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SLOPE STABILITY WITH A CASE STUDY AND ITS SOLUTION

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Dedication

With great pleasure I dedicate this humble work to those who mean more than life to me...my dear parents and my two brothers' Suhaib and Hammam.

To my best friend Safwan and my long path best friends Yazan, Aboud, Mohammed Swaitat, Moath, Wael, Amin, Mehdelli, Muntaser, Hassan, Humam...all my friends and family.

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List of symbols

1. Greek letters

Symbol	Definition
β	Angle of the slope
ϕ'	Soil effective friction angle
γ_d	Unit weight of dry soil
γ_{sat}	Unit weight of saturated soil
γ_w	Unit weight of water
α_i	Inclination of the segment of the slip surface

2. Latin letters

Symbol	Definition
F or Fos	Factor of safety
T_r	Shear force
W_i	Weight of the slice
N	Normal force
C'	Mobilized cohesion
d_d	Height of dry soil
d_w	Height of water table
b	Width of the slice
U	Pore water pressure
H_i	Horizontal interslice force
V_i	Vertical interslice force
f₀	Janbu correction factor
K	Factor of acceleration during earthquake

3. List of acronyms

U.S.G.S : United States Geological Survey

L.T.P.O :Laboratoire des travaux publics de l'Ouest

RN : Route national

Abstract:

The present work discusses the term of slope stability which is a great field of geotechnical engineering and a serious geological hazard around the world. Globally, slope failures and landslides cause billions of dollars in property damage and thousands of human fatalities and injuries annually. In Algerian north coast numerous landslides have been reported during the past four decades. It is therefore imperative that the slope problems need to be addressed urgently. The required solutions need to be comprehensive. An increased adoption of software applications helped engineers to easily analyze and understand slopes in order to obtain the proper treatment with respect to many standards. This work focuses on slope analyses by a program called **Slope/W** to deal with a terrain problem that takes a place on **El Amir Abdelkader** village, and also proposes a solution that have been designed by the software **Geo 5**.

Keywords: Slope failure, Landslide, Slip surface, Investigation, Factor of safety, Reinforcement, Mitigation, Slope analyses, Design.

Résumé:

Le présent travail traite le terme de stabilité des talus qui est un grand domaine de l'ingénierie géotechnique et un risque géologique dans le monde entier. Les échecs et les glissements de terrain de pente aux niveaux mondiaux causent des milliards de dollars en dommages à la propriété et des milliers de pertes humaines et des blessures annuellement. En côte nord algérien, nombreux glissements de terrain ont été signalés au cours des quatre dernières décennies. Il est donc impératif que les problèmes de pente doivent être abordés de toute urgence. Les solutions nécessaires doivent être complètes. Une adoption des applications logicielles aidé les ingénieurs d'analyser et de comprendre facilement les pentes afin d'obtenir le traitement approprié par rapport à de nombreuses normes. Ce travail se concentre sur des analyses pente par un programme appelé **Slope / W** pour faire face à un problème de terrain qui prend une place sur la commune d'**El Amir Abdelkader**, et aussi proposés une solution qui ont été conçus par le logiciel **Geo 5**.

Mots clés: La rupture de pente, Glissement de terrain, La surface de glissement, Investigation, Facteur de sécurité, Renforcement, Confortement, Modélisation des talus, Dimensionnement.

ملخص تجريدي:

هذا العمل يتناول موضوع انزلاقات التربة في المنحدرات الجبلية والذي يعتبر مجالا واسعا في الهندسة الجيوتقنية وخطرا جيولوجيا حقيقيا حول العالم. ان انزلاقات التربة تكبد الأنسان خسائر تقدر بمليارات الدولارات سنويا فضلا عن الخسائر البشرية بين قتلى وجرحى . في الشمال الجزائري تم التبليغ عن عدد من حالات انزلاق التربة في الأربعين عاما الماضية, وبناء على ذلك فإنه من الضروري التبليغ حلا عن أي مشكلة في حال وقوعها. والحلول المتطلبة لمشاكل انزلاق التربة يجب أن تكون شاملة. في الاونة الأخيرة أصبح هناك اهتمام متزايد ببرامج الحاسوب الهندسية التي تساعد المهندسين في تحليل وضع التربة بسرعة وسهولة للتوصل لحل مناسب لمشاكل انزلاق التربة اخذين بعين الاعتبار عدة من المعايير المرتبطة بذلك. هذا العمل يركز على حسابات المنحدرات الجبلية باستخدام برامج حاسوب مخصصة لهذا الغرض لكي يتم التعامل مع المشكلة الكائنة في بلدية الأمير عبد القادر وايجاد حل مناسب لهذه المشكلة.

الكلمات المفتاحية: حركة المنحدرات، انزلاق التربة، سطح الأنزلاق، التحري، معامل السلامة، التقوية، الحماية، حسابات المنحدرات، التصميم.

General introduction

“There are landslides we fix and there are those we name.” The unlimited relation between man and nature, and the growing population imposes many kinds of risks on the human life. Slope instability, also commonly referred to in the plural as slope failures or landslides, is a serious geologic hazard common to many regions of the world. Globally, landslides cause billions of dollars in property damage fatalities, and injuries running into the thousands each year. As civil engineering is always in development which makes it easier to confront these hazards and create several techniques and methods to deal with slope failures.

The general environment of the north Algerian coast has its share of diversity in climate, types of terrains, geographic and geological properties, and seismic profiles, and the routine road cuts and new constructions runs many kinds of risks and natural hazards, including slope failures.

The aim of this project is to deal with a failure prone terrain that takes a place in the town of **El Amir Abdelkader**, in the Wilaya of **Ain Temouchent**. This terrain consists of three separated slopes that have been a subject of many studies, and many solutions were suggested to solve the problem that they represent, and in this project I managed to analyze each slope and to propose a suitable solution for the unstable slopes. The programs used in this project are **slope/w** application from (**Geostudio 2007**) collection to calculate the stability of the slopes, and (**Geo 5**) software to design the solutions.

The present document contains the following four chapters:

Chapter I: this chapter defines slope instability, shows the classification of failure types, causes of slope failures and effects that follow them, it also presents an idea about the factor of safety.

Chapter II: this chapter aims to show the ways and the tools used in landslide investigation, the chapter also presents an explanation about the manual methods of slope analysis, and explains the software program that's been used in this projects investigation.

Chapter III: this chapter introduces and explains the different methods of slope stabilization and failure mitigation systems, the description and characteristics of each method, and how to choose a suitable method.

Chapter IV: this is the last chapter of the project, it manages to do the analyses of the previously mentioned slopes and to propose suitable solution.

The project is finished with a general conclusion that collects the basic ideas of this document.

Chapter I:
Types of mass wasting

1. Introduction

Mass wasting or mass movement occur throughout the world under all climate conditions and in all types of terrains, and that's when the natural slope can't support its own weight, the primary regions of mass wasting occurrence and potential are the costal, mountainous, and hilly areas. Worldwide, mass wasting or slope failures occur and cause thousands of casualties and deaths, and billions of monetary losses annually.

This chapter provides an introduction on understanding the scientific facts about slope failures, there sorts, a description of how they are managed to be initiated, and basic information about the direct causes that can lead these slope failures to become a hazard.

Mass wasting or slope failure is defined as the geomorphic process by which a certain sort of soil can move downwards the slope as a mass, driven by the force of gravity, but frequently affected by specific triggering factors such as rain water, earthquake...etc., there is many characteristic features that define the type of mass movement and each type takes a place over timescales from seconds to years.

2. Types of mass wasting

The proper classification of mass wasting types can be achieved by understanding the way that the mass moves downward the slope, its speed, and the nature of mass components (rocks, soil, debris), after this we can classify mass movements as the following:

2.1. Fall (Collapse)

The terrain movement can be referred to as a fall when mass of rocks or soils (or both) is separated from a steep slope, ending up with an extremely rapid falling down the slope along a surface with no shear displacement, and due to the different angles of the slopes surface, the falling materials usually start a bouncing and rolling movement.

Falls are characterized by the existence of steep or vertical cliff edges and mountains, also coastal areas and rocky banks of rivers as a result of erosion caused by water, and can be unleashed by earthquakes, heavy rain, ice melting...etc., the copulation of rock which settled down the slope after a rockslide is known as talus.

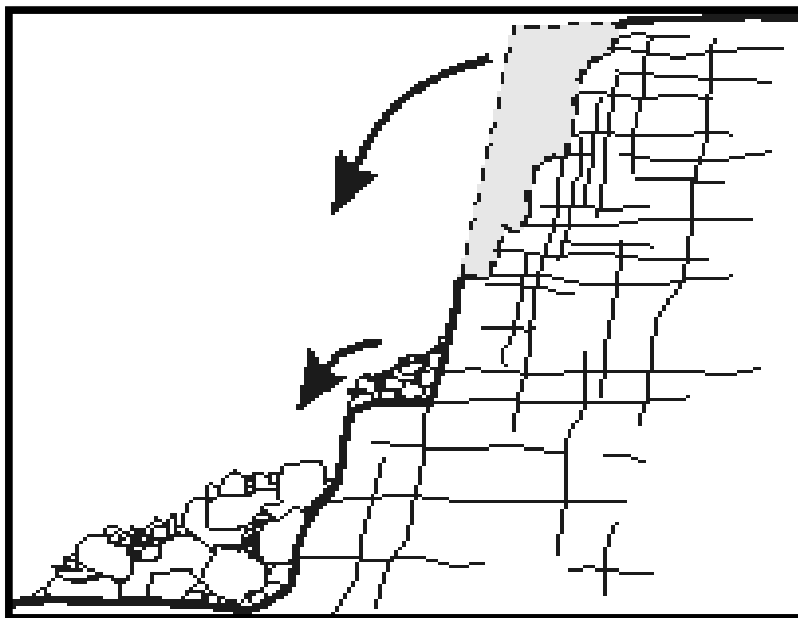


Figure 1.1: Rock fall illustration. (<http://pixgood.com/rockfall-diagram.html>)

Rock falls are the most dangerous and life threatening type of mass wasting, as a result of the high speed messy movement of rocks and the nature of the materials involved in this sort of slope failure, which can destroy the properties underneath the fall line, damage and block the roads and cause life losses by hitting vehicles.

Rock curtains and protective covers such as nets and rock bolts are commonly ways of mitigation used to stabilize cliffs and slopes in case of a potential rock fall, also explosive blasting of hazardous areas to remove the source can be effective to reduce the risks of disastrous rock falls.



Figure1.2: Mitigation by nets.

(http://www.wsl.ch/fe/gebirgshydrologie/massenbewegungen/projekte/KTI_Galleries/index_EN)

2.2. Slumps

A slump is a form of mass wasting that happen when rock and soil materials drop down or slip along a curved surface in closed location, and usually takes the shape of a spoon, also forms a sickle moon shaped cliffs, and the following figures show the shapes of slumps

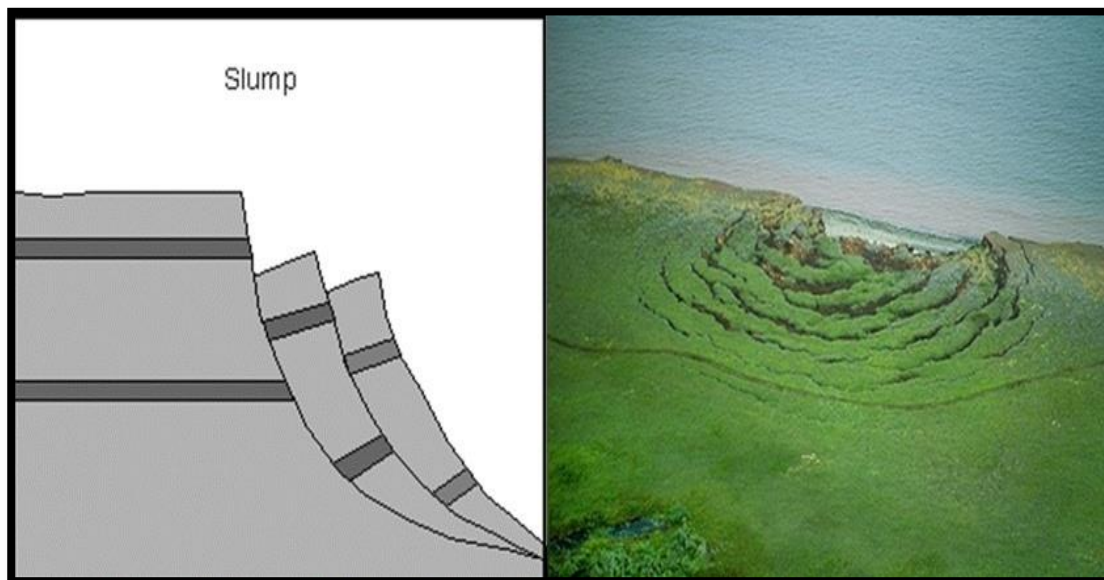


Figure (edited) 1.3: Slump. (<http://www.airphotona.com/image.asp?imageid=78>)

Slumps are characterized by the blocks sliding along planner surface and often undisturbed at the tops of the detached mass parts, the movement is rotational in most cases but it can be transitional in some cases, however in addition of water and loss of cohesion at the toe may transform slumping material into an earthflow, the velocity varies from meters per second to meters per year.

Slumps often occur due to removal of a slope base, from natural or manmade processes, such as wave erosion, excavation and road works, the detachment of the slope's physical support leads to this kind of mass wasting, also water is a common cause, which explains why slumps are usually associated with heavy rainfall, rain lubricates the material making it easily sliding, and increases the self-weight of the material, earthquakes also trigger massive slumps.

Mitigation can be achieved by creating the suitable retaining structures, and mechanical anchoring methods.

2.3. Flows

Flows are characterized by the fluid behavior movement of unconsolidated soil materials, this includes (mudflow or mudslide, debris flow, earth flow), this type of mass wasting is often thin and shallow, and water and air are the essential elements that can be involved in flow failures.

Flows often occur when the pore pressures in a low cohesion mass increase until the weight of the material can't support the pressure in addition to its weight, the pore pressure also decrease the internal shearing strength of the material, as the internal mass gets saturated it loses cohesion which leads it to move in a fluid motion with a speed over 55 km per hour depending on the slopes angle.

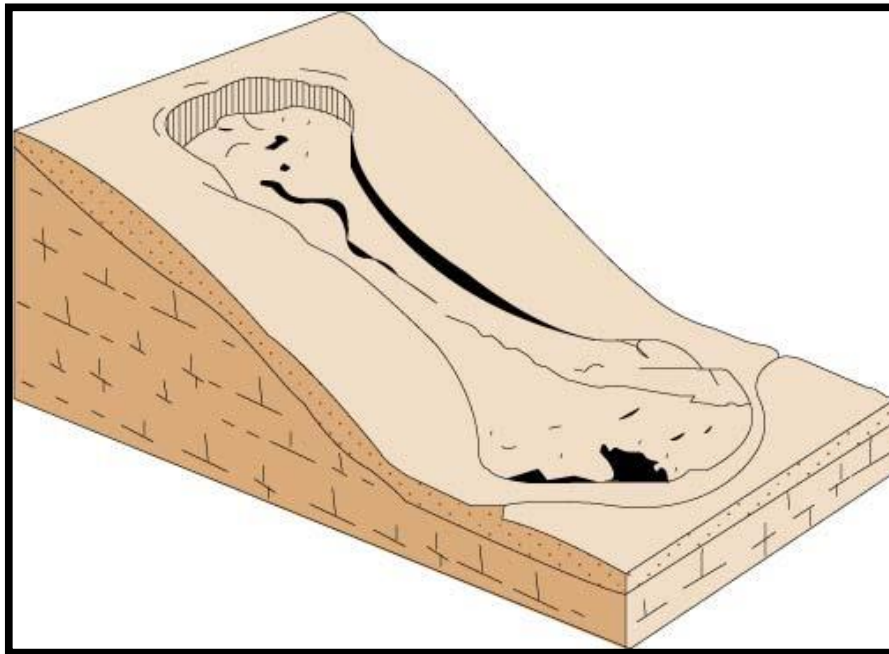


Figure 1.4: Flow. (<http://www.bgs.ac.uk/discoveringGeology/hazards/landslides/flows.html>)

Earth flows are much more potential during high precipitation periods, and that's all worldwide especially in canyons and valleys which have been denuded from vegetation, flows are mostly predicted to occur in the areas with weak soils generally, and they may contain silt, clay, mud, debris, and regolith. This kind of slope failure is very dangerous due to its speed and sudden occurrence without any warnings.

2.4. Creep

This sort of slope failure is described as a long term process when gravity drives an assemblage of little and slow movements of soil or rock down the slope, the steeper the slope, the greater and faster the creep, the speed of creep is usually measured from 1 to 10 mm per year, this slow movement is impossible to see by the naked eye, but can be noticed by the curved trees and fences.

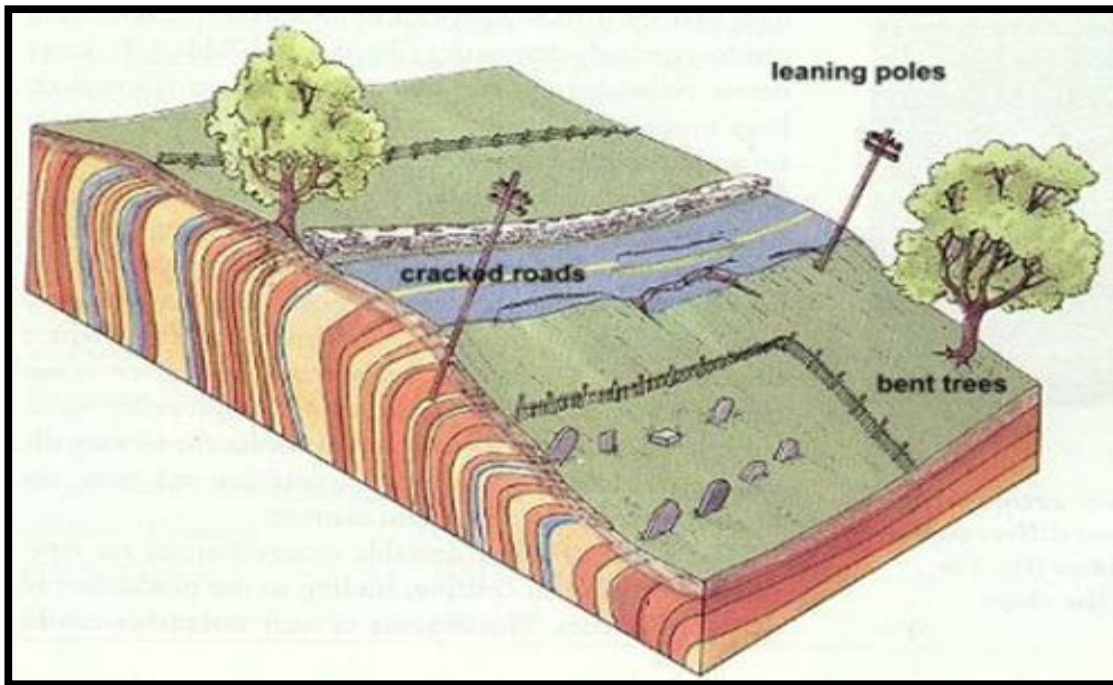


Figure 1.5: Creep. (<http://earthsci.org/flooding/unit3/u3-03-03.html>)

The main causes of creep are the cycles of freezing and thawing, and hot and cold temperatures, also bad drainage and leaking pipelines can lead to this type of slope failure, and gravity is always the main factor that leads earth materials to settle farther and farther than their original place.

Creep is the most common type of slope failure, and it varies in its ranges from small areas to the width of tens of square kilometers, creep affects structures and infrastructures since it's hard to detect and difficult to figure out its boundaries, it can pull apart pipelines, highways, and buildings in a long term process, it can also trigger other types of faster and more destructive failures.

The most common mitigation methods that used in case of a creep process are suitable and proper water drainage, retaining walls, removing or flattening the endangered area or parts of it.

2.5. Topple

A topple is recognized as the forward rotation out of a slope of a mass of soil 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). Topples can be complex and composite.

The topple known to occur globally, often prevalent in columnar-jointed volcanic terrain, as well as along stream and river courses where the banks are steep.

Velocities of traveling between extremely slow to extremely rapid, sometimes accelerating throughout the movement depending on distance of travel.

It's caused 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. It can be extremely destructive, especially when failure is sudden and the velocity is rapid.

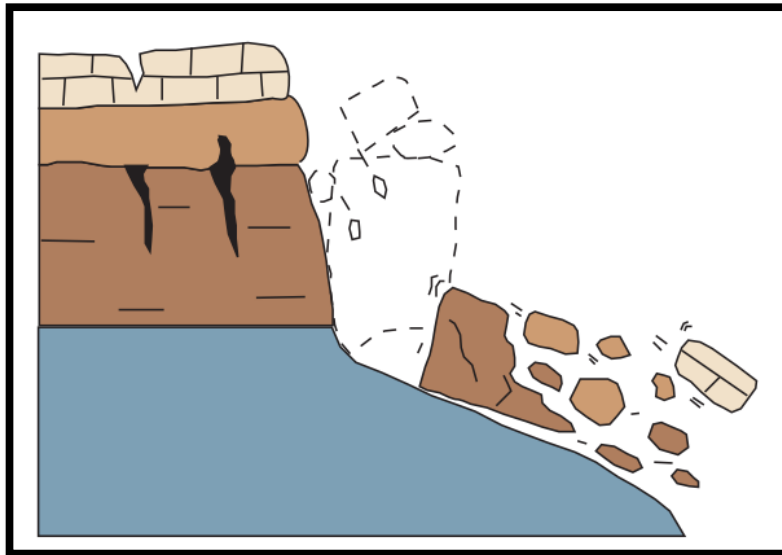


Figure 1.6: Topple.

It's 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 tilt meters. Tilt meters are used to record changes in slope inclination near cracks and areas of greatest vertical movements. Warning systems based on movement measured by tilt meters could be effective.

2.6. Landslide

Also called slip soil or landslip, it's the movement of huge quantities of earth along a surface of rupture down a hill or a slope, heavy rain storms can lubricate the soil and rocks and get it ready to slip and move rapidly under specific circumstances, other triggering factors, such as earthquakes and cutting slopes can also cause this form of mass movement.

With or without flowage, zones with potential landslips are always endangered and threatened to undergo fast and catastrophic movement, and from this point come the importance of landslide investigations.

Parts of a Landslide

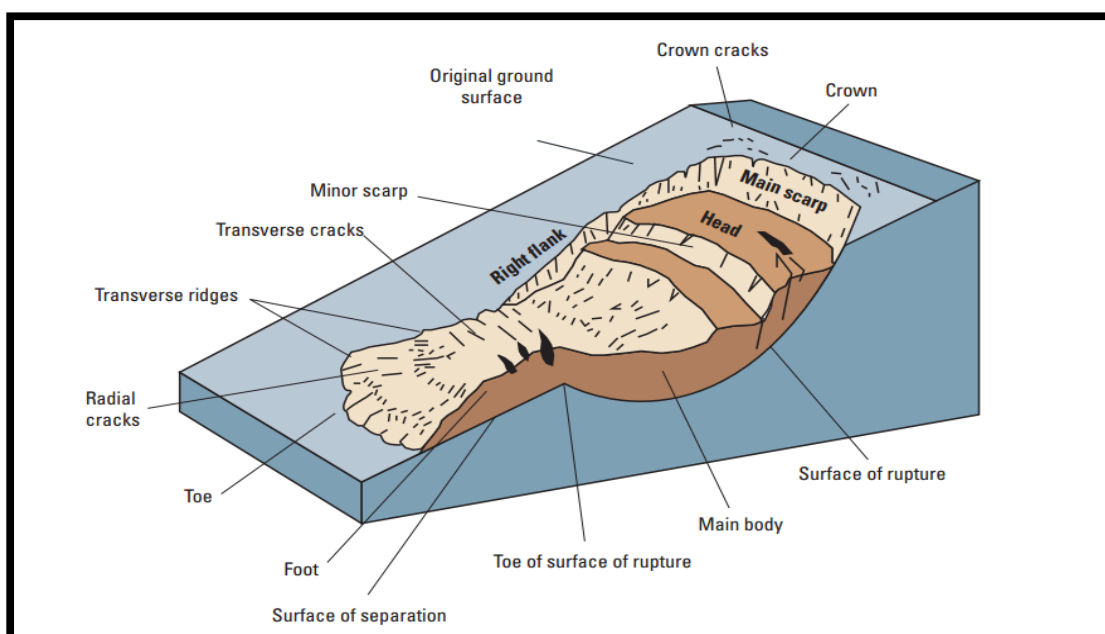


Figure 1.7: Parts of a landslide.

- Accumulation: The volume of the displaced material, which lies above the original ground surface.
- Crown: the practically undisplaced material still in place and adjacent to the highest parts of the main scarp.
- Depletion: The volume bounded by the main scarp, the depleted mass and the original ground surface.
- Depleted mass: the volume of the displaced material, which overlies the rupture surface but underlies the original ground surface.
- Displaced material: Material displaced from its original position on the slope by movement in the landslide. It forms both the depleted mass and the accumulation.
- Flank: The undisplaced material adjacent to the sides of the rupture surface. Compass directions are preferable in describing the flanks, but if left and right are used, they refer to the flanks as viewed from the crown.
- Foot: The portion of the landslide that has moved beyond the toe of the surface of rupture and overlies the original ground surface.
- Head: The upper parts of the landslide along the contact between the displaced material and the main scarp.
- Main body: The part of the displaced material of the landslide that overlies the surface of rupture between the main scarp and the toe of the surface of rupture.
- Main scarp: a steep surface on the undisturbed ground at the upper edge of the landslide, caused by movement of the displaced material away from the undisturbed ground. It is the visible part of the surface of rupture.
- Minor scarp: A steep surface on the displaced material of the landslide produced by differential movements within the displaced material.
- Original ground surface: The surface of the slope that existed before the landslide took place.
- Surface of separation: The part of the original ground surface overlain by the foot of the landslide.
- Surface of rupture: The surface that forms the lower boundary of the displaced material below the original ground surface.
- Tip: The point of the toe farthest from the top of the landslide.
- Toe: The lower usually curved margin of the displaced material of a landslide, it is the most distant from the main scarp.
- Top: The highest point of contact between the displaced material and the main scarp.
- Toe of surface of rupture: The intersection (usually buried) between the lower part of the surface of rupture of a landslide and the original ground surface.
- Zone of accumulation: The area of the landslide within which the displaced material lies above the original ground surface.
- Zone of depletion: The area of the landslide within which the displaced material lies below the original ground surface.

Landslides are generally classified into two large categories which are:

Shallow landslide

Or transitional landslide, and that's when a thin layer of soil and debris moves down and outward along a relatively planar surface down the slope and with backward tilting in some cases, with depth to length ratio less than 0.1. (See the figure)

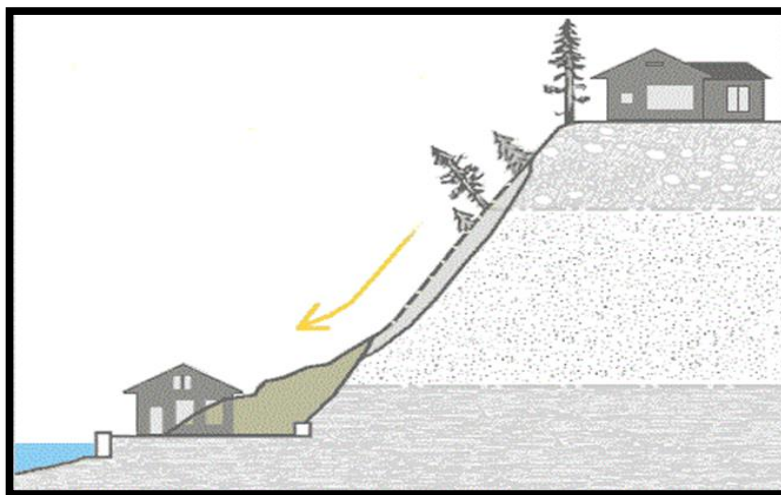


Figure 1.8: Shallow landslide. (Edited image) (<http://www.ecy.wa.gov>).

Rotational landslides

Also known as deep seated landslide, when large blocks of earth shift and slip along a curved upward surface, by the effect of specific causes like ground water, this type is often associated with slopes with an angle ranging between 20 and 40 degrees, and with surface of rupture which has a depth to length ratio between 0.1 and 0.3. (See the figure)

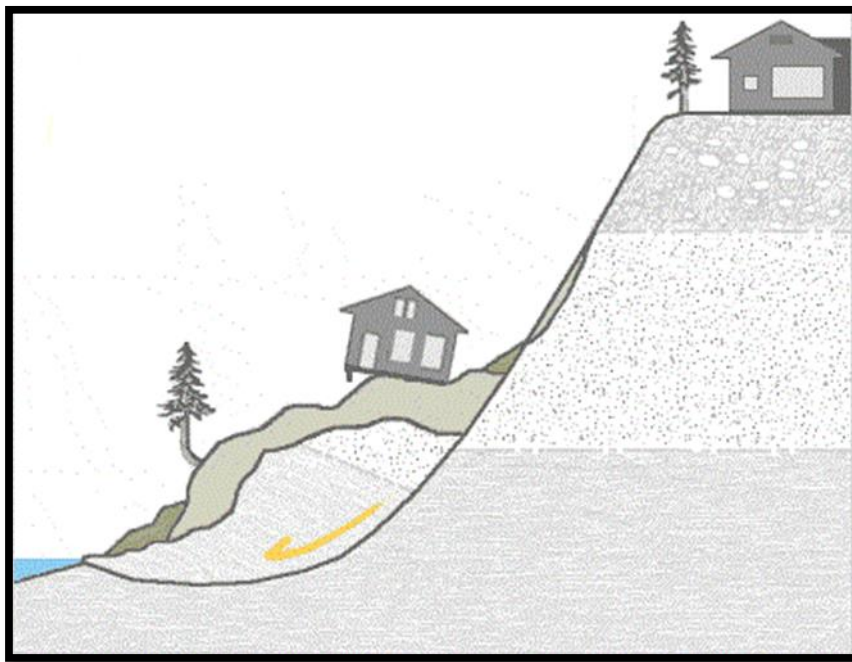


Figure 1.9: Rotational landslide. (Edited image). (<http://www.ecy.wa.gov>)

A landslide is usually a combination of these two ways of movement, which may initially be with a stable and slow velocity of travel but many landslides go with extremely rapid and catastrophic movement.

Landslides are predicted to occur in the areas where they have occurred in the past, and areas with seismic history, they can damage properties, close highways, and Dam Rivers causing floods.

Most effective methods of mitigation are the proper grading and drainage, anchors, bolts and retaining walls, however landslides are very difficult to stabilize permanently in steep slopes, therefore these methods of slope stabilizing always need to be restored and reengineered.

Table1.1: Types of mass wasting.

TYPE OF MOVEMENT		INVOLVED MATERIALS	VELOCITY
FALL		Rocks/Soil/Ice	Extremely fast
SLUMP		Earth/Bedrock	Slow – average speed
FLOW		Soil/Debris/Regolith	Fast – extremely fast
CREEP		Land/Bedrock	Extremely slow
SLIDE	transitional	Soil/Rocks	Slow – extremely fast
	rotational	Soil/Rocks	Slow – extremely fast
COMPLEX		combination of two or more forms of movement	

3. Slope stability and factor of safety

Slope stability is related to many elements which may be internal geological factors or external forces, the changes that may occur in one or more of these elements can directly affect the slope stability, which makes it very important to check the slopes factor of safety according to these elements which are shown below:

- driving force
- resisting force
- cohesion
- slope angle
- soil friction angle
- gravity

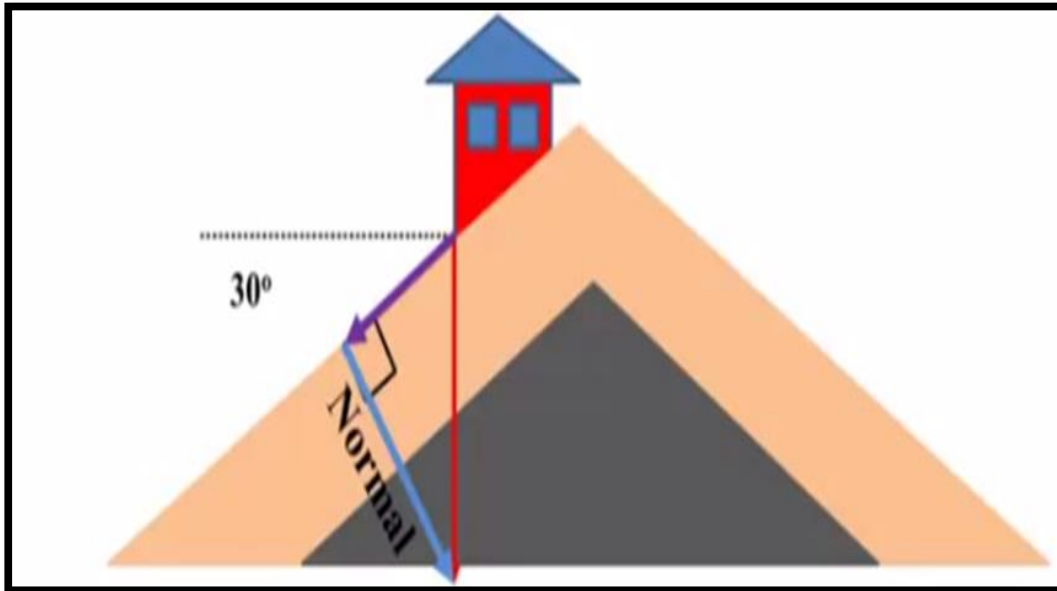


Figure 1.10: Slope acting forces. (Edited image). (<https://www.youtube.com/watch?v=xg-Gw1NrKX8>)

The main question is how stable is a particular slope? And how likely is it to become unstable? This question is to be answered by calculating the relative magnitude of the forces acting on the slope which are:

- Driving force (N/m²) = thickness (m) x density (kg/m³) x G (9, 8 N/kg) x sin (slope angle), and this is the force that promote movement in the slope.
- Resisting force (N/m²) = [thickness (m) x density (kg/m³) x G (9, 8 N/kg) x cos (slope angle)] + cohesion N/m², and this is force that resist the movement.
- In case of saturation or the existence of ground water:
Resisting force (N/m²) = {[thickness (m) x density (kg/m³) x G (9, 8 N/kg) x cos (slope angle)] + cohesion N/m²} - {density of water x saturated thickness x G}.

The factor of safety is found by calculating the resisting to driving forces ratio (factor of safety $F > 1.3$ in normal slopes, and $F > 1.5$ in cut or excavated slopes), the factor of safety is greater in the areas with seismic activities, if the found factor is 1.3 or more that means the slope is stable, otherwise the slope is more likely to undergo some kind of mass wasting.

This simple example shows the calculating evaluating of the factor of safety of a slope with these given data: Slope angle (30 degrees), Slope material thickness(3m), Density(2200 kg/m³), Soil cohesion(1100 N/m²), Saturated thickness(1m), density of water(1000 kg/m³).

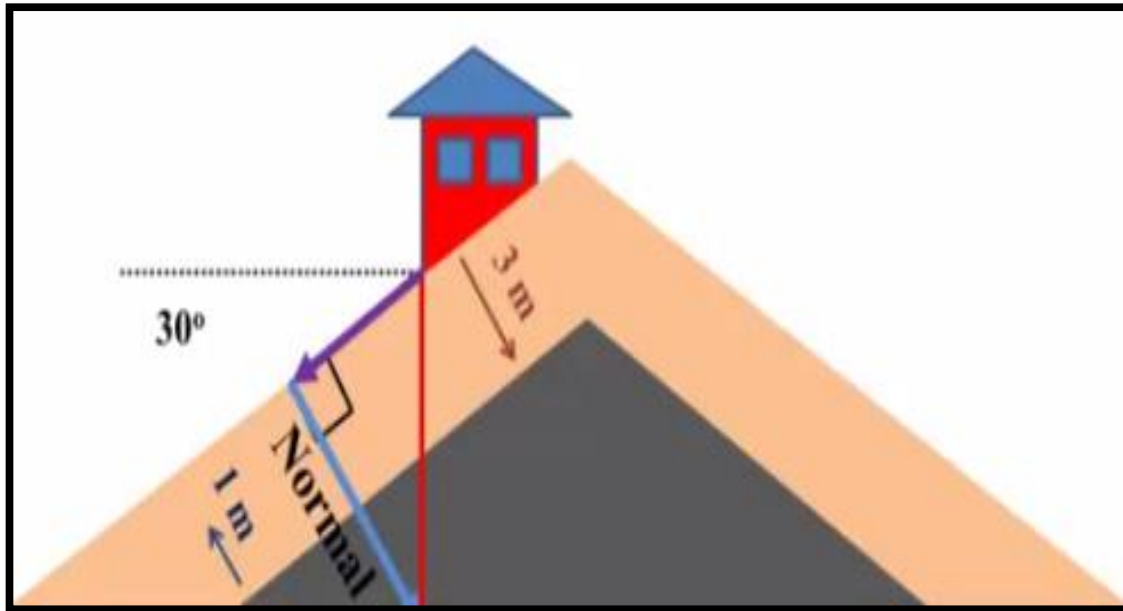


Figure 1.11: Simple slope analyses. (<https://www.youtube.com/watch?v=xg-Gw1NrkX8>)

Driving force (N/m²) = thickness (m) x density (kg/m³) x G (9, 8 N/kg) x sin (slope angle)
 Driving force = 3 x 2200 x 9, 8 x 0.5 = 32,340 N/m².

