only be used with circular slip surfaces.

c. Recommendation for use: The OMS is included herein for reference purposes and completeness because numerous existing slopes have been designed using the method. As the method still finds occasional use in practice, occasions may arise where there is a need to review designs by others that were based on the method. Also, because the OMS is simple, it is useful where calculations must be done by hand using an electronic calculator.

3.The Simplified Bishop Method [4]**:**

a. Assumptions: The Simplified Bishop Method was developed by Bishop (1955). This procedure is based on the assumption that the inter slice forces are horizontal, as shown in Figure III-3. A circular slip surface is also assumed in the Simplified Bishop Method. Forces are summed in the vertical direction. The resulting equilibrium equation is combined with the Mohr-Coulomb equation and the definition of the factor of safety to determine the forces on the base of the slice. Finally, moments are summed about the center of the circular slip surface to obtain the following expression for the factor of safety:

$$F = \frac{\sum\left[\frac{c'\Delta x+(W+P\cos\beta-u\Delta x)\tan\phi'}{m_\alpha}\right]}{\sum W\sin\alpha-\frac{1}{R}\sum Mp} \qquad \text{E (III-4)}$$

Where Δx is the width of the slice, and m_α is defined by the following equation,

$$m_\alpha = \cos\alpha + \frac{\sin\alpha\ \tan\emptyset'}{F} \qquad \text{E (III-5)}$$

The terms W, c', $\emptyset'$, u, P, M_p, and R are as defined earlier for the OMS. Factors of safety calculated from Equation E (III-4) satisfy equilibrium of forces in the vertical direction and overall equilibrium of moments about the center of a circle. The unknowns and equations in the Simplified Bishop Method are summarized in Table (III-2).

Because the value of the term m_α depends on the factor of safety, the factor of safety appears on both sides of Equation E (III-4). Equation E (III-4) cannot be manipulated such that an explicit expression is obtained for the factor of safety. Thus, an iterative, trial and error procedure is used to solve for the factor of safety.

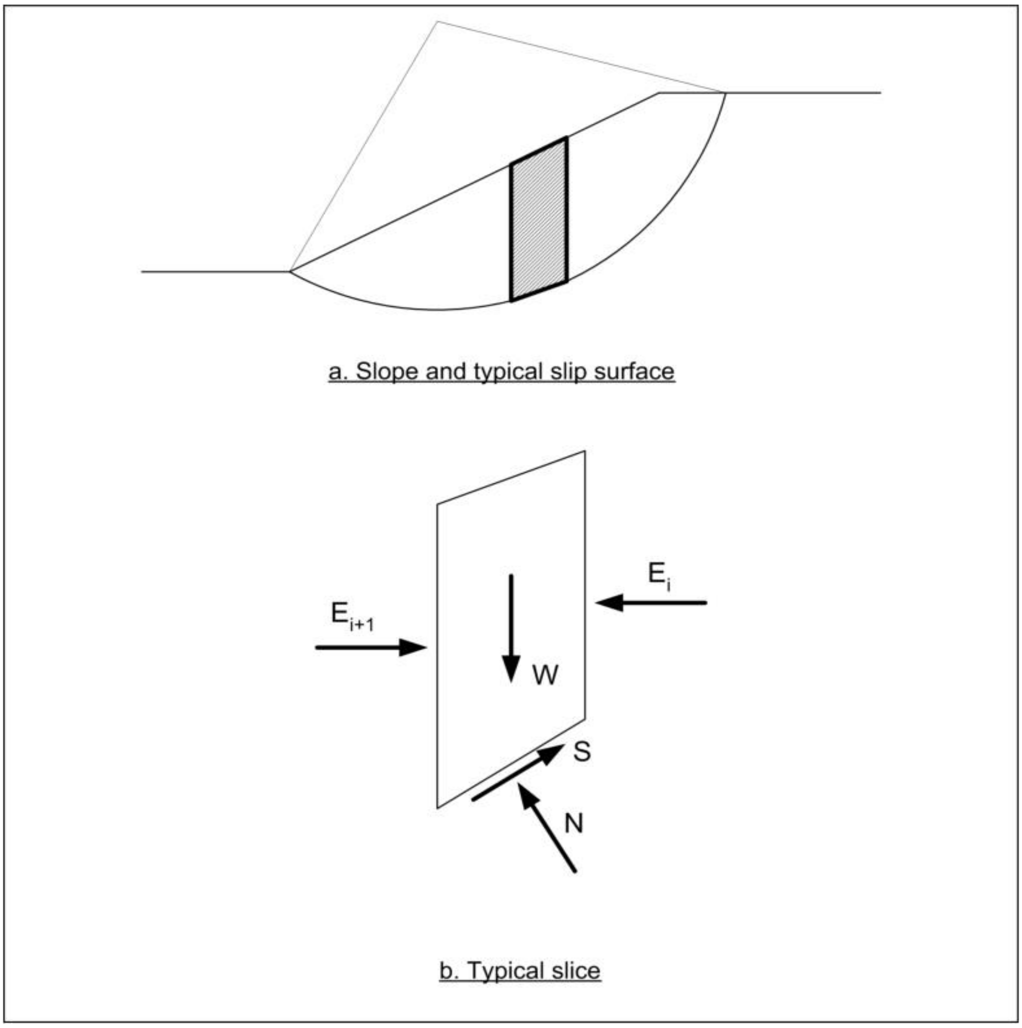


Figure III-3: Typical slice and forces for Simplified Bishop Method [4].

Table (III-2) Unknowns and Equations for the Simplified Bishop Method [4].	
Unknowns	Number of Unknowns for n Slices
Factor of safety (F)	1
Normal forces on bottom of slices (N)	n
TOTAL NUMBER OF UNKNOWNS	n+1
Equations	Number of Equations for n Slices
Equilibrium of forces in the vertical direction, $\sum Fy = 0$	n
Equilibrium of moments of the entire soil mass	1
TOTAL NUMBER OF EQUILIBRIUM EQUATIONS	n+1

b. Limitations [4]: Horizontal equilibrium of forces is not satisfied by the Simplified Bishop Method. Because horizontal force equilibrium is not completely satisfied, the suitability of the Simplified Bishop Method for pseudo-static earthquake analyses where an additional horizontal force is applied is questionable. The method is also restricted to analyses with circular shear surfaces.

c. Recommendation for use [4]: It has been shown by a number of investigators (Whitman and Bailey 1967; Fredlund and Krahn 1977) that the factors of safety calculated by the Simplified Bishop Method compare well with factors of safety calculated using rigorous methods, usually within 5 percent. Furthermore, the procedure is relatively simple compared to more rigorous solutions, computer solutions execute rapidly, and hand calculations are not very time-consuming. The method is widely used throughout the world, and thus, a strong record of experience with the method exists. The Simplified Bishop Method is an acceptable method of calculating factors of safety for circular slip surfaces. It is recommended that, where major structures are designed using the Simplified Bishop Method; the final design should be checked using Spencer's Method.

d. Verification procedures [4]: When the Simplified Bishop Method is used for computer calculations, results can be verified by hand calculations using a calculator or a spreadsheet program, or using slope stability charts. An approximate check of calculations can also be performed using the Ordinary Method of Slices, although the OMS will usually give a lower value for the factor of safety, especially if $\emptyset$ is greater than zero and pore pressures are high.

4. Application of the simplified Bishop method according to the water state of the soil:

The Simplified Bishop Method is only applicable to analyses with circular slip surfaces. Detailed steps are presented below for a total stress analysis of a slope with no water and for an effective stress analysis of a slope with water, internal seepage, and external water loads.

4-a Slope without seepage or external water loads - total stress analyses [4]**:**

Computations for the Simplified Bishop Method for slopes, where the shear strength is expressed in terms of total stresses and where there are no external water loads, are illustrated in Figure (III-4) .As for all of the examples presented, slices are numbered beginning with the uppermost slice and proceeding toward the toe of the slope. Once a trial slip surface has been selected, and the soil mass is subdivided into slices, the following steps are used to compute a factor of safety.

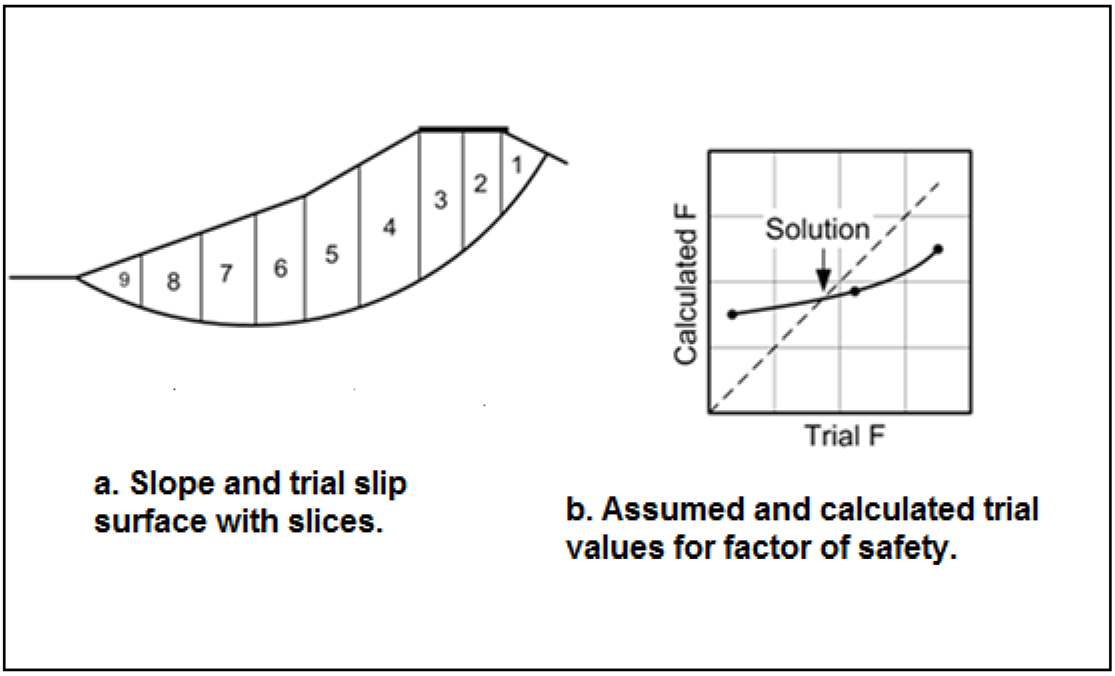


Figure (III-4): Simplified Bishop Method with no water- total stress analyses [4].

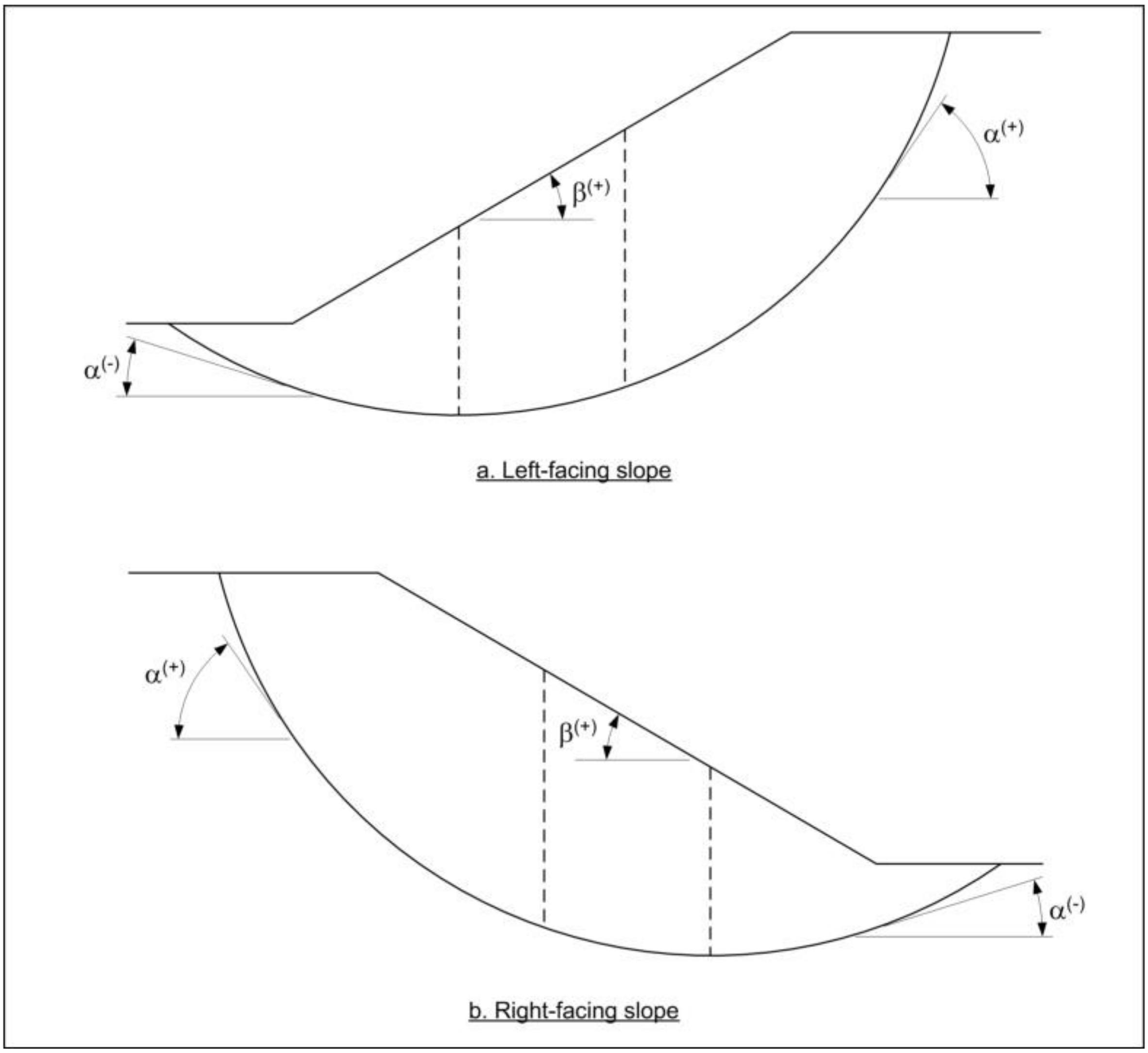


Figure (III-5): Sign convention used for angles α and β [4].

