"Impact of Rainfall Infiltration on a Ground Slope"

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MASTER OFTECHNOLOGY

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Submitted by

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CANDIDATE'S DECLARATION

I, **HARSHIT SINGH, 2K20/GTE/09**, student of M.Tech (Civil Engineering), hereby declare that the project dissertation titled **"Impact of Rainfall Infiltration on a Ground Slope "** is submitted to the Department of Civil Engineering, Delhi Technological University, Delhi, by me in partial fulfillment of requirement for the award of degree of **Master of Technology (Geotechnical Engineering)**. This thesis is original work done by me and not obtained from any source without proper citation. This project work has not previously formed the basis for award of any degree, diploma, fellowship or other similar title or recognition.

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CERTIFICATE

I hereby certify that project dissertation titled **“Impact of Rainfall Infiltration on a Ground Slope”** submitted by **Harshit Singh, 2K20/GTE/09,** Department of Civil Engineering, Delhi Technological University, Delhi, in partial fulfillment for the award of degree of Master of Technology, is a project work carried out by the student under my supervision. To the best of my knowledge, this work has not been submitted in part or full for any degree or diploma to this university or elsewhere.

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ABSTRACT

In many parts of the world, rainfall is one of the most major triggering causes for slope failures.

Rainwater infiltration into a slope and the effect of water infiltration on slope stability have been the subject of several research projects. A review of current research on infiltration analysis and slope stability analysis under rainfall infiltration in Uttarakhand, Almora district. The first section looks at studies on slope stability analysis using conceptual models by using GEOSTUDIO software analysis. Following that, the slope's typical pore water pressure profiles are discussed and recent advances in the use of the limit equilibrium approach to analyses slope instabilities under rainfall conditions and the most important discoveries on essential hydrological parameters related to rainfall-induced slope failure are summarized and addressed.

It is currently challenging to assess the impact of rainwater infiltration on slope stability. Infiltration reduces a slope's stability. The failures were caused mostly by the loss of matric suction in the soils caused by precipitation the Lower conductivity soil slope was more influenced than the Higher conductivity soil slope in terms of stability and rate of reduction in factor of safety was regulated by antecedent rainfall patterns

In this research work we are computing the slope stability using the Slope/W and seepage analysis using Slope/W method of GEOSTUDIO software parametric study was conducted to investigate the effect on safety factor of slope and result shows that short-term rainfall can change low factor of safety while continuous rainfall can result in the rise of ground water table due to which the slope induced instability.

Keywords: Rainfall, Factor of safety, Slope Stability, Pore water pressure, Soil Conditions, Infiltration

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I am genuinely appreciative of my friends for their support and suggestions during my work. Lastly, I would like to thank the Almighty GOD and my parents, whose committed and untiring efforts towards me have brought me at this stage of my life.

HARSHIT SINGH

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CHAPTER 1 - INTRODUCTION

1.1 General

Slope instability caused by flooding is a global threat to people and property. There are countless examples of large-scale slope failure all across the world. Slope instability caused by rain has been the topic of extensive research for many years. Several studies on field observations and laboratory experiments are available. Over the years, various approaches to simulate the slope stability process have been used. Water has a considerable effect on the stability of the slope and stability; slope's rock mass often contains a big amount of groundwater, which is degraded by seasonal rainfall. Global climate irregularity, including severe rainfall, have increased the frequency of numerous geological disasters on slope in recent years.

Rainfall events have diverse effects on slope seepage; short-term rainfall can change low factor of safety while continuous rainfall can result in the increase in ground level due to which the slope induced instability.

Rainfall infiltration is a constant and dynamic process, with considerable changes in the physical composition, sedimentary features, and complicated geological processes on rock and soil mass. It is crucial to examine the impact of rainwater infiltration on the seepage field and soil mass slope stability in depth, taking into account the inherent geographical variability of the seepage field.

Geotechnical engineers and researchers have long been concerned with the inherent and man-made stability slope. Slope stability assessment is a multi-disciplinary area including basic geology, soil mechanics, and rock mechanics principles.

Digging, hill hillsides, earth dams, riverbeds, and seaside slopes are all examples of natural features. are just a few of the many applications of slope stability. Rainfall infiltration, seismic activity, engineering efforts, and other factors, to name a few, have all contributed to the failure of many slopes. The slope is divided into saturated and unsaturated zones by the presence of a ground water level (GWL). Rainwater infiltration happens during periods of heavy rainfall, causing groundwater levels and neutral pressure to rise (Cai and Ugai 2004, Cho and Lee 2001, Cho 2009, Gavin and Xue 2008 Ni et al. 2018). Under infiltration conditions, Shallow slope collapse is caused by an increase pressure of pore water in unsaturated zone. Figure 1.1 depicts rain-induced slope failures.