Resisting force (N/m²) = {[thickness (m) x density (kg/m³) x G (9, 8 N/kg) x cos (slope angle)] + cohesion N/m²} _
 {pore pressure}

Resisting force (N/m²) = {[3x 2200 x 9.8 x 0.866] + 1100} _ {1000 x 1 x 9.8} = 47,312.88 N/m²

F = resisting force / driving force = 47,312.88 N/m²/ 32,340 N/m²

F = 1.46

Then the slope is stable under normal circumstances.

(Note that there is plenty of more expanded method to calculate the factor of safety, and this example is meant to clarify the forces that act on the slope)

4. Slope failure causes and triggering factors

The causes of mass wasting are classified into two large categories, which are (manmade causes and natural causes), including many factors that can increase or decrease driving force, resisting force, slope angle...etc., and these factors can lead to slope failures.

4.1. Natural causes

This category contains two main mass wasting triggering mechanisms, water, seismic activities, these mechanisms depend on the slopes nature and steepness, geological profile, morphology of terrain, the nature of soil...etc.

Water

Saturation is the most common cause of slope failures, and it occurs by heavy rain storms, snowmelt, waves and river banks erosion, seepages, reservoirs, and changing of ground water levels, either one of these factors or a combination of two or more can cause saturation which lubricates the slopes materials, increases its weight, and reduces the resisting force because it exerts a pore pressure on the slope material which may cause landslides, and if the saturation was enough to transform the soils and other materials from solid to liquid state, debris flows or mudflows can occur, flows occurrence is often misunderstood and considered as flooding, in fact, slope failures and floods are closely associated, and each one of them can cause the other, on one hand, flooding can cause slope failure by undercutting slopes which affects the slopes angle of repose, and by saturation of the slopes components, on the other hand, mass wasting can also cause floods when sliding rocks and debris block rivers and channels, which allows large quantities of water to flood or

back up behind dams, mass wasting can even cause dam failures because debris and other solid materials increase the volume and density of the flow.

The next figure shows a landslide that took a place in Puerto Rico, 1985, heavy tropical rainfall caused saturation and triggered this massive landslide, destroying 120 houses and killing 129 people:



Figure 1.12: (Photograph by Randall Jibson, U.S.G.S)

Seismic Activities

All slopes and mountainous areas that experienced earthquakes in the past, are also endangered to undergo mass movement because if a stable ground shake alone under the influence of earthquakes, it won't be stable in the future, soil cohesion automatically decreases during an earthquake, it even can go to zero, which reduces the resisting force, shaking can also lubricate the soil materials in case of existence of ground water causing landslides and soil spreads, moreover, earthquake land shaking can affect the rocky structure of slopes and change its formation causing rockslides and rock falls, mass movements can occur either at the same time with earthquakes or in long term process. The following figure shows the damage of a landslide was induced by an earthquake in Japan:



Figure 1.13: (Photograph by Professor Kamai, Kyoto University, Japan)

4.2. Manmade causes

The increasing population and expanding of cities and towns by creating new buildings is a primary reason that makes human activities a major cause of slope failure. Disturbing the nature of terrains and slopes by excavation and undercutting slopes oversteeps the slopes angle which affects the stability, removing vegetation also can initiate landslides, other human activities such as irrigation, creating reservoirs, and leaking pipelines can change the drainage patterns and affect on the situation of internal materials form and induce landslides, also adding more loads on the top of slopes increases the driving force and leads it to exceed the resistance of soil. Proper engineering and identifying the site's probability of slope failures is necessary to improve the ability of construction on areas prone to landslides.

5. Effects of mass wasting

Mass movement can affect its surrounding environment either immediately in a direct way or indirectly in a long term process, it affects people, built environment, natural environment, and everything in its path.

5.1. Direct effects

Anything on a top of a slope failure or on its way will be exposed to great physical destruction (either partially or completely), the travelling material may block highways, railroads, and supply lines (electricity, water, telecommunication...etc.), it can also cause casualties_ deaths and injuries to people, property and farmland losses.

Mass movement also affects the natural environment, it can change the morphology of the earth, mountain and valley systems, forests and wildlife. As populated areas are expanding there may be an occupation of lands that might have experienced hazards in the past, and with poor or nonexistence of urbanism policies and suitable engineering, buildings can take place in a land that might better be left as green spaces, which induces landslides and such catastrophic failures.

5.2. Indirect effects:

Long term indirect results of a slope failure can be more destructive than the failure itself, the large masses of soil and debris or rocks can end up as sediments in reservoirs in front of dams causing floods or increasing the storage which might overtop the dam during heavy rain periods and increase the possibility that the dam will fail, these large masses can also form heaps which work as dams and block rivers, channels, reservoirs...etc., causing a lake behind the blockage and since these heaps aren't stable, they can collapse any moment under the influence of water that erodes them which makes sudden, large, and catastrophic floods or renewed debris flows, landslides can also change the paths of rivers and channels which affects the natural form of environment, water resources in the area, reducing the storage of tanks and reservoirs. Landslides can also lower the quality of life by death losses in families and the destruction of personal belongings which have a great sentimental value.

6. Conclusion

In this chapter we managed to define slope instability, show its classification and types, causes of slope failures and effects that follow them, it also contains a glimpse on the factor of safety. The next chapter aims to show and clarify methods of landslide investigation, in order to figure out the situation of the slope.

Chapter II:
Landslide investigation

1. Introduction

The determination of the best way of data collecting, geological and geotechnical observation of the threatened areas is very important to define the landslide, and to locate the plan of a potential failure, in this chapter we will manage to show the commonly used methods of landslide investigation.

2. Preliminary investigation

2.1. Prediction and collecting data

Landslides occur at specific locations under certain conditions. Therefore it is important to use the existing data and study the archival materials (history of the problem, records of restoration work, and data review) in order to understand the topography, geology, and properties of similar landslides. It is also important to understand the, period of activity, and notice the existence of any warning signs such as cracks, seepages, tilted trees search ground water conditions, seismic profile...etc., Figure 2.1 shows some signs of potential failure.



Figure 2.1: Warning signs (Photographs courtesy of Utah Geological Survey)

2.2. Topographic Investigation

It is necessary to identify any changes in the site topography. That can be accomplished by recognizing the overall topographic feature of the site understanding the topographic characteristics of the sites slopes, and estimating the regional geologic structure of the site. Such methods include comparing the aerial photographs of the site, studying levels of the threatened site helps to recognize the changes of its form.

2.3. Field preliminary Investigation

a detailed field investigation plan can be developed to delineate the aerial range and the general direction of movement of the landslide zone, assess the geology and geologic structure, estimate the causes of the sliding, it's important to do a proper field preliminary investigation done by local experts including a general observation of the site (is it near to any pipelines?, reservoirs?, seismic or volcanic active area?...etc.).

3. Preparing for an expanded investigation

A detailed investigation should be planned by geologic and topographic observation of the area which can be achieved by the following steps:

- Aerial photography of the range of the landslide, and it's ways of movement
- Location and shape of threatened areas
- Nature of landslide materials
- searching of ground water

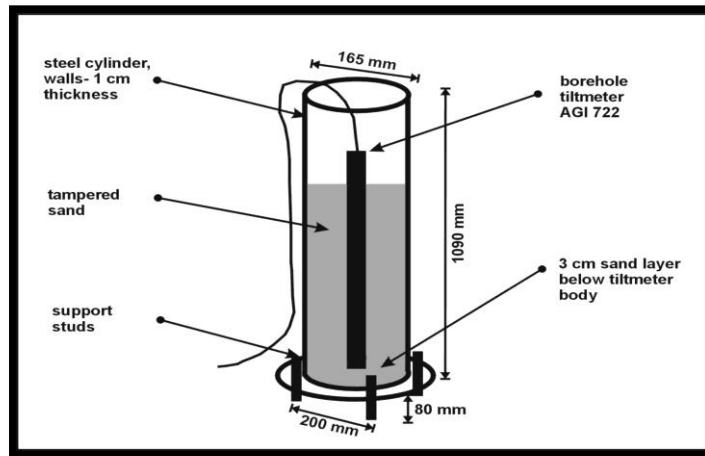


Figure 2.4: Tiltmeter. (<http://www2.geo.uni-bonn.de>)

Simple method of wooden stakes

Maybe the oldest method to understand landslide movement is to drive wooden stakes across cracks along the direction movement. Then attaching them with horizontal boards, and cut through the boards to measure the space between the parts of boards.

GPS and aerial photographs survey

Photographs and global Positioning System is a modern technology that uses aerial photos and signals from satellites to determine a specific three-dimensional positioning of the slide.

4.2. Investigation of geologic structure

At most sites, understanding the geologic structure depends on boring and drilling systems in the first place, and secondly a proper geophysical survey is important to explore the geology of the site.

Borings

borings and drilling are essential to find out the sorts of materials involved in the slide, the depth of the surface of rupture, the thickness and geometry of the landslide mass, the ground water levels, and the degree of disruption of the landslide materials. It also important for taking samples for age dating and testing the properties materials. Finally, drilling is needed for installation of some monitoring instruments and hydrologic observation wells. It's also used for sites that have never had failures but for which the possibility exists.

Geophysical survey

geophysical survey includes seismic surveys which done mostly by using P-wave refraction surveys, electric survey is a specific resistance method (measurement of soil's electrical conductivity and resistivity) and used to understand the distribution of aquifers and to find out the geologic structure, and radioactivity is used to describe the small fracture zones and cracks. Geophysical survey helps to determine subsurface characteristics like the depth to bedrock, stratigraphic layers, saturated zones, and the ground-water table. It can also be used to determine texture, porosity, and degree of consolidation of subsurface materials and the geometry of the units involved.

4.3. Evaluating of slide map/chart

Mapping is commonly done by selecting the appropriate instruments and devices and using them to create a specific plane of the slide itself, this plane aims to show the details of the slide and the distribution of initial, active, and accelerated parts of the slide, the most common instruments used are:

Pipe strain gauge

P.V.C. pipes with strain scales are installed into boreholes to measure the movement by the observing the changes in the strain when the pipe bends, the last two gauges must be anchored into the bedrock underneath the slide, the space between gauges must not be more than one meter, and the circular space between the pipe and the borehole should be filled with concrete, the measurement is more accurate when the spaces between gauges are narrower.

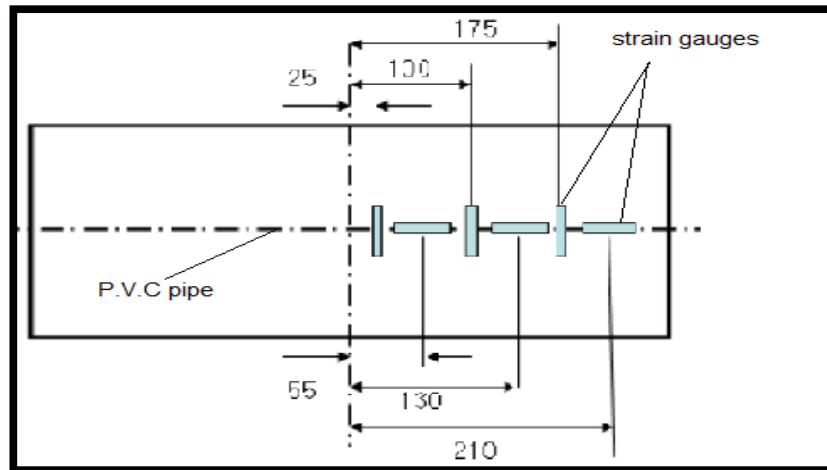


Figure 2.5: Pipe strain gauges. Edited image. (<http://www.mdpi.com/>)

Inclinometer

A grooved casing is inserted into the borehole and anchored into the bedrock, and insulated from the borehole by grout or plaster to guarantee a positive contact with the borehole. Inclinometer is provided with tilt sensor to determine the deformation and movement in the slope. The measurement is more accurate when the deformation is small. When the movement increases the borehole will lean and make the insertion of sensors difficult, or reach the limit of tilt direction of the device.

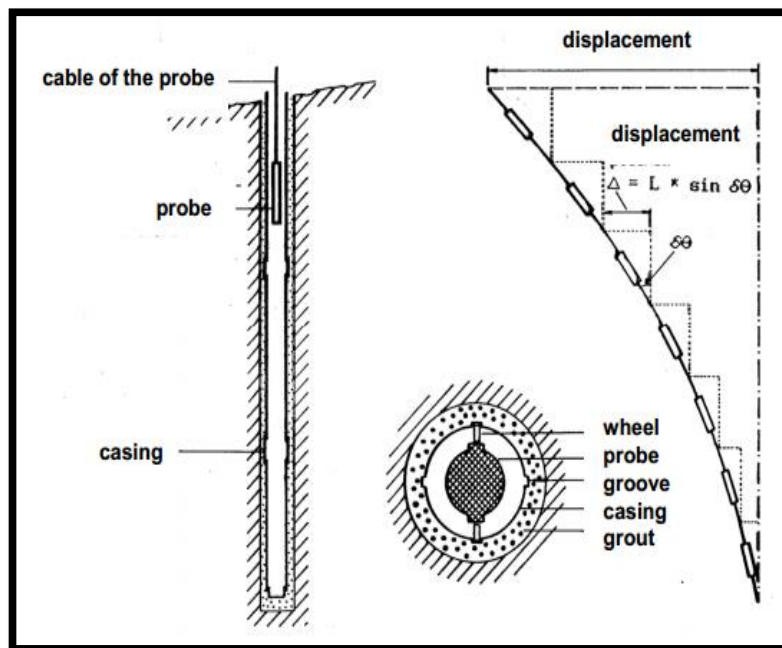


Figure 2.6: Inclinometer. Edited image. (Jan Novotný, Charles University, Czech Republic)

Multi-Layer Movement Meter

Groups of wires installed at different depths in a drilled borehole these wires are attached and extended to the surface. The displacement of each part of the wire is measured directly by a ruler. Every borehole can contain 20 to 30 wires. This technique is not proper for landslides with small deformation, but this method is very effective with large landslide movement, and when it's impossible to use the other instruments. The principle is almost the same as other devices, a vertical extensometer can be fixed into the bedrock below the borehole as show in the following figure.

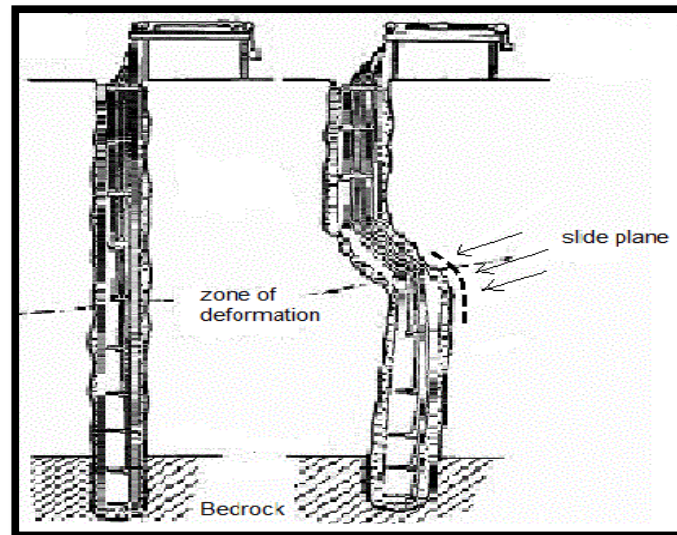


Figure 2.7: Multi-Layer Movement Meter. Edited image (<http://www.tuat.ac.jp/~sabo/lj/ljfg27.htm>)

4.4. Ground water investigation

Ground water takes a great role in slope movement as a main driving force, therefore it's important to make surveys that show the level of ground water, the pore pressure, ground water logging, tracing tests for ground water, pumping analysis, electrical surveys, and geophysical logging (electric logging and radioactive logging), to create a plane for the ground water.

After completing all the stages of landslide investigation, a detailed landslide distribution map should be obtained as a result of all the previous surveys, the next figure show a detailed map for landslides in Japan.

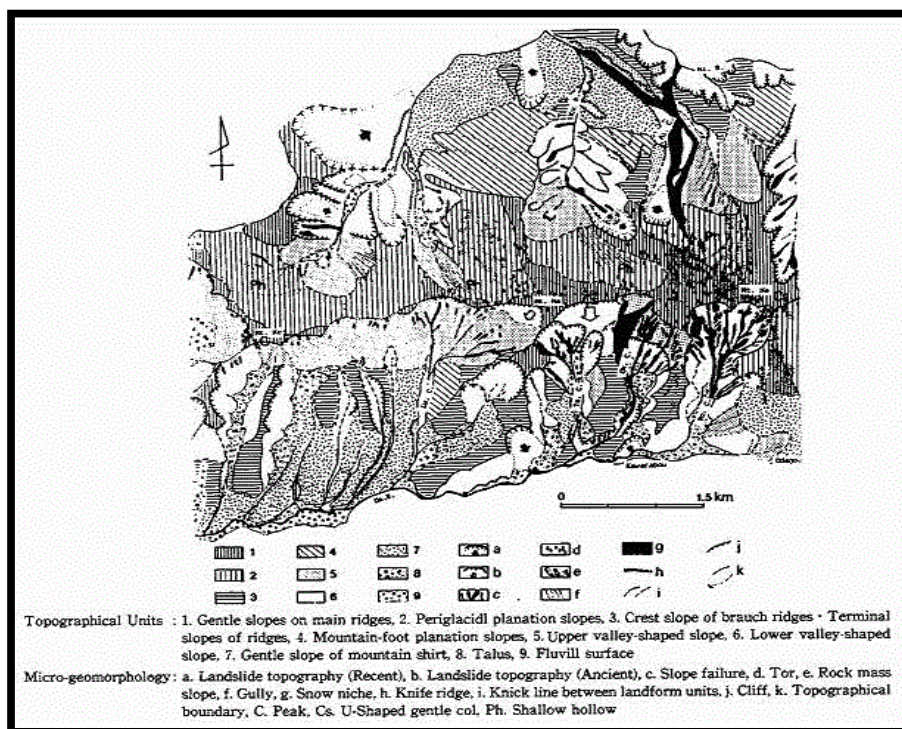


Figure 2.8: Landslide map (<http://www.tuat.ac.jp/~sabo/lj/ljfg29.htm>).

5. Classical (manual) methods of slope analysis

There are several methods of analysis that help to understand the stability of a slope, and that's by calculating the factor of safety, each method depends on many factors and equations, and selecting the suitable method is based on the situation of the slope.

5.1. Infinite slope analysis

When the slope extends for a long distance and has a consistent subsurface profile, it's considered as an infinite slope with a failure plane that's parallel to the surface of the slope and a unite depth into the paper as shown in the figure below.

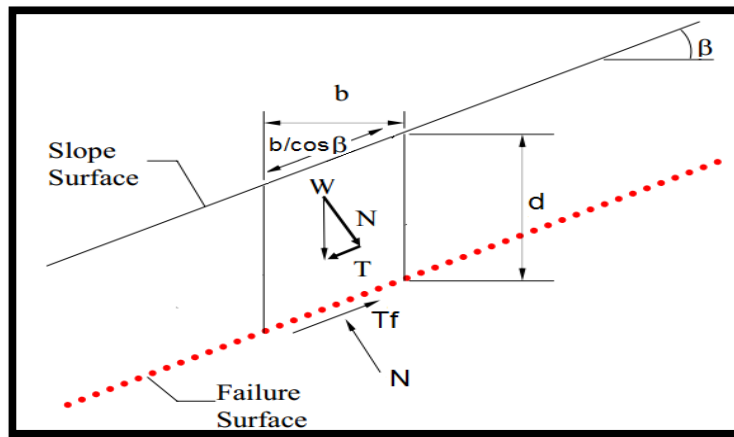


Figure 2.9: Dry infinite slope. Edited image. (Naresh C. Samtani 2006)

In this case we have an infinite slope with no pore water pressure, which have the shear strength (T_f) as a resisting force, and the sin component of weight as a driving force.

$$T = W \sin \beta \quad (1)$$

$$T_f = C + N \tan \phi' \quad (2)$$

Factor of safety for a dry infinite slope:

$$F = \frac{c' + \gamma_d \cdot d \cdot \cos^2 \beta \cdot \tan \phi'}{\gamma_d \cdot d \cdot \cos \beta \cdot \sin \beta} \quad (3)$$

Factor of safety for a dry cohesionless infinite slope ($c' = 0$):

$$F = \frac{\tan \phi'}{\tan \beta} \quad (4)$$

The pore water pressure affects on the infinite slope analysis, it decreasing the resistant force by reducing the normal force by the value of pore water pressure U as shown below:

$$T_f = C + N' \tan \phi', \quad N' = N - U, \quad U = \gamma_w \cdot d_w \cdot b \cdot \cos \beta$$

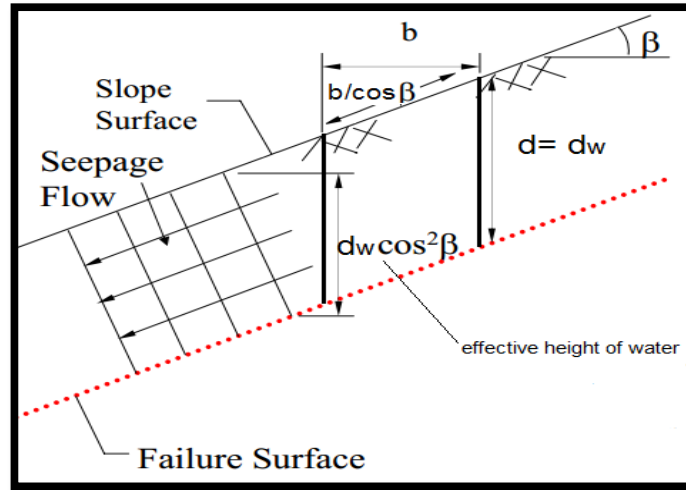


Figure 2.10: Infinite slope with full saturation. Edited image. (Naresh C. Samtani 2006)

Factor of safety for an infinite slope with full saturation:

$$F = \frac{c' + d_w(\gamma_{sat} - \gamma_w) \cdot \cos^2 \beta \cdot \tan \phi'}{\gamma_{sat} \cdot d_w \cdot \cos \beta \cdot \sin \beta} \quad (5)$$

Factor of safety for a fully saturated cohesionless infinite slope:

$$F = \left(1 - \frac{\gamma_d}{\gamma_{sat}}\right) \frac{\tan \phi'}{\tan \beta} \quad (6)$$

When the situation of the slope is complicated (partially saturated slopes) we use the general equation to calculate the factor of safety:

$$F = \frac{c' + (\gamma_d \cdot d_d + \gamma_{sat} \cdot d_w - \gamma_w \cdot d_w) \cos \beta \cdot \tan \phi'}{(\gamma_d \cdot d_d + \gamma_{sat} \cdot d_w) \sin \beta} \quad (7)$$

5.2. Method of slices

The principle of this method is to consider the failure as a circular slide and to divide the sliding mass to several vertical slices with the same width with one unite depth into the paper, and studying the horizontal and vertical forces implicated on each slice.

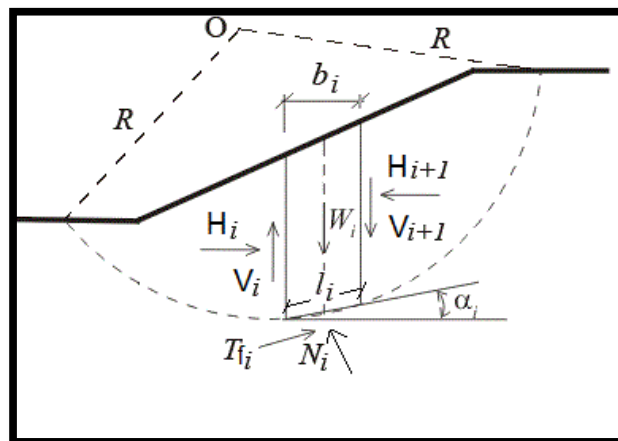


Figure 2.11: Forces on one slice. Edited image. (<http://www.finesoftware.eu/help/geo5/en/circular-slip-surface-01/>).

(H_i and H_{i+1}) Are the horizontal (normal) interslice forces.

(V_i and V_{i+1}) Are the vertical (tangential) interslice forces.

General equation:

$$F = \frac{\sum N'_i \tan \phi + \sum C'l_i}{\sum W_i \sin \alpha_i} \quad (8)$$

There are many methods of solution of this equation according to certain assumptions and derivations, all are based on the ordinary method of slices.

Fellenius method

Also known as the Swedish method of slices and the simplest solution of equation (8), it assumes only the moment of equilibrium with respect to the center of the slip surface, and neglects the shear and normal forces between blocks V_i and H_i , after arranging the equation the result is the following expression:

$$F = \frac{1}{\sum W_i \cdot \sin \alpha_i} \cdot \sum [c'_i \cdot l_i + (N_i - U_i \cdot l_i) \cdot \tan \phi'_i] \quad (9)$$

Since we assume the same factor of safety for all the slices, this method is not considered as accurate as other methods.

Bishop's simplified method

This method assumes that the vertical interslice forces are equal and opposite (zero tangential forces) and satisfies the moment equilibrium, this means that Bishop neglected the interslice shear forces and used the normal forces in the derivation which ended with the following equation.

$$F = \frac{1}{\sum W_i \cdot \sin \alpha_i} \cdot \sum \frac{C'_i \cdot b_i + (W_i - U_i \cdot b_i) \cdot \tan \phi'_i}{\cos \alpha_i + \frac{\tan \phi'_i \cdot \sin \alpha_i}{F}} \quad (10)$$

The equation must be solved iteratively, firstly we assume an initial value for the factor of safety on the right side of the equation (can be obtained from Fellenius method and multiplied by 1, 2) then we insert it into the right side of the equation to find the left side F , the new result we find is inserted again into the right side, and this process is repeated until the left side $F =$ right side F . this method is more accurate and commonly used in computer programs.

Janbu's method

This method is commonly used for the non-circular failure surfaces, because it's difficult to find a single point that many of force components act on which make moment equilibrium methods no more appropriate, in this method we follow the next equation.

$$F = \frac{\sum [c'_i \cdot b_i + (W_i + \Delta V_i - U_i \cdot b_i) \cdot \tan \phi'_i] \cdot \left(\frac{\sec^2 \alpha_i}{1 + (\tan \alpha_i \cdot \tan \phi'_i / F)} \right)}{\sum W_i \cdot \tan \alpha_i} \quad (11)$$

Where: $\sec \alpha = \frac{1}{\cos \alpha}$

This method requires narrow slices, and the formula is to be solved iteratively the same as Bishop's method. Janbu's discovered a certain percentage of inaccuracy in this equation, so he decided to apply correction factor f_0 after solving the equation:

$$F_{corrected} = f_0 \cdot F_{solved} \quad (12)$$

f_0 is obtained from the following chart:

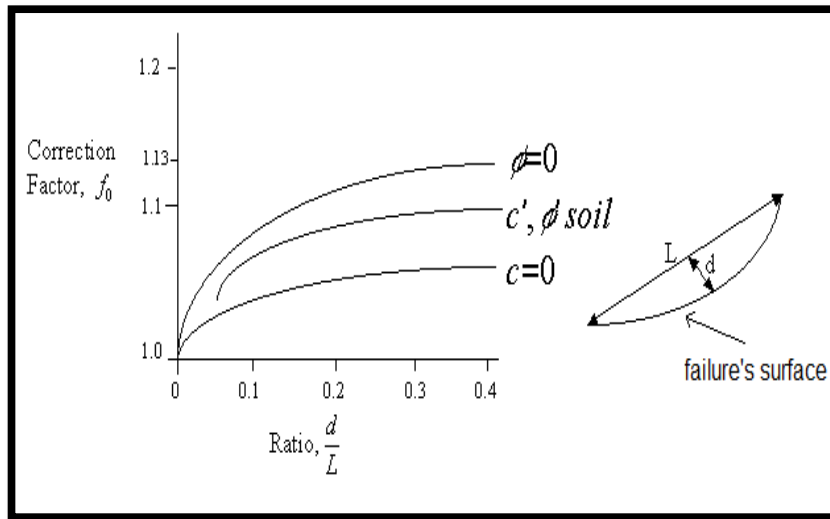


Figure 2.12: Janbu's correcting factor. Edited image. (<http://community.dur.ac.uk/~des0www4/cal/slopes/page5q.htm>)

Spencer's method

This method includes both shear and normal interslice forces (non-zero forces), also considers moment equilibrium and it's more accurate than other methods since it satisfies three equations of equilibrium (vertical, horizontal and moment equilibrium).

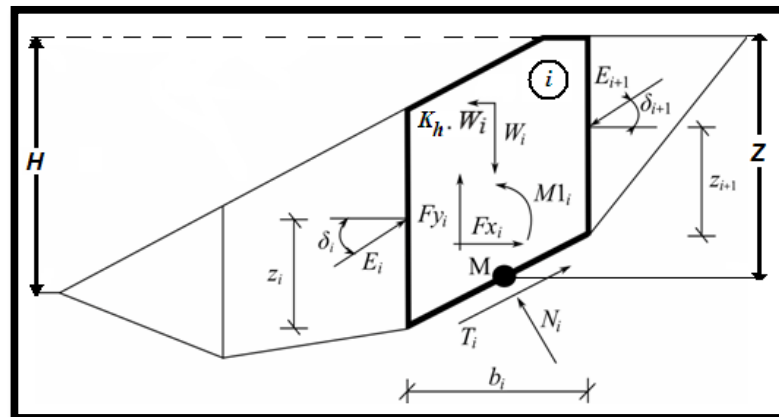


Figure 2.13: Spencer's scheme. (<http://www.finesoftware.eu/help/geo5/en/spencer-01/>)

Spencer assumed that both of W_i and N_i are acting in the center of the slice base, at point M inclination of forces E_i is acting between blocks and it's constant for all blocks and equals to δ , only at slip surface end points is $\delta = 0$. Spencer used five equations in his solution of factor of safety in according to all forces represented in Figure.2.13, and summarized his final results into charts according to these following factors:

$$r_u = \frac{h \cdot \gamma_w}{Z \cdot \gamma} = \frac{U}{Z \cdot \gamma}, \beta, H, \gamma, \phi'$$

(Where r_u is the ratio of pore water pressure and h is the effective water height in the slice, β the slope's angle, H the vertical distance between the toe and the head of the slice).

The factor of safety is obtained by these steps:

- Assume a value for the factor of safety.
- Calculate $c' / [F_{assumed} \times \gamma \times H]$.
- With the value in the previous step and r_u and the slope angle β , inter the proper Spencer's chart and obtain ϕ'_d .
- Calculate $F = \frac{\tan \phi'}{\tan \phi'_d}$.
- Repeat the steps until $F = F_{assumed}$.

Spencer have made many charts according to the previous factors, the next figure shows the charts respectively for $r_u = 0.25$:

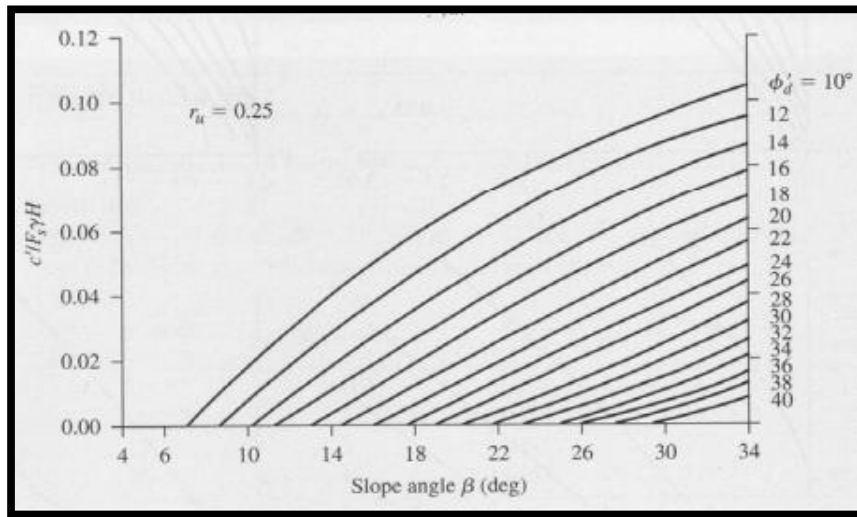


Figure 2.14: example of Spencer’s charts. (Lanbu Liu.CE240. 2006)

5.3. Method of Taylor

This method also known as Taylor’s stability charts, Taylor produced these charts after analyzing a number of slopes with various shapes and soil properties to figure out a stability number (N), which has a relation with the factor of safety, these charts are used in the undrained analysis of the slope:

$$N = \frac{c_m}{\gamma.H}, c_m \text{ (the mobilized cohesion)} = \frac{c}{F}, \text{ so: } N = \frac{c}{F.\gamma.H} \quad (12)$$

There are two charts Taylor produced each of them deals with a certain characteristics of the slope and soil, and both deal with the cases of critical slip surfaces shown in the figure below:

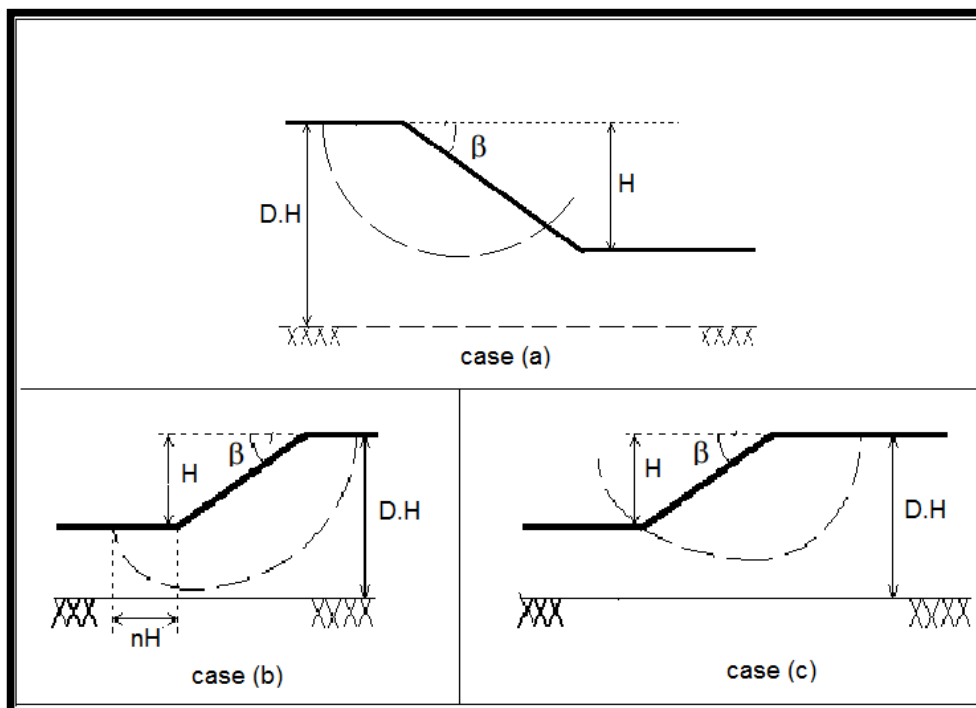


Figure 2.15: slip surface cases.

As seen in the figure in case (a) the slip circle crosses before the toe, in case (b) it crosses after it, and in case (c) the slip circle crosses the toe directly. Each one of these cases (a, b, c) is presented by a line in Taylors charts.

- Chart (1) : Used for general cases except when $\phi = 0$ and $\beta < 53^\circ$:

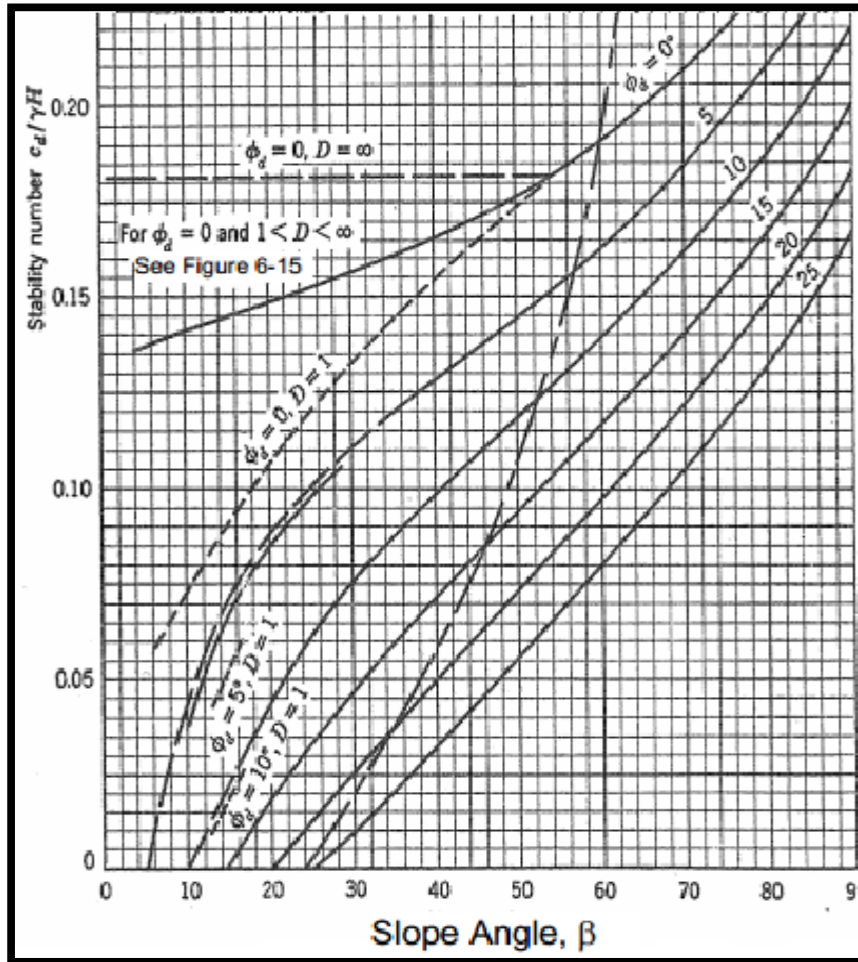


Figure 2.16: Taylor chart (1). (Naresh C. Samtani 2006)

The horizontal axe presents the slopes angle, and the vertical one presents the stability number. For case (a) in figure 2.15 N is presented by short dashed \emptyset lines in chart, for case (b) N is presented by long dashed \emptyset lines, and for case (c) N is presented by full \emptyset lines. The stability number is determined by projecting the slope angle β to \emptyset line, then projecting the cross point to N , and after the stability number is determined we can simply use equation (12) to find the factor of safety.