Table III-3: Stages of calculation of the safety factor, (adopted in our computer program) **on A slope** ***without seepage or external water loads - total stress analyses using*** **Simplified Bishop Method.**

1	Input the following data: (Program receive the necessary Data to make calculation) a) The coordinates (x;y;z) for our slope, and then ; b) Insert the height of each layer of soil, if there are several layers. c) Insert the characteristics of the different types of soil, starting with their naming and then the following characteristics (ϕ /γ_{soil}/c) and trial factor of safety (F1, F2, F3). d) Select loading conditions for analysis (see Chapter II)., **Table II-1.**						
2	Select trial slip surfaces and Draw the cross section, limited by slope and trial slip surface.						
3	Subdivide the cross section of soil mass into slices						
	Steps between 4 to 16 are calculated for each slice. (n slices)						
	Slice	1	2	…	…	**n**	
4	Calculate Horizontal width (b)	..	..	..	..	..	
5	Calculate Average height (h_{avr})	..	..	..	..	..	
6	Area (A)	..	..	..	..	..	**A= b***h_{avr}
7	Weight (W)	..	..	..	..	..	$\boldsymbol{W = \gamma * A}$
8	Base inclination (α),	..	..	..	..	..	
9	Calculate $W \sin\alpha$ and then summing the values for all slices at the end.	..	..	..	..	..	$\sum \boldsymbol{W \sin \alpha} =$
10	$c * b + W \tan(\Phi)$	..	..	..	..	..	
11	mα (Trial F1)	..	..	..	..	..	$m_\alpha = \cos\alpha + \frac{\sin\alpha \ \tan\emptyset}{F1}$
12	Calculate the Numerator (line10 /line11) for each slice and then summing the values for all slices at the end.	..	..	..	..	..	$\sum_{\mathbf{1}} \frac{\mathbf{c * b + W \tan(\emptyset)}}{m_\alpha}$
13	m α (Trial F2)	..	..	..	..	..	$m_\alpha = \cos\alpha + \frac{\sin\alpha \ \tan\emptyset}{F2}$
14	Calculate the Numerator (line10/ line13) for each slice and then summing the values for all slices at the end.	..	..	..	..	..	$\sum_{\mathbf{2}}$
15	mα (Trial F3)	..	..	..	..	..	$m_\alpha = \cos\alpha + \frac{\sin\alpha \ \tan\emptyset}{F3}$
16	Calculate the Numerator (line 10/line 15) for each slice and then summing the values for all slices at the end.	..	..	..	..	..	$\sum_{\mathbf{3}}$

The process of evaluating slope stability involves the following chain of events:

- ***First step :*** You must have and prepare the following data to input it on the program (Line 1 on the table):

- The coordinates (x;y;z) for our slope,
- Insert the names of the different soil layers, if there are several layers.
- Insert the height of each layer of soil
- Insert the characteristics of the different types of soil.
- **$\gamma_{soil\ 1}$, $\gamma_{soil\ 2}$, $\gamma_{soil\ 3}$ ….. :** Unit weight of different type of soil.
- **and γ_{water}:** Unit weight of water.
- cohesion, c or c', and friction angle, ϕ or ϕ' for each slice, The shear strength parameters are those for the soil at the bottom of the slice; they do not depend on the soils in the upper portions of the slice.
- Insert the trial factor of safety (F1, F2, F3).
- *Select loading conditions for analysis (see Chapter II).*, **Table II-1 Shear Strengths and Pore Pressures for Static Design.**
  - *A-* *slope* without seepage or external water loads - total stress analyses (*Undrained conditions, analyses are performed using undrained strengths related to effective stresses*)
  - *B-* Slope with seepage or external water loads -effective stress analyses (*drained conditions, analyses are performed using drained strengths related to total stresses*)
  - *C-* *End-of-Construction (Short-Term Stability)* ***(this option not yet included in our program)***
  - *D-* *Steady Seepage (Long-Term Stability).**(this option not yet included in our program).***
- This data it's necessary to *Establish the 2-D idealization of the cross section, including the surface geometry and the subsurface boundaries between the various materials.*

- ***Second step:*** Select trial slip surfaces and Draw the cross section, limited by slope and trial slip surface, Search schemes for circular arc slip surfaces are illustrated in Figures II-12, II-13, and II-14 on paragraph **II-8 Fundamentals of Slope Stability Analysis (g) in Chapter II. But this option is not yet included in our program that why we have to insert** the radius value as well as the circle center coordinates for the sliding surface.
- ***Third step:*** Subdivide the cross section of soil mass into slices. The program subdivide the cross section using that equation: (L: project width) / (N: slice number), we have to insert the slice number.
- ***Fourth step:*** our program will calculate the three values of safety factor for very trial value (F1,F2,F3) so he start the calculation following the Table III-3 Above from Line 4 through it Line 16.

- The width (b), average height, (h_{avr}), and bottom inclination, (α),of each slice are determined (Line 4, 5, and 8 in Table (III-3).The sign convention used for the inclination (α), is illustrated in Figure (III-5).The inclination is positive when the base of the slice is inclined in the same direction as the slope.

- The area, A, of each slice is calculated by multiplying the width of the slice by the average height i.e.,**A= b***h_{avr}(Line 6 in Table III-3).
- The weight of each slice is calculated by multiplying the total unit weight of soil by the area of the slice, i.e., $\boldsymbol{W = \gamma * A}$. If the slice crosses zones having different unit weights, the slice is subdivided vertically into subareas, and the weights of the subareas are summed to compute the total slice weight (Line 7 in Table III-3).
- The quantity,$\mathbf{W \sin \alpha}$,is computed for each slice, and these values are summed to obtain the term in the denominator of the equation for the factor of safety (Line 9 in Table III-3).
- The quantity $\mathbf{c * b + W \tan}(\phi)$is computed for each slice (Line 10 in Table III-3).
- A trial value is assumed for the factor of safety and the quantity, $\mathbf{m}\alpha$, is computed from the equation shown below (Line 11 in Table III-3):
- $$m_\alpha = \cos \alpha + \frac{\sin \alpha \ \tan \phi}{F} \qquad \text{E (III-6)}$$
- The numerator in the expression for the factor of safety is computed by dividing the term $\mathrm{c * b + W \tan}(\phi)$ by $m_\alpha$for each slice and then summing the values for all slices (Line 12 in Table III-3).
- A new factor of safety is computed from the equation:

$$F = \frac{\sum\left[\frac{\mathbf{c*b+W\,tan}(\phi)}{m_\alpha}\right]}{\sum W \sin \alpha} \qquad \text{E (III-7)}$$

This corresponds to dividing the summation of Line 12 by the summation of Line 9 in Table III-3).

This safety factor value “Fc1” is the computed value corresponds to the trial value F1, so we obtain the first couple of safety factor (F1 trial value: F computed value).

(10) Additional trial values are assumed for the factor of safety and the calculation between (Line 13 through 16) are repeated (Table III-3). For each trial value assumed for the factor of safety, the assumed value and the value computed for the factor of safety using Equation E (III-7) are plotted as shown in Figure III-4b, after three loops we obtain three couple (Trial F1; Computed Fc1) (Trial F2; Computed Fc2). (Trial F3; Computed Fc3). The chart in Figure III-4b serves as a guide to calculate manually the factor of safety Fs1 correspond to the first Trial slip surface, we start the calculation in our program many times (ten times for example) and each time our program will give us a cross section limited by the surface of the slope and the new trial slip surface already calculated by the

program, and the three calculated values of safety factors, that we can calculate the safety factors correspond to the new trial slip surface, at the end if we have ten slip surface with ten value safety factor calculated by hand, we will choose the cross section which has **the lowest safety factor.** The diagram below **Figure III-6** shows how we will determine the most adequate safety factor and how we will choose the failure surface, using our program and a very simple manual calculation.

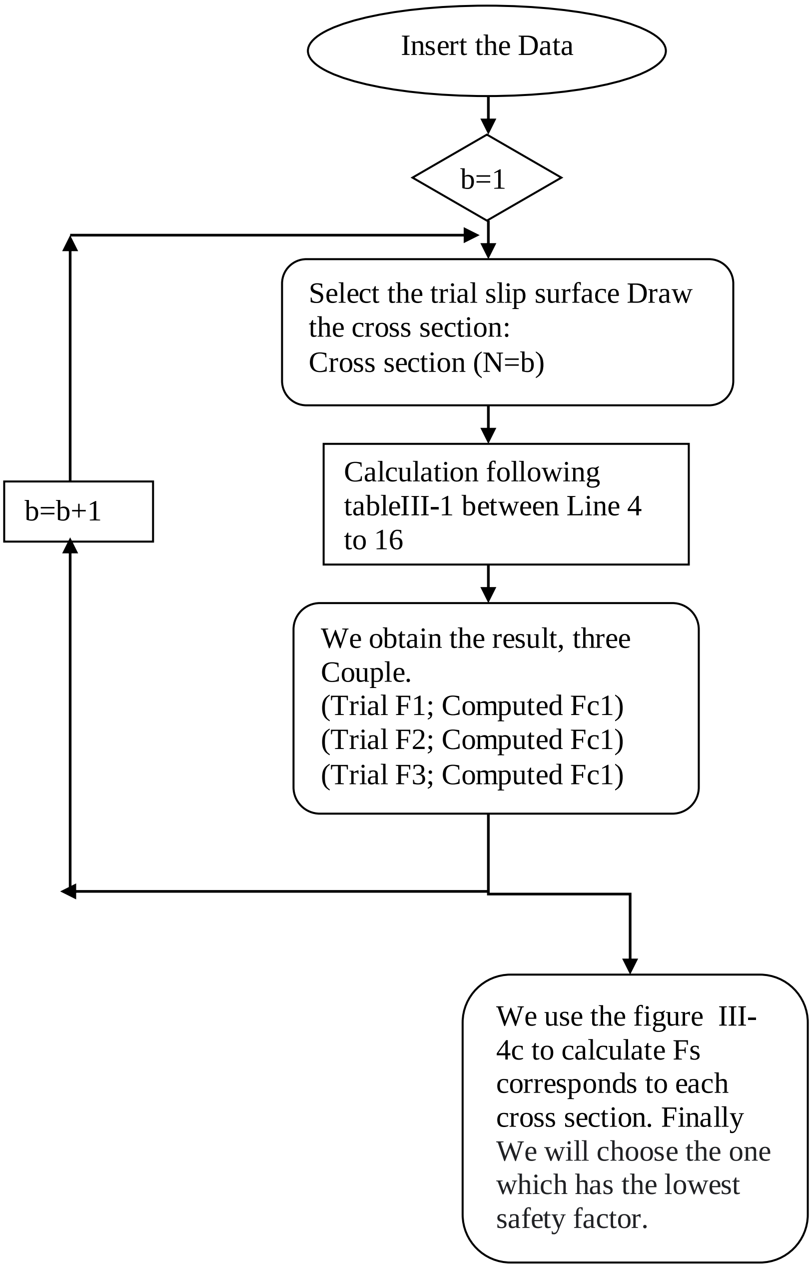


Figure III-6: The diagram of procedure of determination the most adequate safety factor.