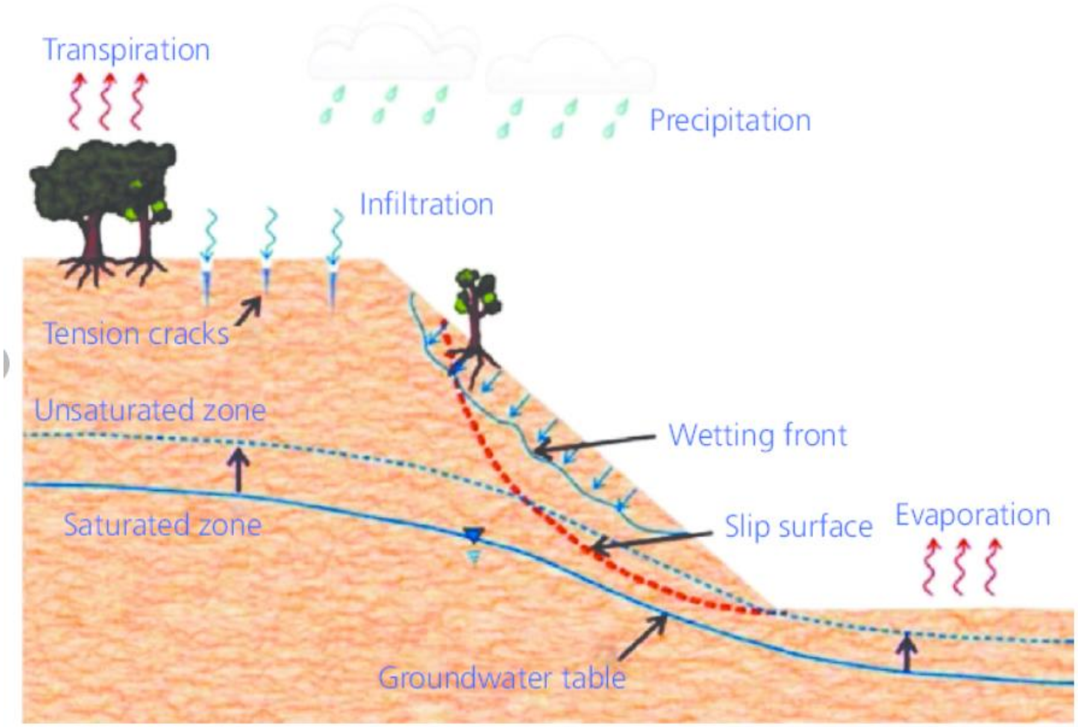


Figure 1.1 Examples of rainfall induced slope failures

1.2 Main importance of rainfall in slope stability

Rainfall infiltration into unsaturated soil slopes was studied by Gavin and Xue (2008), and the consequences on soil stability were examined in increase in ground level of water, matric suction is decreased or an increase in pore water pressures, production of roosted GWL, and expansion in unit weight because of expanded dampness content are ramifications of precipitation invasion. Wet zone emerges out from the surface of slope as rainwater infiltrates of slope.

The transition limit condition varieties (i.e., penetration, dissipation, and happening) brought about by precipitation conditions significantly affect negative pore water pressures in unsaturated soils. Precipitation penetration happens the water is conveyed in the zone of slant which is unsaturated.
The slope infiltration limit and matric attractions decline as invasion proceeds (pore water pressure rises). Therefore, the extra shear strength provided by matric suction will be diminished, making the

incline more powerless against breakdown (Rahardo et al. 2012). Figure 1.2 shows the component of precipitation incited slant breakdown (Rahardjo et al., 2007), in which the wetting front advances and the groundwater level ascents under stormy circumstances (precipitation)