- Chart (2): used in the special case when $\phi = 0$ and $\beta < 53^\circ$:

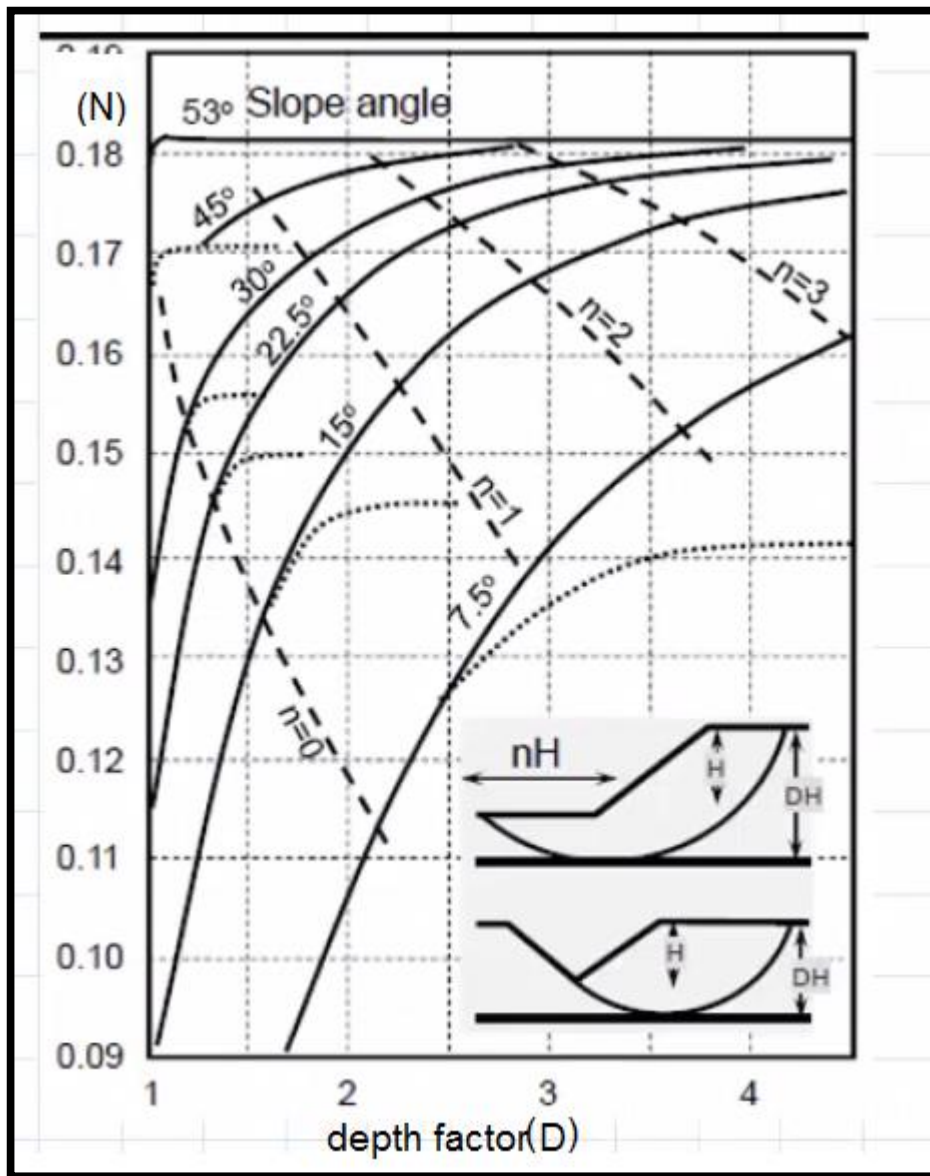


Figure 2.17: Taylor chart (2). (Naresh C. Samtani 2006)

In this chart the vertical axis presents the depth factor D instead of the slope angle, and because D.H is known and H is known we can determine D to project it to the proper line in the chart. The short dashed lines are used for case (c) in figure 2.15, and the full lines are used for case (b).

Each one of these classical methods has its specifications, advantages, and disadvantages. The next table summarizes these features of each method:

Table 2.1: summary for classical methods of investigation.

<i>Method</i>	<i>Principle</i>	<i>Use</i>	<i>Advantages</i>	<i>Disadvantages</i>
Fellenius	Moment equilibrium equation, neglects other forces	Purely cohesive soils with a circular slide	Simplicity- Identical results for purely cohesive soils	Very conservative – gives lower factor of safety than other methods
Bishop	Vertical force and moment equilibrium equations, neglects horizontal force	Circular sliding surfaces	Very efficient- accurate for circular slides and some of shallow slides	Conservative when there is internal distortion _ not accurate when there is horizontal loads involved (such as earthquakes)
Janbu	Vertical and horizontal forces, neglects the moment equilibrium	Shallow slides	Very efficient_ accurate with shallow slides_ accurate with horizontal loads	more conservative_ needs a correction factor
Spencer	Horizontal, vertical forces, and moment equilibrium	Both shallow and circular slides	deals with any geometry and any loads	Less efficient_ iterative solution(may not converge)
Taylor	Two dimensional limit equilibrium analysis	Simple homogeneous slopes, circular slides only	Good use of engineers time_ useful for preliminary analysis	Doesn't consider water tables and pore pressure

Note:

- The engineer must check multiple slip surfaces and consider the one with the lowest factor of safety (the critical slip surface).
- All the areas of the slope must be searched to obtain the lowest factor of safety.
- Any secondary features such as thin soil layers and cracks should be noticed.

6. Slope analysis using software programs.

The manual methods of slope analysis are not practical since they take much time and may not be accurate due to the human possibility of making errors when the analysis are done manually by the engineer they need to be solved iteratively which makes it possible to make mistakes in the results, these classical methods better be implicated in computer programs to make it much easier, faster and more accurate to do the analysis and compute the factor of safety using the slope inputs.

The program used in this project is SLOPE/W which is an application in the engineering program GEOSTUDIO.2007.Version 7.10.4143.

Using this program goes through three main stages, which are:

- Define : to set the model (the inputs of the slope)
- Solve: to calculate the numerical solution
- Contour and display: to view the calculated results and charts

6.1. Define

defining the problem is the first stage to start with in slope analysis by Slope / w, each one of the following steps is very important to accomplish the slope analysis, caution is very important in this stage because any wrong inputs will lead to false results of the factor of safety and the location of the critical slip surface, defining the problem is done by the following steps:

- creating a new slope/w project from Geostudio start page: in the keyin box it's needed to identify the method of analysis (select morgenstern_price) , the interslice force function (chose half sine), the pore water pressure function (select piezometric line), and the selection of critical slip surface finding method(entry and exit).

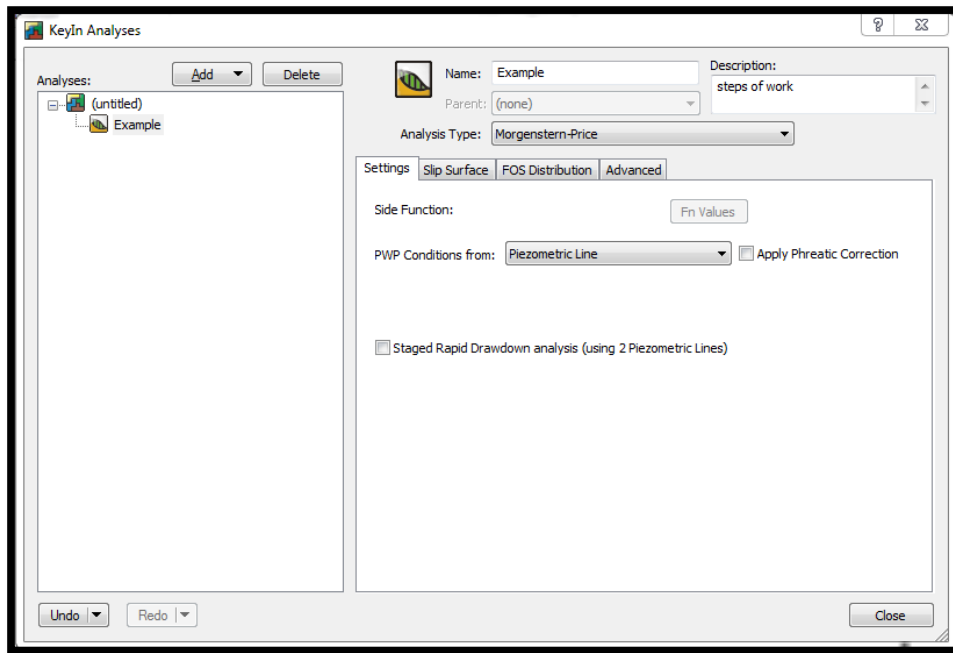


Figure 2.18: KeyIn window (creating a new project).

- Working area settings: from the toolbar set the size of the page and the scale required for the analysis, it's also helpful to set a background grid of points.
- Axes and problem sketching: using the polyline from the sketch menu we can define our axes and a primary shape of the slope that well be analyzed.

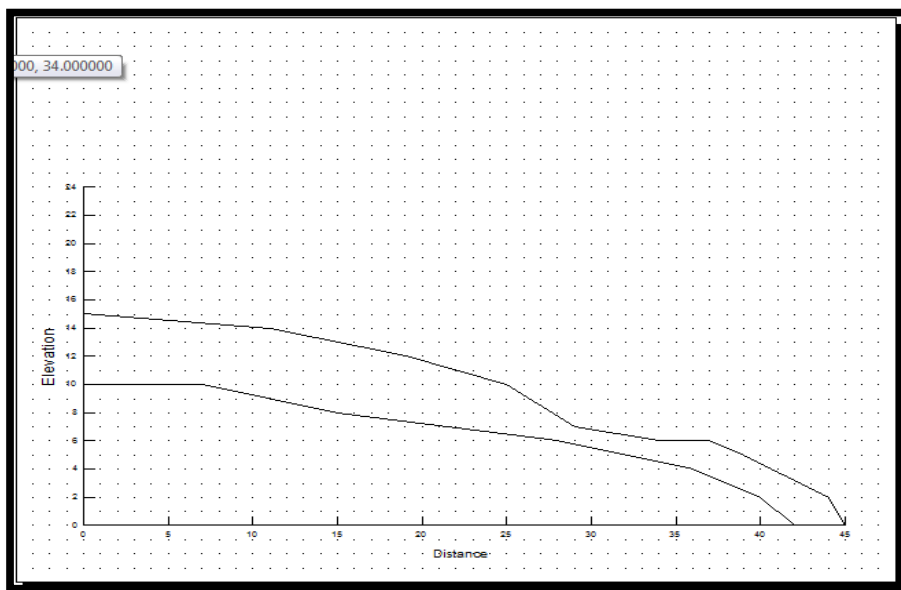


Figure 2.19: sketching the axes and the slope.

- Drawing the geometry: creating individual soil regions by choosing the draw region command, this process will show the distribution of slope materials.

- Assigning material regions to geometry objects: chose materials from the draw menu then click on keyin to add materials with a strength model from the drop down list (Mohr coulomb), and add the characteristics of each material (cohesion, friction angle, and unite weight), then chose the material and assign it in its region.

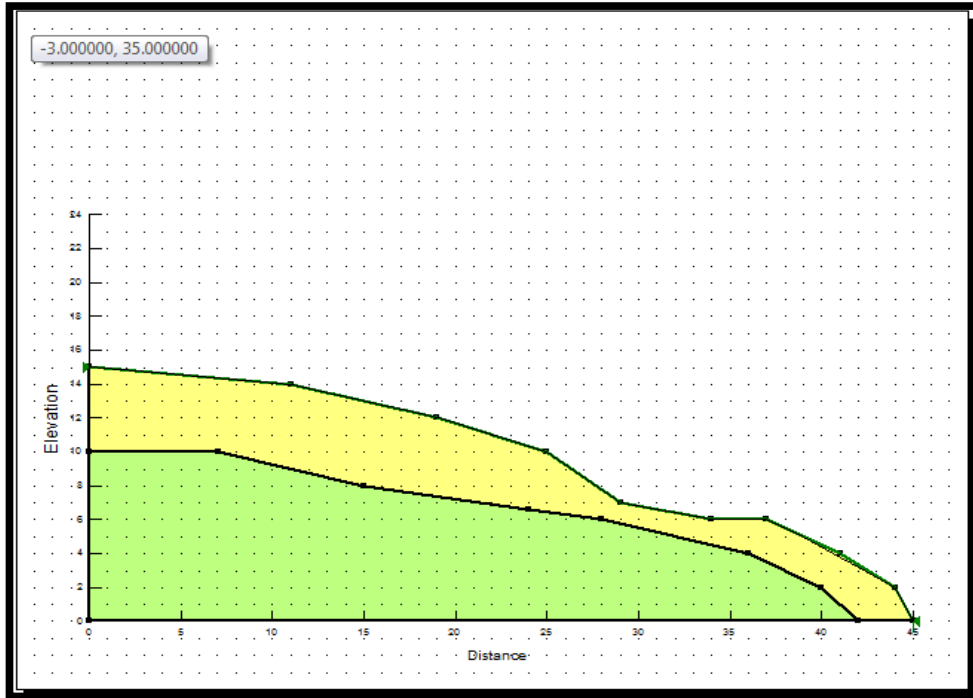


Figure 2.20: material regions (each color defines a material).

- Defining the pore water pressure conditions: and that's by a single piezometric line for all the regions (chose pore water pressure from the draw menu then draw).
- Defining the slip surface entry and exit locations: select slip surface from the draw menu then chose entry and exit and use the mouse to set the locations.

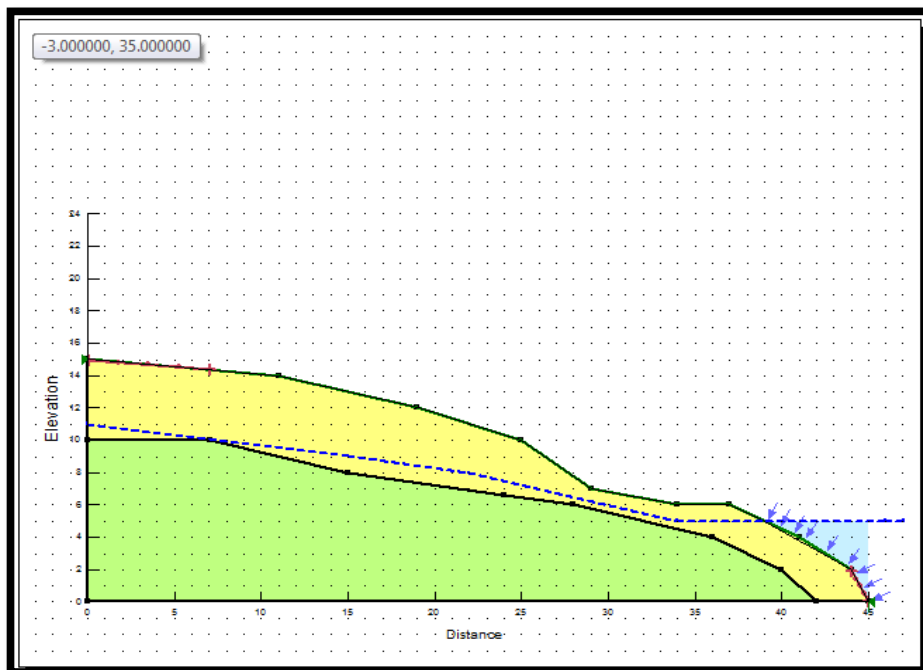


Figure 2.21: completely defined slope.

- Verifying the inputs: select object information from the view menu then click on any region to review the soil properties for that particular region or chose verify from the tools menu and SLOPE/W will run a number of checks and give a warning in case of errors.

6.2. Solve

Select the solve analysis option in the tool bar then click start and the program will show a solver window that provides the calculated factor of safety for each of the various methods.

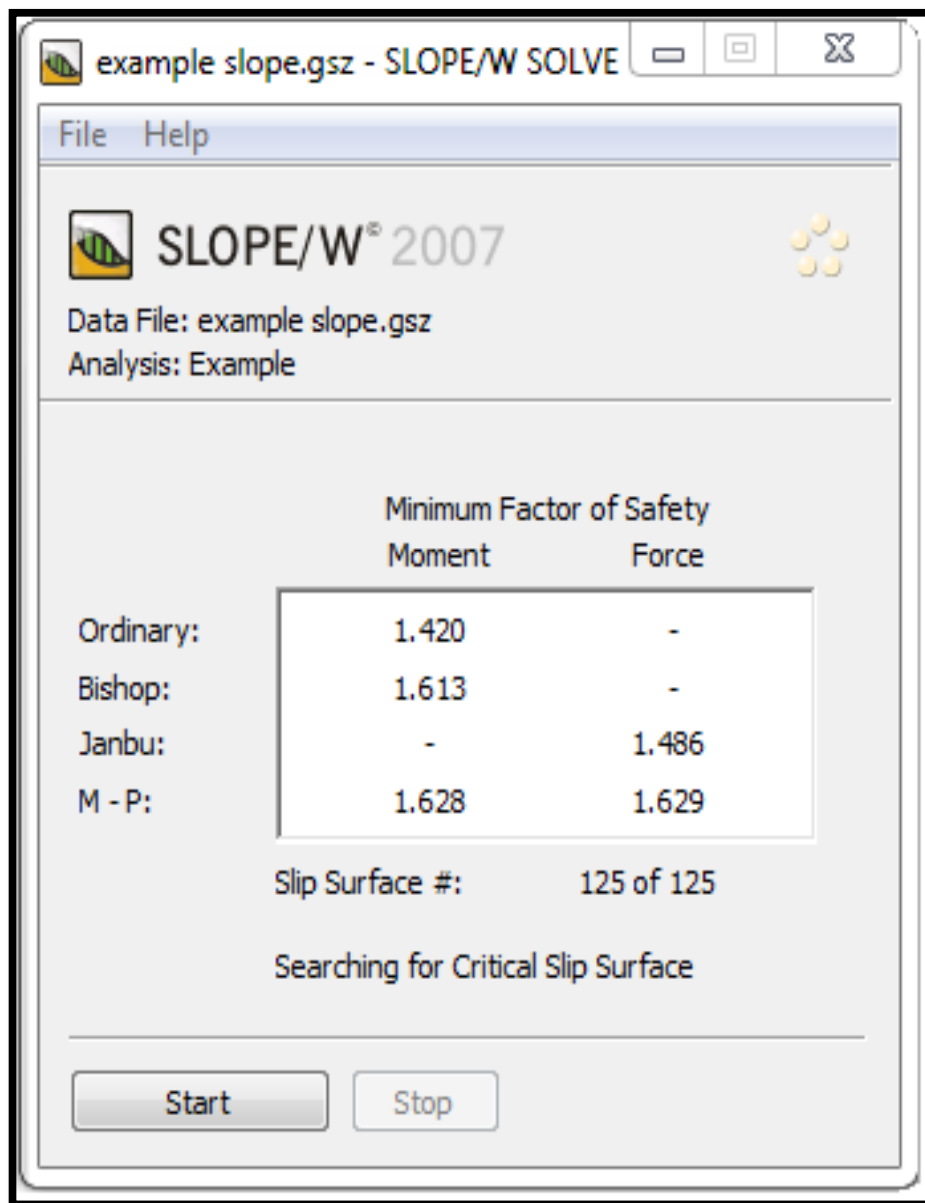


Figure 2.22: solver window.

6.3. Contour and display:

After defining the problem and calculate the factor of safety, there are many options that allow the engineer to obtain the required information in an easy way, the program also provides isolated charts and graphs to display data.

The critical slip surface

And this is the slip surface with the lowest result of the factor of safety, we can review the result directly by selecting the contour icon in the analysis toolbar and the program will view the critical slip surface with the critical factor of safety.

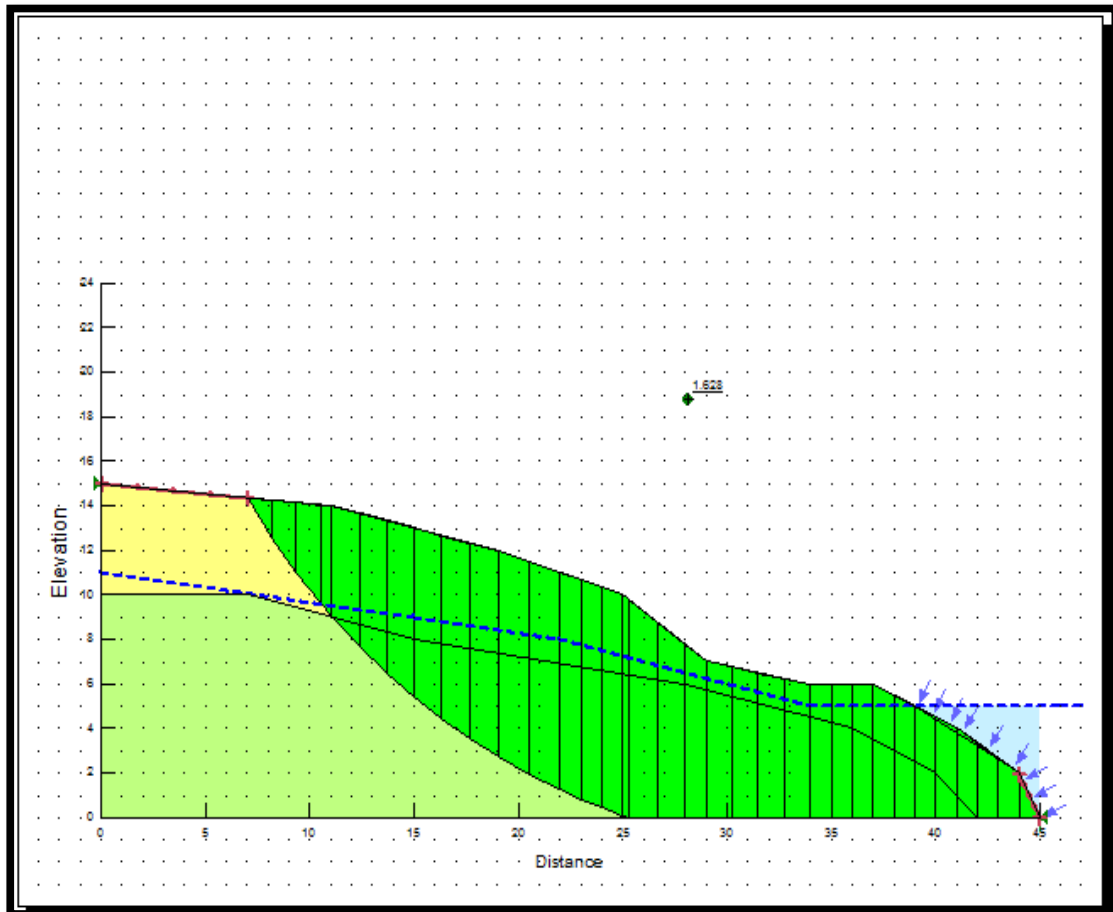


Figure 2.23: contour window (critical slip surface and F).

Analyzed slip surfaces

Chose the slip surfaces command from the draw menu, a dialog box will that summarize the factors of safety of all the slip surfaces that were analyzed, when clicking on any slip surface the program shows the slip surface and its corresponding factor of safety in the contour window in the previous figure.

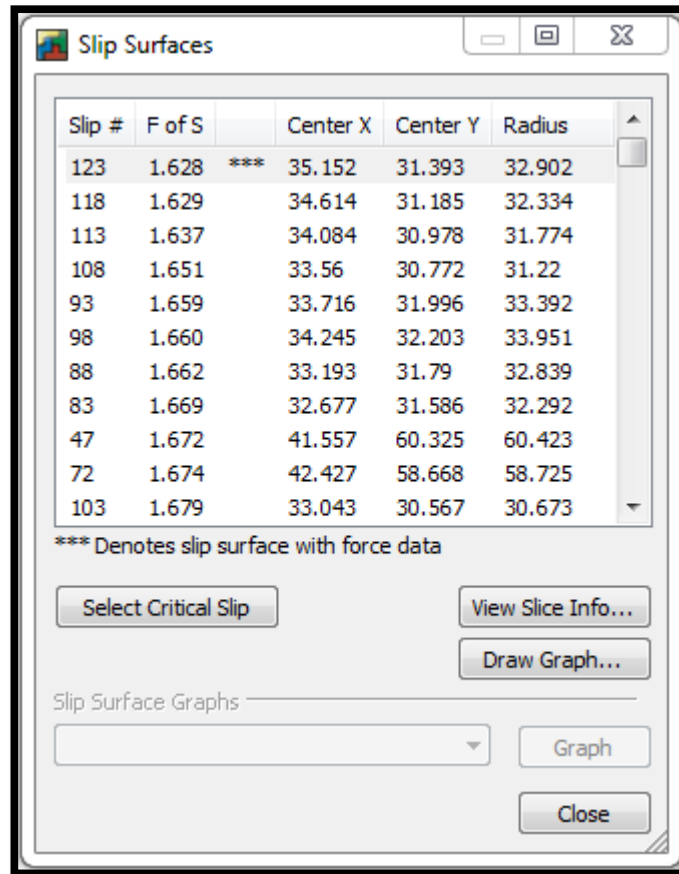


Figure 2.24: Factors of safety dialog box.

Slice force information:

from the previous dialog box we can also review the slice force information window for the most critical slip surface and that's by selecting view slice information command, when clicking on any slice its information will appear in the window.

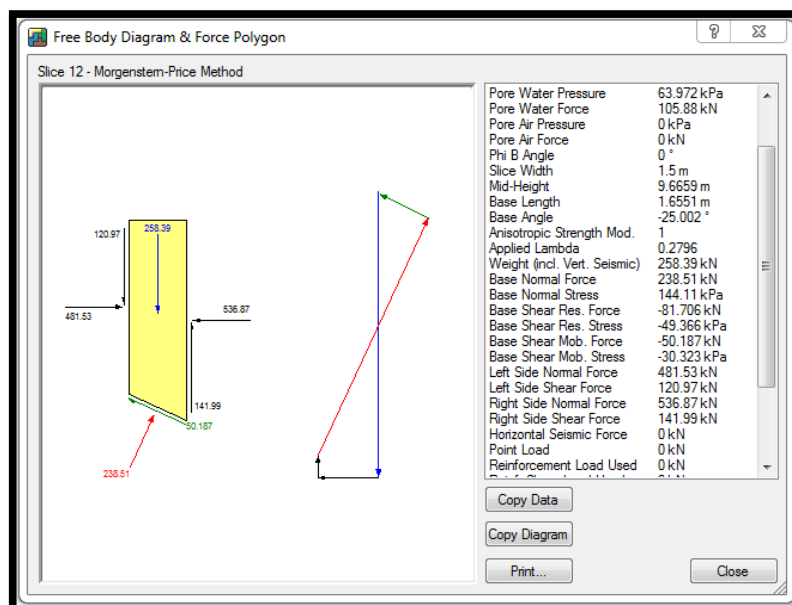


Figure 2.25: slice force information window.

Graphs

When choosing graph command from the draw menu, the program shows a window that allows the engineer to create graphs to show how the parameters vary across the slip surface including pore water pressure, cohesion and other parameters.

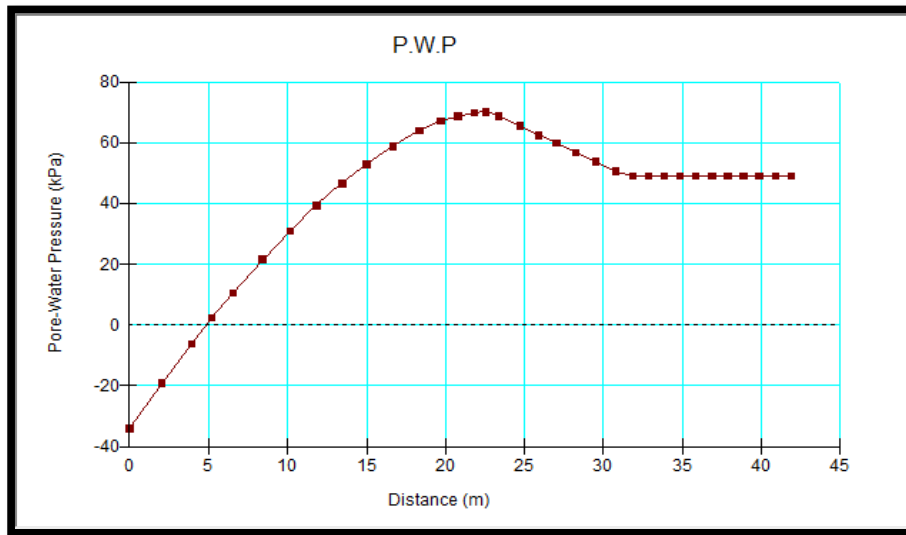


Figure 2.26: Pore water pressure graph.

Failure zone

A safety map can be drawn to indicate a zone where similar factors of safety could develop, and that's by selecting safety map from the draw menu.

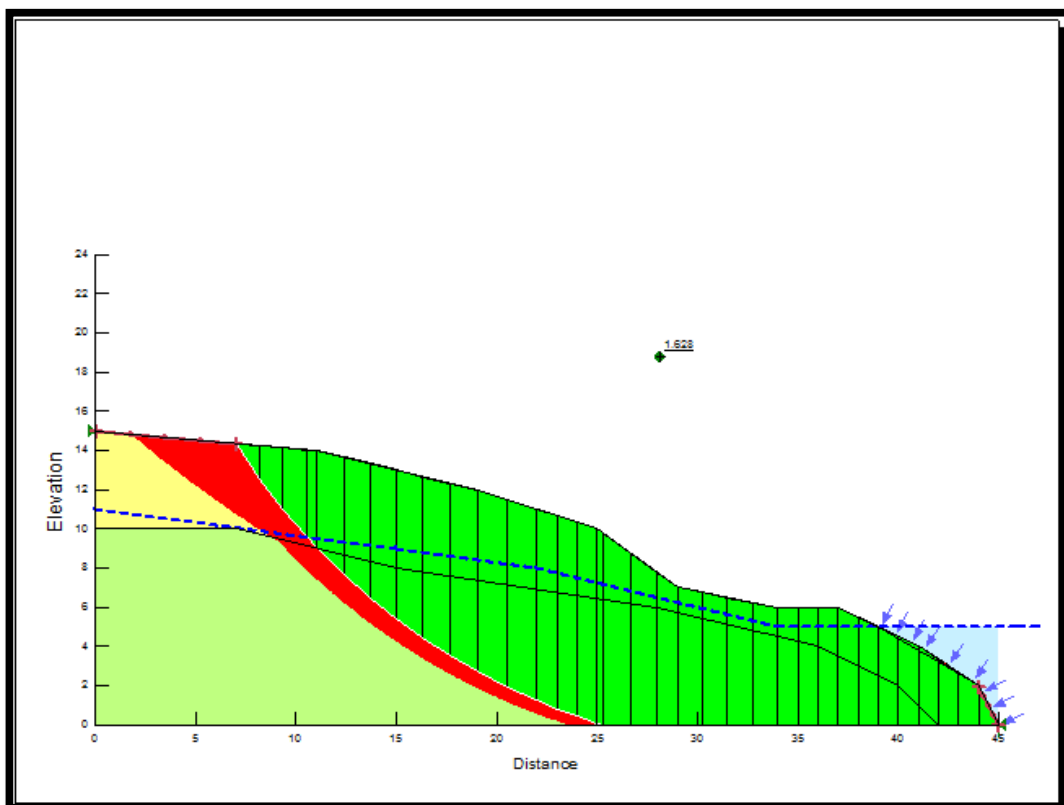


Figure 2.27: safety map.

Other options

many options can be used to gain deeper understanding about the analysis such as, viewing a number of slip surfaces that were analyzed in the contour window by selecting preferences from the view menu, it's also possible to view and

copy a general report for the inputs and outputs that were used in the analysis by choosing report command from the view menu, another powerful feature is the ability to make multiple analysis in one project file, and that's by choosing add or clone analysis from the keyin box, which makes it possible to view results for different input parameters in the same geometry.

7. Conclusion:

In this chapter we aimed to display the ways and instruments used in data collecting and the stages of investigation about landslides, the chapter also contains an explanation about the manual methods of slope analysis, and presents the software program that we used in this project. In the next chapter it's intended to present the methods of slope mitigation and stabilization.

Chapter III:
Landslide mitigation

1. Introduction

In hilly and mountainous terrains, a safer operation of building is very important for highways, transmission facilities, infrastructures and other sorts of constructions, this requires long term stable slopes and control of rock falls, a scientific and economical remediation programs must be involved to figure out the suitable method of mitigation and stabilization, from water draining systems to retaining walls there are many techniques and methods of stabilization which we are aiming to show in this chapter. Methods of stabilization can be used either to protect the slope from failures or to repair it after the failure occurs. Methods of slope stabilization are divided into three large categories which are:

- Modifying the slope
- Drainage
- vegetation
- Strengthening slopes
- Retaining structures

Each one of the used methods found to be appropriate for particular conditions such as:

- Ability of application on the slope
- Available time to start and finish
- Accessibility to the site
- Types of available equipment
- The economical factor

2. Stabilization methods

2.1. Modifying the slope (Excavation)

The basic principle in this type is changing the shape of the slope in a way that make it stable or less likely to fail, this type of stabilization require a schedule of works that contains excavation, cuts, and fills and other processes, and it includes :

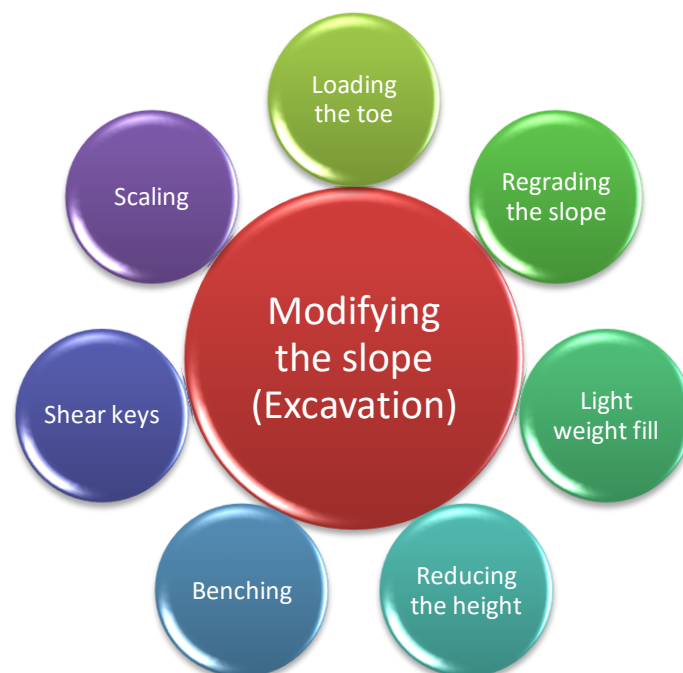


Figure 3.1: ways of modifying the slope.

Loading the toe

This method depends on a quantity of counter weight on the toe of the slope, where the critical slip surface is predicted to take a place, this weight (also called a berm) block the land slide by producing stabilizing moment that increases the resisting force. The berm can be constructed by using materials which is removed from the head or the crest of the slope, or can be brought to the site from elsewhere, it's preferred to use materials with heavy unite weight in this method. This method is more effective in slopes with deep seated failures, because the slip surface is more likely to be circular, the design of berm is done the same way of retaining structures designing by considering the active and passive loads.

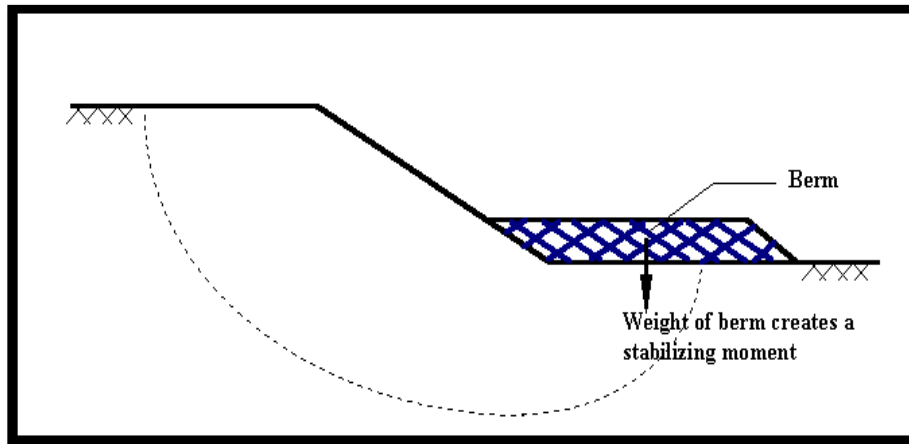


Figure 3.2: loading the toe. (<http://community.dur.ac.uk>)

Regrading the slope

Or serration the slope, the principle in this method is to flatter the angle of the slope making it more stable by a cut and fill process by removing materials from the face of the slope or adding materials to flatter the angle of the slope and loading the toe at the same time the cut and fill techniques should be calculated by considering the factor of safety before and after the execution, this method can be also done by creating low height benches on the slope.