4-b. ***Slope with seepage or external water loads -effective stress analyses*** [4]***:***

Computations for slopes where the shear strength is expressed in terms of effective stresses, and where there are pore water pressures and external water loads, are illustrated in Figure III-7. In this case, the pore water pressures on the base of each slice must be determined. Loads from external water are included in all analyses, whether they are performed using total stress or effective stress. or as an external force. In the description which follows, water is represented as an external load rather than as soil. Accordingly, a force on the top of the slice and the moment the force produces about the center of the circle must be computed. For a given trial circle, the following steps are required:

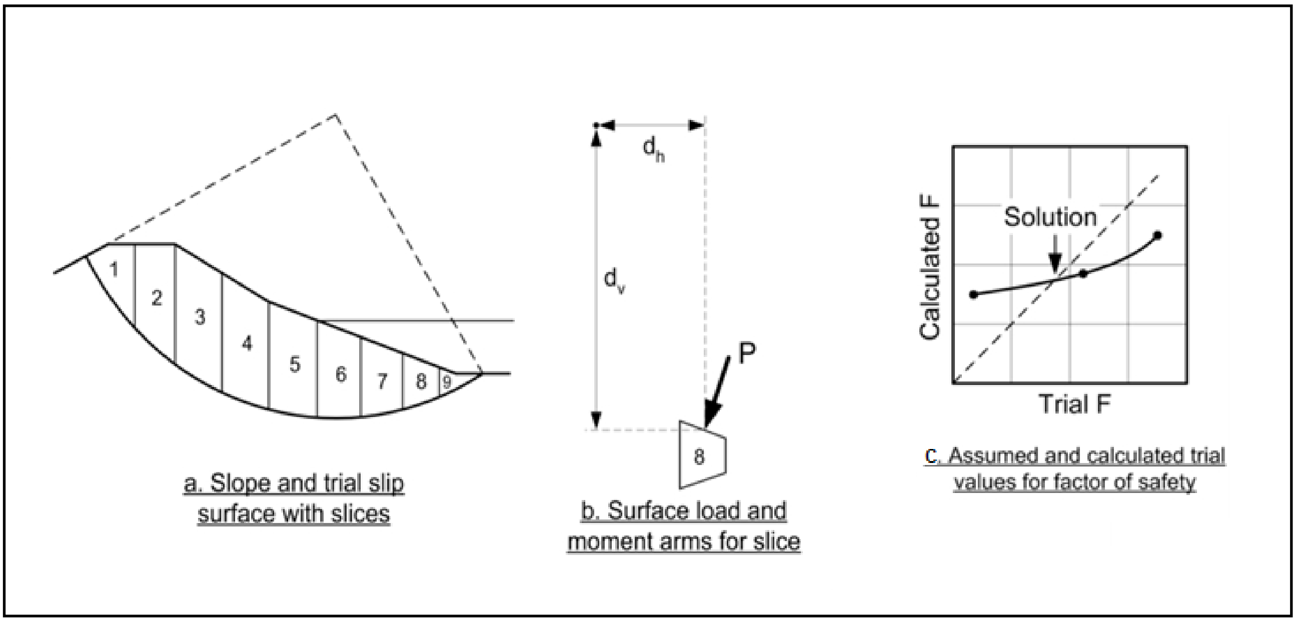


Figure III-7: Simplified Bishop Method with water-effective stress analyses [4].

Table III-4: Stages of calculation of the safety factor, (adopted in our computer program) **on a *Slope with seepage or external water loads -effective stress analyses using* Simplified Bishop Method.**

1	Input the following data: (Program receive the necessary Data to make calculation) The coordinates (x;y;z) for our slope, and then a) Insert the height of each layer of soil, if there are several layers. b) Insert the characteristics of the different types of soil, starting with their naming and then the following characteristics (ϕ'/γ_{soil}/ c') and trial factor of safety (F1, F2, F3). c) Height of surface water (h_s), from bottom of the slope to surface of water. d) Select loading conditions for analysis (see Chapter II)., **Table II-1.**						
2	Select trial slip surfaces and Draw the cross section, limited by slope and trial slip surface.						
3	Subdivide the cross section of soil mass into slices.						
	Steps between 4 to 23 are calculated for each slice. (n slices)						
	Slice	1	2	.	.	**n**	
4	Horizontal width (b)						
5	Average height (h_{avr})						
6	Area (A)						**A= b***h_{avr}
7	Weight (W)						$\boldsymbol{W = \gamma * A}$
8	Base inclination (α),						
9	Calculate W sin α and then summing the values for all slices at the end.						$\boldsymbol{\sum W \sin \alpha =}$
10	Avg. surface press $P_{surface}$ $P_{surface}$= h_s*γ_{water}						
11	The force P is equal to : $P_{surface}$ *b/ cos(β).						P = $P_{surface}$ *b/ cos(β).
12	Horizontal moment arm (d_h)						
13	Vertical moment arm (d_v)						
14	Moment (Mp)						$M_p = P\cos\beta d_h + P\sin\beta d_v$
15	Piezometric height (h_p)						
16	Pore water pressure (u) U=h_p* γ_{water}						
17	c'b+(W+Pcosβ −ub)tanϕ'						
18	m α (Trial F1)						$m_\alpha = \cos\alpha + \frac{\sin\alpha\ \tan\emptyset'}{F1}$

19	Calculate the Numerator (line17 /line18) for each slice and then summing the values for all slices at the end.						$\sum_{\mathbf{1}} \frac{\mathbf{c}' * \mathbf{b} + (\mathbf{W} + \mathbf{p}\ \mathbf{cos}\beta - ub)\ \mathbf{tan}(\phi)}{m_\alpha}$
20	m α (Trial F2)						$m_\alpha = \cos\alpha + \frac{\sin\alpha\ \tan\emptyset'}{F2}$
21	Calculate the Numerator (line17/ line20) for each slice and then summing the values for all slices at the end.						$\sum_{\mathbf{2}}$
22	mα (Trial F3)						$m_\alpha = \cos\alpha + \frac{\sin\alpha\ \tan\emptyset'}{F3}$
23	Calculate the Numerator (line17/lin22) for each slice and then summing the values for all slices at the end.						$\sum_{\mathbf{3}}$

The process of evaluating slope stability involves the following chain of events:

(1) From the first step to the third one we follow same clarification on the case of (**slope *without seepage or external water loads - total stress analyses)***

(2) Fourth step: our program will calculate the three values of safety factor for every trial value (F1,F2,F3) so it start calculation following the Table III-4 Above from Line 4 through Line 23.

- For each slice The width (b), average height, (h_{avr}), bottom inclination, (α),are determined (Line 4,5,and 8 in the Table III-4).The sign convention used for the angle,(α),is illustrated in Figure III-5.
- The area, A, of each slice is calculated by multiplying the width of the slice by the average height,i.e., **A= b***h_{avr} (Line 6 in the Table III-4).
- The weight of each slice is calculated by multiplying the total unit weight of soil by the area of the slice, i.e., $\boldsymbol{W} = \boldsymbol{\gamma} * \boldsymbol{A}$. If the slice crosses zones having different unit weights, the slice is subdivided vertically into subareas, and the weights of the subareas are summed to compute the total slice weight (Line 7 in the Table III-4).
- The quantity,$\mathbf{W}\ \mathbf{sin}\,\alpha$, is computed for each slice, and these values are summed to obtain the term in the denominator of the equation for the factor of safety (Line 9 in the Table III-4).
- The average water pressure on the top of the slice, $p_{surface}$, is calculated by multiplying the

average height of water, h_s, by the unit weight of water (Line 10 in the Table III-4).

- The length of the top of the slice is multiplied by the average surface pressure, $P_{surface}$, to compute the external water force, P ,on the top of the slice (Line 11 in the Table III-4).The force P is equal to :$P=P_{surace} * b/\cos(\beta)$.
- The horizontal and vertical distances, d_h and d_v, respectively, between the center of the circle and the points on the top center of each slice are determined (Line 12 and 13 in the Table III-4). Positive values for these distances are illustrated in Figure III-7b. Loads acting at points located upslope of the center of the circle (to the left of the center in the case of the right-facing slope shown in Figure III-7) represent negative values for the distance, d_h.
- The moment, M_p, the result of external water loads is computed from the following (Column 14 in the Table III-4):
  - $M_P = P\cos\beta d_h + P\sin\beta d_v$ E (III-8)

  The moment is considered positive when it acts opposite to the direction of the driving moment produced by the weight of the slice mass,i.e.,positive moments tend to make the slope more stable. Positive moments are clockwise for a right-facing slope like the one shown in Figure III-7.
- The piezometric height, h_p, at the center of the base of each slice is determined (Column 15 in the Table III-4).The piezometric height represents the pressure head for pore water pressures on the base of the slice.
- The piezometric height is multiplied by the unit weight of water to compute the pore water pressure U (Column 16 in the Table III-4).For complex seepage conditions, or where a seepage analysis has been conducted using numerical methods, it may be more convenient to determine the pore water pressure directly, rather than evaluating the piezometric head and converting to pore pressure. In such cases Step11 is omitted, and the pore water pressures are entered in Column16.
- The cohesion, c', and friction angle, ϕ', The shear strength parameters are those for the soil at the bottom of the slice; they do not depend on the soils in the upper portions of the slice.
- The following quantity is computed for each slice (Column17 in the Table III-4):

$$c'b+(W+P\cos\beta - ub)\tan\phi' \qquad \text{E (III-9)}$$

- A trial factor of safety, F_1,is assumed and the quantity,m_α , is computed from the equation shown below (Column 18 in Table III-4):

$$m_\alpha = \cos\alpha + \frac{\sin\alpha\ \tan\emptyset'}{F1} \qquad \text{E (III-10)}$$

- The numerator in the equation used to compute the factor of safety is calculated by dividing the term c'b+(W+Pcosβ −ub)tanϕ' by m_α for each slice and then summing the values for all slices (Column 19 in Table III-4).
- A new value is computed for the factor of safety using the following equation:

$$F = \frac{\sum\left[\frac{c'b+(W+P\cos\beta-ub)\tan\phi'}{m_\alpha}\right]}{\sum W\sin\propto - \frac{1}{R}\sum Mp} \qquad \text{E (III-11)}$$

Where: R is the radius of the circle.

This safety factor value “Fc1” is the computed value corresponds to the trial value F1, so we obtain the first couple of safety factor (F1 trial value: F computed value)

(10) Additional trial values are assumed for the factor of safety and the calculation between (Line 20 through 23) are repeated (Table III-4). For each trial value assumed for the factor of safety, the assumed value and the value computed for the factor of safety using Equation E (III-11) are plotted as shown in Figure III-7c, after three loops we obtain three couple (Trial F1; Computed Fc1) (Trial F2; Computed Fc2). (Trial F3; Computed Fc3). The chart in Figure III-7c serves as a guide to calculate manually the factor of safety Fs1 correspond to the first Trial slip surface, we start the calculation in our program many times (ten times for example) and each time our program will give us a cross section limited by the surface of the slope and the new trial slip surface already calculated by the program, and the three calculated values of safety factors, that we can calculate the safety factors correspond to the new trial slip surface, at the end if we have ten slip surface with ten value safety factor calculated by hand, we will choose the cross section which has the lowest safety factor. The diagram below **Figure III-8** shows how we will determine the most adequate safety factor and how we will choose the surface of the break. using our program and a very simple manual calculation.

5. Case of a soil composed of many layers "example of verification of the stability of a highway embankment structure":

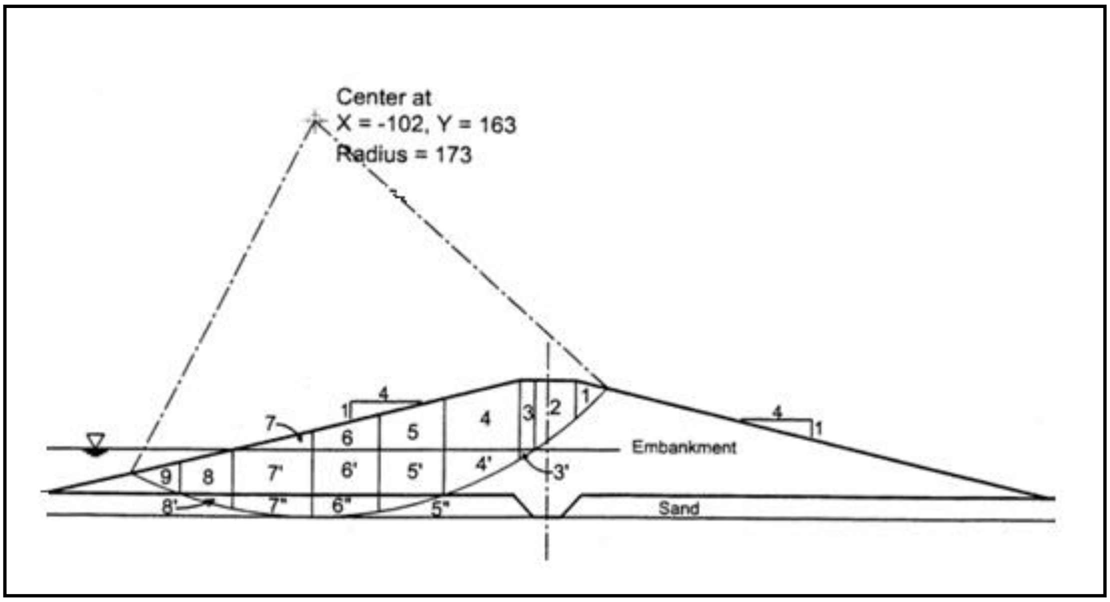


Figure III-8 . Case of a soil composed of many layers [4].