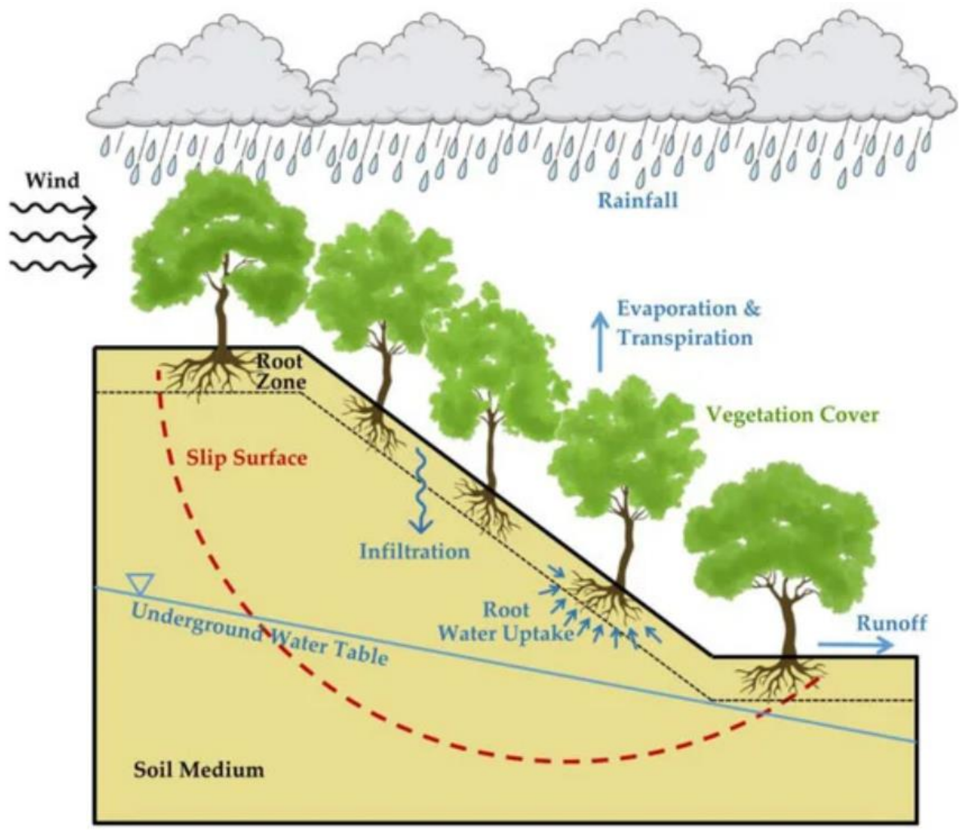


Figure 1.2 Mechanism of precipitation prompted incline failure (after Rahardjo et al., 2007)

1.3 The following are the primary elements that impact infiltration:

- The kind of soil (texture, structure, hydrodynamic characteristics). Capillary forces and adsorption are influenced by soil properties.
- Covering of the soil Infiltration is aided by vegetation because it lengthens the time it takes for water to penetrate the soil.
- The slope topography and morphology

- The supply of flow (rain intensity, irrigation flow)
- The humidity of the soil is a significant component in the infiltration regime. For dry or wet soils, the infiltration regime varies differentially over time.
- Soil compaction caused by raindrop impact and other causes the use of heavy agricultural equipment might have an impact on the soil's surface layer.

1.4 Extent of the research study

The general objective of this exploration is to check at the steadiness of slopes with various safety of factor during rainy conditions. The focus will be on slopes in the given regional area and focus on their stability analysis at the maximum rainfall in terms of safety factor in the regional area

1.4.1 The objectives of the present study are:

The study's major goal is to look at the stability of different types of soil slopes under varied rainfall conditions and analyze the slopes stability under rainfall infiltration, the detailed scope of work is as follows

- Varied slopes with different mechanical and hydraulic properties are chosen and their safety factors are evaluated.
- To understand the slopes' results in a systematic manner, the slopes' behavior with various parameters will be explored during rainfall infiltration first. Slopes will be subjected to parametric study with variable rainfall magnitude, time, angle of slope, and height of slope.
- Different slopes investigated under various rainfall infiltration scenarios. The impact of several variables such as rainfall magnitude, time, angle of slope, and height of slope.
- The many types of failure processes from basic slip surfaces that happen on inclines will be analyzed.

CHAPTER 2 – LITERATURE REVIEW

2.1 Outline of research study carried out

The review of literature is a summation of information collected from previous researchers and stakeholders' use of various publications, articles, manuals, reports, and tools, and it serves as the basis for any desk study as well as the development of specific problem-solving process.

Many scientists, academics, and other stakeholders are spending more time and resources to slope failure research to measure, quantify, and perhaps prevent the enormous economic losses caused by slope unstable. As a result, several approaches have been suggested, applied, compared, and verified, leading into an enormous number of publications in the recent decade both nationally and globally.