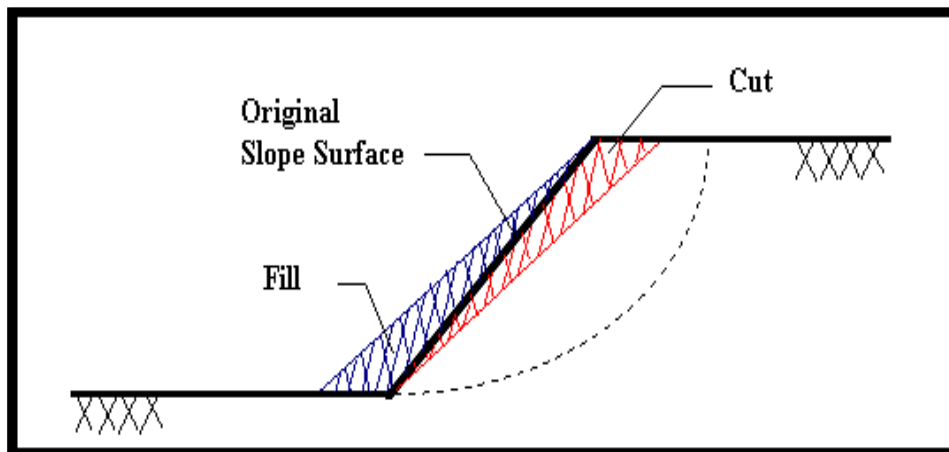


Figure 3.3: Regrading the slope. (<http://community.dur.ac.uk>)

Reducing the height

The rock or soils in the upper portion of a cut slope which presents a driving force is necessary to remove in some cases, this method reduces the driving force and provides an access road above the main road and forms a lower slope after the excavation, reducing the height must start with back analysis of the unstable slope, this method is not commonly preferred in manmade slopes as the height of the slope is not usually able to be changed due to design.

This method is effective in increasing the stability of the slope, it only increases the factor of safety by (10_15) %, and a final solution requires extra modification of the land.

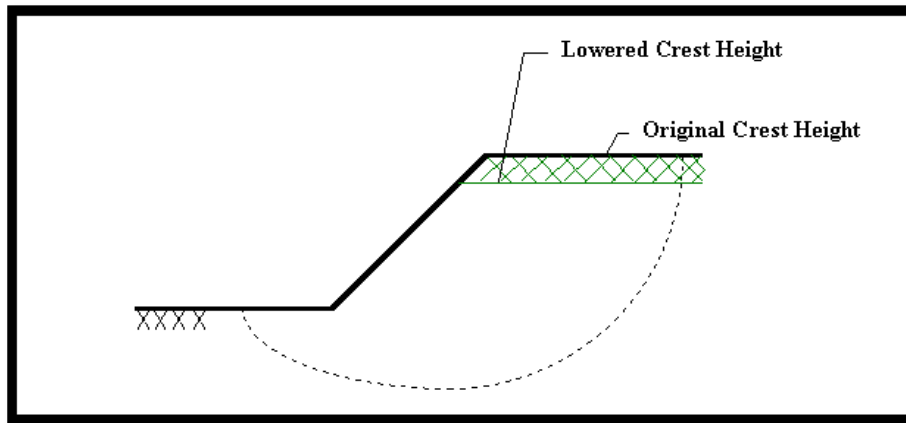


Figure 3.4: reducing the height. (<http://community.dur.ac.uk>)

Light weight fill

This method is related to the height reduction, but with replacing the removed materials by lightweight materials, such as wood fiber, wood chips, logging slash, shredded rubber tires, polystyrene foam, and seashells, choosing the material depends on its cost and availability in the local area, then material is to be covered with a thin layer of gravel or coarse aggregate, this reduces the driving force and increases the stability of slopes without changing the slope profile or angle, which doesn't affect the design.

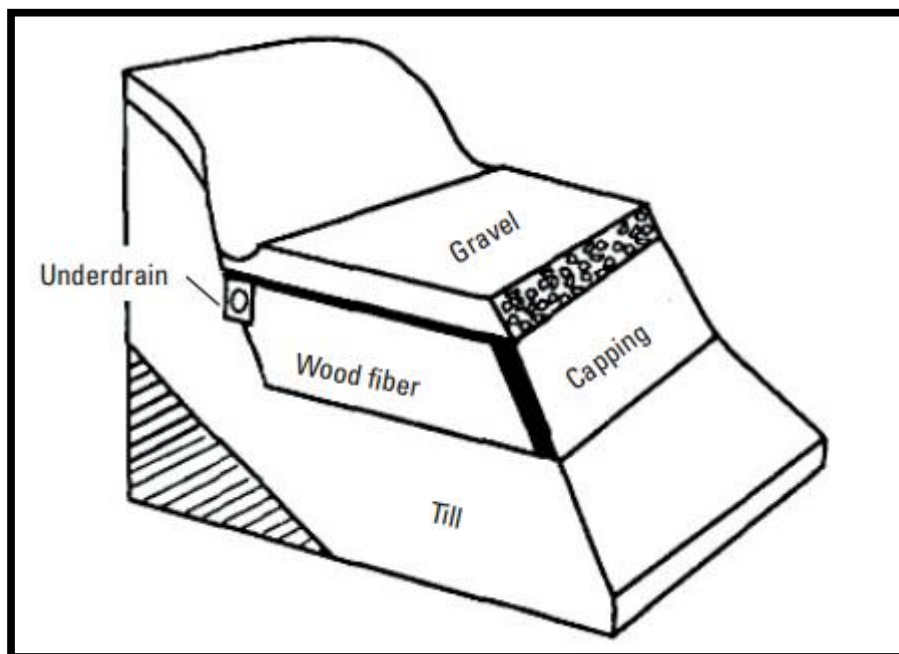


Figure 3.5: light weight fill.

Benching

Maybe the most popular excavation method, and the main idea in this method is to transform a high slope into several lower slopes (to give it the shape of stairs), benching is used on cut slopes in mining, beside roads and highways, benches heights vary from 3 to 5m in highways and reaches about 30 m in mining areas.

This method is effective in reducing the driving force and retaining rock falls on slopes with rocky cliffs, it also helps in surface draining. Benching is useful in reducing the danger of shallow failures, but generally it's not very effective for which other methods are recommended.



Figure 3.6: benching the slope. (<http://a10.jlansford.com>)

Shear keys

Shear key is a technique to replace the loose soil by a stronger material, this method is effective to provide additional slide resistance. The main purpose of a shear key is to change the location of the critical slip surface forcing it to go deeper into a stronger formation, increasing the resistance along the slip surface. This method is very effective and economical if the stronger formation is only a few meter below the soft soil. The execution of shear keys requires excavation of a trench at the level of the toe to install the material of the shear key.

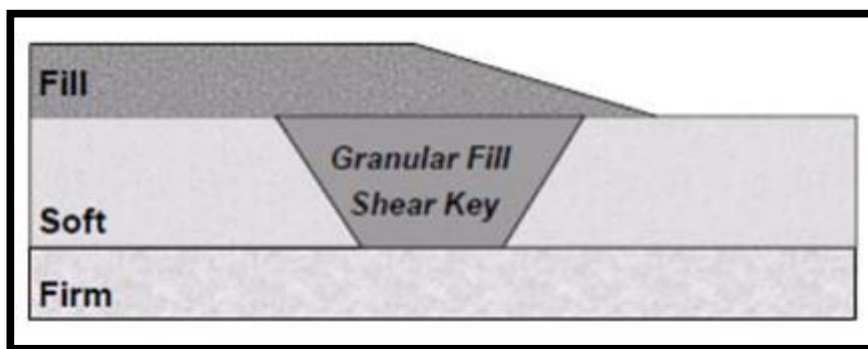


Figure 3.7: shear key.

Scaling

Scaling is the removing of weak non detached soil materials, rocks, and vegetation on the slopes face by using manual tools like scaling bars, shovels and chain saws. The plants roots that grow in the cracks on the rock can further widen the fractures and cause rock falls. Also, when the wind moves the trees it influence the roots to loosen the blocks, which permits the water infiltration into the rock on the face of the slope which, under some climate circumstances, can freeze and expand causing further widening of the fractures. Since this method is done by hand works, on steep slopes, it's very important for the workers to be supported by safety equipment such as highly resistant to cut ropes anchored at the crest of the slope, and the strategy followed in these works makes The scaling workers start from the head and end in the toe of the slope, to make sure that there is no loose rock above them.



Figure 3.8:Slopescaling.

2.2. Drainage techniques

Water is very important factor of causing and triggering slope failures, water draining techniques describes the process of disposal of the ground water, rain water, or water from other sources (such as reservoirs, rivers, channels...etc.), getting the water away from landslides prone areas is very effective of decreasing the driving force by reducing the pore water pressure in the slope, which increases the factor of safety. Water control is generally maintained through installation of shallow and/or deep drainage devices within and adjacent to potentially unstable slopes. Disposing or infiltration of water along the face of the slope helps to limit the erosion caused by water.

Some important criteria must be satisfied when using drainage techniques which are:

- Disposing the gathered water
- Disposing the ground water
- Making sure that the disposed water is completely out of the boundaries of the prone area
- Aiming for a minimum disturbing of the natural drainage pattern
- Preventing the collection of water in the unstable area

Drainage is the most frequently used method of slope stabilization, because failures are very closely related to the rising of the ground water levels, therefore reducing the groundwater levels by using suitable drainage techniques is important to improve the stability, in addition this method is less expensive than many other methods, when deciding the drainage as a solution to improve the stability, it must be maintained to be practical and functional, for this purpose the following methods can be used :

- Squeezing water out of the ground by the application of external loads
- Using gravity or pumping to drain the pore water (wells and blankets)
- Using electrical consolidating / stabilization (electro osmosis) by passing a direct electrical current through the saturated soil, this will make the water move towards the cathodes and consolidate the soil, the current can also make ion exchange which rearrange the particles and decompose the electrode electrochemically which changes the nature of the soil
- Implicate the Thermal stabilization by cooling or heating the soil, the change of temperature of the soil can changes its properties, for example, increasing the temperature can decrease the electrical repulsion in the clay which strengthen it

Water drainage techniques are classified into two main strategies, each one of them has its principles and methods of application:

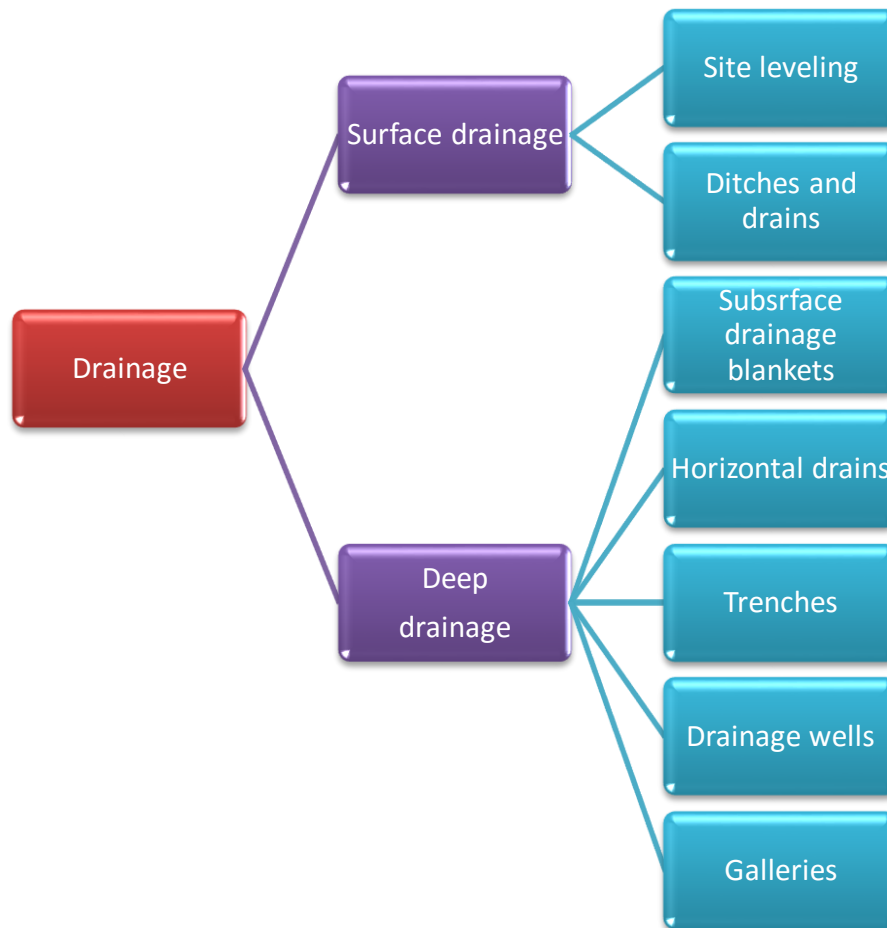


Figure 3.9:drainage techniques classification

Surface drainage

Surface drainage describes the control of water flow on the face of the slope, it usually targets the rainwater. Since the shape of the slope is the important factor that controls the behavior of water on the slopes face, the topographic shaping, grading, and runoff structures are used to control the direction of water, and to prevent further erosion of the slopes surface:

a) Site leveling:

Changing the topography of the slopes face and the features of the surface can prevent the collected surface water from connecting or mixing with the deep ground water. And this can be achieved by removing the depressions on the slope that might retain water, and filling the cracks in the slopes surface by grading and site leveling, this method is effective to prevent surface water from reaching the failure plane.

b) Ditches and drains:

Another way of the application of surface drainage is done by ditches or shallow subsurface drainpipes, these are the best ways of controlling the direction of water on the face of the slope, and a network of cutoff ditches and lateral drains or trenches is very effective to run the water around the edge of the slide. The gradient of ditches should be 2% or more to make sure of fast flow of water. This method is especially important to be at the head of the slide, and it's more effective and economical for shallow soils above impermeable bedrock, the trenches are excavated until the base of the shallow soil to interrupt the shallow ground water flow and backfilled with gravel.

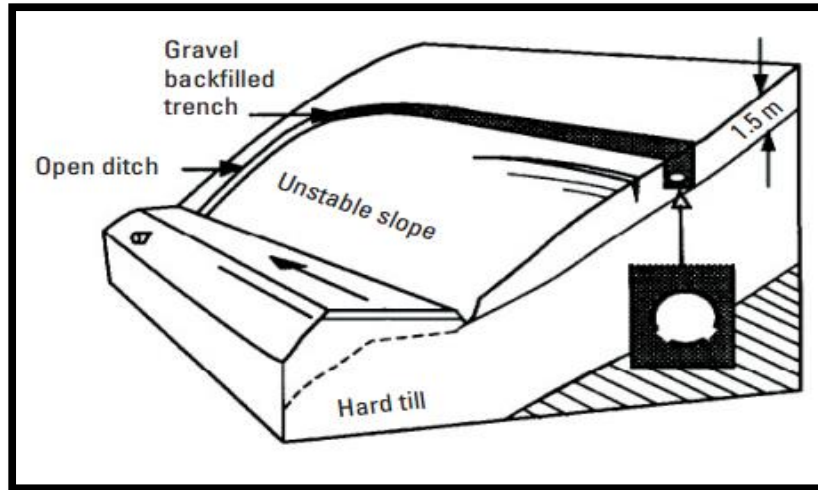


Figure 3.10: drain ditch_trench system. (Lynn M. Highland & Peter Bobrowsky)

Deep drainage

Deep drainage systems target the ground water, the reason that they are used in prone areas is that they are very effective in lowering the water table, and by that reducing the pore water pressure and transporting its application to a level lower than the level of the potential slip surface, this can be done by the following commonly used methods in deep drainage systems:

a) Subsurface drainage blankets:

In case of existence of saturated soil layers with no drainage ability, it's effective to replace these layers with subsurface drainage blankets of good drainage quality. At first the saturated layers of soil must be excavated and at the base of excavation should be covered with a layer of filter stones with a depth of 15 to 60 cm, this layer should contain a drainpipe with holes in it to catch the water flow, the last 1.5 m before the exit of the drainpipe must be let without holes to avoid the blockage of holes by plant roots, at the end of the pipe there should be a drainage ditch to transport water to a suitable place where it can't cause any erosion in the slope.

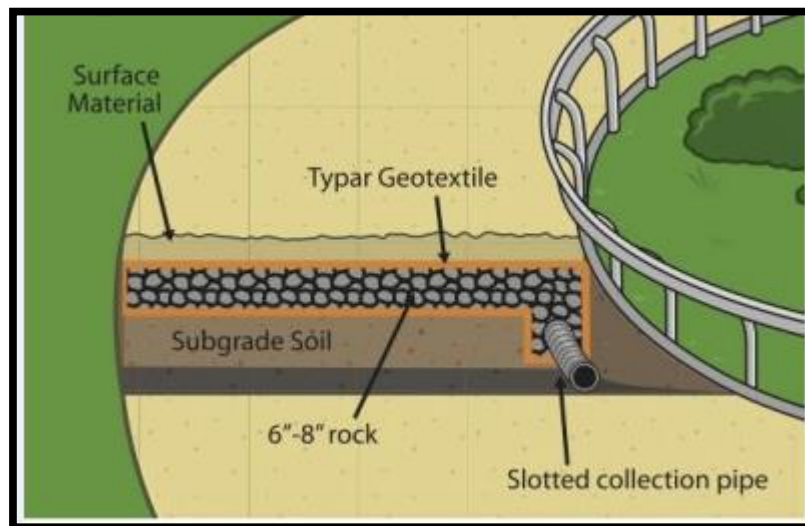


Figure 3.11: Draining blanket. (<http://www.typargeosynthetics.com>)

b) Horizontal drains:

Horizontal drains are perforated drainpipes installed in drilled holes in the face of the slope, these drainpipes manage to use the gravity to drain the ground water out of the slope to decrease the water table. The commonly used drainpipes in this situation are PVC pipes with holes, these drains are installed by using hollow stem augers to drill in the slope, after inserting the drain the auger is withdrawn leaving the drain inside the slope. Drains are inserted without any filtering layers around them, the hole is left to collapse around the drains, the drains must be

inserted at a low point in the slope to be more functional, and the flow must be transported from these drains to lateral ditches that dispose water.

This method is usually used in slopes with so great depth to the groundwater that the excavation and installing trenches has very expensive cost. Horizontal drains should be designed to lower the seepage pressures. The length of these drains depends on the geometry of slope and the location of the groundwater and seepages. The length can be obtained by a cross section of the slope with its probable critical slip surface and the water table of the slope. The drilled holes should extend beyond the critical slip surface. The optimum design is to intersect the maximum number of significant discontinuities for each unit length of drilled hole.

Drains must be installed in locations that can be automatically cleaned by the pump of water flow. In fact, it's difficult to install these pipes in places that contain silty sands and rock fragments since these materials tend to collapse during drilling. This method usually takes a period of time to lower the water table, this period depends on the kind of soil material, for example in clay soils it takes up to 5 years to make a full change in the water table.

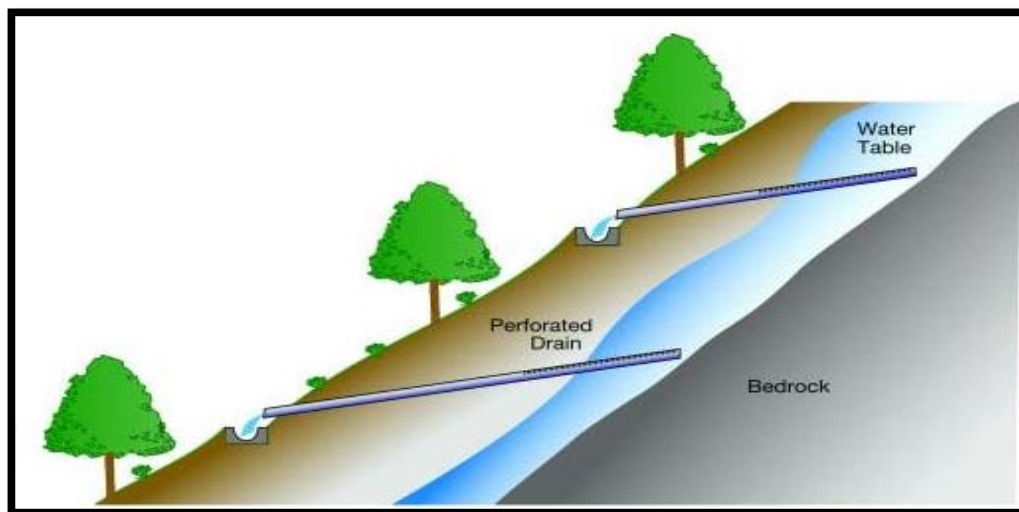


Figure 3.12: Horizontal drains. (<http://sigra.com.au/groundwater/>)

c) Trenches:

Trenches can be constructed deeply when internal water or saturated soil with unknown strength is discovered at deep points that excavation of the soil is not practical. Due to construction period trenches should be excavated at the steepest and the most stable side of the slope. The depth of the excavation of trenches should extend under the water bearing layer and must be backfilled with draining stone layer encased in filter fabric such as geotextile that contains a slotted drainpipe running through it. The suitable number of trenches depends on the hydraulic behavior and the geomorphologic situation of the slope.

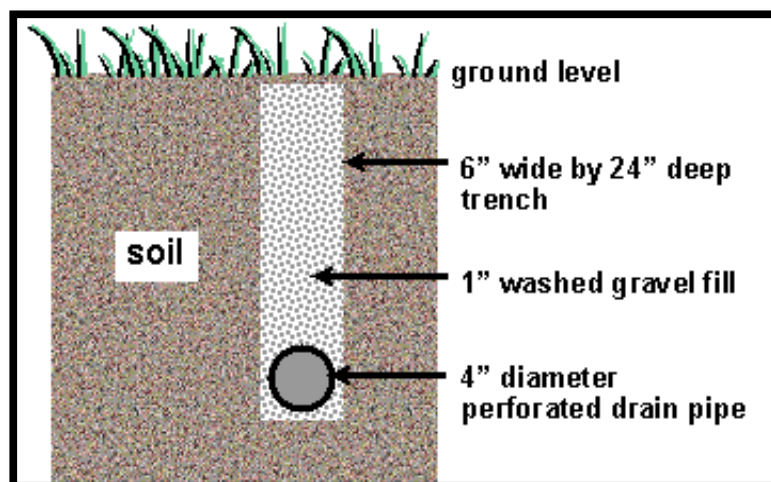


Figure 3.13: drainage trench. (<http://www.askthebuilder.com/drainage/>)

d) Drainage wells:

The use of drainage wells practical in areas where the horizontal drains can't prevent or affect seepages when soil permeable layers are situated horizontally a vertical drainage that crosses the layers is more effective. Drainage Wells have many working techniques and many types.

- **Relief wells:**

Relief wells are made by drilling vertical holes with a diameter varies from 40 to 60 cm. A slotted pipe of 10 to 20 cm diameter must be situated through the hole. The annular space between the borehole and the pipe should be filled with geotextile or other filter material.

The main process of relief wells is to decrease the pore water pressures in deep seated soil in the slope. Water is disposed from the well by a disposal system using a pump deep inside or surface pumping and disposal channels are required to transport water to a suitable place.

Discharging the water may be expensive due to the need of periodic maintenance to make it long term effective. The spaces between relief wells are a main factor because it's closely related to the system performance and the cost of the system. Commonly used spaces vary from 5 to 13 m. The depth of relief wells depends on the location of the slip surface and the unstable zone.



Figure 3.14: relief well. (<http://www.earthcityld.com/floodc.aspx>)

- **Well points and deep wells:**

Well points vacuum holes with small diameters driven into the land. Vacuum is applied to the top of the well points through a header to water up the well points. These wells are more effective in sand and clean soils but not in fine grained soils. These wells are functional when they are limited to 7 to 8 m.

Deep wells are provided with buried pumps to push water up to the top points of the well and are deeper than well points. Every deep well has its own pump and works isolated from other wells. The usual diameter of these wells varies from 30 to 60 cm and supported filters surrounding a slotted pipe or casing. The same as well points, they must be maintained continuously to stay effective.

Dewatering wells are created primarily to decrease the ground water level to a previously determined depth and to maintain that depth, until all under the ground activities are completed.

e) Galleries:

When drainage is needed deep within the side of a slope, a drainage tunnel called gallery is useful. A gallery with extended outward drains can discharge the water throughout the slope. Galleries situated into a slope or high wall to catch the groundwater can provide a useful drainage technique.

Where using galleries, drain holes should be drilled from the location of the gallery upward in a fan shape to make the system more functional. For high rock cuts, installation of drain holes at different levels is suggested. Where rock is taken out in several lifts, drain holes should be drilled at the toe of every lift.

Galleries are usually supported with other drainage techniques to dispose the water from it to a far location from the prone area, these techniques are usually ditches, water collectors, and surface drainpipes.

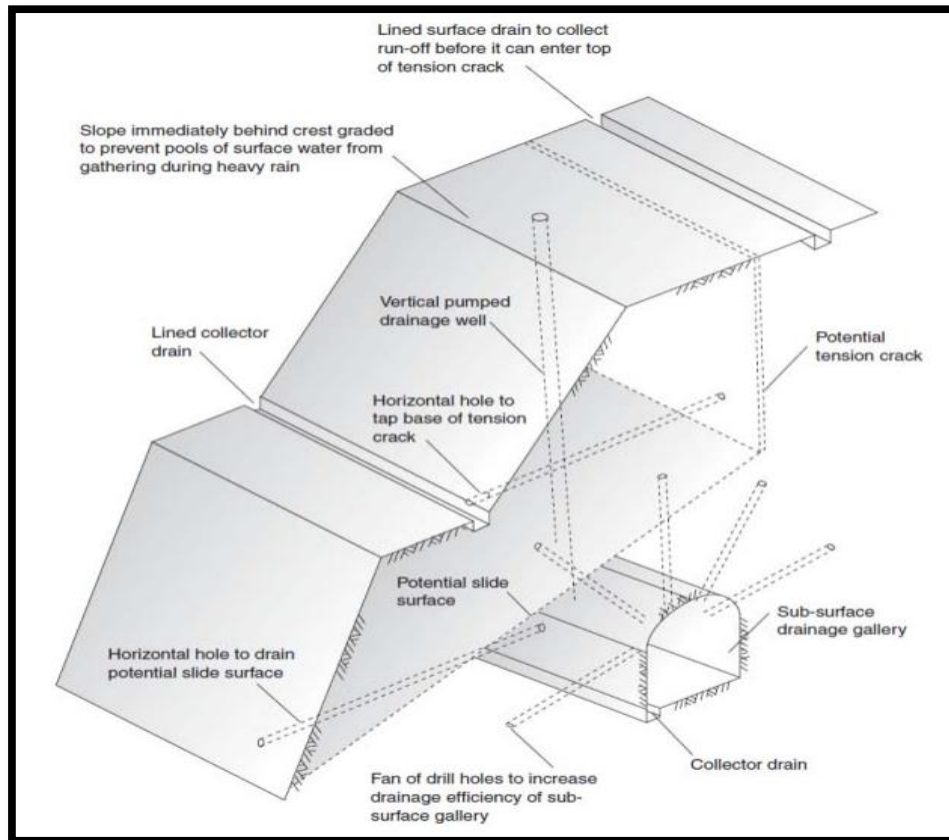


Figure 3.15: Drainage system provided with a gallery. (Duncan and Christopher, 2005)

2.3. Biotechnical reinforcement (vegetation)

Biotechnical stabilization and soil bioengineering are both manage to use of seeding grasses, vegetation, and mechanical elements or structures in combination with the plants to prevent erosion which can cause slope failure. Biotechnical stabilization is an association between vegetation with retaining structures. Plant material improves soil strength and cohesion through the extension of root system that also increases soil shear strength. Bioengineering methods provide additional support beyond that which can be provided by single plants. As the plants grow they increase the strength and the resistance to water and wind erosion, and shallow sliding. Roots reinforce the soil and increase cohesion that improves stability against failures. Plant roots reduce pore pressures inside slopes by absorbing the groundwater. The spread of flexible roots mobilize their tensile strength by friction between them and the soil and provides extra shear strength. Roots with large size intersect the failure plane behaving like anchors into the soil. Roots can also prevent crack forming in the slope.

A good planning is required before execution of this method of reinforcement, a local person with experience based on the success or failure of seeding projects in the area should be consulted to ensure that the solution will be effective in slope stabilization.

Before seeding begins, the slope should be as stable as possible to make the solution functional in increasing the slope resistant to erosion and future landslides. Controlling surface water drainage, removing loose rocks and cuts, decreasing the angle of the slope, and benching could make vegetation more effective. Seeding should be done in disturbance, every six weeks before dry periods or frost seasons. After seeding is done, it's useful to mulch the vegetated land, and that's by spreading materials which provide protection against surface erosion by rain and retention of soil moisture such as, grass fiber, wood fiber, seaweed and other types of mulching materials

A mixture of 2 to 5 species is the usual seed mix used to control erosion. The suitable seeds largely depend on the type of local soil, climatic situation, and species replacement. Local conditions control the used type of seeds, there is no global recommended type of grasses or legumes, and therefore it's better to take the advice from local people who are familiar with the growing conditions of the area. There are two types of plant seeding techniques used in this field:

Dry seeding

Dry seeding is done with rotary disk and air-blown seeders. These methods are less costly than hydraulic seeding but are limited to rough soil surfaces and gentler slopes. Rotary disk seeders spread seed and fertilizer by centrifugal force. The simplest seeder is the cyclone-type, hand-held seeder. Air-blown seeders use air to blow or shoot seed and fertilizer

a distance of 5 to 8 meters (15 to 24 feet). Equipment can be adapted for motorized vehicles. (Lynn M. Highland & Peter Bobrowsky, 2008)

Hydraulic seeding

This type of seeding is the application of seed in a water slurry that contains fertilizer, soil binder, and (or) mulch. The system requires a mixing tank with mechanical hydraulic agitation and volume pumping capacity. Hydraulic seeding is effective for seeding slopes 1:1 and steeper, where tacking of the seed to the slope is necessary. (Lynn M. Highland & Peter Bobrowsky, 2008)

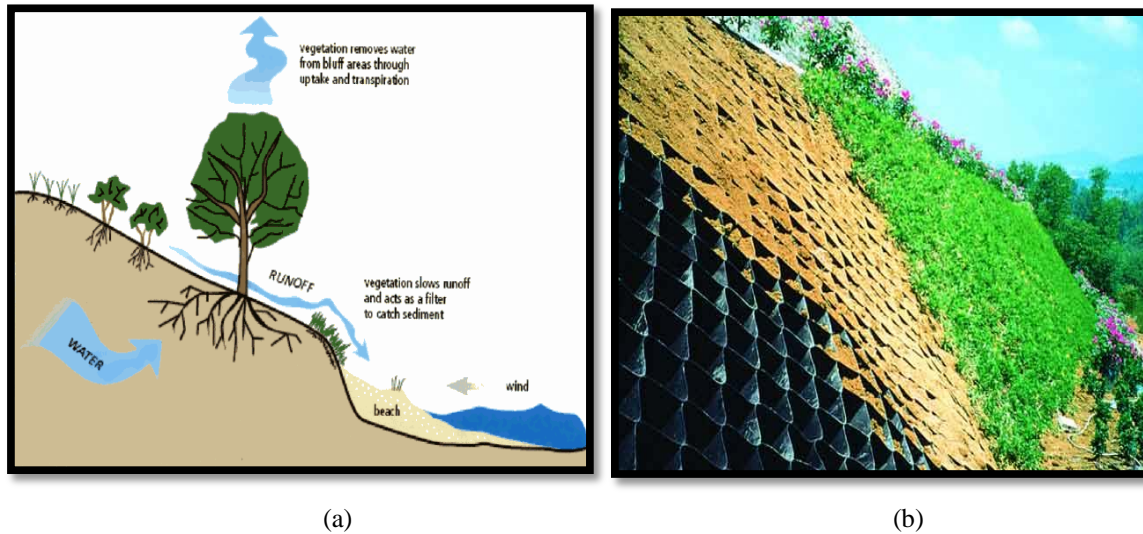


Figure 3.16: Slope vegetation.

(a) Function of vegetation. (<http://lakehuron.ca/>), (b) Embankment vegetation. (<http://www.mining-technology.com/>)

2.4. Support by tieback elements

This method is a main type of reinforcing slopes by materials with high resistance including steel reinforcement, anchors, nails, bolts, and high strength steel tendons. Many factors are involved in the selection of a suitable tieback material to ensure a long-term capacity such as tensile strength, creep characteristics, installation damage, and durability, resistance against pullout and reinforcement stiffness and tolerable strain within the slope.

There are number of methods which can be used to tieback the slope, each of them can be suitable for particular conditions. In choosing most suitable method a number of conditions must be considered and the method should be technically practical a number of parameters such as the purpose of stabilization, available time, equipment accessibility of site and the value of repair and maintenance.

Anchors

Anchors are usually units of steel materials that behave like chords or tendons, these units are placed in rock or soil to control movement and provide vertical or lateral support for natural slopes and retaining structures. The primary purpose of rock anchors is to control the normal and shear forces acting on the failure planes. These anchors may be fully injected and relieved, or anchored to the end and tensioned.

Tieback anchors are consists of a steel bar or cable of high strength installed in a drilled hole and tensioned to about 60 to 70% of its maximum strength. Tension in the member is transported to the rock mass around it by the points at the end of the anchor. The length of the anchor varies from 3 m to over 100 m. Holes for installation of the anchors are drilled in normal direction to cross the potential slip surface.

Normally, the lowest third of the hole is loaded with quick set cartridges of sticky material or resin and provided with a catalyst, and the top two thirds of the hole is loaded with slow setting sticky cartridges. Then the bar is installed into the borehole and rotated via a rock drill, to smash the plastic containers and mix the resin and the catalyst. After the resin takes its place, the anchor plate, bevel or washers, and the end nut are added to the anchor. Wedge washer may also be used where the end plate is not vertical to the bar. Then we load the bar by tension by tightening the end nut.

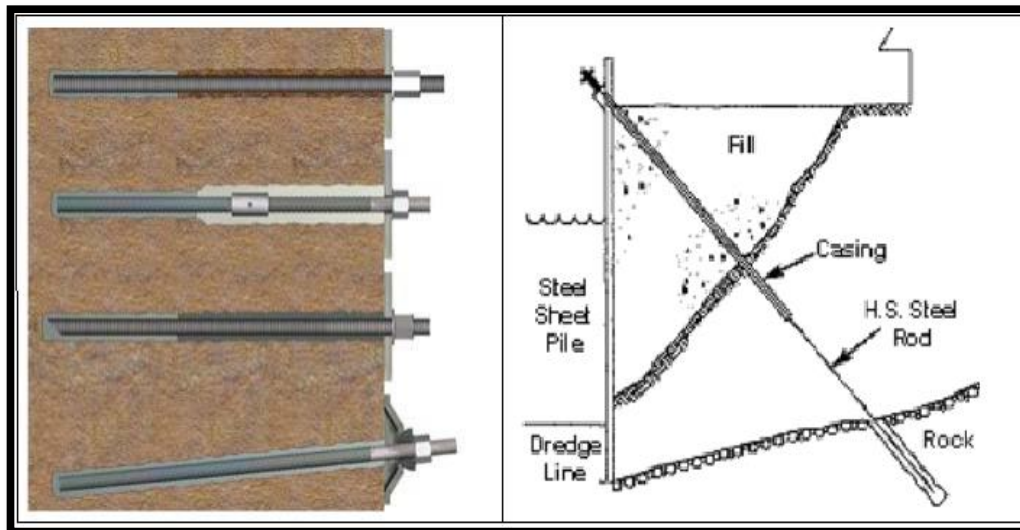


Figure 3.17: Rock Anchor. (<http://www.williamsform.com/>)

Rock dowels

Rock dowels are steel reinforcing bars or cables (reinforcement bars) that are planted into drilled holes. These bars usually being tensioned but in some cases they are not tensioned, Dowels without tension don not provide the slope with any normal force, but they add extra shear resistance across the slip surface.

Dowels are usually used to create additional support for steeply dipping and flat rocks on mountains formations. They also provide anchor keys and tieback slopes for more shear resistance, they also might be used to support retaining walls by adding them at the toe and flanks of the wall. Dowels can also be used to anchor rock catchments in case of potential rock fall, moreover they can be used to anchor draped wire mesh, pin wire mesh to the face of high walls.

The same as the thread bar anchors, dowels can be grouted in place with pumped grout or via cartridges of resin. When resin cartridges are used, the reinforcement bar is rotated and driven through the cartridges with the rock drill, to breaking the container and mixing the resin.



Figure 3.18: Rock dowels. (<http://www.iitbhu.ac.in/>)

Rock bolts

Rock bolts are used to support rock slopes and to strengthen fissured and loose rocks in cut slopes, by transfer the loads from the unstable face to the strong interior mass. Rock bolts come with variable lengths, they commonly vary from (1.2 to over 12) m, there diameters range from (10 to 51) mm. The use of wire nets or straps makes the reinforcement more useful with a rock-bolt pattern. In locations with highly jointed or fissured rocks, wire nets and meshes can be useful to hold the small rocks between the face plates in their place.