Table III-5 use to compute factor of safety. (Case of a soil composed of many layers "example of verification of the stability of a highway embankment structure").

1	**Slice Number**	**1**	**2**	**3**	**3'**	**4**	**4'**	**5**	**5'**	**5''**	**6**	**6'**	**6''**	**7**	**7'**	**7''**	**8**	**8'**	**9**	
2	Horizontal width (b)																			
3	Average slice height (h_{avr})																			
4	Slice Area (A)																			**A= b*** h_{avr}
5	Total Unit Weight (γ_i)																			$\boldsymbol{W = \gamma * A}$
6	Partial Weight (W_i)																			
7	Total Weight (W)																			

8	Base inclination (α),										
9	$\mathbf{W \sin \propto}$										$\sum \boldsymbol{W} \sin \boldsymbol{\alpha} =$
10	Height of surface water (h_s)										
11	Avg. surface press $P_{surface}$										
12	Surface inclination (β),										
13	Surface load (P)										
14	Horizontal moment arm (d_h)										
15	Vertical moment arm (d_v)										
16	Moment (Mp)										$M_p = P\cos\beta d_h + P\sin\beta d_v$
17	Piezometric height (h_p)										
18	Pore water pressure (u)										
19	Cohesion (c')										
20	Friction angle (Φ'),										

21	c'b+(W+P cosβ −ub) tanΦ'										
22	m∝ (Trial F1)										$m_{\alpha} = \cos\alpha + \frac{\sin\alpha \ \tan\emptyset'}{F1}$
23	Numerator (line 21/ line 22)										$\sum_{\mathbf{1}} \frac{\mathbf{c' * b + (W + p\ cos}\beta - ub\mathbf{)\ tan}(\Phi)}{m_{\alpha}}$
24	m∝ (Trial F2)										$m_{\alpha} = \cos\alpha + \frac{\sin\alpha \ \tan\emptyset'}{F2}$
25	Numerator (line 21/ line 24)										$\sum_{\mathbf{2}}$
26	m∝ (Trial F3)										$m_{\alpha} = \cos\alpha + \frac{\sin\alpha \ \tan\emptyset'}{F3}$
27	Numerator (line 21/ line 27)										$\sum_{\mathbf{3}}$

Remark: As you see from the table III-5 we find that the calculation will be the same except that in lines 3, 4, 5 and 6 the calculation of the parameters for each slices must be carried out according to the geotechnical parameters of different layers.

Conclusion :

1) In this chapter we have clearly illustrated how to calculate the safety factor according to the simplified Bishop method for the following three cases:
    - ❖ A slope without seepage or external water loads - total stress analyses for soil with one layer.
    - ❖ Slope with seepage or external water loads -effective stress analyses soil with one layer.
    - ❖ A soil composed of many layers "example of verification of the stability of a highway embankment structure".
2) Bishop method is:
    - o A Special case of the method of slices.
    - o Circular method.
    - o Iterative calculation on the equation of moment.
    - o Widely used method, easy generation of circles of slip surface.

Chapter IV: Presentation of the application and example of calculation.

Chapter IV: **Presentation of the software and application:**

1- **Introduction:** Recently, many software developer companies are available in the international markets. These companies provide variety of software packages exclusively for different disciplines of civil engineering that serve design, construction and operation of the world's infrastructure. Engineers, architects, constructors and owner-operators are practicing their work in specialized subsets in civil engineering like geotechnical, structural, hydraulic, transportation. Environmental engineering project and construction management, land surveying comprehensive engineering and architecture software solution for construction and the sustaining activities.

2- **Definition:** Our software has been designed to calculate the safety factor according to the simplified Bishop method, the calculation of the safety factor will be almost entirely automatic, that is to say 99% of calculation will be done by the software, but the last step will be a manual calculation using a diagram to find the value of the security factor which in fact is the intersection between the line which is drawn by the three couple of the point : Point 1(trial F1; calculated F1), Point 2 (trial F2; calculated F2), Point (trial F3; calculated F3) and the diagonal line which represents in fact the equality between the calculated safety factor and the proposed safety factor See Figure III-4.b, our Software was designed and developed with my supervisor **Mr. Bakhti Rachid.**

3- **Structure of Our application:**

Our software will be composed of many logarithms of the calculation,

First: An algorithm to draw the overall geometry of the project (cut slope, embankment slope).

• Define the different soil layers and their types (backfill layer, foundation layer, embankment layer, etc.)

• Define their physical characteristics and their names,

• The slope of the embankment, the height of each layer,

• At the end display present all these given by drawing well illustrated, and well detailed.

Second: a logarithm for a purely mathematical calculation, namely:

- Division of the structure of the project on vertical slices according to the method of slices.
- The mathematical calculation of the angle α and the angle β, the calculation of the areas of each slice.

Third: mathematical calculation of the safety factor according to the formulas of the simplified Bishop method, illustrated in the tables Tab III-3 and Tab III-4 and Tab III-5 in chapter III, and according to both cases either an undrained soil short-term behavior or the case of a drained soil long-term behavior.

4- Interface of the application:

Our software will be presented with the interface shown in Figure IV-1.

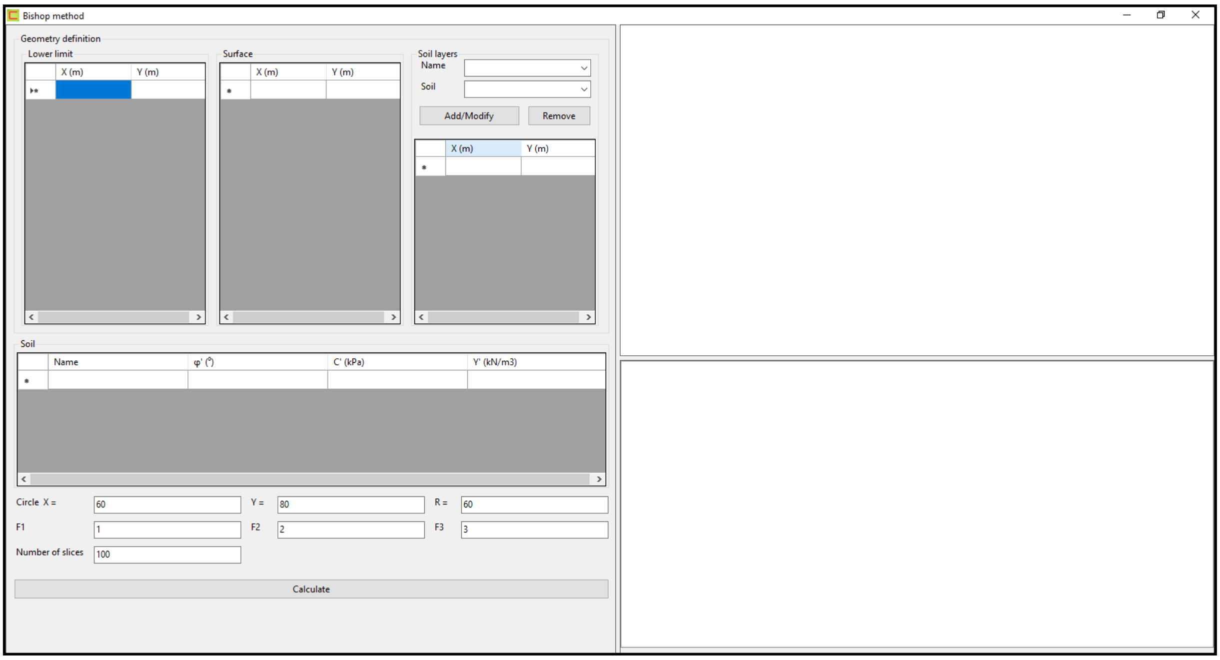


Figure IV-1: Interface of our software.

Figure IV-2: Naming of windows on the software interface.

Window number 01 (F01): it is called "lower limit" it allows you to insert the coordinates (x;y) for the foundation limit of our project, you can enter directly as you can copy them from an Excel file (cf Figure IV.2 and IV.3).

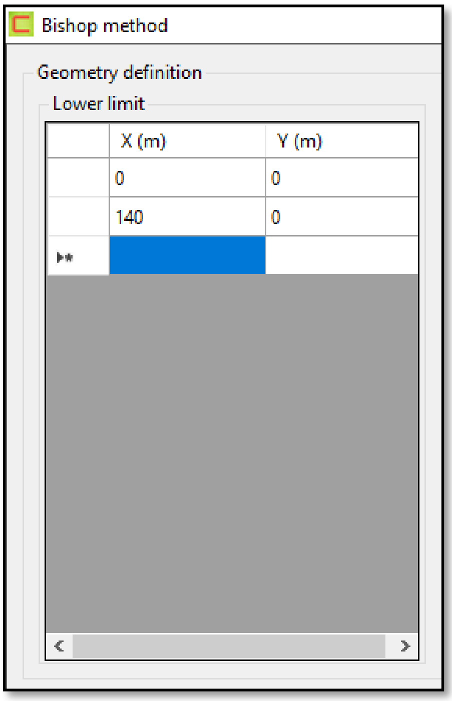


Figure IV-3: Window number 01 (F01)

Window number 02 (F02): it is called "Surface" allows you to insert the coordinates (x;y) for our slope so at least we must have four points see figure IV-4, so this is the same thing as we had already told you, you can enter directly as you can copy them from an Excel file.

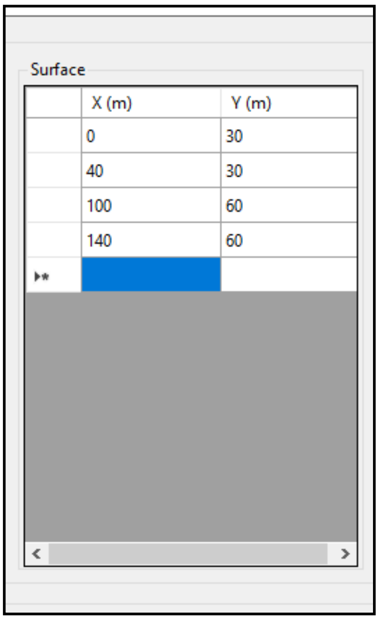


Figure IV-4: Window number 02 (F02).

Window number 03 (F03): it is called "Soil layers" there are two buttons the first will allow you to insert the name of each layer for example "layer 1" and the second button is to insert the type of soil for example “clay, sand, Silt, marl…. ", to add another layer we simply click on the button "Add/Modify" and to delete an already defined layer we click on the button "Remove", of course for the moment our software is designed to study a single layer so the option to study more than one layer is not yet inserted, below these two buttons we must insert the coordinates (x; y) of this layer. (cʆ Figure IV.2 and IV.5).

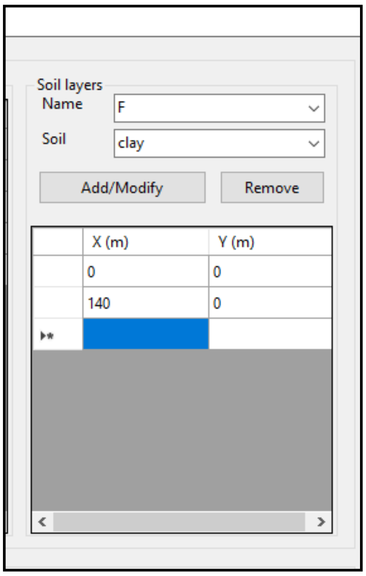


Figure IV-5: Window number 03 (F03)

Window number 04: it is called "Soil" from which we will insert the physical characteristics of our soil according the case: (cʆ Figure IV.2 and IV.6).

a)- For total stresses

c : cohesion intercept

σ : normal stress

φ : total stress friction angle.

γ = total unit weight of soil

b)- For effective stresses

c' : effective stress cohesion intercept

σ' : effective normal stress

ϕ' : effective stress friction angle.

γ : total unit weight of soil.

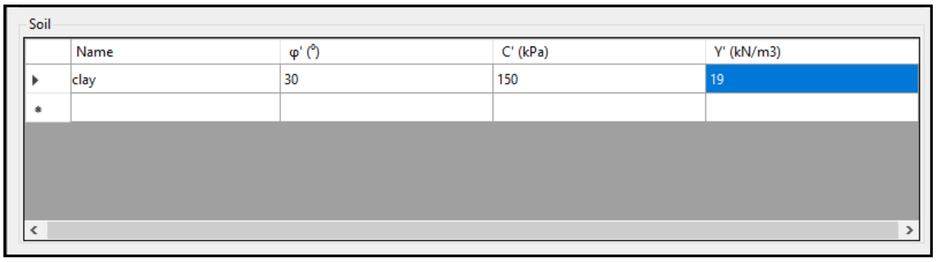


Figure IV-6: Window number 04 (F04)

Window number 05:

In the first line: (cƒ Figure IV.2 and IV.7). you can easily insert the coordinates (X;Y) for the center of the circle as well as the radius, this option as we indicated before is to choose the slip failure, from which the software will check the balance of the slices, this stage of the calculation which is not yet inserted in our program, the insertion of this option of automatic calculation in the program, it is very important because the software will make an iterative calculation so perhaps thousands of operations in a fraction of a second, which will select the most appropriate slip failure with very high precision. So we are going to gain time and precision at the same time.