The multi-faceted nature of these mishaps, however, makes creating a general "reasonable" solution incredibly hard, with some of the most significant challenges being the classification of main factors specific to a region, identification of relevant of appropriate data analysis and predictive modelling techniques. External factors such as collected data, altitude, and so on are extremely dependent on these solutions. In regions where such disasters have occurred, slope collapse research, such as susceptibility and hazard mapping, early warning systems, and so on, is supported at all levels. Moreover, this research contributes to other practitioners' ongoing work in better understanding slope instability mechanisms in the Indian state of Uttarakhand, Almora District and seeking to designate regions sensitive to future slope failures using numerous methods.

The purpose of this research is to prepare slope instability susceptibility for the area under investigation by applying different methodologies of seep//w and slope//w and comparing BOTH slope factors of slope according their region area rainfall infiltration data as well as examining the regional links between different causative factors and historical slope failure incidents

The soil properties of unsaturated are discussed first, then comes the procedures of rainfall infiltration and stability analysis methods. Finally, the slope stability graphs and algorithms are summarized, and gaps in the research are noted in the identified literature

2.1 Moist and undrained soil

There are two periods of soaked soil.: The strong period of immersed soil will be soil particles, and the fluid stage is water. There are three periods of unsaturated soil: The strong stage is soil particles, the fluid stage is water, and the vaporous stage is air.

In the soil incline the ground water viewed bound between soaked and unsaturated zones in a slope of soil, displayed in Fig 2.1. Pore pressure is positive in the wet zone. (i.e., in a state of compression), that decreased essential stress and thus incline of slope is reduced.

Pore-water pressure is negative in the unsaturated zone (i.e., in a condition of strain), which improves soil particle shearing protection (Fig 2.2) and subsequently increments stability of slope.

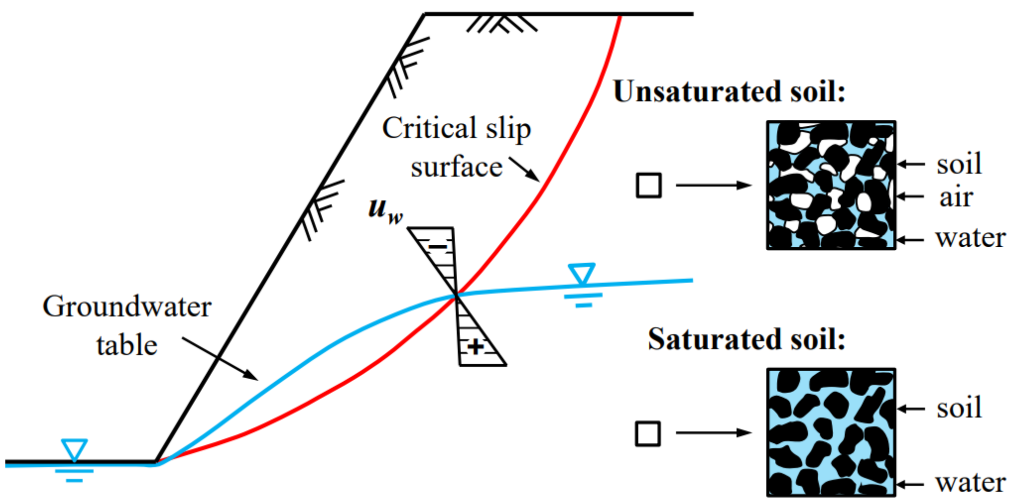


Fig 2.1 Saturated and unsaturated soil

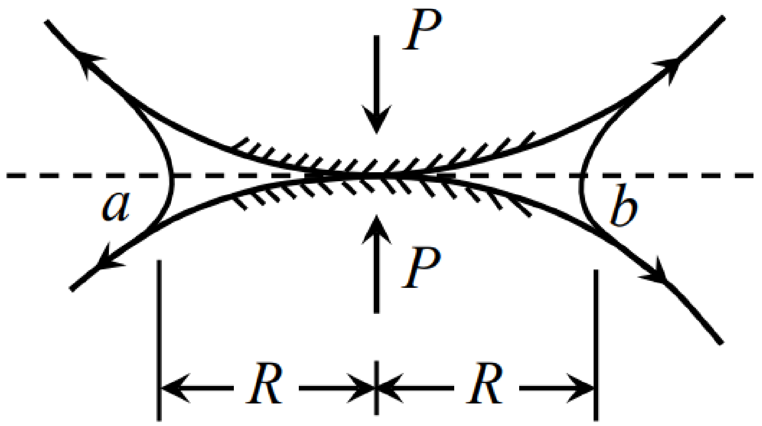


Fig 2.2 Soil particles between adhesion delivered by the contact dampness (from Terzaghi, 1943)

Terzaghi (1936) describe that viable pressure (σ'), which is equivalent to the contrast between absolute typical pressure (σ) and water of pore pressure (u_w), decides the volume change and shearing obstruction of immersed

$\sigma' = \sigma - u_w$ (2.1)

The shear strength of immersed soil is composed as (Terzaghi, 1936) utilizing the Mohr-Coulomb disappointment model:

$\tau = a' + \sigma' \tan \phi' = c'' + (\sigma - u_w) \tan \phi'$ (2.2)

shear strength is τ, powerful attachment is a′, and viable point of inside erosion is φ′.