A general rule for rock bolts spacing is that the distance between face plates should be approximately equal to three times the average spacing of the planes of weakness in the rock mass and the bolt length should be twice the bolt

spacing (Hock and Wood, 1988). Rock bolts generally have heads that expand following installation and are classified according to their method of anchorage: expansion, wedge and grouted. (Rajesh Rai, IIT)

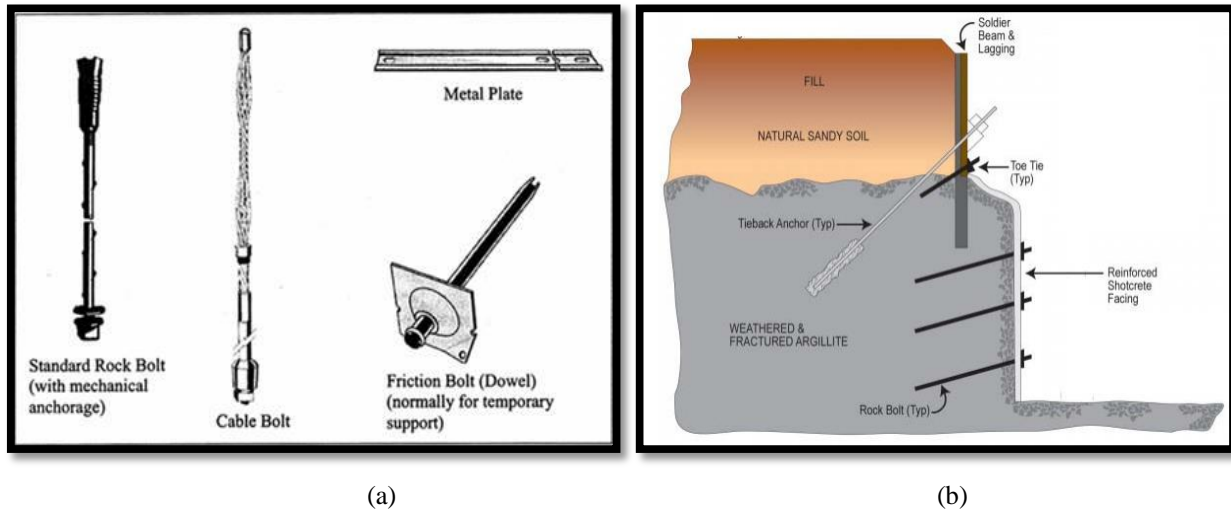


Figure 3.19: Rock bolt use in slopes. (<http://www.moretrench.com>). (a) Standard rock bolts. (b) The role of bolts in strengthening slopes.

Soil nailing

Nailing is a soil tieback technique that describes the anchoring of closely spaced tension resisting metal elements (nails) into the slope to add extra strength to the soil mass by resisting against tension, increases shear resistance, and bending stresses. Soil nails are either inserted in boreholes or installed with grout machines. Soil nails are commonly attached to facing concrete plates or shotcrete facing placed at the surface of the slope. The purpose of the facing is to interrupt the erosion of the surface material around the nails, rather than providing structural support.

This method is generally done by wall construction from the top down. A drainage system should be used on the exposed face, then the reinforced shotcrete facing is implicated. Precast facing panels can be used instead of shotcrete, by fixing them to the top points of soil nails, this process is repeated until reaching the depth of the designed wall.

The advantage of soil nailing is that its equipment is small enough to reach existing steep slopes and areas with difficult accessibility, soil nails can also be easily installed beneath existing structures or retaining walls. This method can be either permanent slope stabilization or temporary support to excavation works.



Figure 3.20: Soil nailing and shotcrete. (<http://www.haywardbaker.com>)

2.5. Retaining structures

Retaining structures are designed and engineered structure constructed to resist lateral forces produced by slope movements and pore water pressure. The commonly used structures in this method are the usual retaining walls which

are used in combination with fill slopes to prevent the slope extension and allow roads to be wider and to make additional space around construction areas. Retaining structures consist of gravity walls, cantilever and wall anchored walls, piles, and sheet piles.

The most important factor in designing and installation of retaining walls properly is to take in consideration that the retained land materials tend to move forward and down the slope because of gravity. This movement implicates lateral pressure behind the wall which retains it back, this pressure depends on friction angle and the mobilized cohesion of the soil behind the wall.

Lateral soil pressure is nonexistent at the head of the wall and in homogenous ground it increases with the increasing of depth. Lateral pressure can push the wall away from the slope or rotate it is not suitably considered in the design. Also, any groundwater behind the wall that is not discharged by suitable draining elements causes hydrostatic pressure on the wall. Unless this pressure is considered in the design of the wall, it is useful to have a suitable drainage system behind the wall to reduce the pressure value in the design and by that, reducing the cost. The following figure shows a typical retaining wall.

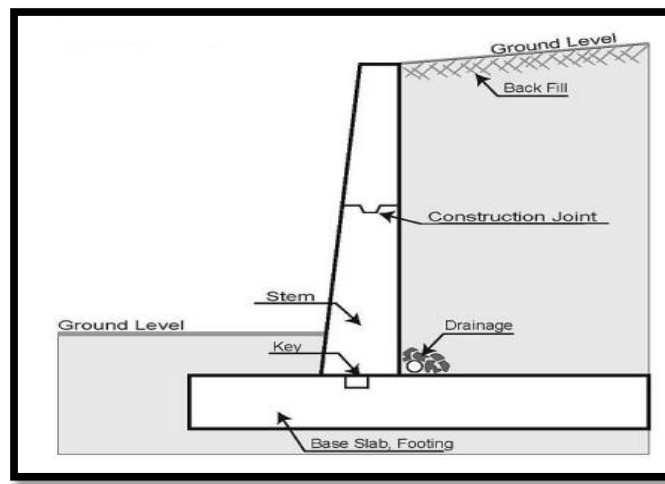


Figure 3.21: Retaining wall illustration. (<http://www.wikiwand.com/>)

Gravity walls

A gravity wall is a structure that depends on its weight for its own stability, and the slope stability. Weight is able to hold back the retained material, due to the wall construction. For this purpose, the mass of the structure must be enough to provide frictional resistance to sliding or overturning, and the base of the wall must be wide enough to develop a moment that resists overturning earth forces.

The thickness of the wall at the base must be more than that at the top. Construction of gravity walls requires high quantity of materials. That is the reason why these walls are difficult to build and get heavier as they get higher. Today, taller retaining walls are increasingly built as composite gravity walls such as: Geosynthetic or with precast facing; gabions (stacked steel wire baskets filled with rocks); crib walls (cells built up log cabin style from precast concrete or timber and filled with soil); or soil-nailed walls (soil reinforced in place with steel and concrete rods). (Rajesh Rai, IIT)

Gravity Retaining Walls

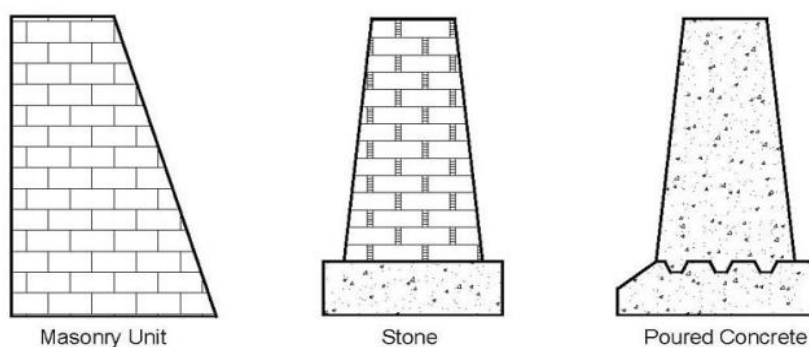


Figure 3.22: Types of gravity walls. (<http://www.wikiwand.com/>)

Cantilever walls

Cantilever walls retaining walls having uniform thickness and tied to a heel like footing. Suitably designed cantilever walls hold back enough amount of soil to keep the slope stable. These walls cantilever loads (like a beam) to larger structural footing converting horizontal pressures from behind the wall to vertical pressures on the ground below. Typical basements in a house are an example of these types of retaining walls. Cantilever walls are made in an inverted (T) form .which helps the walls in transforming the horizontal pressures. The footer of cantilever walls should be wide enough to prevent the wall from overturning. The thickness of the wall is also important. These walls are built with steel reinforcement.

Sometimes cantilevered walls are buttressed on the front, or include a counterfort on the back, to improve their strength resisting high loads. Buttresses are short wing walls at right angles to the main trend of the wall. These walls require rigid concrete footings below seasonal frost depth. This type of wall uses much less material than a traditional gravity wall.

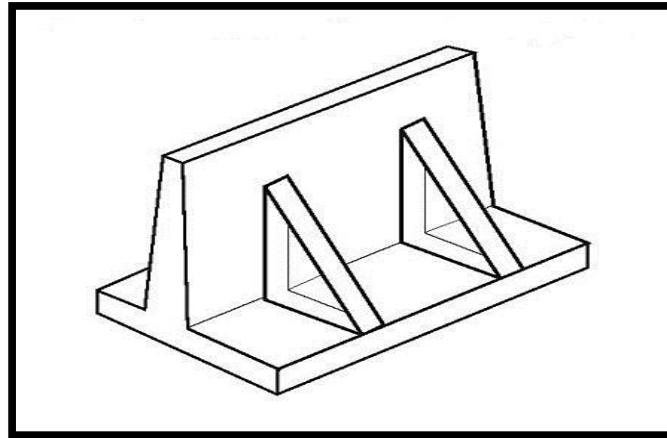


Figure 3.23: Cantilever wall with Counterfort/Buttress. (<http://www.wikiwand.com/>)

Sheet piling

Sheet pile retaining walls are usually used in soft soils and tight spaces. Sheet pile walls are made out of steel, vinyl or wood planks which are installed into the ground vertically. For a quick estimate the material is usually driven 1/3 above ground, 2/3 below ground, but this may be altered depending on the failure plane and other characteristics.

Tall sheet pile walls should be tied back by anchors, or "dead-man" placed in the soil to a calculated distance behind the sheet piles, that is tied to the wall, usually by a cable or a rod. Anchors are then placed behind the potential slip surface in the slope. Proper drainage system should also be involved to reduce the water pressure that may affect the stability of the wall.

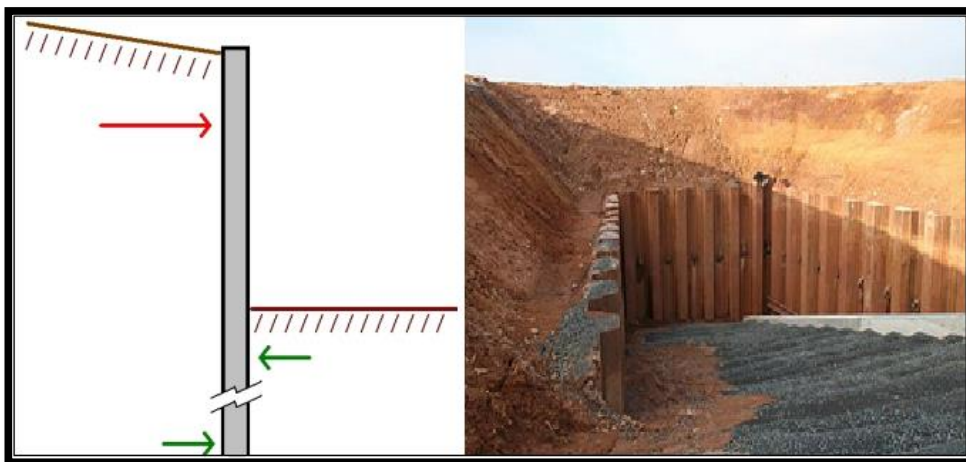


Figure 3.24: Sheet piling wall. (<http://www.wikiwand.com/>)

Anchored retaining walls

An anchored retaining wall can be any type of the previous retaining walls, but also includes additional support using cables or rods or other kinds of anchors secured in the rock or soil behind it. Commonly installed boreholes that reach strong substrata, or bedrock anchors are then expanded at the end of the cable, either by mechanical means or often by injecting concrete, which expands to form a bulb in the soil. Technically complex, this method is very useful where high loads are expected, or where the wall itself has to be slender and would otherwise be too weak.

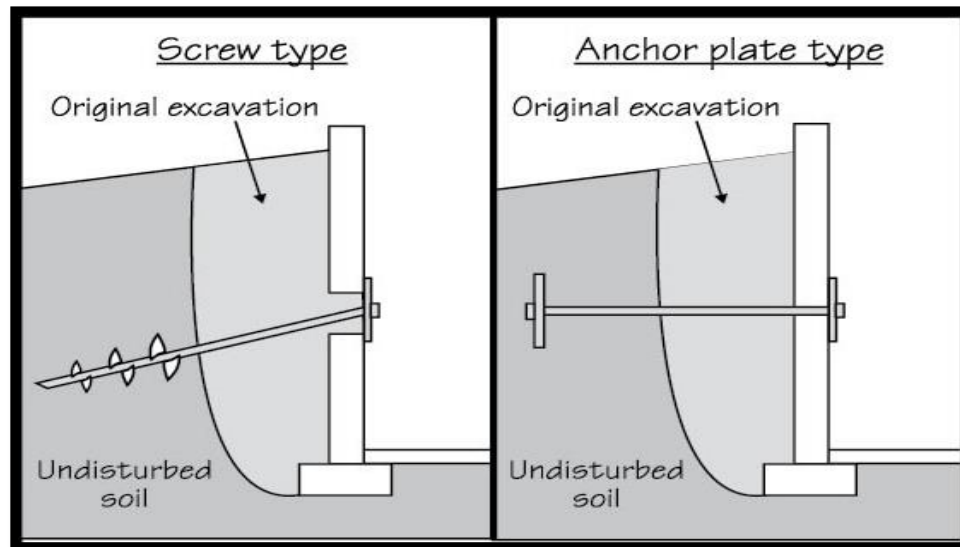


Figure 3.25: Anchored retaining walls. (<http://www.soundhomeinspections.com/>)

Gabions

This type of slope strengthening is often used without an outside wall. Gabions consist of wire mesh “boxes”, cylinders, or cages, which are filled with cut stone, large rock blocks or other material. The net cages reduce some internal movement and forces by the same principle as gravity walls, and also reduce erosion. Gabion walls can provide water drainage since they consist of stones that allow the water to flow into the wall and as such are usually built in areas that contain ground water. However, considering and controlling of the water in and around all retaining walls is important.

Gabion walls usually are inexpensive and are simple and quick to construct. Due to their flexibility, they can withstand foundation movement, and they do not require elaborate foundation preparation. Because of their coarse fill, they are very permeable and thus provide excellent drainage. Gabion walls work because the friction between the individual gabion rows is very high, as is the friction between the basal row and the soil underneath. When failure occurs, it is almost always in the foundation soil itself. (Lynn M. Highland & Peter Bobrowsky, 2008)



Figure 3.26: Gabion wall. (<http://galleryhip.com/>)

Reinforced earth walls

This type of retaining walls is a system of fill construction at very steep to vertical angles without the use of supporting structures at the face of the fill. The system uses horizontal layers of flexible metal strips within the fill to form a composite earth-metal system with high strength.

Reinforced earth retaining walls are an economical method of stabilization earth retention needs for highways, railways and bridge grade separations, and mass transit systems, waterfronts, airports, loading docks, industrial facilities and commercial and residential developments.



Figure 3.27: Reinforced earth. (<http://www.retainingsolutions.com.au/>)

Timber crib

Timber crib walls are box structures built of interlocking logs and backfilled with coarse aggregate. They work by intersecting the critical sliding surface, thus forcing the potential failure surface to a deeper, less critical depth. The structure must be able to withstand shearing, overturning, and sliding at the base. It must, therefore, be strongly built by burying to sufficient depth and extending beyond the critical failure plane. Crib walls are only effective where the volume of soil to be stabilized is relatively small. They are most efficient where a thin layer of unstable soil overlies a deeper, more stable layer of soil. Crib wall structures should have a volume equal to 10 to 15 percent of the volume of the soil to be stabilized. This relatively small volume provides little counterweight support at the toe; therefore, virtually the entire resistance to failure comes from the strength of the crib. (Lynn M. Highland & Peter Bobrowsky, 2008)

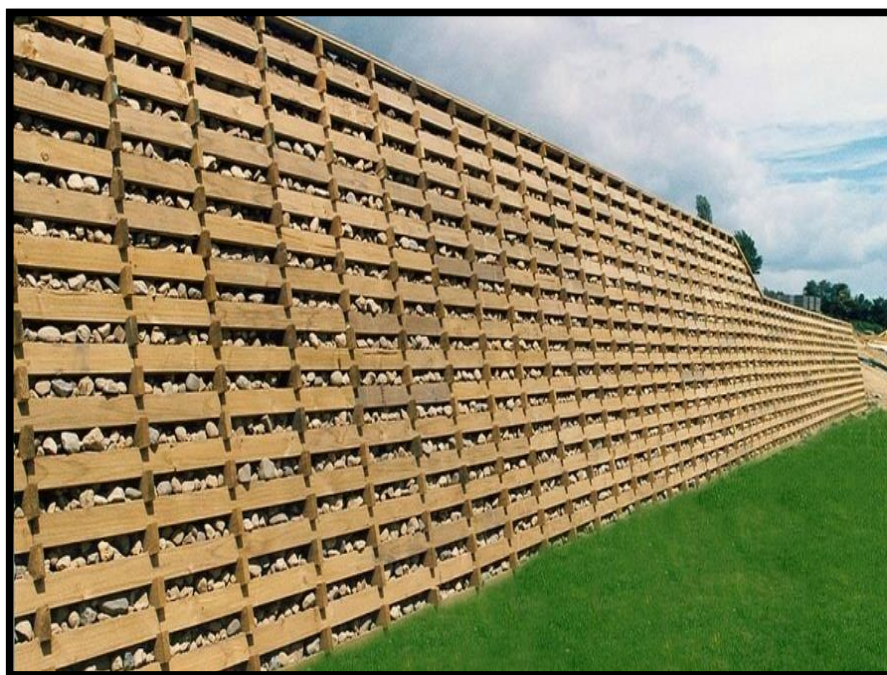


Figure 3.28: Timber crib wall. (<http://www.ccsmidlandsltd.com/>)

2.6. Geosynthetic reinforcement

Geosynthetics are high flexible manufactured fabrics used to strengthen and provide the stability of structures like earth fills, and by that allow steeper cut slopes and less grading in hillside terrain.

Geosynthetics with different tensile strengths are used for a different of stability problems, with a common use being reinforcement of sides of roads constructed on loose soils. Geosynthetics and their related materials are generally classified according to their manufacturing process. Geosynthetics can be knitting, woven, non-woven or composite. Related Geosynthetic products in use are webs, mats, nets, grids, plastic sheets or composite structure. Geosynthetics are also good for filtration, drainage process, separation, reinforcement, fluid barrier and protection. And they are classified into the following:

Geotextiles

These are permeable textiles woven or non-woven synthetic polymers. Woven fabrics consist of two threads (warp and weft) combined systematically by making them cross each other perpendicularly. Threads could be multi-filaments or thick mono filaments, or tape threads. Multifilament threads are made of polyester and polyamide; polypropylene and polyethylene are used to make tape threads. Non-woven fabrics consist of randomly placed short fibers (60 to 150 mm) or continuous filaments.

Geotextiles are permeable fabrics which associate with soil. They are able to create isolation, filtering, reinforcing, protecting, or to control drainage. These materials are generally made from polypropylene or polyester, geotextile fabrics and come in three basic forms: woven (resembling mail bag sacking), needle punched (resembling felt), or heat bonded (resembling ironed felt).

Originally, geotextiles were manufactured as filter materials, but the use of these materials has developed to introduce erosion control when used behind or under precast walls, and most importantly geotextiles are used in slope stabilization engineered application, to improve soil strength, in these applications two important factors must be considered:

- The required tension for the equilibrium
- The suitable layer of geotextile reinforcement

Geogrids

This type of reinforcement is relatively stiff and manufactured as meshes with large spaces between the ribs that make. Geogrids are commonly used to reinforce retaining walls and they can be used to reinforce aggregate layers in pavements and for construction of geo-cells to improve bearing capacity. Geogrids are formed by a regular network of tensile elements with apertures of enough size to interlock with the fill material around them.

Opposite to soil, this material has high resistance to tension, and the main principle in utilizing Geogrids is to transfer tension forces to larger area of soil. Geogrids are usually made of polymer materials, like polyester, polyethylene or polypropylene. They may be woven or from strings, welded by heat from strips of material, or produced by punching a regular design of holes in sheets of material, then stretched into a grid.

Geomembranes

This type is an extremely low permeability synthetic membrane liner or barrier composed of asphaltic, polymeric materials with sufficiently low permeability so as to control fluids, drain water, and to control gas migration into structures. Geomembranes are made from relatively thin continuous polymeric sheets, or they can also be manufactured from the impregnation of geotextiles with asphaltic materials, elastomeric or polymer resin sprays. By far, mostly common used type is the continuous polymer sheet Geomembranes.

These materials have to pass a number of physical, and mechanical tests that have been developed to determine the strength of these materials, these tests represent the quality control, design, performance, and attempt to chart the lifetime of these fabrics. Tear resistance, tensile strength, impact resistance, interface shear strength, thermal behavior, radioactive and chemical degradation, and other properties are managed to be determined by these tests.

Geocomposites

These are various combinations of geotextiles, Geogrids, Geomembranes and/or other materials to serve all the primary functions with better performance. Most Geosynthetics are made from synthetic polymers such as polypropylene, polyester, polyethylene, polyamide, PVC, etc. These materials are highly resistant to biological and chemical degradation. Natural fibers such as cotton, jute, bamboo, etc., can be used as geotextiles and Geogrids, especially for temporary applications. In contrast to the smooth surfaces that steel reinforcements usually have, most Geosynthetic have fabric-like surfaces (geotextiles) or grid structures (Geogrids) that produce much better bonding between soil and the reinforcement. (Rajesh Rai, IIT)

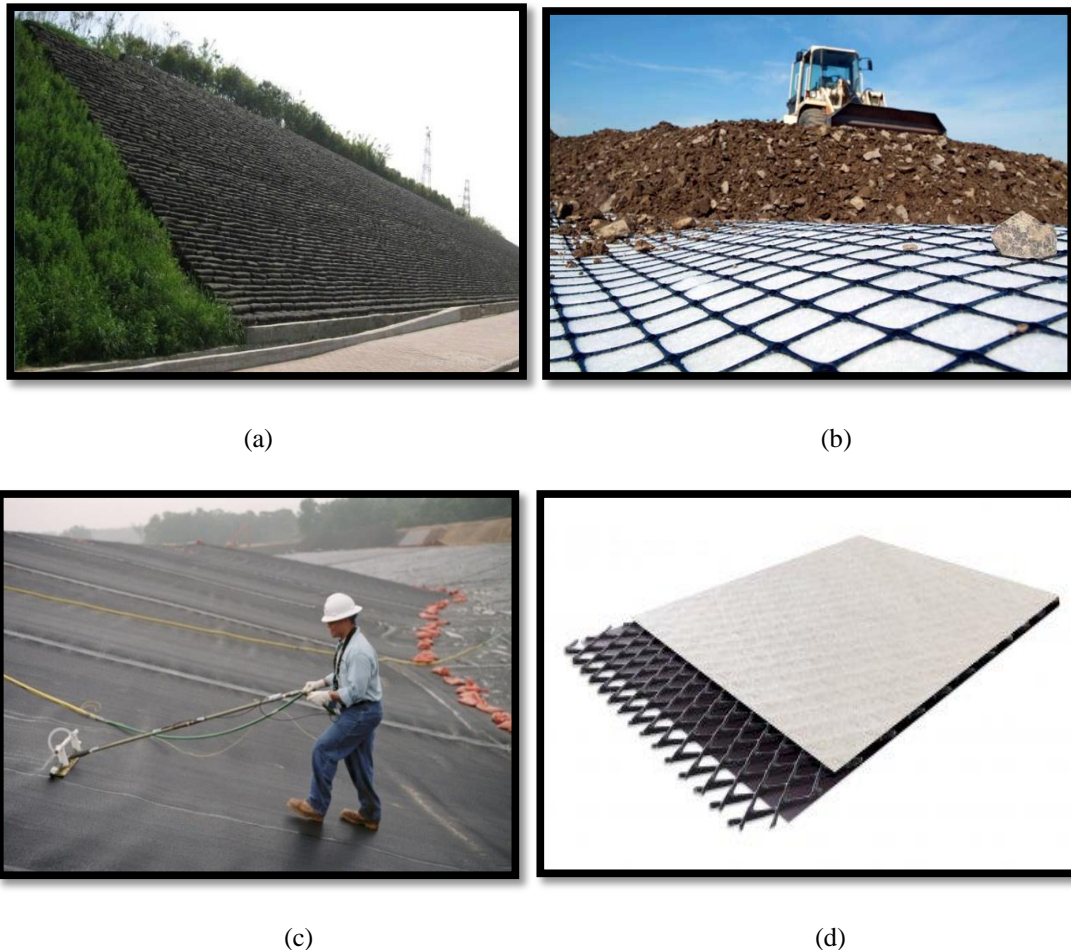


Figure 3.29: Geosynthetic products. (a) Geotextile, (b) Geogrids, (c) Geomembranes, (Geocomposites (<http://www.ilsa.com/>))

2.7. Other methods of stabilization

In addition to the previous methods, there is many methods that have been developed, as slope engineering and stabilization makes a great field of countering hazards, to protect human lives and properties. Some of these methods are the following:

Grouting

Grouting is cement, silicate, polyurethane or acrylamide based slurry, viscose enough to be poured or injected into the slopes face or layers and thereby fill, seal, or compact the soil around it. Grouting is implicated through pressure injection of the slurry in boreholes screwed into fissured, jointed, permeable rocks and compressible soils to reduce their permeability and increase their strength. The type and amount of grout that is needed in a stabilization of slope is generally based upon grain size distribution, density, water content, and chemistry of the soil, as well as desired function of the grout. Grouting is often viewed as a versatile method of ground improvement for application in difficult soil and rock conditions.

Check dams

Check dams are small, sediment storage dams built in the channels of steep gullies to stabilize the channel bed. They are commonly used in Europe and Japan to control channelized debris-flow frequency and volume. A less common use of check dams is to control raveling and shallow slides in the source area of debris slides. Check dams are expensive to construct and therefore are usually built only where important installations or wildlife habitat, such as a camp or unique spawning area, lie down the slope. Channelized debris flows are associated with channel gradients over 25 degrees and obtain most of their volume by scouring the channel bed. Check dams serve three purposes when installed in the channels. (Lynn M. Highland & Peter Bobrowsky, 2008)

- To protect from the incident of failure by reducing the channel gradient in the upper channel
- To reduce the volume of channel stored material by preventing down cutting
- To store the debris flow sediment in the lower part of the channel

When installed on debris flows, the dams store material, which creates small stairs on the slide, reducing the slopes surface. Check dams can be constructed of reinforced concrete or log cribs. Concrete reinforced rock dams do not usually exceed 8 m in height, and log crib dams must not exceed 2 m. The spacing of dams depends on channel gradient and dam height. For example, 2 meters high dam in a 20-degree channel with 10 degree sloping channel infill will be spaced every 12 m. Lateral stream erosion and scour by spillway water are the main challenges that face this type.

To failures during construction, the concrete wing walls and log crib ends must be tied securely into the canyon wall and streambed to resist backfill pressures. Wing walls gradient should be about 70 percent and its minimum length should be about 1–2 meters extending into the banks. The foundation of the dam should have a minimum width of one-third of the total height of the dam and be deeper than any scour holes likely to develop. Backfilling the dam, rather than allowing it to fill naturally, reduces the dynamic loading on the structure and results in a more stable design. The gradient of the backfill should be less than the half of the channel gradient. Dams that have been back filled usually will resist flows. The backfill material will not be scoured during or after a torrent.



Figure 3.30: Check dams. (<http://www.crossvermont.org>)

Catchments

Catch ditches are used to contain rockfalls, wide ditches should be designed with considering the cliff geometry, and it is better be designed by to a professional engineers to set the specifications. The bottom of the catchment ditch should be covered with loose earth to prevent falling rock from bouncing or breaking into pieces. If there is not enough space to install ditches with the specified width, then groups of smaller ditches with a gabion or rock wall along their downhill edges can be used.

These catchments can be constructed with a mesh form, cables, ditches, or rock curtains. Cable lashing and wire nets are practical and inexpensive methods for protecting roads from rockfalls. For bigger, rock blocks, strains or fences of steel cable should be placed on to contain the blocks and tied to the slope by anchoring. Where the rock is too fractured to be restrained by individual cables, cable nets are used. Wire mesh can is useful to prevent smaller rocks, less than 0.75 meters in size, from falling. The mesh is either loosely draped over a uniform rock face or anchored by bolts or otherwise firmly secured where the cliff face is irregular and the mesh cannot make close contact with the rock. Bolting the mesh to the rock face can prevent rock from displacing and provides additional stability of the slopes face. Wire mesh also effective on steep soil cuts.

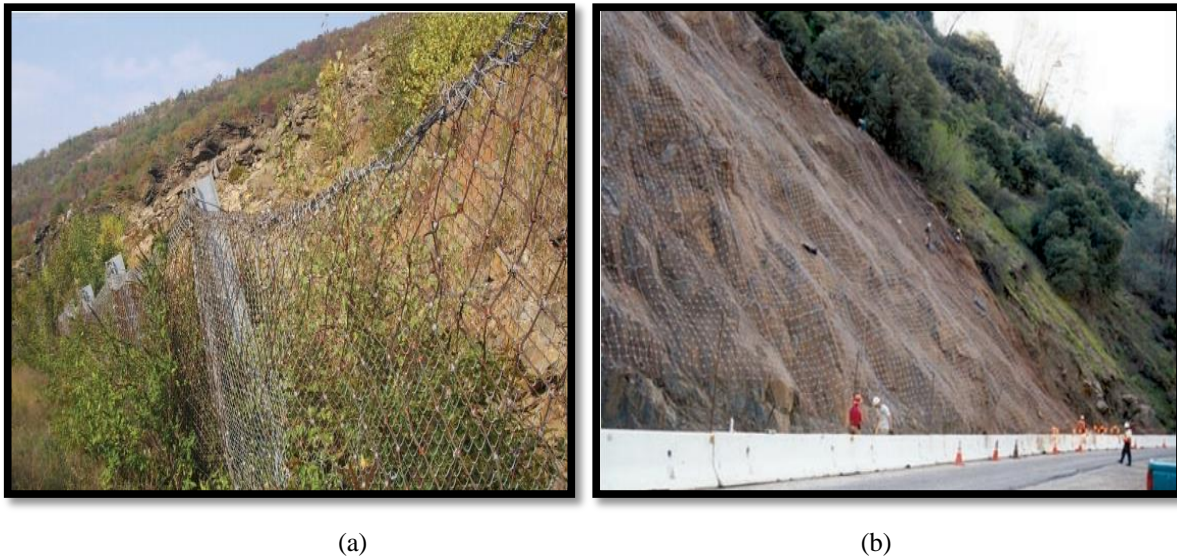


Figure 3.31: Rock catchments. (a) Rock barrier fence. (b) Wire mesh.
(Lynn M. Highland & Peter Bobrowsky, 2008)

Shotcrete

Shotcrete and gunites are types of concrete that are applied either by wet or dry application, or directly jetted onto the surface of unstable slopes. For dry mix shotcrete, mortar and additional materials (chemicals) are mixed on site and pumped using compressed air to the nozzle, where they are provided with water. The wet mix is premixed to specific measures and then transported to the site in bulk.

Mesh reinforcement, steel or polypropylene fibers are accompanied with the shotcrete mix and form reinforcement throughout the shotcrete layer. The steel fibers are made of high strength carbon steel with a length of 30–38mm and diameter of 0.5 mm. The purpose of fibers is to add more shear, tensile and post crack strengths of the shotcrete.

Steel fibers, when used in the mix, increase the tensile strength of the shotcrete by providing numerous bonding surfaces within a small area. The fiber reinforcement also reduces the risk that mix shrinking cracks will show up during curing. In many cases, the addition of fibers can replace wire mesh as reinforcement, thus reducing the cost of this method.

It is important to add drainage holes to reduce water pressure behind the shotcrete. Metal PVC pipes, are installed before the shotcrete application into joints in the slope face where seepages may occur, these pipes will partially drain the water. Other drain holes should be created at regular intervals along the slope face.



Figure 3.32: Shotcrete. (<http://www.knowlesindustrial.com/>)

Piles

Piles with large diameters can be inserted into the toe of a slope to create a wall of vertical closely spaced piles wall. Pile walls are normally used as a pre-excavation restraint system, the cut slope excavation is done in front. Whereas large diameter concrete pile and culvert pile walls have been used successfully on highways, wood or steel piles that are small in diameter have not. For most earth or rock movement, wood piles are not adequate to provide enough shearing resistance.

They are suitable only where the volume of soil to be stabilized is small. On average, one wood pile is necessary for every 50 cubic meters of soil, which is not sufficient for large stabilization projects. Too few piles can result in toppling and (or) breakage by the moving mass of soil, as well as by soil movement between the piles.

A major limitation when log piles are used is depth, as many failure surfaces lie below the height of the piles. Wood piles are the best for shallow soil failures over deeper stable soils. The piles should extend well below the potential failure surface and be firmly driven into firm subsoil. If the depth of placement is not sufficient to allow the piles to act as a cantilever system, then the piles must be tied back with an additional anchor system. (Lynn M. Highland & Peter Bobrowsky, 2008)



Figure 3.33: Pile Wall. (<http://www.aiclasspiling.com.au/>)

Steel bin walls

These walls consist of corrugated galvanized steel attached together to create a box and then filled with soil materials. The stability of a steel bin wall comes from the weight of the wall itself, and the weight of soil in front of the wall. The bulk of the weight is from the filled soil, not from the steel, and this must be considered when making the wall foundation. Large walls must be individually engineered, with load and foundation requirements calculated. Structural and civil engineering design charts provide stringer (horizontal member) specifications and height to width ratios for typical loading conditions. The widths of walls generally vary from 2 to 5 meters and are one half to three fifths the height of the wall. To aid the wall with extra sliding resistance, the foot of the wall is usually 0.5 to 1.0 meter below grade, although the design should not rely on the additional toe support, as it can erode or be removed inadvertently. The factor of safety is improved if the wall is at a 1:6 slope. Fill material must be well drained and compacted, preferably in 20-centimeter lifts. Material behind the wall also should be well drained and moderately compacted.

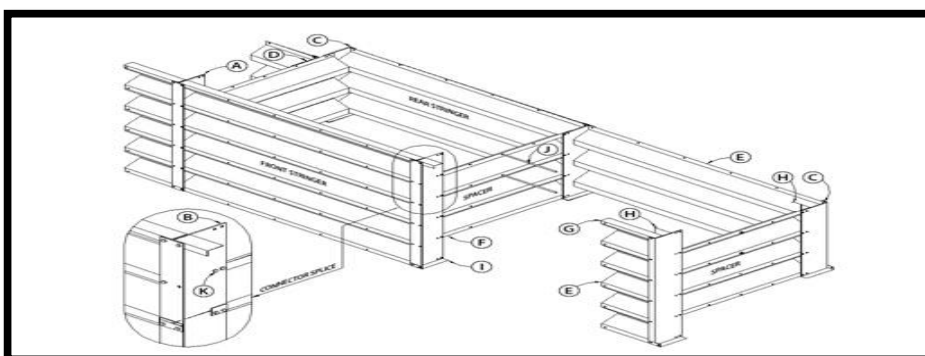


Figure 3.34: Steel bin wall. (<http://www.aill.ca/>)

3. How to choose the stabilization method??

The selection of appropriate mitigation measures should be based on an assessment of risk, uncertainty, possible consequences, constructability, environmental impacts and costs. A final mitigation approach usually consists of a creative combination of several methods. Environmental constraints and requirements can influence the selection and overall design of mitigation measures.

When selecting a specific stabilization method, it is best keep it simple to match the capabilities of contractors and the availability of materials. Constructability and construction requirements should be evaluated, including sequencing, temporary support, and protection of nearby property, facilities, utilities, traffic and the public. Construction can be further complicated if slide movements are occurring or can be triggered by excavations, grading and changes in water conditions. The possible unstable conditions that can be caused or encountered during construction should be identified and potential solutions determined. Timing of construction could be an issue, particularly to avoid periods when groundwater conditions are adverse and when ground movements are significant.