In the second line: we will insert the three trial safety factor values proposed by the person who is going to make calculation, so we must consecutively insert the values of F1, F2, F3.

In the third line: we can insert the number of slices, (the greater number, the more our calculation will be very precise), but we have to give the following advice concerning the number of slices, so the minimum width of one slice must be greater than or equal to 50 cm, the number of slices must be at least 25 slices.

Below there is a button "Calculate", we notice that before clicking on this button the two windows (F06) and (F07) are empty, white, after having filled in all the data in the two windows (F01) and (F02) and (F03) and (F04) and (F05) we click on this button, and everything follows the background of the windows (F06) and (F07) changes.

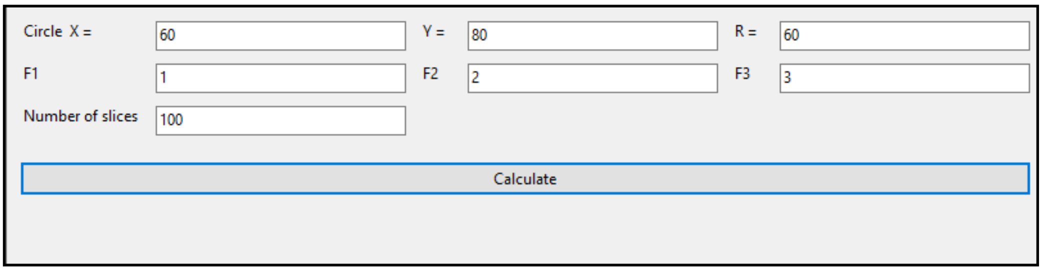
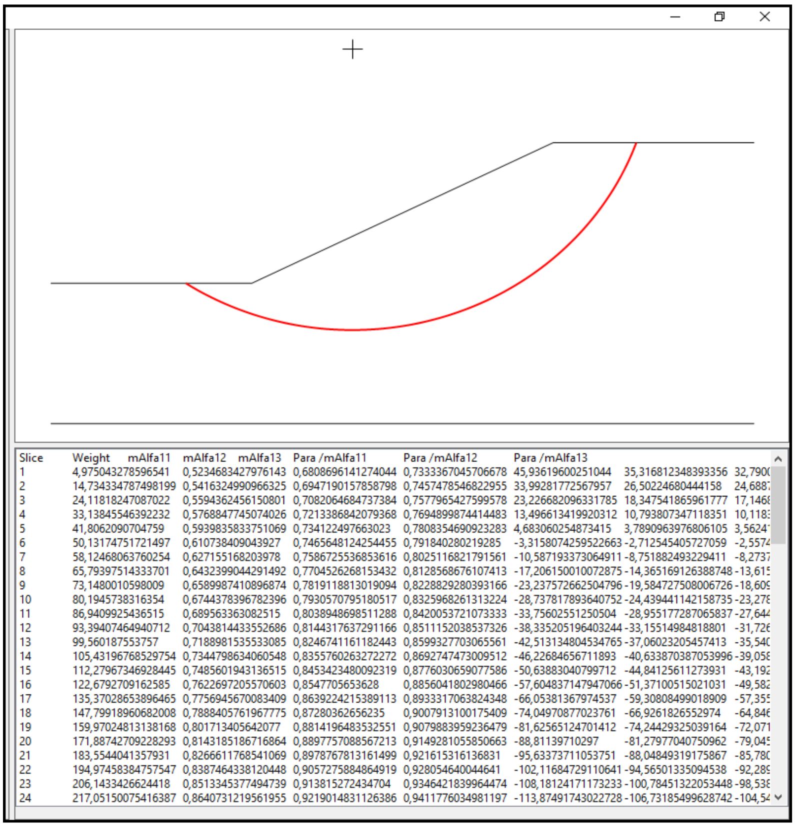


Figure IV-7: Window number 05 (F05)

The two windows number (F06) and (F07) (cƒ Figure IV.8), are intended to display the results of the calculation, so the window (F06) displays the drawing of our project the slope with the limit of the layer which supports our project, thus the line of slip failure, the window (F07) displays the result of our calculation. Including the values of safety factors calculated by our program we can drag the window (F07) we use the mouse we click on the vertical scroll bar to see all the results, we can copy these results directly on a Word or Excel page.



Slice	Weight	mAlfa11	mAlfa12	mAlfa13	Para /mAlfa11	Para /mAlfa12	Para /mAlfa13
1	4,975043278596541	0,5234683427976143	0,6808696141274044	0,7333367045706678	45,93619600251044	35,316812348393356	32,790
2	14,734334787498199	0,5416324990966325	0,6947190157858798	0,7457478546822955	33,99281772567957	26,50224680444158	24,688
3	24,11818247087022	0,5594362456150801	0,7082064684737384	0,7577965427599578	23,226682096331785	18,347541865961777	17,146
4	33,13845546392232	0,5768847745074026	0,7213386842079368	0,7694899874414483	13,496613419920312	10,793807347118351	10,118
5	41,8062090704759	0,5939835833751069	0,734122497663023	0,7808354690923283	4,683060254873415	3,7890963976806105	3,5624
6	50,13174751721497	0,610738409043927	0,7465648124254455	0,791840280219285	-3,3158074259522663	-2,712545405727059	-2,5574
7	58,12468063760254	0,627155168203978	0,7586725536853616	0,8025116821791561	-10,587193373064911	-8,751882493229411	-8,2737
8	65,79397514333701	0,6432399044291492	0,7704526268153432	0,8128568676107413	-17,206150010072875	-14,365169126388748	-13,61
9	73,1480010598009	0,6589987410896874	0,7819118813019094	0,822882928039316	-23,237572662504796	-19,584727508006726	-18,60
10	80,1945738316354	0,6744378396782396	0,7930570795180517	0,8325968261313224	-28,737817893640752	-24,439441142158735	-23,27
11	86,9409925436515	0,689563363082515	0,8038948698511288	0,8420053721073333	-33,75602551250504	-28,955177287065837	-27,644
12	93,39407464940712	0,7043814433552686	0,8144317637291166	0,8511152038537326	-38,335205196403244	-33,15514984818801	-31,72
13	99,560187553757	0,7188981535533085	0,824674116118243	0,8599327703065561	-42,513134804534765	-37,06023205457413	-35,54
14	105,43196768529754	0,7344798634060548	0,8355760263272272	0,8692747473009512	-46,22684656711893	-40,633870387053996	-39,05
15	112,27967346928445	0,7485601943136515	0,8453423480092319	0,8776030659077586	-50,63883040799712	-44,84125611273931	-43,19
16	122,6792709162585	0,7622697205570603	0,8547705653628	0,8856041802980466	-57,604837147947066	-51,37100515021031	-49,58
17	135,37028653896465	0,7756945670083409	0,8639224215389113	0,8933317063824348	-66,05381367974537	-59,30808499018909	-57,35
18	147,79918960682008	0,7888405761967775	0,87280362656235	0,9007913100175409	-74,04970877023761	-66,9261826552974	-64,84
19	159,97024813138168	0,801713405642077	0,8814196483532551	0,9079883959236479	-81,62565124701412	-74,24429325039164	-72,071
20	171,88742709228293	0,8143185186716864	0,8897757088567213	0,9149281055850663	-88,81139710297	-81,27977040750962	-79,04
21	183,5544041357931	0,8266611768541069	0,8978767813161499	0,92161531613683	-95,63373711053751	-88,04849319175867	-85,78
22	194,97458384757547	0,8387464338120448	0,9057275884864919	0,928054640044641	-102,11684729110641	-94,56501335094538	-92,28
23	206,1433426624418	0,8513345377494739	0,913815272434704	0,9346421839964474	-108,18124171173233	-100,78451322053448	-98,53
24	217,05150075416387	0,8640731219561955	0,9219014831126386	0,9411776034981197	-113,87491743022728	-106,73185499628742	-104,54

Figure IV-8: Window number 06 (F06) **and 07 (F07)**

5- Calculating examples: The slopes are made on the highway project North south between Chiffa and Berrouaghia. The table below show the geotechnical characteristics of three variants of soil that we are going to study.

Table IV-1: Geotechnical characteristics of three variants of soil.

Type (Cut Slope)	Lithological symbol	Nomination	γ_h (g/cm3)	C (Kpa)	ϕ (°)	Status	Color	GTR Class
Variant 01 Slope (1.00/1.00)	AP	Few-plastic clay	1.95	36	20	firm	Brownish	**A1, A2, A2h,A2m, A2s,A2ts, A3,A3m, A3S**
Variant 02 Slope (1.00/1.00)	RG	sandstone strongly altered	2.3	50	28	Sandy aspect of strong resistance	Lividity-gray	**C2B1**
Variant 03 Slope (1.00/1.30)	GA	Clay Gravel	1.95	8	27	half-hard	Brown	**B6**

Variant 01 **:** After that we have to Input the following data from Excel Table (See Figure IV-9). Program receives the necessary data to make calculation.

a) The coordinates (x;y) geometric dimension for Lower limit and for The surface of Our slope and finally (x; y) of the center of slip failure, and the value of Radius R1.

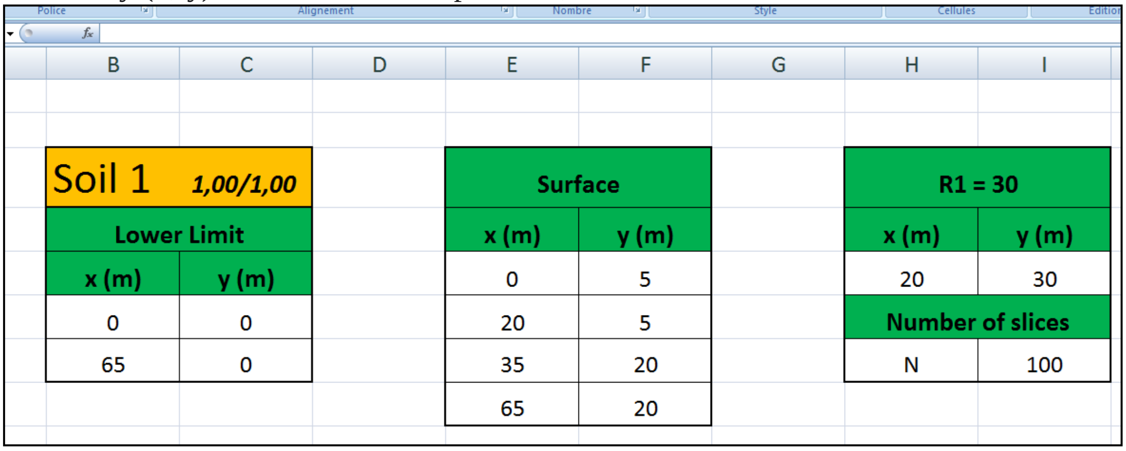


Figure IV-9: Geometric characteristics of soil (01).

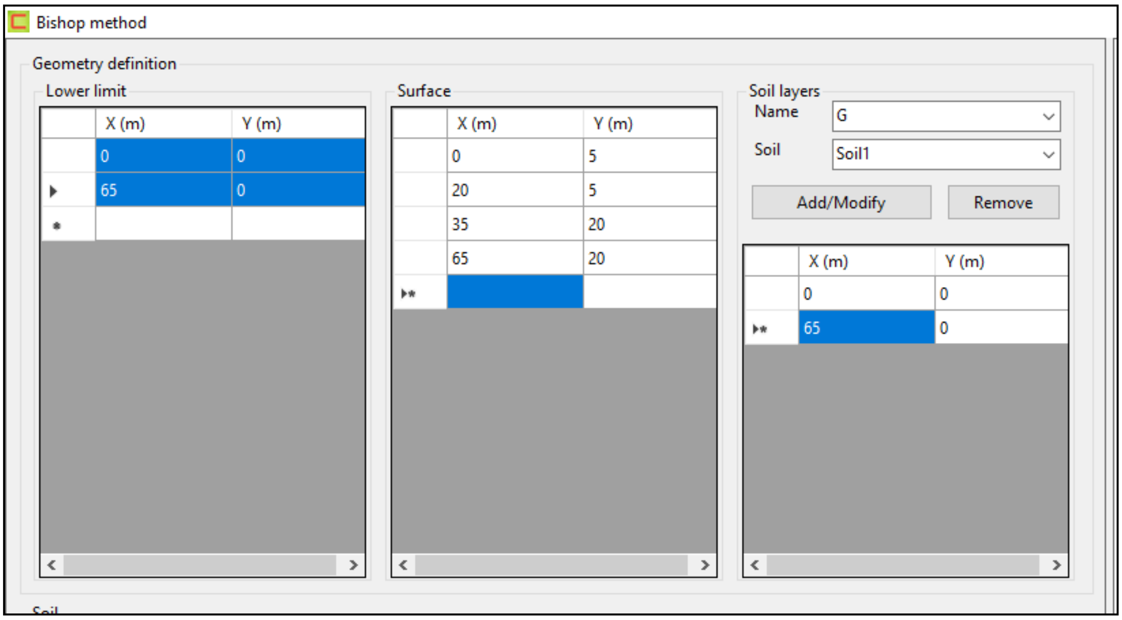


Figure IV-10: Geometric characteristics already included of soil (01).

b) Insert the geotechnical characteristics of the soil, starting with their naming and then the following characteristics (ϕ /γ_{soil}/c) and trial factor of safety (F1=1, F2=2, F3=3).