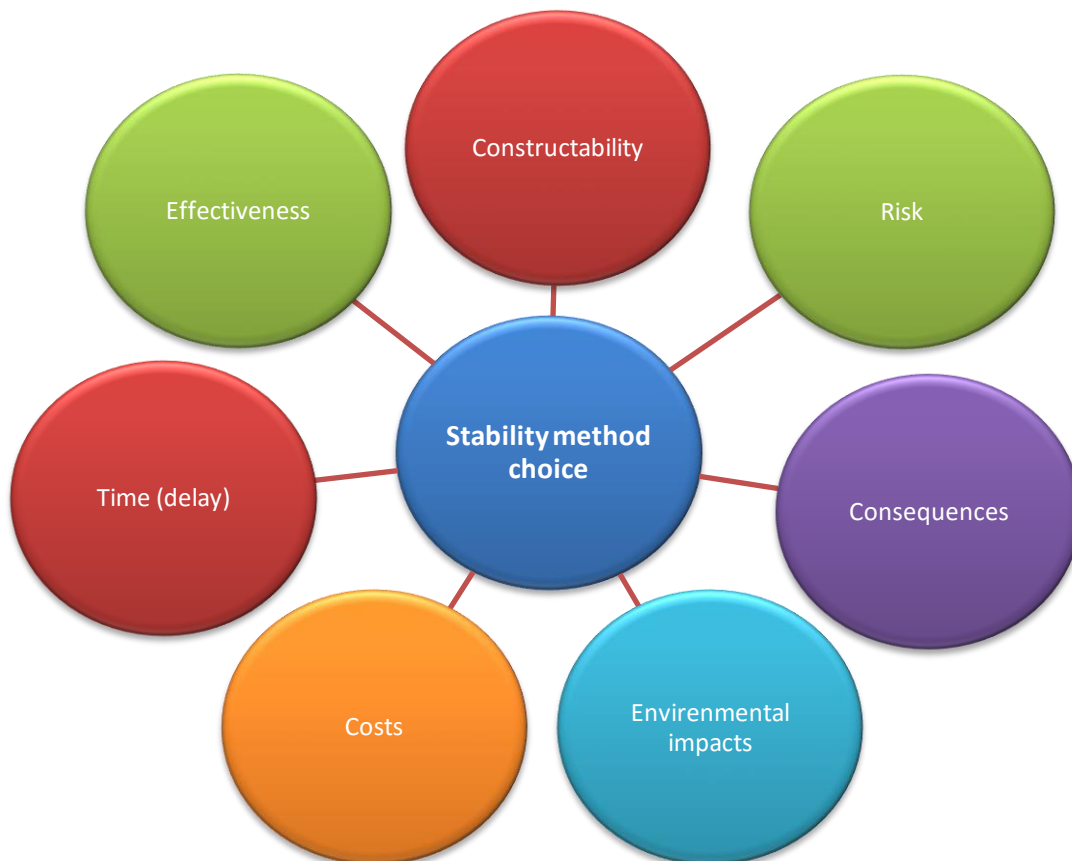


Figure 3.35: Standards of choosing the stability method

In difficult and constrained situations, it might be necessary to use structural solutions, which could increase the complexity of construction. Structural systems require special design and sequencing to account for possible slide movement during construction and to provide sufficient capacity in each structural member that will not be exceeded at any time during or after construction. In many cases, weak and clayey soils exist in landslides that could creep when loaded, and could be a factor in design of foundations and anchors. The mere act of constructing mitigation measures does not always stop ground movements immediately. Often, cracks caused by land sliding leave voids in the ground that could take time to compress or fill-in. Mitigation measures often rely on movement of the slide mass to mobilize new resistive forces. Following mitigation, slide movements tend to slow down prior to stopping and could take years to reach final stability. Where on-going movement is anticipated, the selected option must be capable of accommodating such movements. The maintenance requirements associated with each mitigation option should be considered to understand the potential long-term impacts and costs. This includes identifying procedures, equipment, frequency and level of effort that would be required for maintenance and the consequences when such maintenance is not performed. Another consideration is to evaluate whether the mitigation measure will experience a reduction in effectiveness over time due to potential damage, weakening, plugging, vandalism, or due to indirect effects of nearby development and activities.

4. Conclusion

Since landslides and other kinds of slope failures pose a threat to human lives, buildings, roads, and environment, it's very important for us to confront this danger by carefully studied ways, this confrontation is better be by avoiding the catastrophe rather than reparation, many methods has proven their effectiveness in this field. The present chapter introduces the mostly used methods of slope stabilization and failure mitigation systems, the description and characteristics of each method, and when to use each one of these solutions, this of course after a proper investigation. The next chapter will treat a real case study with a solution.

Chapter IV:
Case study

1. Introduction

In this chapter we managed to analyze a real case landslide and to study and try to find a suitable solution for the prone area. The project site is located immediately adjacent to the national route to the westbound of the state of Ain Temouchent, exactly in the AEK village.

The project site is divided into three independent slopes, all of them are situated to the north side of the national route n35. Including the human activity of cutting the slope in order to make a path for the previous road, the slide is a result of many other factors, such as, the rainwater, the geological nature of the site, and the geometry of the slopes.

These analyses aim to determine the critical factor of safety and the potential slip surface of each slope, in order to find a long term stabilization method for the site, the analyses are based on a geotechnical experiment done by the L.T.P.O, and done by the software application Slope/w that presented chapter 2, and the elevation of the hills is determined by Google Earth Pro.

2. Site description

2.1. Location and geography

The prone area is situated in the village of El Emir Abdelkader to the west of the state of Ain Temouchent, on the north coast of Algeria.



Figure 4.1: Site location. (Google Earth Pro)

The site on the national route n35 is divided into three sections or slopes in these analyses, slope 1, slope 2, slope 3, with lengths of approximately 300 m, 310 m, and 385 m for each slope respectively, and to the west side of the route. The site is about 750 m away from the village center, but the slopes extend directly beside the route, which threatens the travelers and the vehicles.

2.2. Geology of the site

The terrain basically consists of marl, this type of soil is generally a calcium carbonate or lime-rich mud or mudstone which contains variable amounts of clays and silt. The dominant carbonate mineral in this type of soil is calcite, but it maybe contains other carbonate minerals such as aragonite, dolomite, and siderite. The term Marl can describe many materials, such as, earthy deposits consisting chiefly of an intimate mixture of clay and calcium carbonate, formed under freshwater conditions, specifically an earthy substance containing 35–65% clay and 65–35% carbonate. In our

terrain the marl contains a percentage of soft sulfate minerals (Gypsum) in layer forms. The characteristics of the basic materials of the slope are:

- Unit weight γ [KN/m³]: 19 for the marl and 10 for the gypsum
- Friction angle ϕ' [°]: 20 for the marl and 35 for the gypsum
- Cohesion C' [KPa] : 10 for the marl and 5 for the gypsum

2.3. Geotechnical report

According to the geotechnical report done by L.T.P.O after borings and soil experiments in the year 2009, we have distinguished the characteristics:

- The sliding mass is affected by natural and human factors such as, the angle of the slope, the angle of repose of marl, the road cut and excavation, rainwater, and the increasing interslice pressure.
- The slip surface takes the shape of a curve (considered as a deep seated landslide)
- The marl is perfectly situated for the rain water to flush and run along the slope surface which caused erosion and tension cracks
- The cracks allow the water to leak increasingly to the substrata of the soil which lubricated, saturated, and increased the volume and weight of the marl, and drove the terrain to the phenomenon of landslide
- The changing of the geomorphological nature generated bigger cracks at the toes of the slopes. The gypsum and calcite joints through the marl are sediments caused by these cracks and fractures, these fractures make paths for the water to escape to the substrata.
- There are opened cracks behind the head scarp of the slide, these cracks are with several forms along the crown of the slide, making yet another path for the rain water
- The gypsum masses which vary on the face degrade by time which creates cavities on the surface
- Due to the presence of limestone there are blackish oxidized areas related to the water flow
- There are many tension cracks that threat the condition of the slopes
- The thin gypsum layers makes it easy for the mass to slide

2.4. Summary of the current situation

The basic component (marl) is red with blackish areas due to oxidation by the water, there are also visible signs of cavity caused by the water flow on the gypsum parts. There are many areas that experienced partial mudflows and erosion due to rain water on the three slopes. The three slopes were a subject for a benching stabilization process, the first slope is already stabilized by a masonry unit wall, Geotextile, and a surface drainage system. The second slope also contains surface drainage system.

3. Case study and analysis

These analyses are done by using an application of Geostudio 2007 (Slope/w), the elevation of each slope is determined by adding a path on the studied area on Google Earth, and choosing the command (show elevation profile). Due to the long distance that each slope extends on, we divided each slope into two areas, and we analyzed each area twice, once before the road cut and benching, and another after each slope took its current shape.



Figure 4.2: Analyzed sections. (Google Earth Pro)

3.1. The first slope

Area 1.1



Figure 4.2: Area 1.1 section. (Google Earth Pro)

- Before cut and benching :

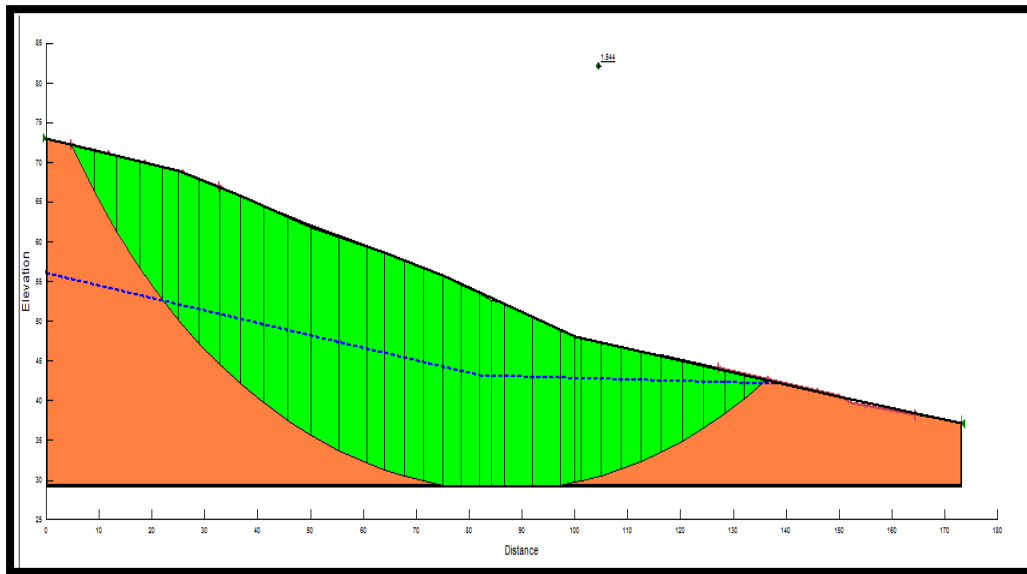


Figure 4.3: Area 1.1 the critical slip surface at initial situation

Table 4.1. Result summary, area 1.1 (initial)

Method	Factor of safety	Situation
Ordinary	1.35	Unstable
Bishop	1.542	Stable
Janbu	1.394	Unstable
M_P	1.544	Stable

- After cut and benching :

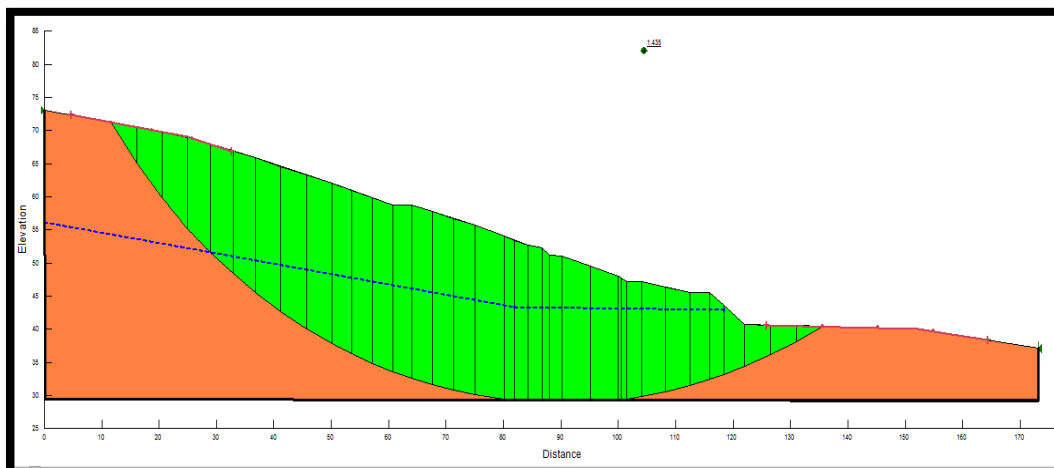


Figure 4.4: Area 1.1 the critical slip surface at final situation

Table 4.2. Result summary, area 1.1 (final)

Method	Factor of safety	Situation
Ordinary	1.268	Unstable
Bishop	1.433	Unstable
Janbu	1.3	Unstable
M_P	1.435	Unstable

Area 1.2



Figure 4.5: Area 1.2 section. (Google Earth Pro)

- Before cut and benching :

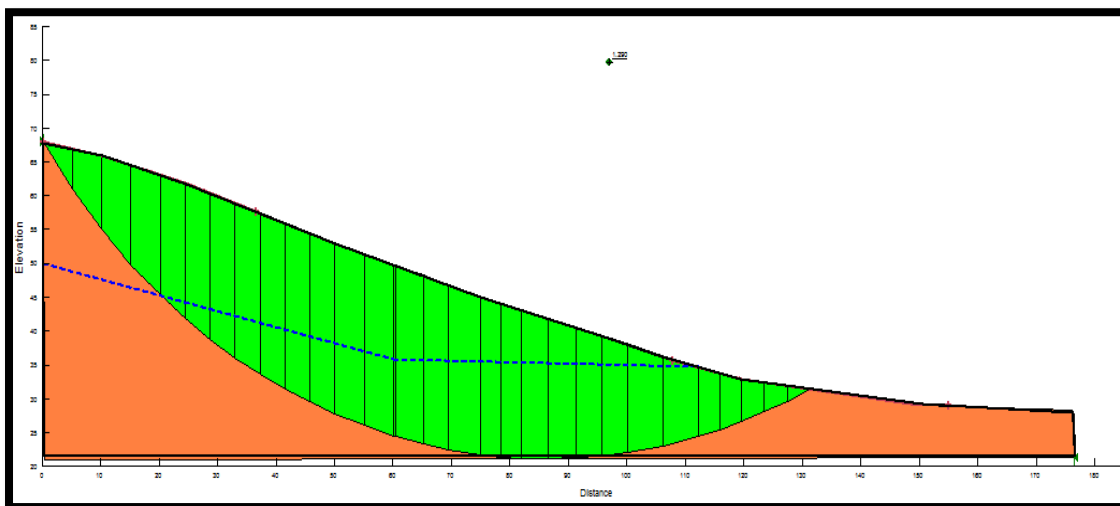
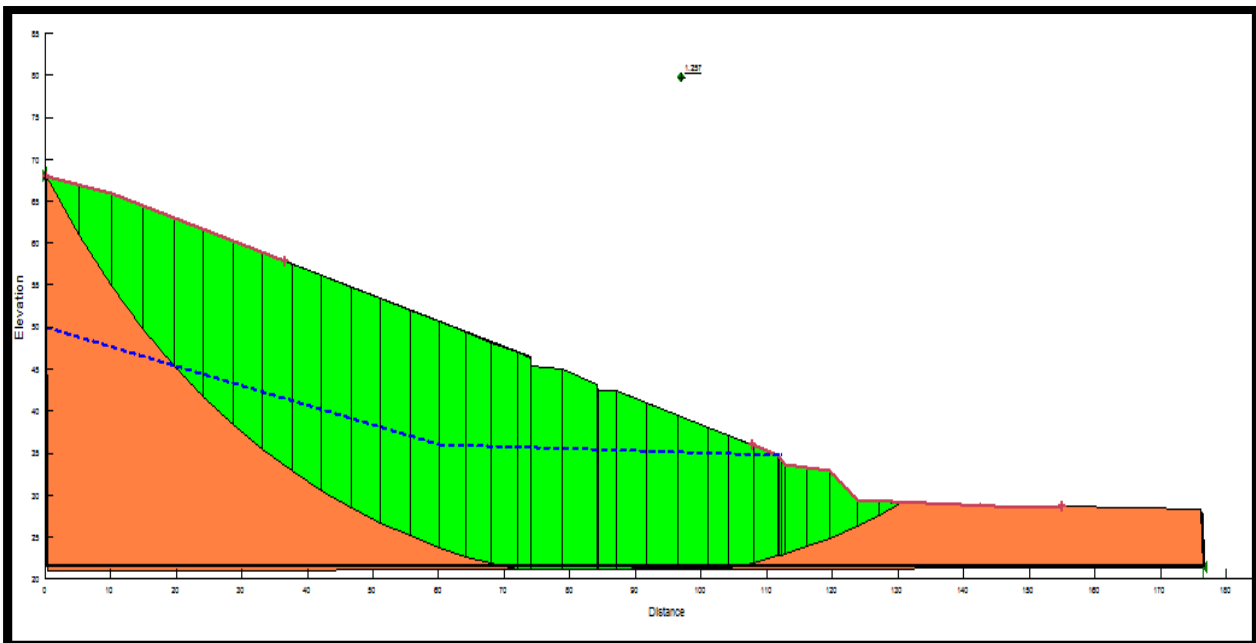


Figure 4.6: Area 1.2 critical slip surface initial situation

Table 4.3. Result summary, area 1.2 (initial)

Method	Factor of safety	Situation
Ordinary	1.138	Unstable
Bishop	1.288	Unstable
Janbu	1.174	Unstable
M_P	1.29	Unstable

- After cut and benching :

**Figure 4.7:** Area 1.2 critical slip surface final situation**Table 4.4.** Result summary, area 1.2 (final)

Method	Factor of safety	Situation
Ordinary	1.122	Unstable
Bishop	1.255	Unstable
Janbu	1.144	Unstable
M_P	1.257	Unstable

3.2. The second slope

Area 2.1

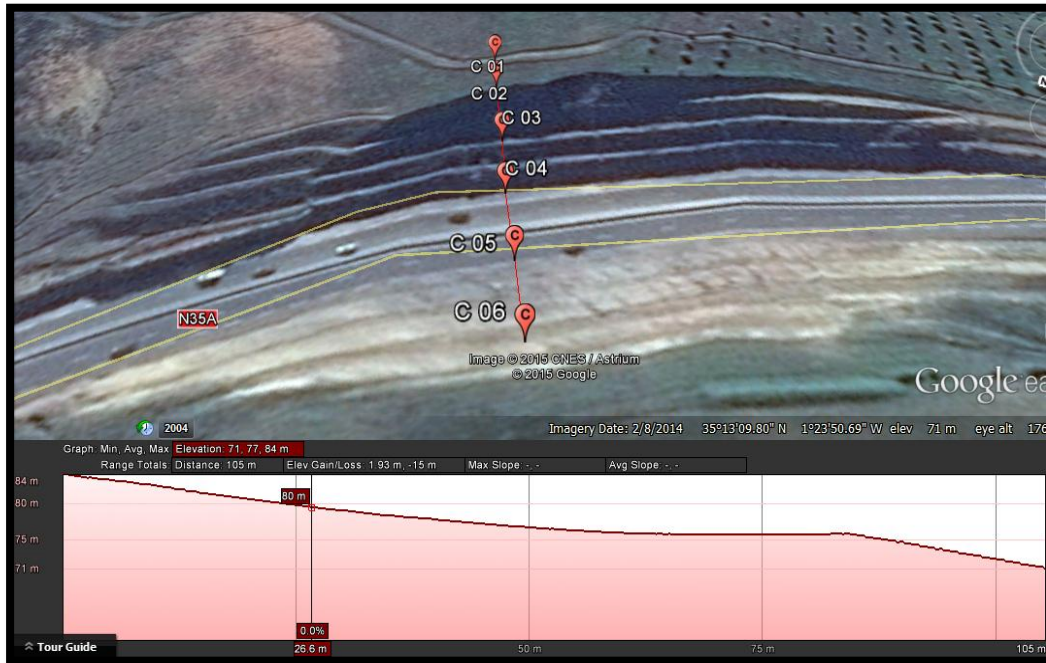


Figure 4.8: Area 2.1 section. (Google Earth Pro)

- Before cut and benching :

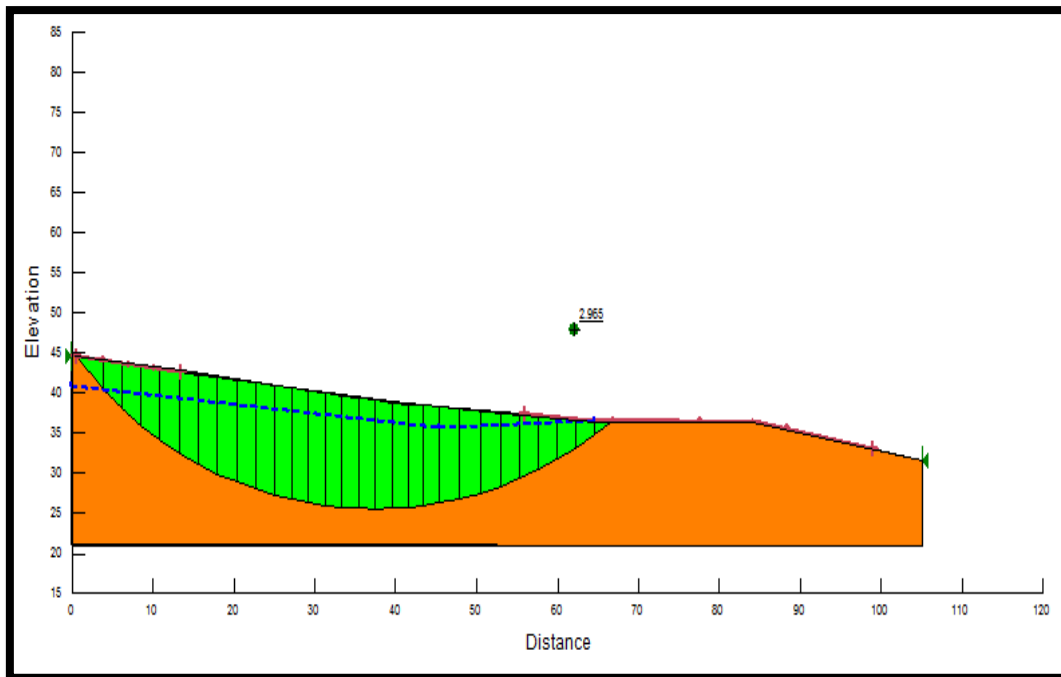
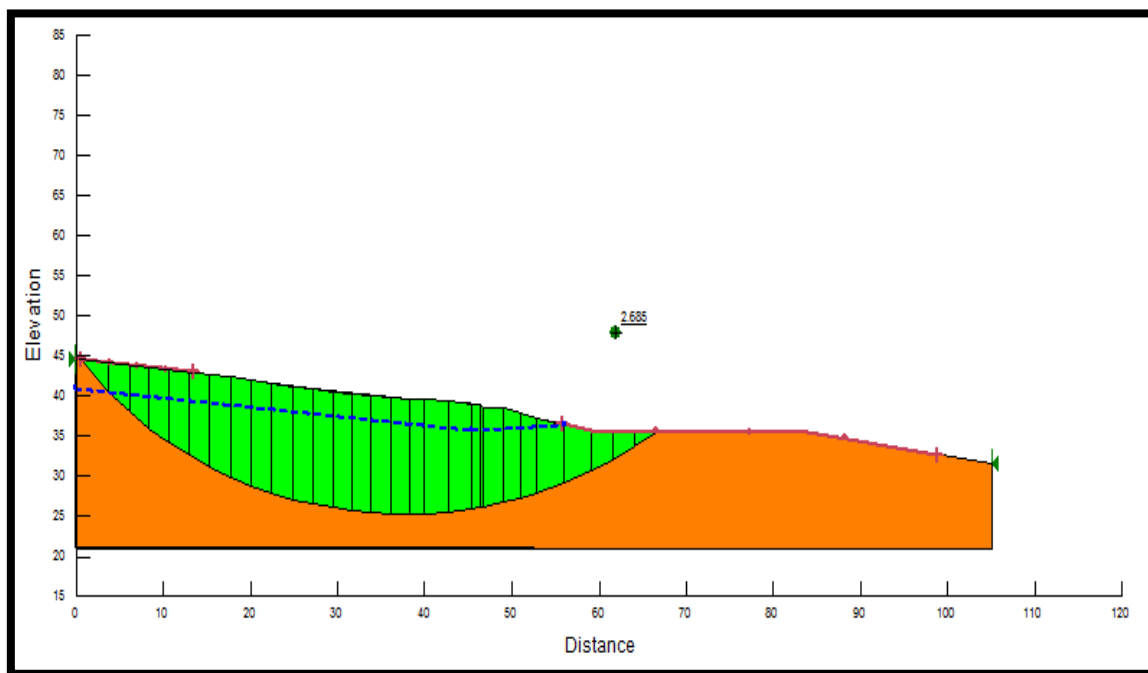


Figure 4.9: Area 2.1 critical slip at the initial situation

Table 4.5. Result summary, area 2.1 (initial)

Method	Factor of safety	Situation
Ordinary	2.48	Stable
Bishop	2.963	Stable
Janbu	2.622	Stable
M_P	2.963	Stable

- After cut and benching :

**Figure 4.10:** Area 2.1 critical slip surface final situation**Table 4.6.** Result summary, area 2.1 (final)

Method	Factor of safety	Situation
Ordinary	2.274	Stable
Bishop	2.683	Stable
Janbu	2.382	Stable
M_P	2.683	Stable

Area 2.2

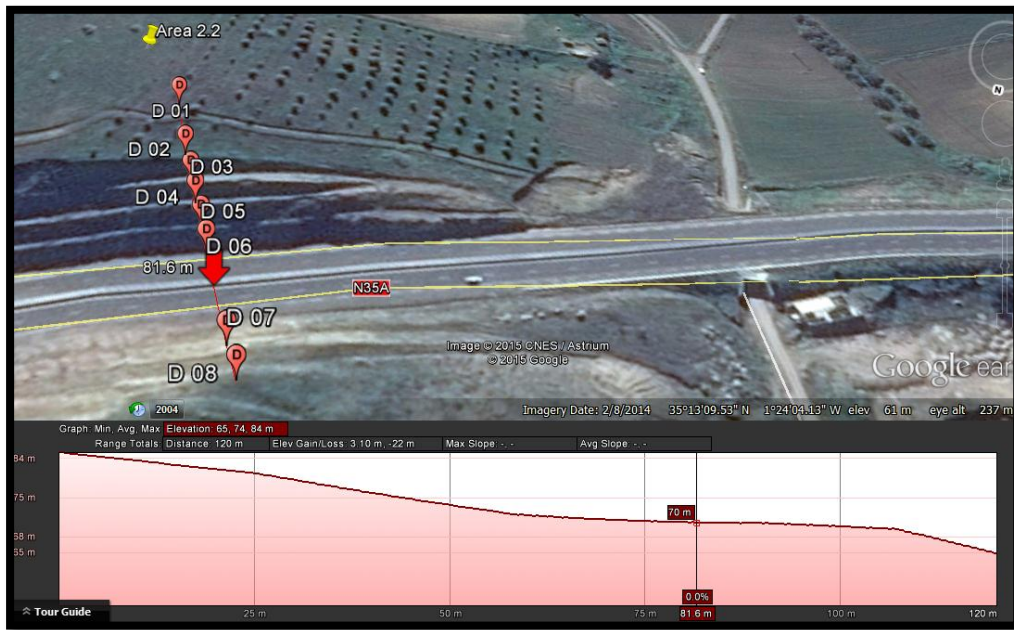


Figure 4.11: Area 2.2 section. (Google Earth Pro)

- Before cut and benching :

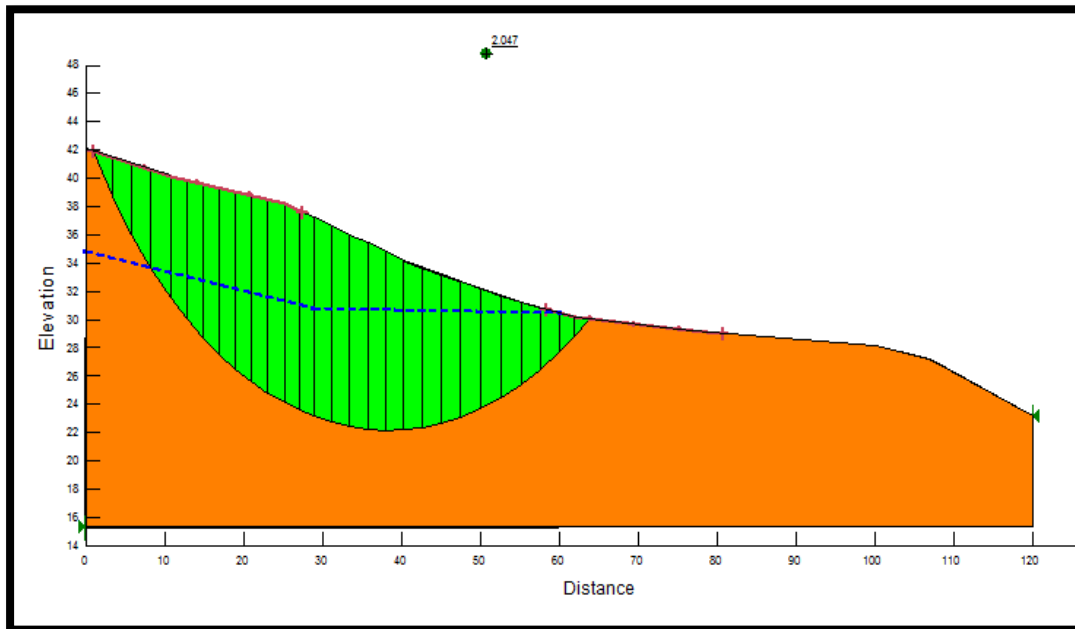


Figure 4.12: Area 2.2 critical slip surface initial situation

Table 4.7. Result summary, area 2.2 (initial)

Method	Factor of safety	Situation
Ordinary	1.786	Stable
Bishop	2.046	Stable
Janbu	1.85	Stable
M_P	2.047	Stable

- After cut and benching :

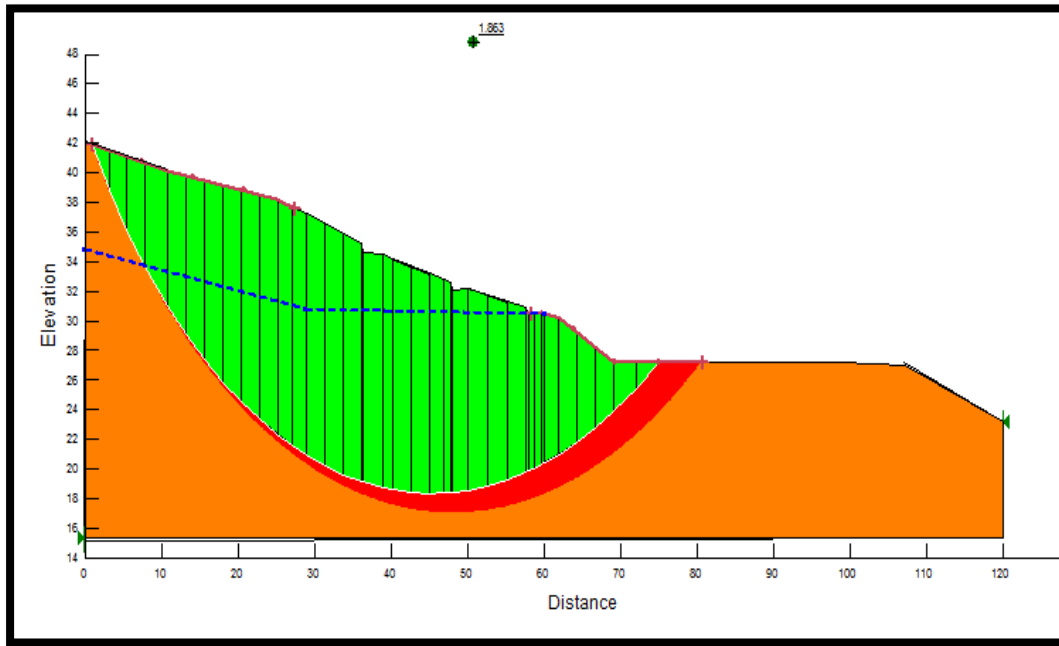


Figure 4.13: Area 2.2 critical slip surface and safety map at the final situation

Table 4.8. Result summary, area 2.2 (final)

Method	Factor of safety	Situation
Ordinary	1.621	Stable
Bishop	1.861	Stable
Janbu	1.682	Stable
M_P	1.863	Stable

3.3. The third slope

Area 3.1

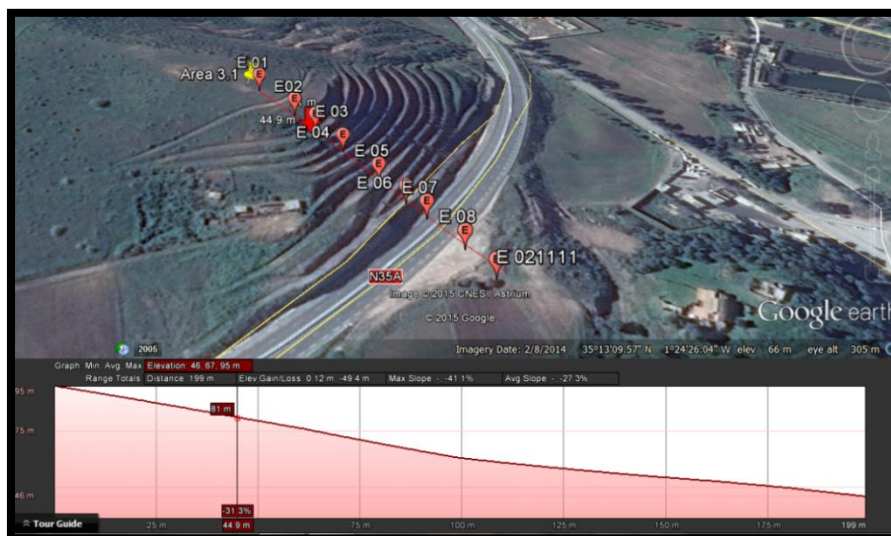


Figure 4.14: Area 3.1 section. (Google Earth Pro)

- Before cut and benching :

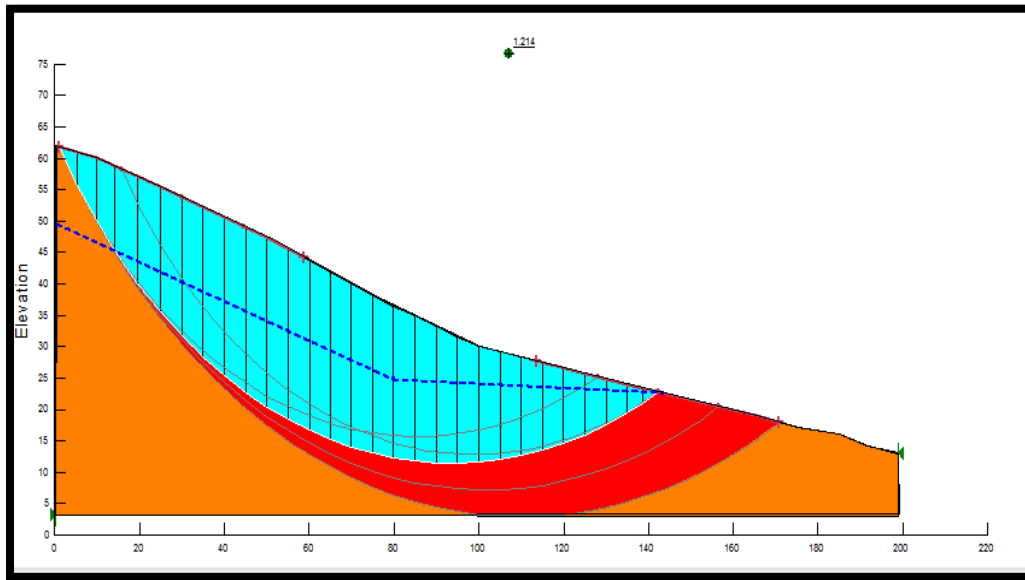


Figure 4.15: Area 3.1 critical slip surfaces and safety map at the initial situation

Table 4.9. Result summary area 3.1(initial)

Method	Factor of safety	Situation
Ordinary	0.986	Unstable
Bishop	1.211	Unstable
Janbu	1.087	Unstable
M_P	1.214	Unstable

- After cut and benching :

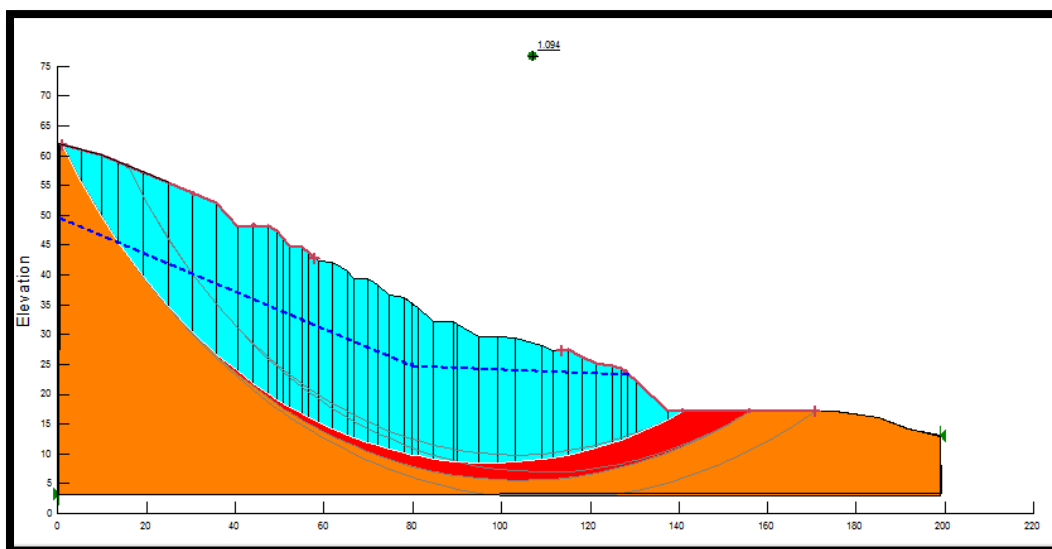


Figure 4.16: Area 3.1 critical slip surfaces and safety map for the final situation

Table 4.10. Result summary area 3.1 (final)

Method	Factor of safety	Situation
Ordinary	0.907	Unstable
Bishop	1.091	Unstable
Janbu	0.99	Unstable
M_P	1.094	Unstable