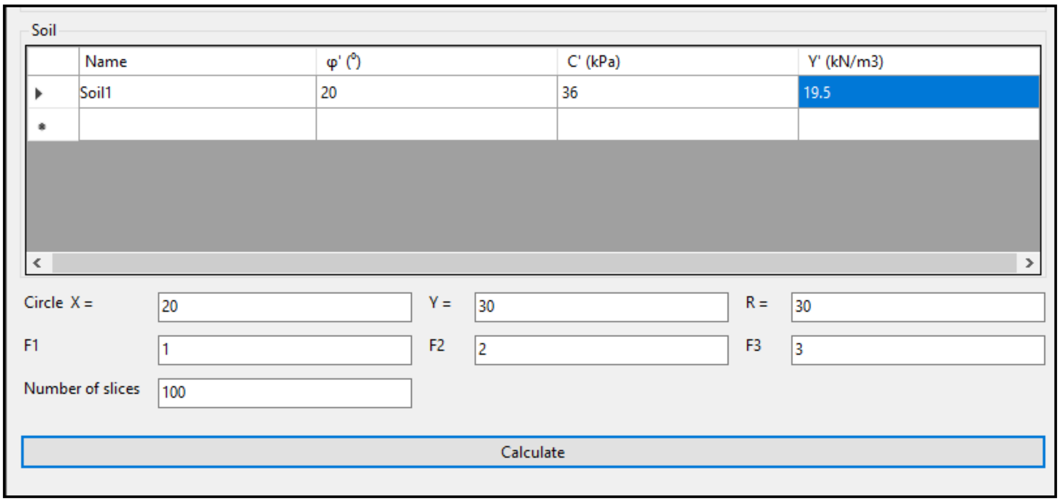


Figure IV-11: Geotechnical characteristics already included and the trial facture of safety, Soil (01).

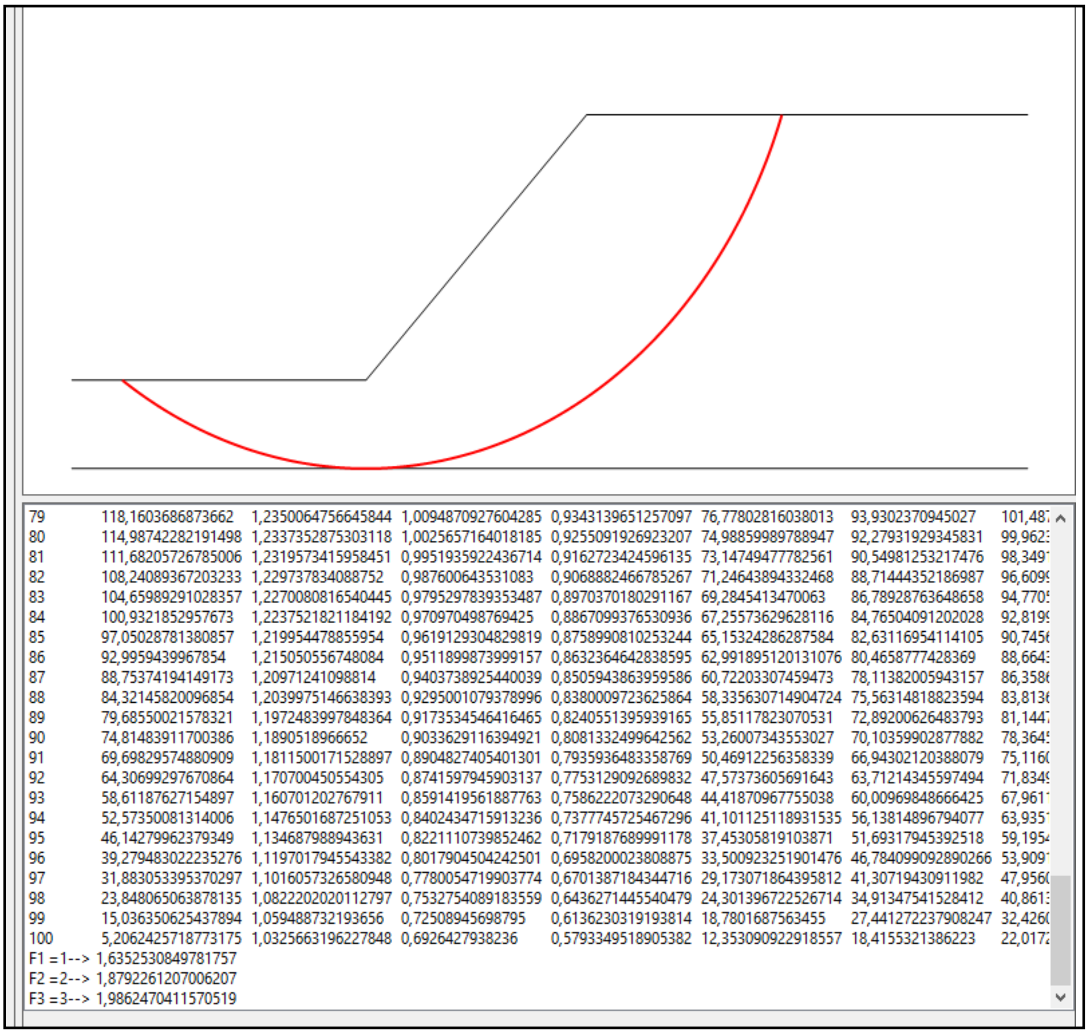


Figure IV-12: Results of the calculation, the cross section of our slope as well as the values of the calculated security factor, Soil (01).

We obtain three points: P1 (Trial F1; Computed Fc1), P2 (Trial F2; Computed Fc2), P3(Trial F3; Computed Fc3). after all that it's time to calculate the safety factor using a diagram drawn on Autocad (see the figure IV-13 after), just it is enough to draw the curve which passes through the three points

(P1,P2,P3) the point of intersection between this curve and the line of the diagonal it is the value of the safety factor.

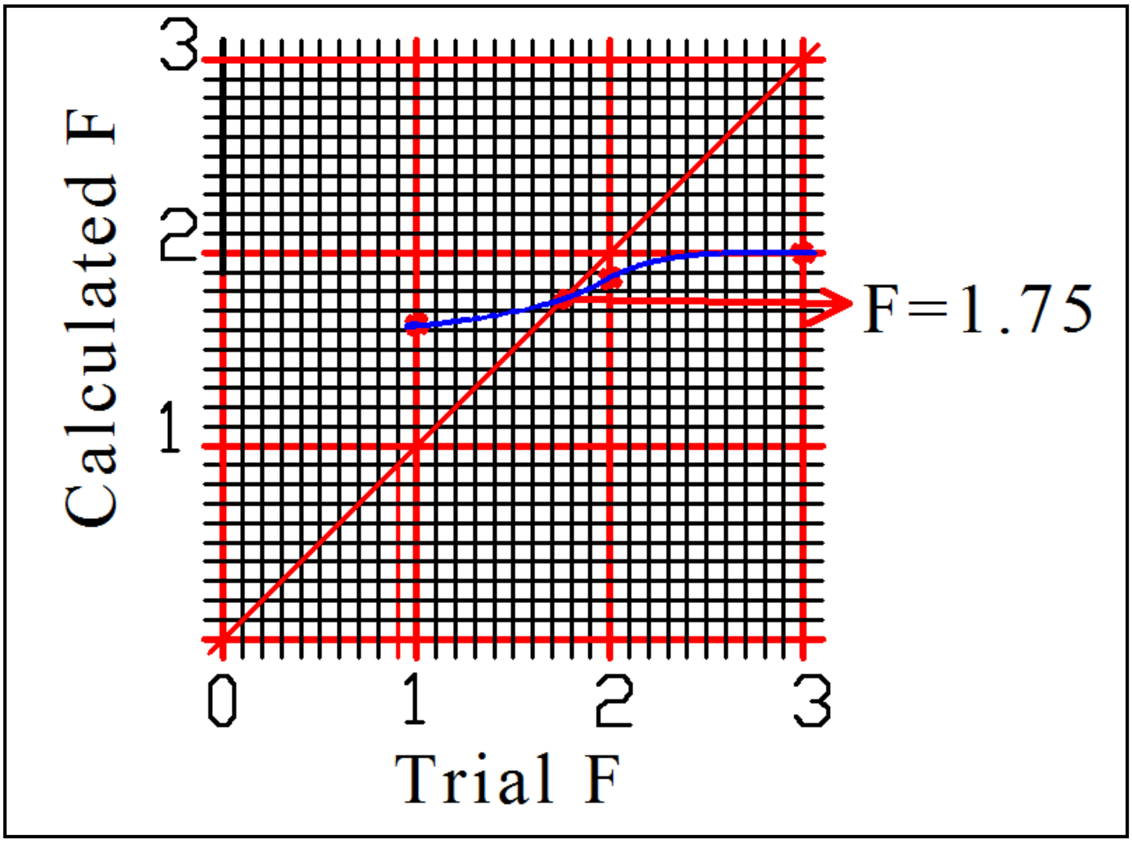


Figure IV-13: Calculation of the factor of safety using the diagram on Autocad, Soil (01).

Variant 02 :

We Input the following data from Excel Table (See Figure IV-14).

Program receive the necessary data to make calculation:

a) The coordinates (x;y) geometric dimension for Lower limit and for The surface of Our slope and finally (x; y) of the center of slip failure, and the value of Radius R2, (cf Figure IV.15).

Soil 2	1,00/1,00
Lower Limit	
x (m)	y (m)
0	0
70	0

Surface	
x (m)	y (m)
0	13
20	13
42	35
70	35

R3 = 38	
x (m)	y (m)
30	40
Number of slices	
N	100

Figure IV-14: Geometric characteristics of soil (02).

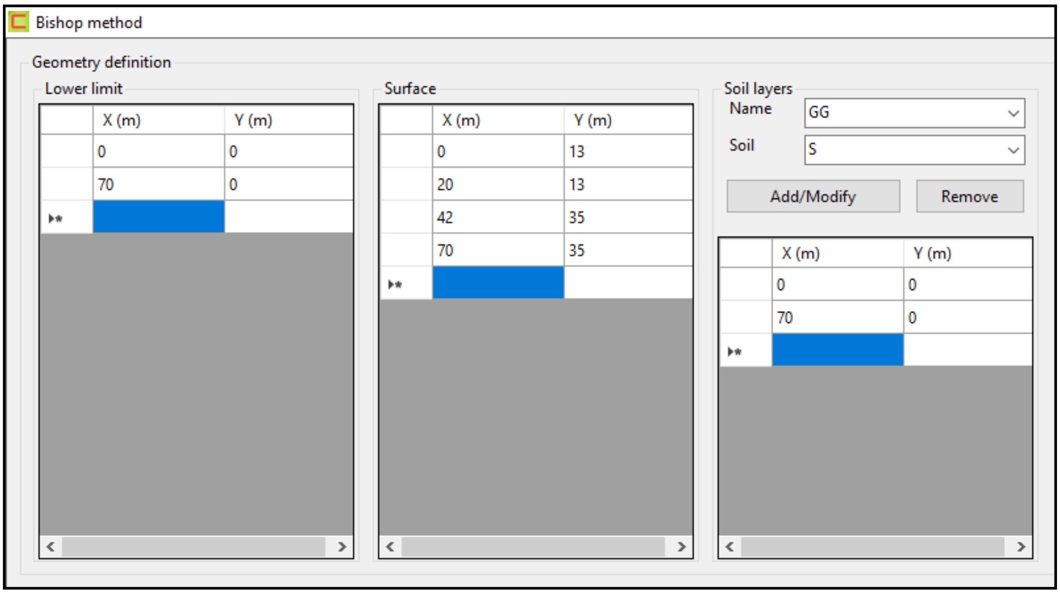


Figure IV-15: Geometric characteristics already included of soil (02).

b) Insert the geotechnical characteristics of the soil, starting with their naming and then the following characteristics (ϕ /γ_{soil}/c) and trial factor of safety (F1=1, F2=2, F3=3), (cf Figure IV.16).

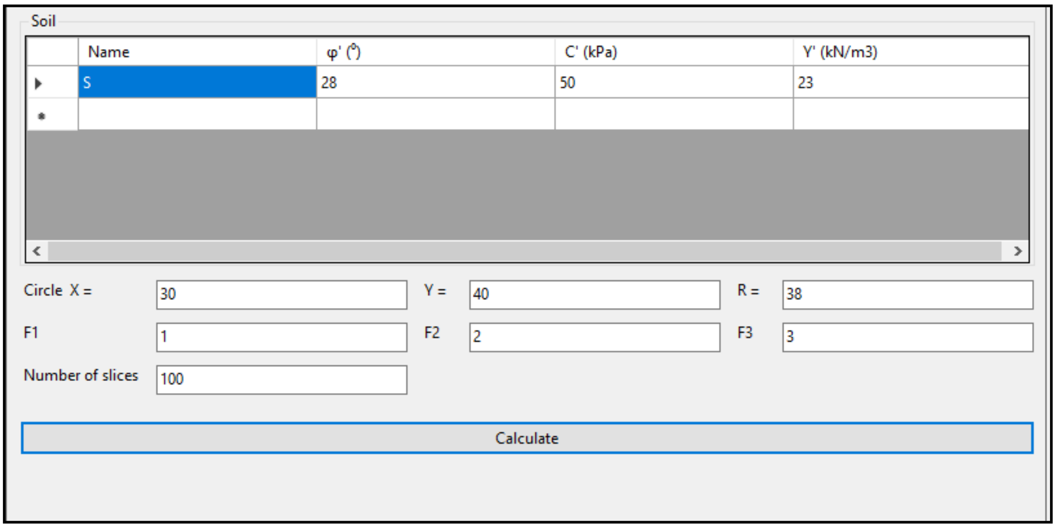


Figure IV-16: Geotechnical characteristics already included and the trial factor of safety, Soil (02).

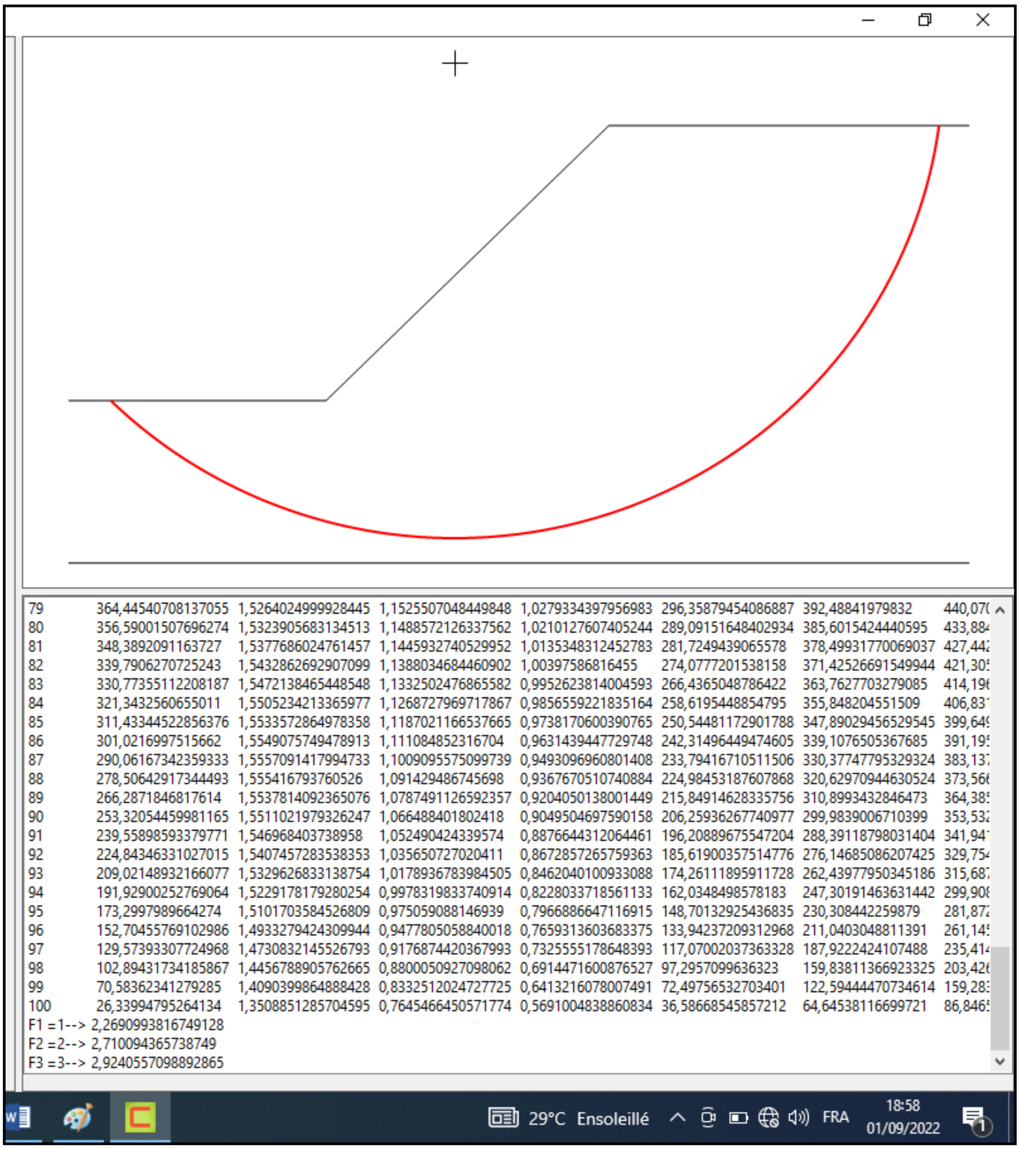


Figure IV-17: Results of the calculation, the cross section of our slope as well as the values of the calculated safety factor, Soil (02).

So we obtain three points: P1 (Trial F1; Computed Fc1), P2 (Trial F2; Computed Fc2), P3(Trial F3; Computed Fc3). after all that it's time to calculate the safety factor using a diagram drawn on Autocad (see the figure IV-18 after); just it is enough to draw the curve which passes through the three points (P1,P2,P3) the point of intersection between this curve and the line of the diagonal it is the value of the safety factor.

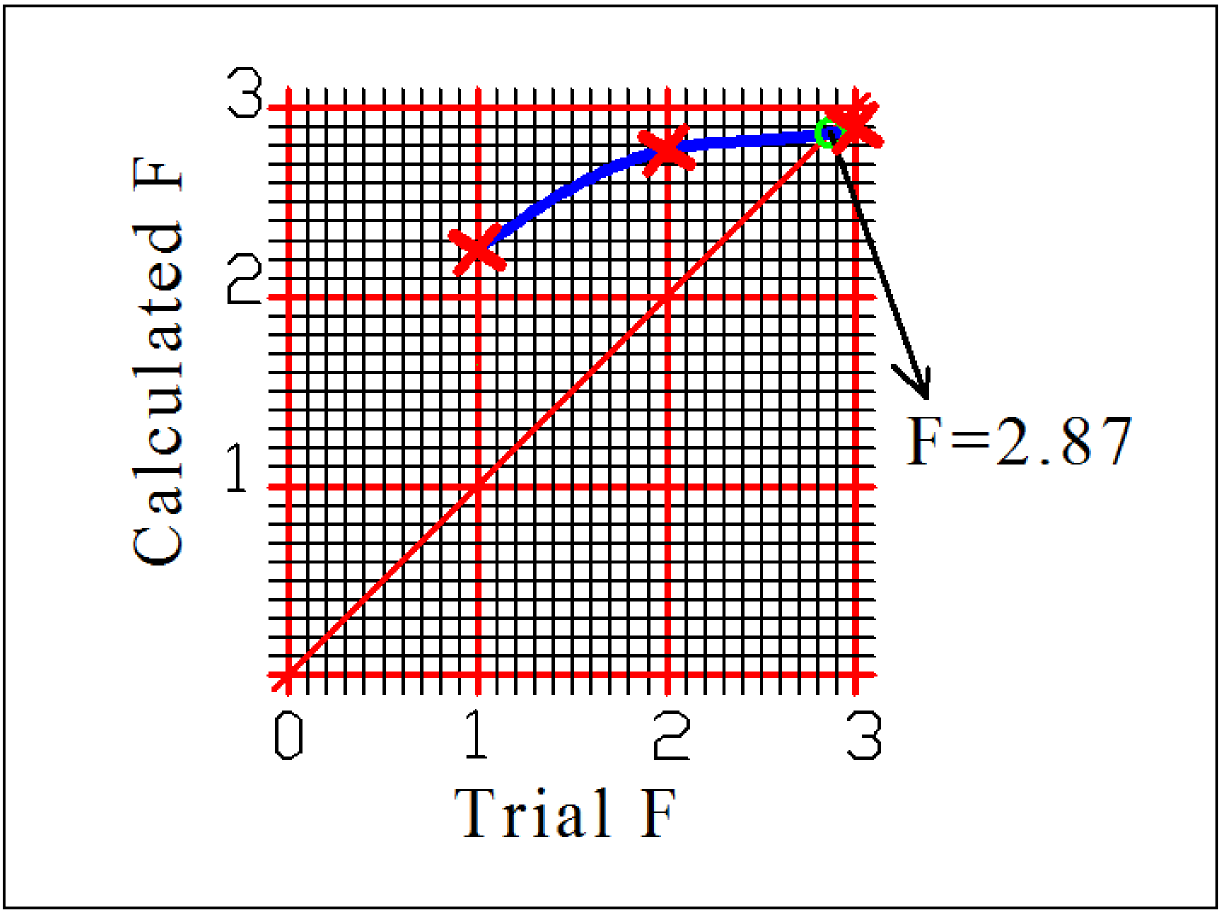


Figure IV-18: Calculation of the safety factor using the diagram on Autocad, Soil (02).

Variant 03 :

We Input the following data from Excel Table (See Figure IV-19).

Program receive the necessary data to make calculation

a) The coordinates (x;y) geometric dimension for Lower limit and for The surface of our slope and finally (x; y) of the center of slip failure, and the value of Radius R1.

Soil 3	*1,00/1,30*
Lower Limit	
x (m)	y (m)
0	0
100	0

Surface	
x (m)	y (m)
0	12
30	12
60	35
100	35

R2 = 50	
x (m)	y (m)
60	70
Number of slices	
N	100

Figure IV-19: Geometric characteristics of soil (03).

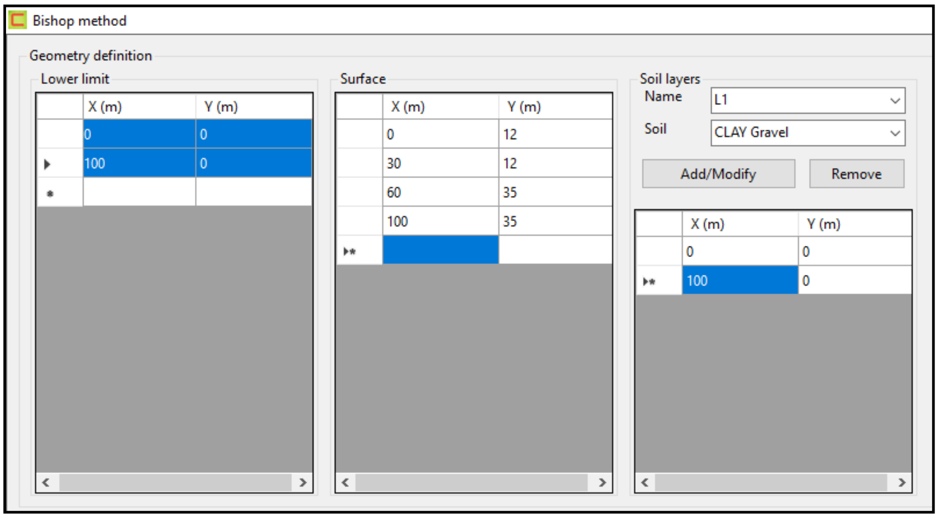


Figure IV-20: Geometric characteristics already included of soil (03).

a) Insert the geotechnical characteristics of the soil, starting with their naming and then the following characteristics (ϕ /γ_{soil}/c) and trial factor of safety (F1=1, F2=2, F3=3). (cf Figure IV.20 and IV-21).

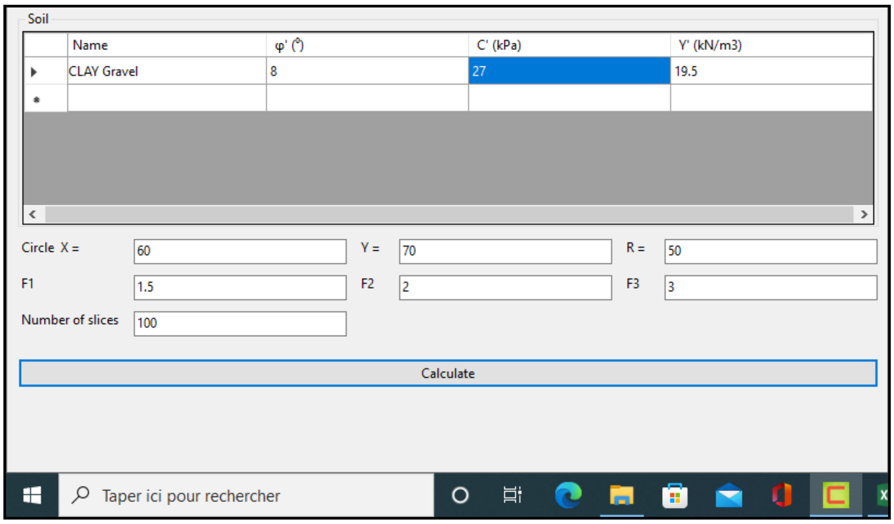


Figure IV-21: Geotechnical characteristics already included and the trial factor of safety Soil (03).