Area 3.2

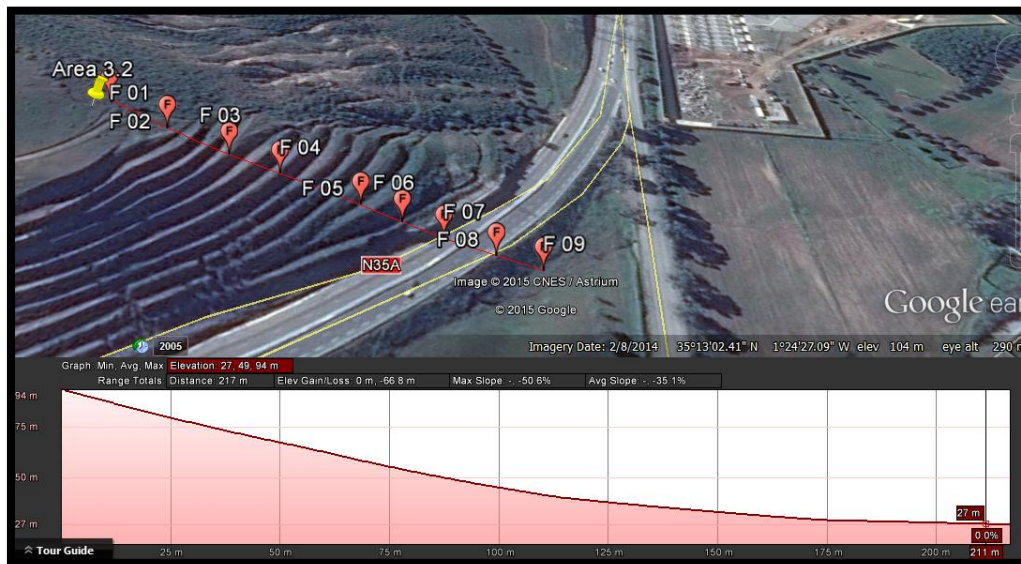


Figure 4.17: Area 3.2 section. (Google Earth Pro)

- Before cut and benching :

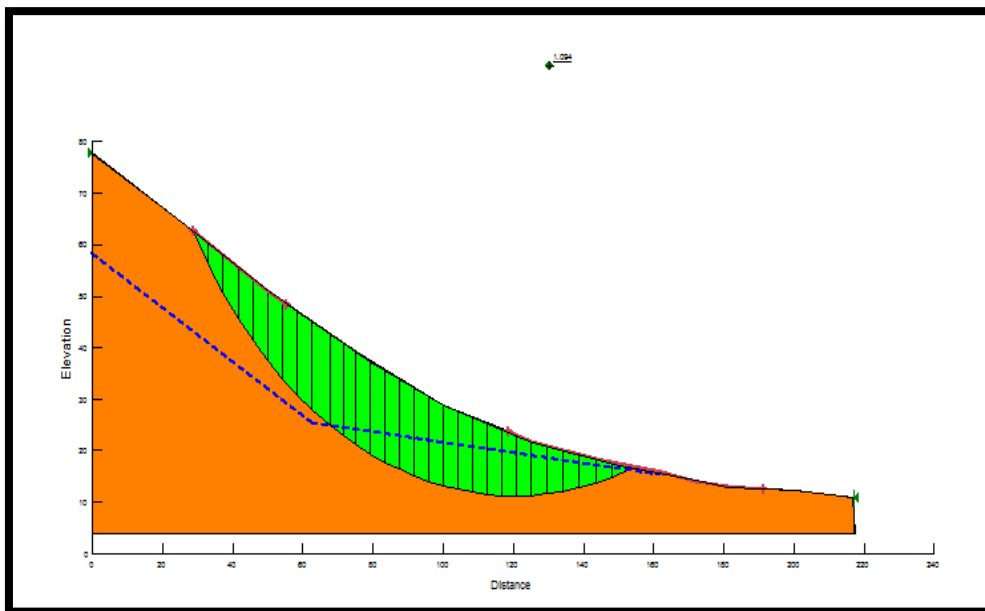
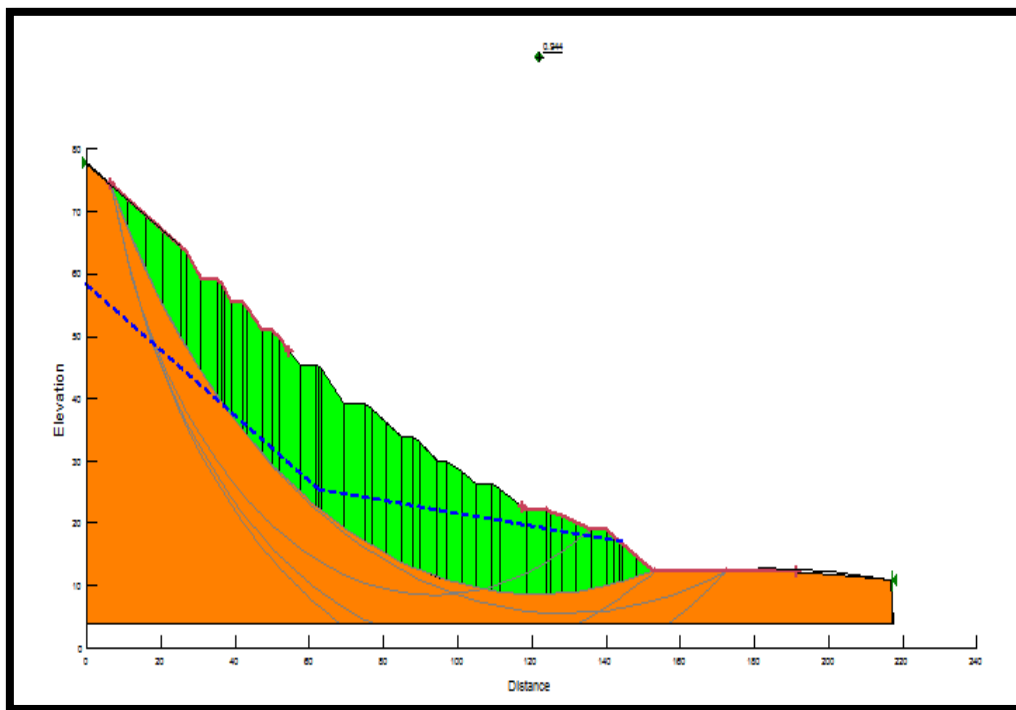


Figure 4.18: Area 3.2 critical slip surface initial situation

Table 4.11. Result summary area 3.2 (initial)

Method	Factor of safety	Situation
Ordinary	0.897	Unstable
Bishop	1.093	Unstable
Janbu	0.941	Unstable
M_P	1.094	Unstable

- After cut and benching :

**Figure 4.19:** Area 3.2 critical slip surface final situation**Table 4.12.** Result summary area 3.2 (final)

Method	Factor of safety	Situation
Ordinary	0.742	Unstable
Bishop	0.938	Unstable
Janbu	0.802	Unstable
M_P	0.944	Unstable

4. Analyses report

After the previous analyses we conclude that:

- The second slope is considered stable with a most critical factor of safety of: 1.863. Because of the limited height and the low slope angle comparing the other two slopes the soil is in stable condition.
- The stability of slope 1 and 3 is not satisfied, with a critical factors of safety of: 1.257 and 0.944 but since the first slope is already treated, the third slope will be our subject in the treatment.

Due to cracks, future rainfall, and erosion, the condition of the slope is endangered to go even worse, the factor of safety will continue decreasing which puts the slope in a complicated situation, and under the threaten to undergo sudden failures, therefore the slope should be engineered and stabilized .

5. Treatment for slope 3

After a number of studies it became clear that the major causes of instability in our case are, the rainwater, groundwater, the type of terrain material, the angle of the slope, and the erosion, which makes it important to include drainage system or units in our reinforcement whatever it will be. In this article we managed to propose two solutions with design, study and cost estimation to finally choose one of the two solutions which are:

5.1. Gabion wall

Gabion walls are gravity walls that depend on the self-weight to stabilize the slopes. To increase the resistance of the wall it should be anchored in the earth and leaned backwards to the slope, so in this case we managed to design a gabion wall by using the civil engineering software (Geo 5).

The gabion wall is a simple reinforcement solution, it consists of cages or meshes filled with special stone materials, which makes it heavy and able to resist high lateral forces implicated by the slope material and the ground water pressure. Because of the combination of stones and meshes the wall provides high quality water drainage, so the wall itself can be considered as a drainage system.

The software (Geo 5) that we used in design considers the ground water, the risk of the slide, overturning, and the stability of the gabion, and verifies the earthquake resistance.

Stages of construction

- Excavation: excavation is necessary to fix the wall in the ground (anchoring the wall)
- Geotextile layer: non-woven geotextile prevents the erosion of the backfill material and should encase the gabion from all sides that connects with soils
- Installing the meshes
- Filling the meshes with specified fill material
- Repeating the previous two points until the gabion reaches its designed height
- Backfill and compacting

Design

In the following design the maximum height of the toe is considered 4m from the original ground level, the gabion is designed to be anchored 0.5 m into the ground and with a gradient of 10° towards the slope, the design is accomplished by (Geo 5) software and it includes:

- Overturning verification
- Slip verification
- Bearing capacity verification
- Eccentricity verification
- Slope stability verification

The details are shown in the next figures.

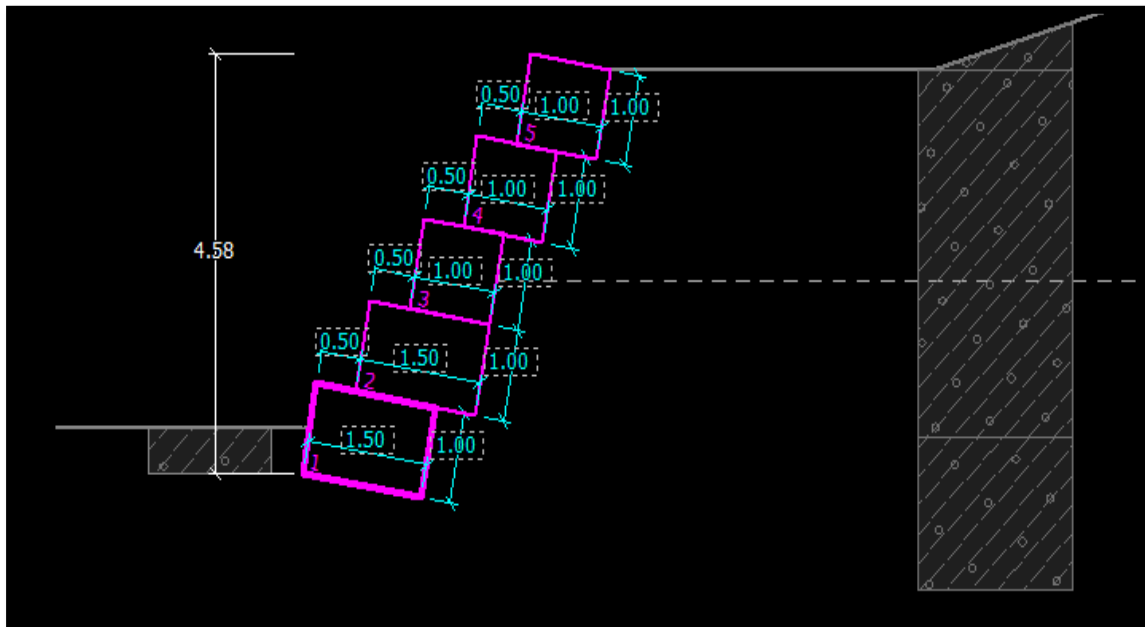


Figure 4.20: Geometry of a gabion wall design by(Geo 5)

Verification of complete wall

Table 4.13. Forces acting on construction

Name	F_{hor} [kN/m]	App.Pt. z [m]	F_{vert} [kN/m]	App.Pt. x [m]	Coeff. overturn.	Coeff. sliding	Coeff. stress
Weight - wall	0.00	-1.96	108.00	1.87	0.900	0.900	1.250
FF resistance	-1.54	-0.17	0.41	0.03	0.900	0.900	1.350
Active pressure	19.26	-0.71	1.48	1.93	1.500	1.500	0.900
Water pressure	27.93	-0.53	-5.24	1.80	1.000	1.000	1.000
Uplift pressure	0.00	-4.40	0.00	3.82	1.000	1.000	1.000

- Check for overturning stability

$$\text{Resisting moment } M_{res} = 158.78 \text{ kNm/m}$$

$$\text{Overturning moment } M_{ovr} = 34.99 \text{ kNm/m}$$

Wall for overturning is SATISFACTORY

- Check for slip

$$\text{Resisting horizontal force } H_{res} = 41.92 \text{ kN/m}$$

$$\text{Active horizontal force } H_{act} = 38.18 \text{ kN/m}$$

Wall for slip is SATISFACTORY

Overall check - WALL is SATISFACTORY

Maximum stress in footing bottom: 91.44 kPa

- Slope stability verification (Bishop)

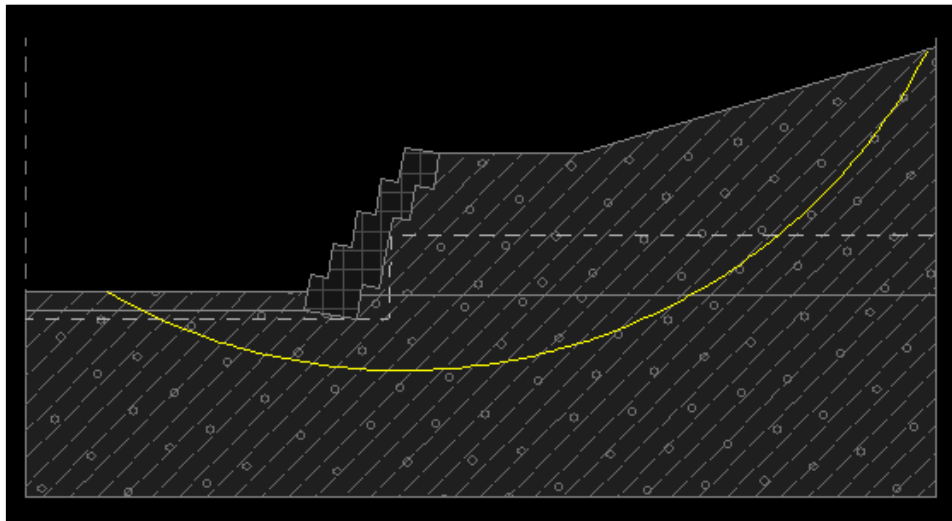


Figure 4.21: Slope stability of the gabion (Geo 5)

Sum of active forces : $F_a = 425.71 \text{ kN/m}$

Sum of passive forces : $F_p = 762.31 \text{ kN/m}$

Sliding moment : $M_a = 7122.10 \text{ kNm/m}$

Resisting moment : $M_p = 12753.40 \text{ kNm/m}$

Factor of safety = 1.79 > 1.50

Slope stability ACCEPTABLE

- Verification of foundation soil (bearing capacity)

Table 4.14. Design load acting at the center of footing bottom

No.	Moment [kNm/m]	Norm. force [kN/m]	Shear Force [kN/m]	Eccentricity [-]	Stress [kPa]
1	-121.39	137.15	18.72	0.000	91.44
2	-71.58	102.75	36.76	0.000	68.50

Table 4.15. Service load acting at the center of footing bottom

No.	Moment [kNm/m]	Norm. force [kN/m]	Shear Force [kN/m]
1	-90.92	110.52	23.87
2	-77.53	100.35	27.69

Eccentricity verification

Max. eccentricity of normal force $e = 0.000$

Maximum allowable eccentricity $e_{alw} = 0.333$

Eccentricity of the normal force is SATISFACTORY

Verification of bearing capacity

Design bearing capacity of foundation soil $R = 200.00 \text{ kPa}$

Partial factor on bearing capacity	γ_{Rv}	=	0.55
Max. stress at footing bottom	σ	=	91.44 kPa
Bearing capacity of foundation soil	R_d	=	110.00 kPa
Bearing capacity of foundation soil is SATISFACTORY			

Overall verification - bearing capacity of found. soil is SATISFACTORY

Cost estimation

BGM020 m³ Gabion wall. 7.773,98DA

Gabion wall composed of 4x1x1 m cage galvanized steel mesh of 2,00 mm diameter, a hexagonal grid of 50x70 mm, filled with imported limestone with an excavator placed on wheels.

Table 4.16. Gabion cubic meter cost (<http://www.algerie.prix-construction.info/>)

Internal code	Designation	Quantity	Unit	Unit price	Total price
mt07aen020i	4x1x1 m cage triple torsion mesh galvanized steel of 2 mm in diameter, a hexagonal grid of 50x70 mm, for gabion.	0,265	U	5.946,75	1.575,89
mt50spr100a	Steel cable 2 mm in diameter, for fixing metal grid.	1,750	m	89,97	157,45
mt36tie010da	PVC pipe, Series B, 75 mm in diameter and 3 mm thick, with flared end, according to EN 1329-1.	0,050	m	330,78	16,54
mt08eme080	Metal panels of 500x2000 mm, redeemable in 50 uses; comprises support elements for fixing and bracing.	2,000	U	176,24	352,48
mt06psm010a	Limestone with a particle size between 100 and 200 mm.	1,100	m ³	1.625,68	1.788,25
mq01exn020a	Retro hydraulic backhoe loaders, 105 kW.	0,808	h	3.679,68	2.973,18
mo040	Professional Companion III / CP2 VRD public spaces.	0,737	h	453,89	334,52
mo085	Professional worker II / OP VRD public spaces.	0,737	h	273,06	201,25
	Assistance moyens	2,000	%	7.399,56	147,99
	Indirect costs	3,000	%	7.547,55	226,43
Ten year Upkeep: 1.166,10DA the first 10 years.				Total amount HT:	7.773,98

Table 4.17. Designed gabion cost

NO	Width b (m)	Height h (m)	Slopeextension l (m)	Volume v (m ³)
1	1.5	1	385	577.5
2	1.5	1	385	577.5
3	1	1	385	385
4	1	1	385	385
5	1	1	385	385
Total price = Total volume × Unit price = 2310 m³ × 7,773.98 DA = 17,957,893.8 DA				

Specifications (<http://www.algerie.prix-construction.info/>)

- Technical terms : Forming a gabion wall composed of 4x1x1 m cage triple torsion mesh galvanized steel of 2.00 mm diameter hexagonal mesh of 50x70 mm, filled with limestone imported grain size of between 100 and 200 mm, placed with an excavator on wheels. Includes preparation of the support base, the steel cable for the docking of the cage, shoring the sides of the cage and drainage.
- Measuring criteria: Volume is measured according to the theoretical calculation section, according to graphic documentation of the Project.

- Execution stage: Implantation. Preparation of the support surface. Extension of the cages. Attaching the edges. Shoring the sides of the cages. Setting up the drainage units. Filling the cages. Closing and final tie cages. Removing the excess material.
- Criteria of the memo: We measure the theoretical volume performed according to project specifications.

Additional costs

ATF030 m³ **Excavation.** (<http://www.algerie.prix-construction.info/>) 441,91DA

Excavation of basements of more than 2 m deep in a soil of semi-hard clay with mechanical means, removal of excavated material and load the truck.

EED040 m² **Drainage layer and outer filter for paving in contact with the ground, with tablecloths excrescences with a geotextile.**(<http://www.algerie.prix-construction.info/>) 393,24DA

Drainage of a pavement in contact with the ground by its outside with drainage sheet Studded high density polyethylene (HDPE / HDPE), with growths of 8 mm high, with incorporated polypropylene geotextile, compressive strength 150 kN / m² according to DIN EN ISO 604, drainage capacity 5 l / (s • m) and nominal weight 0.7 kg / m², placed on the ground and prepared to receive the concrete of pavement.

ATR020 m³ **backfill.**(<http://www.algerie.prix-construction.info/>) 315,40DA

Main backfill trenches for installations with earth excavation and compaction 95% of Modified Proctor with hand held vibrating plate.

Table 4.18. Additional costs estimation (gabion wall)

Category	Quantity	Unit price	Total price
Excavation	2.15 x 0.85 x 386 = 705.415 m ³	441.91 DA	311,729.94265DA
Geotextile	(7.5 + 6.5) x 388 = 5,432 m ²	393.24 DA	2,136,079.68 DA
Backfill(0.5 m behind each cage line)	{3x(0.5x1) + 2x(0.5x1)} x 385 = 992.5 m ³	315.4 DA	313,034.5 DA
Total additional price = the sum of total prices = 2,760,844.12265 DA			

Total cost of the project

Total cost of the project = Designed gabion cost + Total additional costs = 17,957,893.8 + 2,760,844.12265 = 20,718,737.92265 DA

5.2. Cantilever retaining wall

Cantilever retaining walls are popular in slope stabilization they provide high quality resistance of lateral forces and the implicated moment forces. Cantilever walls are more complicated in their design and execution than gabion walls due to the steel reinforcement. An anchored cantilever retaining wall by at least 0.5 m can provide high resistance. The design is also obtained by using the civil engineering software (Geo 5) such as the gabion wall.

The cantilever wall consists of concrete and longitudinal reinforcement and drainage units, this combination can resist the pressure that implicated by the slope material and the ground water pressure.

Stages of construction

- Excavation: in case of using cantilever walls, excavation is related the foundation and the same as gravity walls it's necessary to fix the wall in the ground (anchoring)
- Geotextile layer: non-woven geotextile such as the gabion wall to prevent the erosion of the backfill material
- Pouring the concrete cleanliness: usually with a depth of 10 cm and with a length that make it out of the wall edges by 10 cm to each side
- Installing the foot foundation reinforcements
- Installing the foot foundation cover (5 cm away from the four sides of the reinforcement)

- Installing drainage units
- Pouring the foundation concrete
- Installing the vertical wall reinforcement
- Installing the wall cover (5 cm away from the four sides of the wall reinforcement)
- Pouring the wall concrete
- Backfill and compacting

Design

The design is the same as the gabion design considerations, the maximum height of the toe is considered 4 m from the original ground level, the wall is designed to be anchored 1 m into the ground, the design is accomplished by (Geo 5) software and it includes:

- Overturning verification
- Slip verification
- Bearing capacity verification
- Eccentricity verification
- Slope stability verification

The details are shown in the next figures.

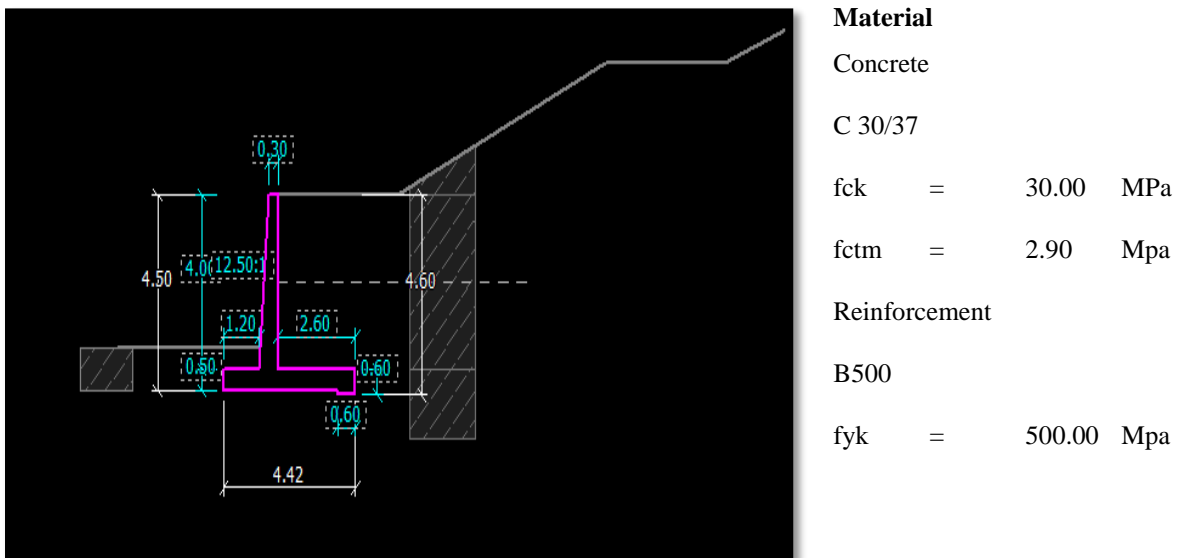


Figure 4.22: Geometry of a cantilever retaining wall design by (Geo 5)

Verification of complete wall

Table 4.19. Forces acting on construction

Force	F_x [kN/m]	F_z [kN/m]	App.Pt. x [m]	App.Pt. z [m]	Coeff. [-]
Weight - wall	0.00	94.53	1.96	-1.15	1.000
FF resistance	6.24	0.20	1.17	-0.33	1.000
Weight_ earth wedge	0.00	83.35	2.64	-2.19	1.000
Active pressure	-63.83	59.53	3.83	-1.25	1.000
Water pressure	-33.80	0.00	2.16	-0.77	1.000
Uplift pressure	0.00	0.00	1.82	-4.5	1.000

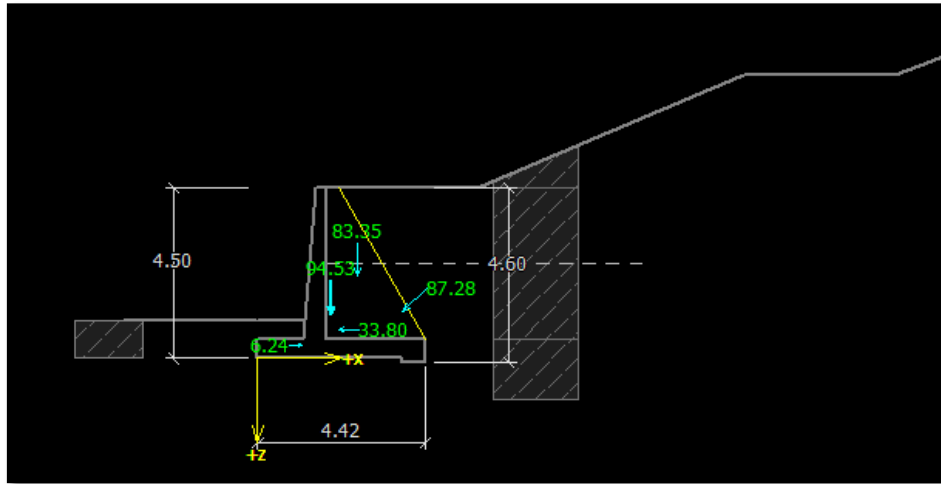


Figure 4.23: Forces implicated on the wall

- Check for overturning stability

$$\text{Resisting moment } M_{res} = 633.79 \text{ kNm/m}$$

$$\text{Overturning moment } M_{ovr} = 103.32 \text{ kNm/m}$$

$$\text{Safety factor} = 6.13 > 1.50$$

Wall for overturning is SATISFACTORY

- Check for slip

$$\text{Resisting horizontal force } H_{res} = 131.42 \text{ kN/m}$$

$$\text{Active horizontal force } H_{act} = 85.99 \text{ kN/m}$$

$$\text{Safety factor} = 1.53 > 1.50$$

Wall for slip is SATISFACTORY

Overall check - WALL is SATISFACTORY

- Slope stability verification (Bishop)

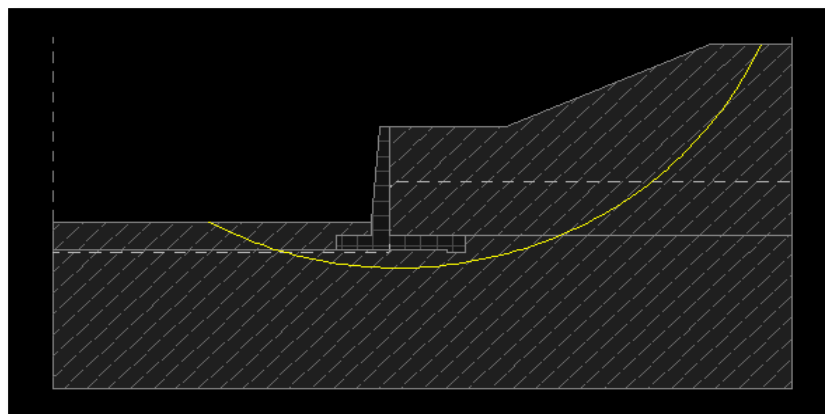


Figure 4.24: Slope stability of the cantilever wall (Geo 5)

Sum of active forces : $F_a = 376.46 \text{ kN/m}$

Sum of passive forces : $F_p = 602.97 \text{ kN/m}$

Sliding moment : $M_a = 5070.87 \text{ kNm/m}$

Resisting moment : $M_p = 8122.04 \text{ kNm/m}$

Factor of safety = $1.60 > 1.50$

Slope stability ACCEPTABLE

- Verification of foundation soil (bearing capacity)

Table 4.20. Design load acting at the center of footing bottom

No.	Moment [kNm/m]	Norm. force [kN/m]	Shear Force [kN/m]	Eccentricity [-]	Stress [kPa]
1	-0.78	239.62	85.94	0.000	54.20

Table 4.21. Service load acting at the center of footing bottom

No.	Moment [kNm/m]	Norm. force [kN/m]	Shear Force [kN/m]
1	-0.78	239.62	85.94

Eccentricity verification

Max. eccentricity of normal force $e = 0.000$

Maximum allowable eccentricity $e_{alw} = 0.333$

Eccentricity of the normal force is SATISFACTORY

Verification of bearing capacity

Max. stress at footing bottom $\sigma = 54.20 \text{ kPa}$

Bearing capacity of foundation soil $R_d = 120.00 \text{ kPa}$

Safety factor = $2.21 > 1.50$

Bearing capacity of foundation soil is SATISFACTORY

Overall verification - bearing capacity of found. soil is SATISFACTORY

Cost estimation

ATS020 m³ Reinforced concrete retaining wall. 11,213.59DA

Retaining wall of rectilinear base of land, with shoe and heel, reinforced concrete, up to 3 m high, realized with crafted concrete on the construction site BCN: CPJ-CEM II / A 32.5 - TP - B 30 - 15/25 - E: 2a - BA - P 18-305, casting with manual means and steel Fe E 500, quantity 22 kg / m³, not including the formwork.

Table 4.22. Retaining wall cubic meter cost. (<http://www.algerie.prix-construction.info/>)

Internal code	Designation	Quantity	Unit	Unit price	Total price
mt07aco020d	Approved separator walls.	8,000	U	6.50	52.00
mt07aco055e	High adherence steel bars Fe E 500, developed in workshop and set up in site, of various diameters.	22,000	kg	109.84	2,416.48
mt36tie010da	PVC pipe, Series B, 75 mm in diameter and 3 mm thick, with flared end, according to EN 1329-1.	0,050	m	333.72	16.69
mt08aaa010a	Water.	0,263	m ³	121.71	32.01
mt01arg000	Sand screened for poured concrete on site.	0,751	t	740.13	555.84
mt01arg001k	Gros homogenised aggregate, maximum size 15/25 mm, for poured concrete on site.	0,966	t	1,061.56	1,025.47
mt08cem000	Cement in bags, concrete crafted on site.	366,450	kg	14.82	5,430.79
mo041	Professional Companion III / CP2 concrete.	0,501	h	476.53	238.74
mo087	Professional worker II / OP concrete.	0,501	h	286.77	143.67
mo111	Worker performing I / OE1 VRD private spaces.	1,403	h	262.38	368.12
mo110	Worker performing I / OE2 VRD private spaces.	1,470	h	267.82	393.70
	Assistance moyens.	2,000	%	10,673.51	213.47
	Indirect costs.	3,000	%	10,886.98	326.61
Ten Year Upkeep: 448,54DA the first 10 years.				Total amount HT: 11,213.59	

Table 4.23. Designed wall cost

Section	Area of the section A (m ²)	Slope extention l (m)	Volume v (m ³)
Base	$[(2.62+1.2) \times 0.5] + [0.6 \times 0.6] = 2.27$	385	873.95
Wall	$[(0.62+0.3) / 2] \times 4 = 1.84$	385	708.4
Total price = Total volume × Unit price = 1,582.35 m³ × 11,213.59 DA = 17,743,824.1365 DA			

Specifications (<http://www.algerie.prix-construction.info/>)

MEASURES TO ENSURE COMPATIBILITY BETWEEN THE DIFFERENT PRODUCTS AND COMPONENTS AND CONSTRUCTIVE SYSTEMS THAT MAKE UP THE UNIT OWNER.

According to the aggressiveness of the field or the presence of water with aggressive substances, one will choose the proper cement for the production of concrete and its strength and the permeability and thickness of the frames overlap.

- Technical terms: construction of a retaining wall of rectilinear base of land, with shoe and heel, reinforced concrete, up to 3 m high, built with concrete crafted on site BCN: CPJ-CEM II / A 32.5 - TP - B 30 - 15/25 - E: 2a - BA - P 18-305, casting with manual means and steel Fe E 500 with an approximate amount of 22 kg / m³, not including the formwork in this price. Includes retaining wall, construction joints, opes to evacuate runoff can accumulate, the openings for the passage of facilities and plugging of hole with an elastic sealant.
- Element carrier: We will verify the existence of the cleanliness concrete layer, which will present a horizontal ground plane and a clean surface.
- Climate conditions: The concrete work will be suspended in case of heavy rain, snow, excessive wind, if the ambient temperature exceeds 40 ° C or if it is expected that the temperature drops below 0 ° C in the 48 next hours.

- Sub changes: We have a set of means on the site, in anticipation of possible sudden changes in ambient conditions during concreting or the next period of outlet, the concreting of the different elements that cannot be started without the written permission of the Director of execution of the work.
- Execution process: Implantation of the foundation wall. Placing frames with approved separators. Placing elements for passage of installations. Resolution drains, and concrete joints. Casting and compacting the concrete. Concrete drying. Sealing the orifices.
- Finishing: The wall surface will be clean.
- Conservation and maintenance: Avoid the item risks that the mechanical actions not provided for in the calculation. Vehicle traffic and placement of loads near the back of the wall will be prevented.
- Criteria of the memo: We will measure the theoretical volume performed according to project specifications.

Additional costs

GFO010 m² Cleanliness concrete layer.(<http://www.algerie.prix-construction.info/>) 929.21DA

Cleanliness concrete layer BCN: CPJ-CEM II / A 32.5 - P - B 16 - 15/25 - E: 1 - NA - P 18-305, casting with manual means, 10 cm thick.

Table 4.24. Additional costs estimation (cantilever retaining wall)

Category	Quantity	Unit price	Total price
Excavation	$4.82 \times 1.1 \times 386 = 2,046.572 \text{ m}^3$	441.91 DA	904,400.63252 DA
Cleanliness concrete	$4.62 \times 385.2 = 1,779.624 \text{ m}^2$	929.21 DA	1,653,644.417 DA
Geotextile	$10.8 \times 388 = 4,190.4 \text{ m}^2$	393.24 DA	1,647,832.896 DA
Backfill(1 m away from the upright the edge of the base point beside the top of the wall)	$\{4 \times (0.5 \times 1) + (2.6 \times 4)\} \times 385 = 4,774 \text{ m}^3$	315.4 DA	1,505,719.6 DA
Total additional price = the sum of total prices = 5,711,597.549 DA			

Total cost of the project

Total cost of the project = Designed gabion cost + Total additional costs = 17,743,824.1365 + 5,711,597.549 = 23,455,421.6855 DA

6. Choosing the solution

Considering the requirement and resources available, we have decided the Gabion Gravity wall as a final solution. It has been decided to consider up to maximum 4 meter of height for the wall. Gabion Retaining walls are flexible structures which are very suitable in case of retaining structures for protection. It is also very effective for the protection in areas with water tables, as the form of the wall provides high quality drainage. Gabions are flexible in nature and can accommodate differential settlement very well. In future, with due design consideration height of wall may be increased, if required. Gabion Wall was designed by the civil engineering software (Geo 5). There is a requirement of filter behind the Gabion wall, to avoid erosion of backfill material. Nonwoven Geotextile is to be placed around the backfill of the gabion wall which acts as filter.

Gabion construction is fast and can be done using unskilled labors. Boulders are available in the vicinity, reduced the overall project cost and make the project very cost effective. Excavation for minimum 0.85 meter depth is to be carried out in the virgin soil. Any unsuitable soil removed and replaced with good quality soil. Nonwoven Geotextile are used beneath and behind the Gabion wall for filtration purpose. Compacted filling was proposed and is to be carried out at site. Metal Gabion and Nonwoven Geotextile satisfy all the technical parameters for their effective usage.

The advantages of the gabion wall over the cantilever wall are:

- Flexible structure which can accommodate differential settlement.

- Free draining structure with no pore pressure development behind wall.
- Easy in construction, as it does not require skilled laborers.
- Does not require curing time as in case of cantilever Retaining wall.
- Eco-friendly, as the vegetation growth over it, is compatible with surrounding environment.
- Used under full or partial submergence.
- Smaller base than the cantilever wall which does not disturb the route space.
- Cost incurred is very less compared to R.C.C Retaining Wall and depends only on the local availability of boulders.

7. Conclusion

In this last chapter of the project we managed to deal with a real life problem. We calculated the stability of the concerned slopes sited along National route n35 in El Emir Abdelkader village by using the software (Slope/W). The third slope to the west turned out to be unstable, therefore we proposed two stabilization methods with the design and the cost estimation. The designs of the two solutions were obtained by the civil engineering software (Geo 5). The first proposed solution was a gravity gabion wall, and the other was a cantilever retaining wall. After the design and the cost study it turned out that the gabion is more effective solution than the cantilever wall, so that it was decided to be a final solution for the prone slope.