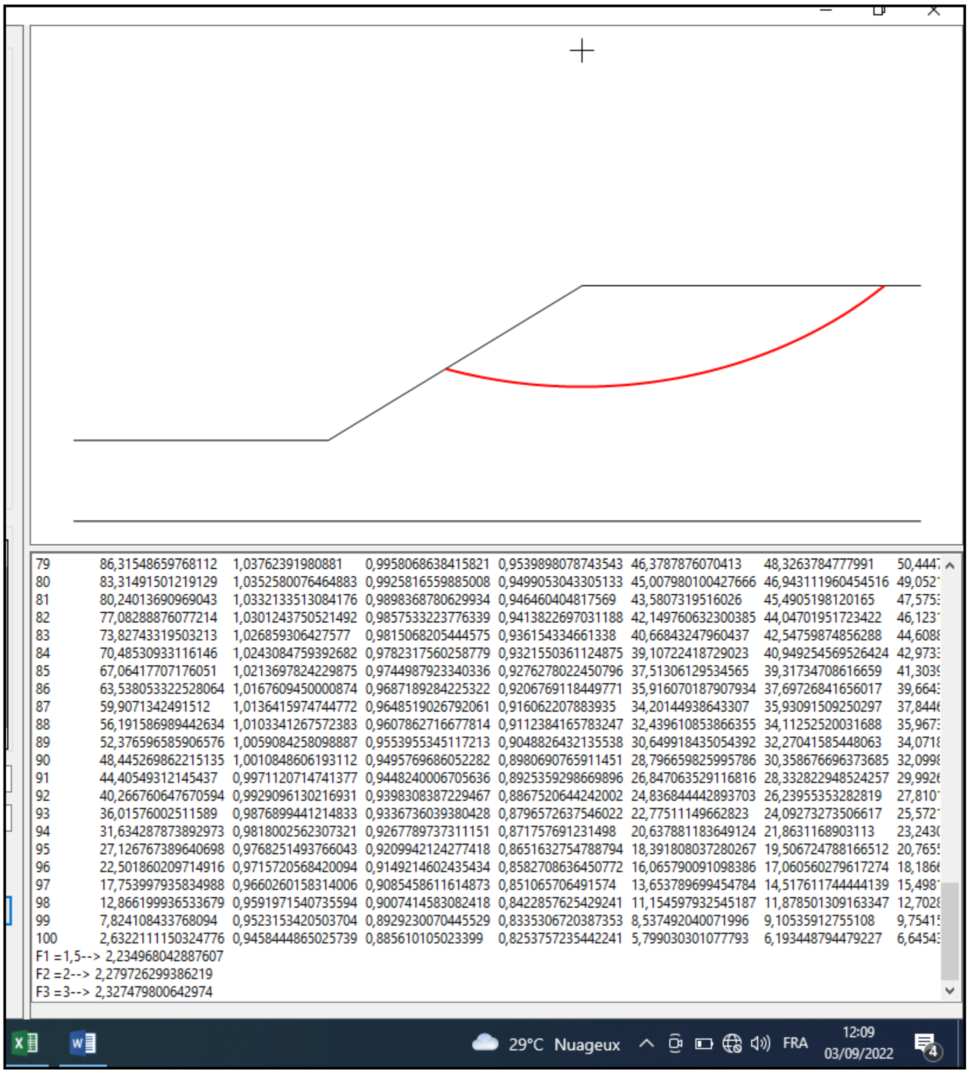


Figure IV-22: Results of the calculation, the cross section of our slope as well as the values of the calculated safety factor, Soil (03).

So, we obtain three points: P1 (Trial F1; Computed Fc1), P2 (Trial F2; Computed Fc2), P3(Trial F3; Computed Fc3), (cf Figure IV.22), after all that it's time to calculate the safety factor using a diagram drawn on Autocad, (see the figure IV-23 after); just it is enough to draw the curve which passes through the three points (P1,P2,P3) the point of intersection between this curve and the line of the diagonal it is the value of the safety factor.

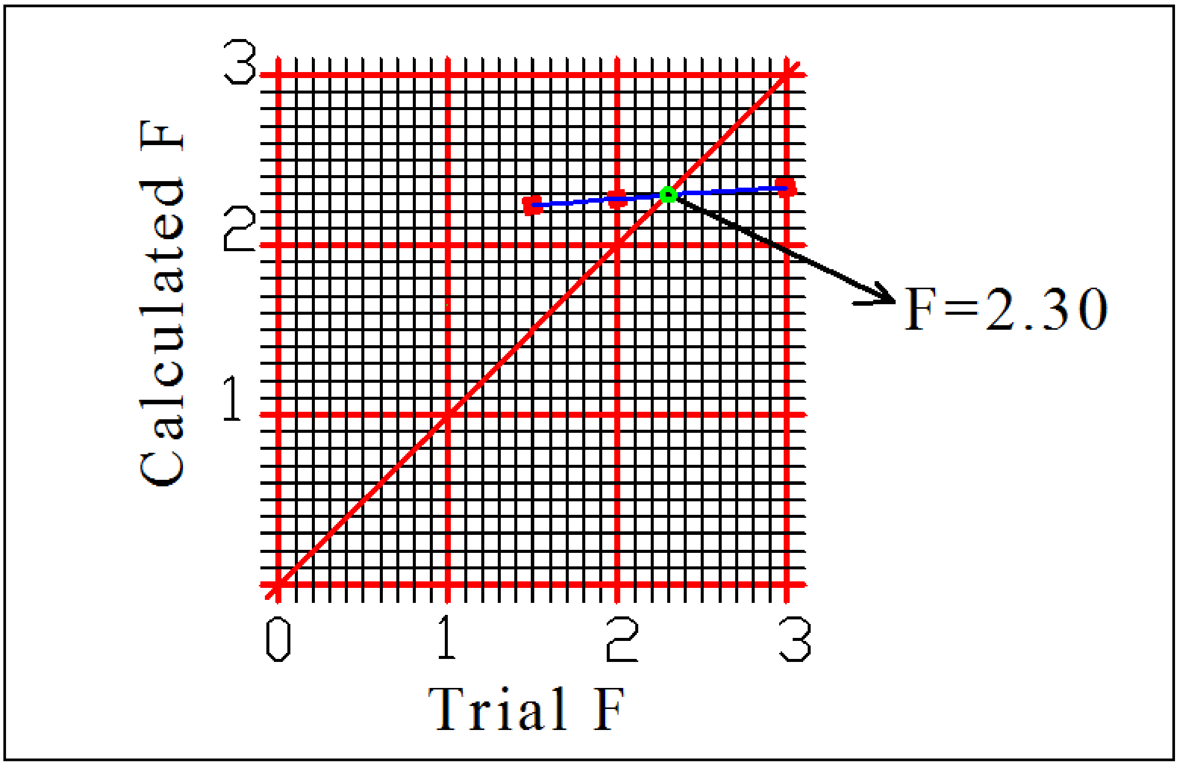


Figure IV-23: Calculation of the factor of safety using the diagram on Autocad, Soil (03).

Conclusion :

- Software can be defined as the instructions, which provide functional of the program that requires performing a specific type of data processing in a professional manner to accomplish a task, the number size and application domains of computer programs have grown dramatically. As a result, hundred billion are being spent on software development and the live hood and live of most people depends on the effectiveness of this development.
- in this chapter we used our program to calculate the safety factor for soils of different geotechnical (marl, clay, etc.) and physical characteristics (firm or altered or hard soil), we found the following result :
  1) The use of the software facilitates the calculation in an incredible way.
  2) The efficiency of use of the software in the design of civil engineering works is shown in the precision and speed of the calculations and also in the interpretation of the results through well-illustrated diagrams of the drawings which facilitate understanding and the presentation of these results.
  3) The change in the safety factor is directly related to the geotechnical characteristics of the soil (C, γ_h, ϕ), and also with the geometric characteristics of the slope (the slope, the height, the width of the upper slope).

General Conclusion

- ❖ A landslide is defined as the movement of a rock mass, debris, or earth down a slope. Landslides are a type of "mass wasting," which denotes any down-slope movement of soil and rock under the direct influence of gravity.
- ❖ Stability can depend on a number of complex variables, which can be placed into four general categories as follows:

a) Topography — in terms of slope inclination and height.
b) Geology — in terms of material structure and strength.
c) Weather — in terms of seepage forces and run-off quantity and velocity.
d) Seismic activity — as it affects inertial and seepage forces.

- ❖ The factors to consider in a classification of landslide and their risk.
- ✓ *Prediction:* Some failures can be predicted, others cannot, although most hazardous conditions are recognizable.

1) *Occurrence:* Some forms occur without warning; many other forms give warning, most commonly in the form of early surface cracks.
2) *Movement velocities:* Some moves slowly, others progressively or retrogressively, others at great velocities.
3) *Movement distances:* Some move short distances; others can move for many miles.
4) *Movement volume:* Some involve small blocks; others involve temendous volumes.
5) *Failure forms:* Some geologic formations have characteristic failure forms; others can fail in a variety of forms, often complex.
6) *Mathematical* analysis: Some conditions can be analyzed mathematically, many cannot.
7) *Treatments:* Some conditions cannot be treated to make them stable; they should be avoided.

- ❖ The conventional limit equilibrium methods of slope stability analysis used in geotechnical practice investigate the equilibrium of a soil mass tending to move down slope under the influence of gravity. A comparison is made between forces, moments, or stresses tending to cause instability of the mass, and those that resist instability. Two-dimensional (2-D) sections are analyzed and plane strain conditions are assumed. These methods assume that the shear strengths of the materials along the potential failure surface are governed by linear (Mohr-Coulomb) or nonlinear relationships between shear strength and the normal stress on the failure surface.

(1) A free body of the soil mass bounded below by an assumed or known surface of sliding (potential slip surface), and above by the surface of the slope.

(2) The requirements for static equilibrium of the soil mass are used to compute a factor of safety with respect to shear strength.

(3) The factor of safety is defined as the ratio of the available shear resistance (the capacity) to that required for equilibrium (the demand). Limit equilibrium analyses assume the factor of safety is the same along the entire slip surface.

(4) A value of factor of safety greater than 1.0 indicates that capacity exceeds demand and that the slope will be stable with respect to sliding along the assumed particular slip surface analyzed. A value of factor of safety less than 1.0 indicates that the slope will be unstable.

(5) The most common methods for limit equilibrium analyses are methods of slices. In these methods, the soil mass above the assumed slip surface is divided into vertical slices for purposes of convenience in analysis. Several different methods of slices have been developed. These methods may result in different values of factor of safety because: (a) the various methods employ different assumptions to make the problem statically determinate, and (b) some of the methods do not satisfy all conditions of equilibrium.

(6) Most procedures assume a two-dimensional (2D) cross section and plane strain conditions for analysis. Successive assumptions are made regarding the potential slip surface until the most critical surface (lowest factor of safety) is found.

(7) If the shear resistance of the soil along the slip surface exceeds that necessary to provide equilibrium, the mass is stable. If the shear resistance is insufficient, the mass is unstable.

❖ Stability analysis of slopes by mathematical procedures is applicable only to the evaluation of failure by sliding along some definable surface. Like: Rotational or Planar slide, Block slide, Lateral spreading, Debris slide.

The Basic principles of Bishop Method are:

- Circular.
- Iterative resolution on the moment equation.
- Widely used method, easy generation of circles of rupture.
- The moving ground is cut into vertical slices (at least 25)
- Friction is defined by Coulomb's law.
- The driving forces are those of gravity.
- The failure surface is the key to interpretation and understanding of phenomenon.
- The equations are based on the balance of a block placed on an inclined plane

❖ After using this simple program to calculate the safety factor for soils of different geotechnical (marl, clay, etc.) and physical characteristics (firm or altered or hard soil), we found the following results:

1) The use of the software facilitates the calculation in an incredible way for example we can do hundreds of iterative calculation operations in a few minutes (2min). Otherwise if we do this manual calculation it will take more than 1 day.
2) The efficiency of use of the software in the design of civil engineering works is shown in the precision and speed of the calculations and also in the interpretation of the results through well-illustrated diagrams of the drawings which facilitate understanding and the presentation of these results.
3) The change in the safety factor is directly related to the geotechnical characteristics of the soil (C, γh, φ), and also with the geometric characteristics of the slope (the slope, the height, the width of the upper slope).
4) The three values of safety factor greater than 1.0 so, the three slopes will be stable.
5) It is very clear that hard soil is very stable compared with firm soil, that why soil 2 (sandstone strongly altered, F=2.87), is more stable than the soil 3(Clay Gravel, F=2.30), and the soil 3 is more stable than the soil 1(Few-plastic clay, F=1.75).
6) The total stress friction angle φ it has a great influence on the soil stability, more the value is very important, more the soil is stable Soil 2 (φ =28), is more stable than the soil 3(φ =27), and the soil 3 is more stable than the soil 1(φ =20).

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