General conclusion

This humble graduation project has allowed me to improve my knowledge about geotechnical engineering especially the field of terrain movements. It also improved my skills of using software applications to do the analyses and to design stabilization structures to confront the problems that face the engineers at the level of terrain hazards. The project is based on a geological survey done by the L.T.P.O that provided the soil properties in our terrain.

The major mission in this document is to analyze and provide a treatment for a terrain that takes a place in El Amir **Abdelkader** Township in the **Wilaya** of **Ain Temouchent**, Algerian west.

Firstly we analyzed the terrain which consists of three slopes by a software program that allowed us to do so, these analyses aim to figure out the stability of the slopes by detecting the critical slip surface and factor of safety.

Secondly and according to the previous analyses, I proposed two solutions that were designed by another software program which are:

- Gabion wall.
- Cantilever retaining wall.

I also estimated the economic cost of each solution.

Finally it has been decided to use the gabion wall as a solution, the choice was based on the standards that were presented in Chapter III. The main purpose of this solution is to guarantee the safety of the travellers and the vehicles on the national route n35.

At the end I hope that I introduced a suitable and effective solution for the problem. It's important to note that the details of the solution are able to change in case of changes occurred to the surrounding environment and the terrain properties such as the change of water table and/or the geological and geotechnical properties of the soil, which makes it important to do periodic surveys.

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Geo5 support document/online help:(<http://www.finesoftware.eu/help/geo5/en/circular-slip-surface-01/>)

Générateur de prix de la construction. Algérie. CYPE Ingenieros, S.A.(http://www.algerie.prix-construction.info/espaces_urbains/)

Annexe

Sliding verification:

$$\text{Factor of safety} = \frac{\text{Horizontal resisting forces}(Fr)}{\text{Horizontal activating forces}(Fa)} = 1.5$$

Fa = active force horizontal component (Pah) + Water pressure on back (U)

Fr = Friction on base (S) + Passive force on front (Rp)

$$= N_1 \cdot \tan \delta_b + R_p, \text{ where } N_1 = W + P_{av} - U$$

Overturning verification:

$$\text{Factor of safety} = \frac{\text{Resisting moments}(M_{res})}{\text{Overturning moments}(M_{ovr})} = 2$$

$$M_{ovr} = P_{ah} \cdot y_p - P_{av} \cdot x_p + U_{ih} \cdot y_{u1} - U_{lv} \cdot x_{u1} + U_2 \cdot x_{u2}$$

$$M_{res} = M_{(\text{Wall weight})} + M_{(\text{Passive pressure})}$$

$$= W \cdot x_w + R_p \cdot y_r$$

Bearing capacity verification:

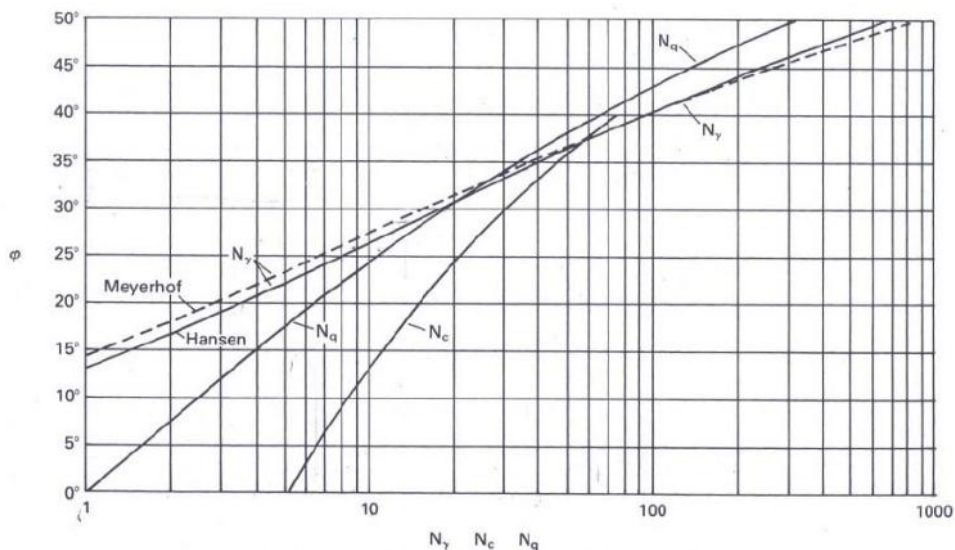
$$\text{Factor of safety} = \frac{\text{Bearing capacity of ground}(q_f)}{\text{Mobilized base pressure}(q_{mob})} = 2 \text{ to } 3$$

$$q_{(mob)} = N_1 / (B - 2e)$$

Eccentricity of the reaction from the centerline $e = B/2 - (M_{res} - M_{ovr})/N_1$, where B is the width of the base.

$$q_f = 0.5 \gamma_1 \cdot b \cdot N_\gamma + C' \cdot N_c + \gamma_2 \cdot D \cdot N_q$$

N_γ, N_c, N_q are the bearing capacity factors:



(Figure from SEACAP 21\004 Landslide Management)

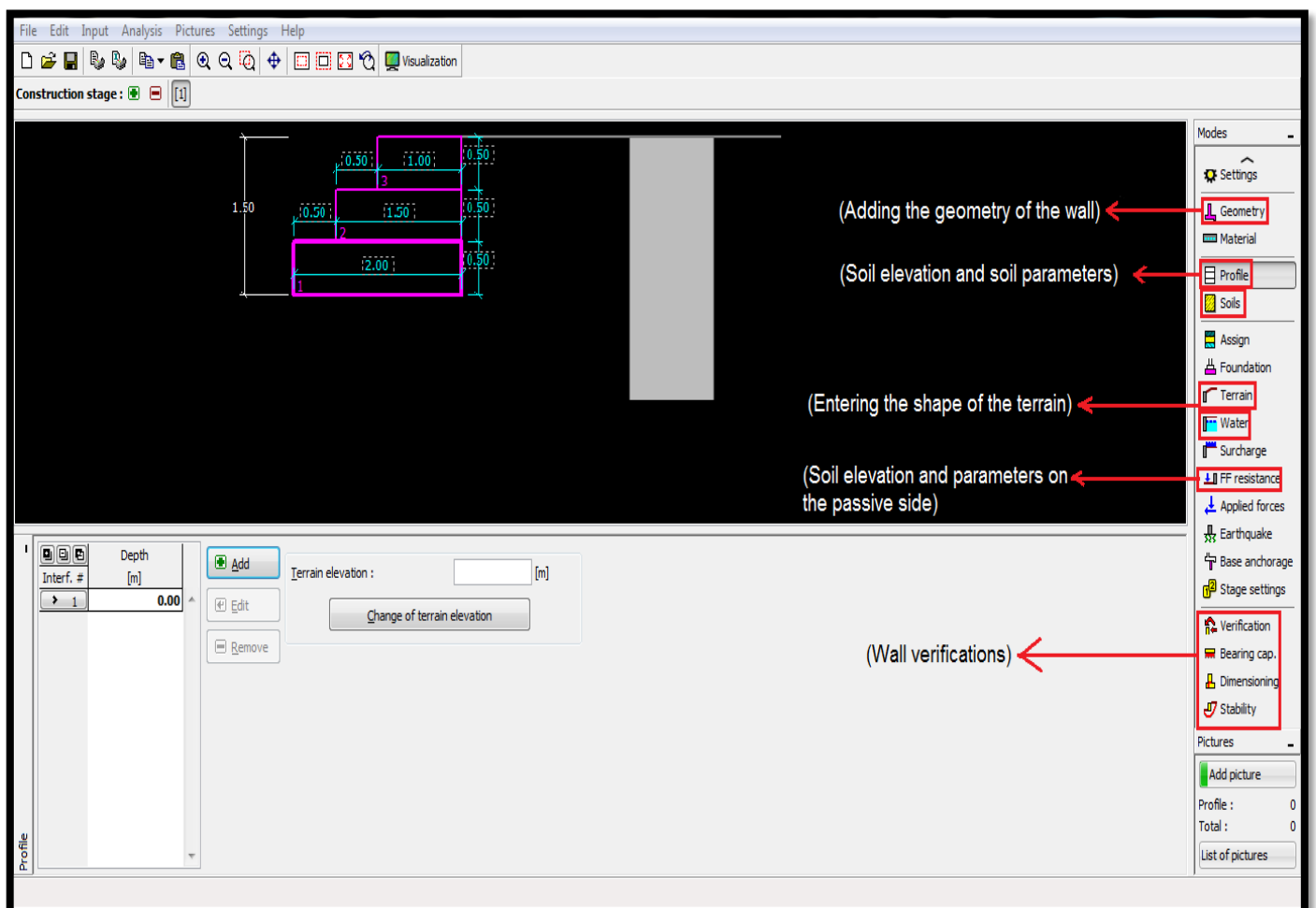
γ_1 and γ_2 are unit weights = γ_b if the soil is above water table, and $\gamma_b - \gamma_w$ if the soil is below it

b is the width of the loaded area $b = B - 2e$

γ_b bulk unit weight of the soil

D the depth of the base.

Using Geo5



Geo 5: Gabion application

SLOPE 2 AREA 2.1 After Cut Report

Report generated using GeoStudio 2007, version 7.10. Copyright © 1991-2008 GEO-SLOPE International Ltd.

1. File Information

Created By: [Mohammed](#)
Revision Number: [3](#)
Last Edited By: [Mohammed](#)
Date: [5/26/2015](#)
Time: [3:01:14 AM](#)
File Name: [slope 2 area 2.1 before analyze cut.gsz](#)
Directory: [C:\Users\DAHRAWI\Desktop\](#)

2. Project Settings

Length(L) Units: [meters](#)
Time(t) Units: [Seconds](#)
Force(F) Units: [kN](#)
Pressure(p) Units: [kPa](#)
Strength Units: [kPa](#)
Unit Weight of Water: [9.807 kN/m³](#)
View: [2D](#)

3. Analysis Settings

3.1. SLOPE 2 Area 2.1

Description: [to the west](#)
Kind: [SLOPE/W](#)
Method: [Morgenstern-Price](#)
Settings
 Apply Phreatic Correction: [No](#)
 Side Function
 Interslice force function option: [Half-Sine](#)
 PWP Conditions Source: [Piezometric Line](#)
 Use Staged Rapid Drawdown: [No](#)
SlipSurface
 Direction of movement: [Left to Right](#)
 Allow Passive Mode: [No](#)
 Slip Surface Option: [Entry and Exit](#)
 Critical slip surfaces saved: [1](#)
 Optimize Critical Slip Surface Location: [No](#)
 Tension Crack
 Tension Crack Option: [\(none\)](#)
FOS Distribution
 FOS Calculation Option: [Constant](#)
Advanced
 Number of Slices: [30](#)
 Optimization Tolerance: [0.01](#)
 Minimum Slip Surface Depth: [0.1 m](#)
 Minimum Slice Width: [0.1 m](#)

Optimization Maximum Iterations: 2000
Optimization Convergence Tolerance: 1e-007
Starting Optimization Points: 8
Ending Optimization Points: 16
Complete Passes per Insertion: 1

4. Materials

4.1. marl

Model: Mohr-Coulomb
Unit Weight: 19 kN/m³
Cohesion: 10 kPa
Phi: 20 °
Phi-B: 0 °
Pore Water Pressure
Piezometric Line: 1

5. Slip Surface Entry and Exit

Left Projection: Range
Left-Zone Left Coordinate: (0.54396554, 44.579029) m
Left-Zone Right Coordinate: (13.485334, 42.977233) m
Left-Zone Increment: 4
Right Projection: Range
Right-Zone Left Coordinate: (55.750012, 36.542151) m
Right-Zone Right Coordinate: (98.878892, 32.754556) m
Right-Zone Increment: 4
Radius Increments: 4

6. Slip Surface Limits

Left Coordinate: (-0.08065, 44.65634) m
Right Coordinate: (105.0926, 31.60668) m

7. Piezometric Lines

7.1. Piezometric Line 1

Coordinates

	X (m)	Y (m)
	-0.08065	40.96304
	45.36545	35.761643
	56.019567	36.469525

8. Regions

	Material	Points	Area (m ²)
Region 1	marl	3,14,12,13,11,10,8,9,5,7,6,2,1,4	1788.6539

9. Points

	X (m)	Y (m)
Point 1	105.0926	21.01922
Point 2	105.0926	31.60668
Point 3	-0.08065	44.65634
Point 4	-0.08065	21.080775
Point 5	52.8929	37.26974
Point 6	83.878167	35.525682
Point 7	59.1775	35.66931
Point 8	46.749	38.418767
Point 9	49.099803	38.416622
Point 10	46.372839	38.906637
Point 11	39.998911	39.695559
Point 12	27.222967	40.819412
Point 13	38.2601	39.588312
Point 14	15.308256	42.751604

SLOPE 2 AREA 2.2 After Cut Reoprt

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1. File Information

Created By: [Mohammed](#)
Revision Number: [5](#)
Last Edited By: [Mohammed](#)
Date: [5/26/2015](#)
Time: [3:21:53 PM](#)
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Directory: [C:\Users\DAHRAWI\Desktop\](#)

2. Project Settings

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Time(t) Units: [Seconds](#)
Force(F) Units: [kN](#)
Pressure(p) Units: [kPa](#)
Strength Units: [kPa](#)
Unit Weight of Water: [9.807 kN/m³](#)
View: [2D](#)

3. Analysis Settings

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 Interslice force function option: [Half-Sine](#)
 PWP Conditions Source: [Piezometric Line](#)
 Use Staged Rapid Drawdown: [No](#)
SlipSurface
 Direction of movement: [Left to Right](#)
 Allow Passive Mode: [No](#)
 Slip Surface Option: [Entry and Exit](#)
 Critical slip surfaces saved: [1](#)
 Optimize Critical Slip Surface Location: [No](#)
 Tension Crack
 Tension Crack Option: [\(none\)](#)
FOS Distribution
 FOS Calculation Option: [Constant](#)
Advanced
 Number of Slices: [30](#)
 Optimization Tolerance: [0.01](#)
 Minimum Slip Surface Depth: [0.1 m](#)
 Minimum Slice Width: [0.1 m](#)

Optimization Maximum Iterations: 2000
Optimization Convergence Tolerance: 1e-007
Starting Optimization Points: 8
Ending Optimization Points: 16
Complete Passes per Insertion: 1

4. Materials

4.1. marl

Model: Mohr-Coulomb

Unit Weight: 19 kN/m³

Cohesion: 10 kPa

Phi: 20 °

Phi-B: 0 °

Pore Water Pressure

Piezometric Line: 1

5. Slip Surface Entry and Exit

Left Projection: Range

Left-Zone Left Coordinate: (0.95888372, 41.949268) m

Left-Zone Right Coordinate: (27.479195, 37.616971) m

Left-Zone Increment: 4

Right Projection: Range

Right-Zone Left Coordinate: (58.410897, 30.437669) m

Right-Zone Right Coordinate: (80.786272, 27.229832) m

Right-Zone Increment: 4

Radius Increments: 4

6. Slip Surface Limits

Left Coordinate: (-0.0613253, 15.34) m

Right Coordinate: (120.07765, 23.18) m

7. Piezometric Lines

7.1. Piezometric Line 1

Coordinates

	X (m)	Y (m)
	0.04043279	34.8002
	28.949806	30.78
	60.203394	30.458564

8. Regions

	Material	Points	Area (m ²)
Region 1	marl	3,12,11,22,23,21,10,9,19,20,18,8,16,17,15,7,14,6,5,4,2,1,13	1970.9816

9. Points

	X (m)	Y (m)
Point 1	120.07765	15.35
Point 2	120.07765	23.18
Point 3	0.078656	42.11
Point 4	107.37435	27.04
Point 5	98.835487	27.18
Point 6	77.103385	27.24
Point 7	62.046642	30.185
Point 8	50.104485	32.195
Point 9	45.012664	33.2
Point 10	40.288294	34.205
Point 11	25.196557	38.225
Point 12	10.839721	40.145
Point 13	-0.0613253	15.34
Point 14	69.194439	27.24
Point 15	59.713677	30.577664
Point 16	57.75098	30.908008
Point 17	58.153412	30.41
Point 18	48.022263	32.1
Point 19	46.97301	32.813076
Point 20	47.824843	32.644945

Point 21	39.043873	34.536478
Point 22	36.222946	35.28789
Point 23	36.473803	34.61

SLOPE 3 AREA 3.1 After Cut Report

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10. File Information

Created By: [Mohammed](#)
Revision Number: 6
Last Edited By: [Mohammed](#)
Date: [5/26/2015](#)
Time: [11:05:58 PM](#)
File Name: [s 3 a 3.1 bef.gsz](#)
Directory: [C:\Users\DAHRAWI\Desktop\](#)

11. Project Settings

Length(L) Units: [meters](#)
Time(t) Units: [Seconds](#)
Force(F) Units: [kN](#)
Pressure(p) Units: [kPa](#)
Strength Units: [kPa](#)
Unit Weight of Water: [9.807 kN/m³](#)
View: [2D](#)

12. Analysis Settings

12.1. SLOPE 3.1 before cut

Description: [to the west](#)
Kind: [SLOPE/W](#)
Method: [Morgenstern-Price](#)
Settings
 Apply Phreatic Correction: [No](#)
 Side Function
 Interslice force function option: [Half-Sine](#)
 PWP Conditions Source: [Piezometric Line](#)
 Use Staged Rapid Drawdown: [No](#)
SlipSurface
 Direction of movement: [Left to Right](#)
 Allow Passive Mode: [No](#)
 Slip Surface Option: [Entry and Exit](#)
 Critical slip surfaces saved: [1](#)
 Optimize Critical Slip Surface Location: [No](#)
 Tension Crack
 Tension Crack Option: [\(none\)](#)
FOS Distribution
 FOS Calculation Option: [Constant](#)
Advanced
 Number of Slices: [30](#)
 Optimization Tolerance: [0.01](#)
 Minimum Slip Surface Depth: [0.1 m](#)
 Minimum Slice Width: [0.1 m](#)

Optimization Maximum Iterations: 2000
Optimization Convergence Tolerance: 1e-007
Starting Optimization Points: 8
Ending Optimization Points: 16
Complete Passes per Insertion: 1

13. Materials

13.1. marl

Model: Mohr-Coulomb
Unit Weight: 19 kN/m³
Cohesion: 10 kPa
Phi: 20 °
Phi-B: 0 °
Pore Water Pressure
Piezometric Line: 1

14. Slip Surface Entry and Exit

Left Projection: Range
Left-Zone Left Coordinate: (1.0008274, 61.837188) m
Left-Zone Right Coordinate: (57.898107, 42.832788) m
Left-Zone Increment: 4
Right Projection: Range
Right-Zone Left Coordinate: (113.76841, 27.381373) m
Right-Zone Right Coordinate: (170.89346, 17.110603) m
Right-Zone Increment: 4
Radius Increments: 4

15. Slip Surface Limits

Left Coordinate: (0.2646859, 3.2398) m
Right Coordinate: (198.95379, 13.0398) m

16. Piezometric Lines

16.1. Piezometric Line 1

Coordinates

	X (m)	Y (m)
	0.43460853	49.63839
	79.858563	24.8398
	128.49628	23.2698

17. Regions

	Material	Points	Area (m ²)
Region 1	marl	3,13,12,42,43,41,11,39,40,38,36,37,35,33,34,32,31,10,30,28,29,27,26,8,25,23,24,22,20,21,18,9,17,19,7,6,4,5,2,1,14,15	5905.1313

18. Points

	X (m)	Y (m)
Point 1	198.95379	3.0798
Point 2	198.95379	13.0398
Point 3	0.4796592	61.9398
Point 4	185.08801	16.0798
Point 5	191.53721	14.1198
Point 6	175.03801	17.0798
Point 7	165.61949	17.1498
Point 8	94.960439	29.7398
Point 9	127.08552	24.2298
Point 10	74.564844	36.5398
Point 11	49.359221	47.4798
Point 12	24.879133	55.4798
Point 13	9.7235126	60.1198
Point 14	0.2646859	3.2398
Point 15	0.44091253	51.359745
Point 16	80.073536	26.6798
Point 17	130.47135	22.1298
Point 18	124.94922	24.8598
Point 19	137.44454	17.0298

Point 20	118.09694	26.2798
Point 21	121.36185	25.0698
Point 22	115.01979	27.443679
Point 23	109.06806	28.1198
Point 24	111.72836	27.2798
Point 25	103.04068	29.508533
Point 26	89.935438	31.7798
Point 27	89.068641	32.143339
Point 28	81.121531	34.4998
Point 29	84.614848	32.0998
Point 30	78.202331	36.183405
Point 31	72.012036	38.3798
Point 32	69.776951	39.303301
Point 33	65.267248	40.6398
Point 34	66.610831	39.3798
Point 35	61.932321	42.133462
Point 36	56.560828	43.8798
Point 37	58.629946	42.2598
Point 38	55.02154	44.725971
Point 39	50.864034	46.1398
Point 40	52.288233	44.9398
Point 41	47.457123	48.277953
Point 42	35.600928	51.9998
Point 43	40.437828	48.1198

SLOPE 3 Area 3.2 After Cut Report

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19. File Information

Created By: [Mohammed](#)
Revision Number: 6
Last Edited By: [Mohammed](#)
Date: [5/27/2015](#)
Time: [1:42:26 AM](#)
File Name: [s 3 a 3.2 before c.gsz](#)
Directory: [C:\Users\DAHRAWI\Desktop\](#)

20. Project Settings

Length(L) Units: [meters](#)
Time(t) Units: [Seconds](#)
Force(F) Units: [kN](#)
Pressure(p) Units: [kPa](#)
Strength Units: [kPa](#)
Unit Weight of Water: [9.807 kN/m³](#)
View: [2D](#)

21. Analysis Settings

21.1. SLOPE 3 Area 3.2 before cut

Description: [to the west](#)
Kind: [SLOPE/W](#)
Method: [Morgenstern-Price](#)
Settings
 Apply Phreatic Correction: [No](#)
 Side Function
 Interslice force function option: [Half-Sine](#)
 PWP Conditions Source: [Piezometric Line](#)
 Use Staged Rapid Drawdown: [No](#)
SlipSurface
 Direction of movement: [Left to Right](#)
 Allow Passive Mode: [No](#)
 Slip Surface Option: [Entry and Exit](#)
 Critical slip surfaces saved: [1](#)
 Optimize Critical Slip Surface Location: [No](#)
 Tension Crack
 Tension Crack Option: [\(none\)](#)
FOS Distribution
 FOS Calculation Option: [Constant](#)
Advanced
 Number of Slices: [30](#)
 Optimization Tolerance: [0.01](#)
 Minimum Slip Surface Depth: [0.1 m](#)
 Minimum Slice Width: [0.1 m](#)

Optimization Maximum Iterations: 2000
Optimization Convergence Tolerance: 1e-007
Starting Optimization Points: 8
Ending Optimization Points: 16
Complete Passes per Insertion: 1

22. Materials

22.1. New Material

Model: Mohr-Coulomb
Unit Weight: 19 kN/m³
Cohesion: 10 kPa
Phi: 20 °
Phi-B: 0 °
Pore Water Pressure
Piezometric Line: 1

23. Slip Surface Entry and Exit

Left Projection: Range
Left-Zone Left Coordinate: (6.3893192, 74.58544) m
Left-Zone Right Coordinate: (54.50037, 47.704007) m
Left-Zone Increment: 4
Right Projection: Range
Right-Zone Left Coordinate: (117.50132, 22.709841) m
Right-Zone Right Coordinate: (191.32583, 12.192468) m
Right-Zone Increment: 4
Radius Increments: 4

24. Slip Surface Limits

Left Coordinate: (0.152146, 77.924691) m
Right Coordinate: (217.04928, 10.889316) m

25. Piezometric Lines

25.1. Piezometric Line 1

Coordinates

	X (m)	Y (m)
	-0.0734528	58.170409
	62.675242	25.488131
	144.49778	17.055379

26. Regions

	Material	Points	Area (m ²)
Region 1	New Material	3,11,44,45,43,41,42,40,38,39,10,36,37,35,33,34,9,31,32,30,28,29,27,26,25,2 3,24,22,8,20,21,19,13,18,7,6,5,17,4,2,1,12,15	6165.3011

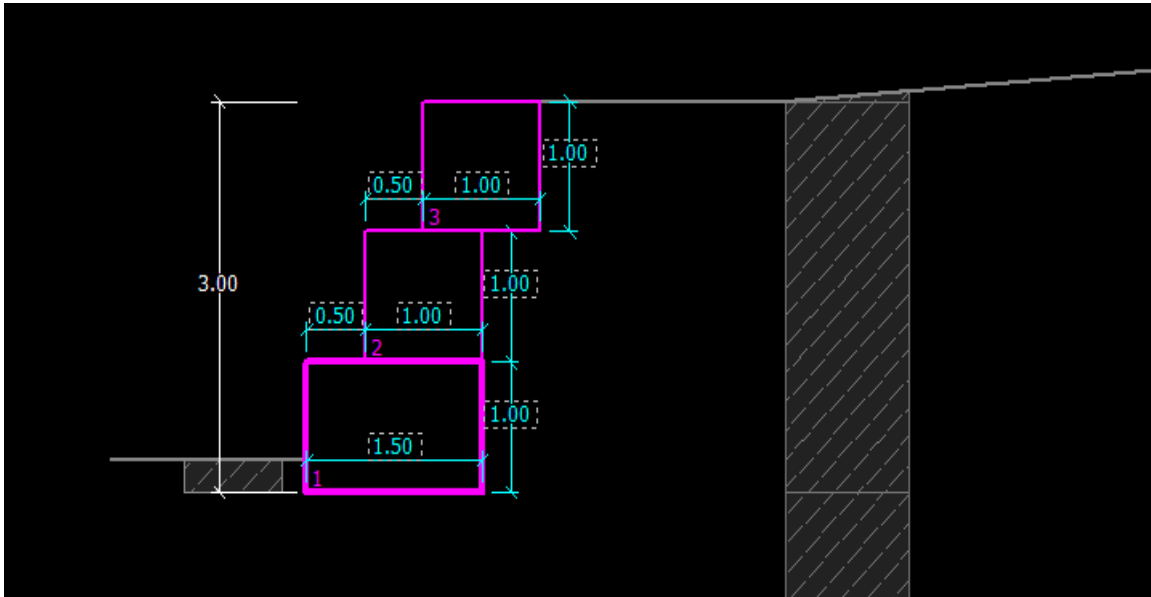
27. Points

	X (m)	Y (m)
Point 1	217.04928	3.977224
Point 2	217.04928	10.889316
Point 3	0.152146	77.924691
Point 4	202.07919	11.732273
Point 5	183.62843	12.367868
Point 6	175.0879	12.228832
Point 7	163.24396	12.407593
Point 8	124.99691	21.942705
Point 9	75.123462	39.073967
Point 10	49.98531	51.050954
Point 11	25.250013	64.487822
Point 12	0.152146	3.977224
Point 13	141.94636	17.969046
Point 14	59.29126	26.262762
Point 15	0.152146	60.704048
Point 16	60.09697	29.361286
Point 17	187.22727	12.367868
Point 18	152.07145	12.566491

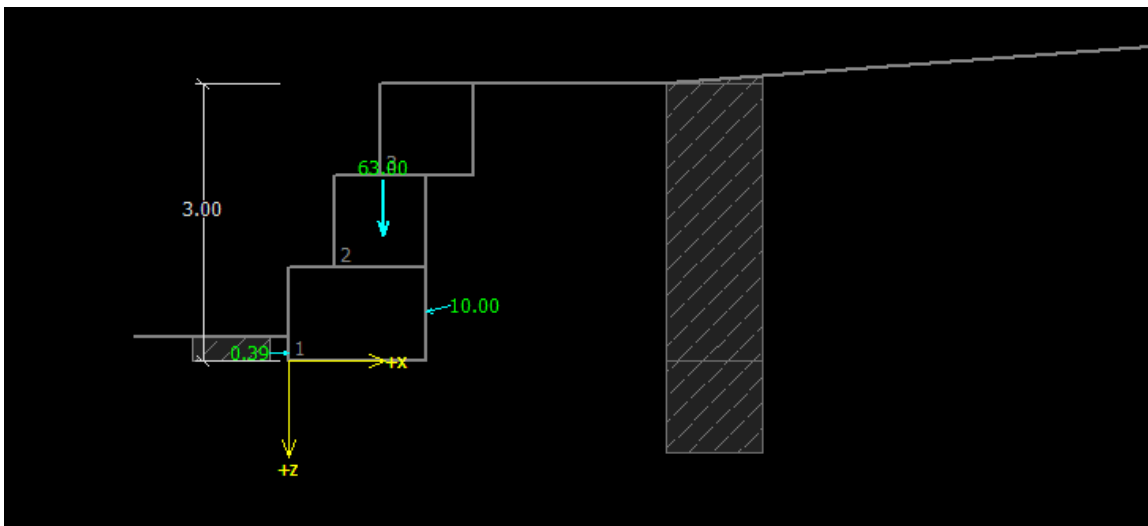
Point 19	140.17259	19.015666
Point 20	127.92701	21.266193
Point 21	135.87668	19.02175
Point 22	123.94509	22.231917
Point 23	111.43681	25.457146
Point 24	118.71506	22.159998
Point 25	109.09623	26.314823
Point 26	104.99113	26.311226
Point 27	97.065846	30.008664
Point 28	89.736355	33.004832
Point 29	94.490044	29.926171
Point 30	88.00092	33.753758
Point 31	76.764424	38.288213
Point 32	84.821524	33.779463
Point 33	63.121068	44.862645
Point 34	69.378749	39.261467
Point 35	61.936668	45.35677
Point 36	51.921699	49.828229
Point 37	57.346813	45.359204
Point 38	43.112603	54.674638
Point 39	47.302295	50.960382
Point 40	42.045696	55.363962
Point 41	36.210354	58.527931
Point 42	38.949768	55.36982
Point 43	35.029543	59.175323
Point 44	26.810404	63.63255

Point 45	30.51667	59.362149
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Second slope reinforcement design



Verification of complete wall



Check for overturning stability

Resisting moment $M_{res} = 69.38 \text{ kNm/m}$
 Overturning moment $M_{ovr} = 4.96 \text{ kNm/m}$

Safety factor = $13.98 > 1.50$
 Wall for overturning is SATISFACTORY

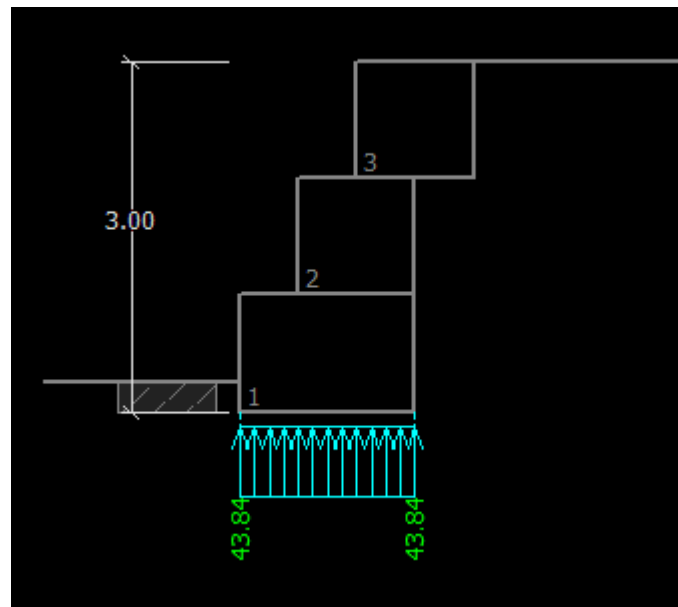
Check for slip

Resisting horizontal force $H_{res} = 38.93$ kN/m
Active horizontal force $H_{act} = 9.22$ kN/m

Safety factor = 4.22 > 1.50
Wall for slip is SATISFACTORY

Overall check - WALL is SATISFACTORY

Bearing capacity verification



Design load acting at the center of footing bottom

No.	Moment [kNm/m]	Norm. force [kN/m]	Shear Force [kN/m]	Eccentricity [-]	Stress [kPa]
1	-15.10	65.76	9.22	0.000	43.84

Service load acting at the center of footing bottom

No.	Moment [kNm/m]	Norm. force [kN/m]	Shear Force [kN/m]
1	-15.10	65.76	9.22

Verification of foundation soil

Eccentricity verification

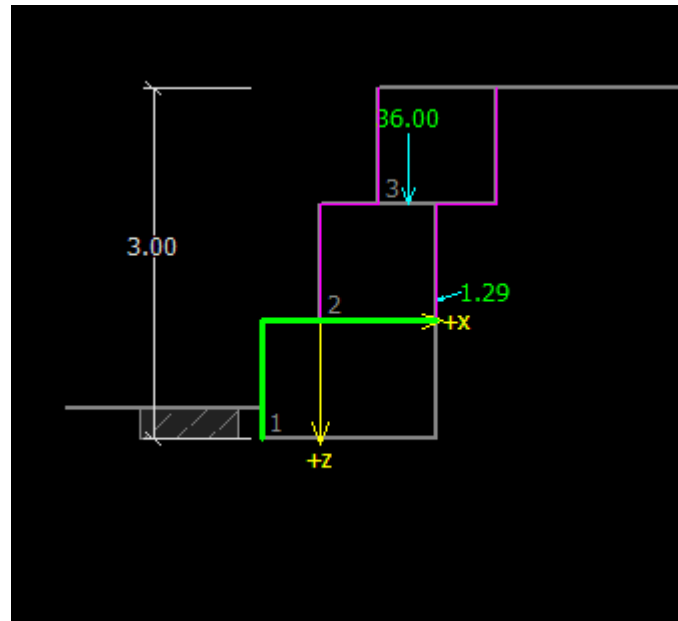
Max. eccentricity of normal force $e = 0.000$
Maximum allowable eccentricity $e_{alw} = 0.333$
Eccentricity of the normal force is SATISFACTORY

Verification of bearing capacity

Max. stress at footing bottom $\sigma = 43.84$ kPa
Bearing capacity of foundation soil $R_d = 120.00$ kPa
Safety factor = 2.74 > 1.50
Bearing capacity of foundation soil is SATISFACTORY

Overall verification - bearing capacity of found. soil is SATISFACTORY

Verification of construction joint above the block No.: 1



Check for overturning stability

$$\begin{aligned} \text{Resisting moment } M_{res} &= 27.35 \text{ kNm/m} \\ \text{Overturning moment } M_{ovr} &= 0.23 \text{ kNm/m} \end{aligned}$$

$$\text{Safety factor} = 118.48 > 1.50$$

Joint for overturning stability is SATISFACTORY

Check for slip

$$\begin{aligned} \text{Resisting horizontal force } H_{res} &= 20.99 \text{ kN/m} \\ \text{Active horizontal force } H_{act} &= 1.24 \text{ kN/m} \end{aligned}$$

$$\text{Safety factor} = 16.96 > 1.50$$

Joint for slip is SATISFACTORY

$$\begin{aligned} \text{Maximum pressure on the bottom block} &= 36.35 \text{ kPa} \\ \text{Red.Coeff. by offset of top block} &= 0.13 \\ \text{Average value of pressure on face} &= 5.78 \text{ kPa} \\ \text{Shear force transmitted by friction} &= 13.99 \text{ kN/m} \end{aligned}$$

Bearing capacity against transverse pressure:

$$\begin{aligned} \text{Joint bear.capacity} &= 40.00 \text{ kN/m} \\ \text{Computed stress-state} &= 2.89 \text{ kN/m} \end{aligned}$$

$$\text{Safety factor} = 13.84 > 1.50$$

Transverse pressure check is SATISFACTORY

Joint btw. blocks check:

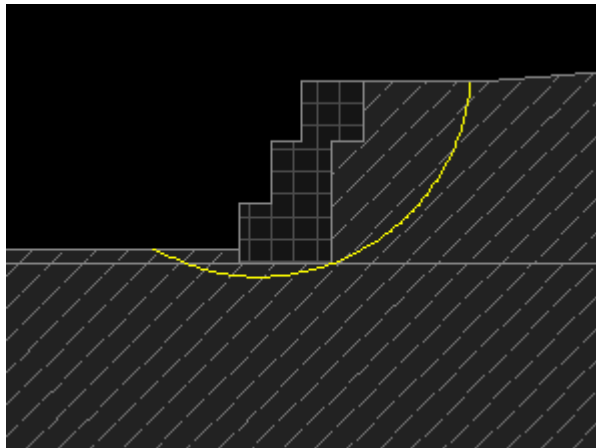
Mesh material bear.capacity = 40.00 kN/m

Computed stress-state = 2.89 kN/m

Safety factor = 13.84 > 1.50

Joint between blocks is SATISFACTORY

Slope stability verification (Bishop)



Sum of active forces : $F_a = 62.72$ kN/m

Sum of passive forces : $F_p = 124.19$ kN/m

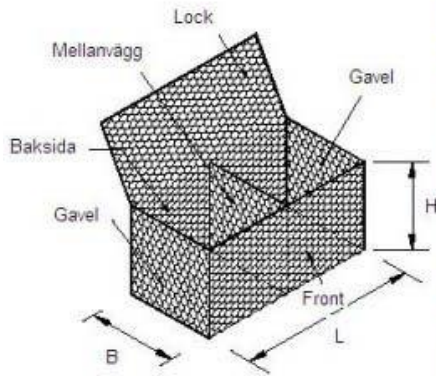
Sliding moment : $M_a = 217.64$ kNm/m

Resisting moment : $M_p = 430.93$ kNm/m

Factor of safety = 1.98 > 1.50

Slope stability ACCEPTABLE

Gabion excution



Gabion Assembly