Conditions (2.1) and (2.2) are as it were applicable to soaked soils with water-filled voids. Cleric and Blight (1963) gave an altered detailing of the powerful pressure condition of record the presence in both water and air in holes of unsaturated soils.

$\sigma'' = \sigma - u_b + \chi(u_b - u_c)$ (2.3)

where the pore pressure is u_b, χ is a variable which is mostly connected to the saturation level As a result, unsaturated soil shear strength can be written as:

$\tau = a' + [(\sigma - u_b) + \chi(u_b - u_c)] \tan \phi'$ (2.4)

As per Morgenstern and fredlund (1977) Eq. (2.3) is a relation of constitutive, instead of a specification the state of pressure, in light of the fact that the pressure state unable to contain a boundary (i.e., χ) that is connected with properties of the dirt (e.g., immersion of level). Fredlund et al. (1978) introduced net ordinary pressure ($\sigma - u_b$) and matric attractions ($u_b - u_c$) free unsaturated soil pressure state factors, and the Unsaturated soils' shear strength was acclimated to be

$$\tau = a' + (\sigma - u_b)\tan\ \phi' + (u_b - u_c)\tan\ \phi^b (2.5)$$

where $\phi^b$is a point that shows the rate at which shear strength expansions according to matric attractions? $(u_b - u_c)$. Condition (2.5) is called as drawn-out Mohr-Coulomb disappointment measure for unsaturated soils. The type of conditions (2.4) and (2.5) has all the earmarks of being equivalent. Likening Eq. (2.4) and (2.5) for indistinguishable soils (e.g., soils compacted at a similar water content and dry thickness), the association among χ and ϕ^bcan be communicated as (Fredlund and Rahardjo, 1993; Sheng, 2011; Fredlund et al., 2012):

$$\chi = \frac{\tan \phi^b}{\tan \phi'}$$

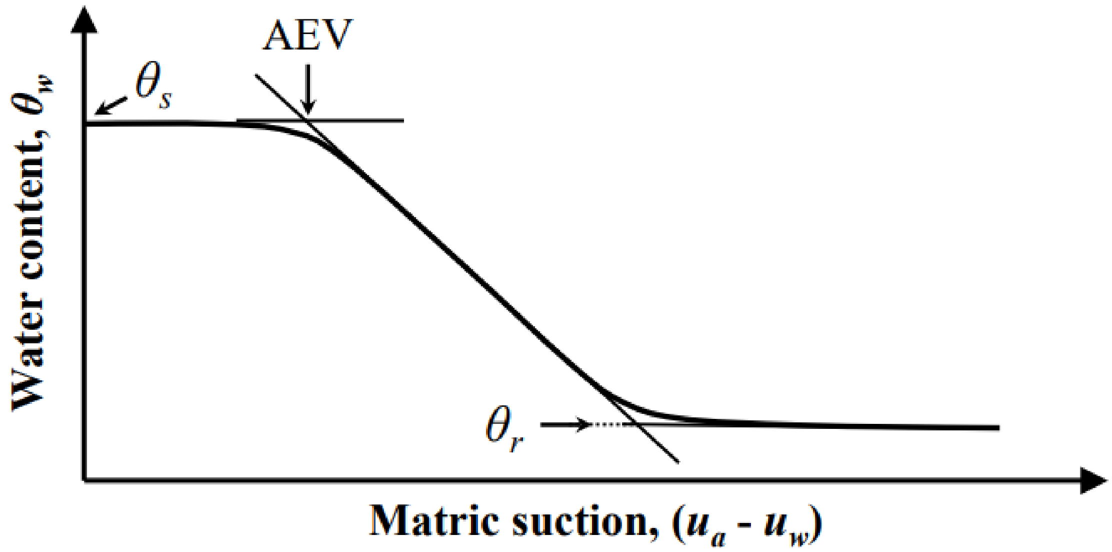
The autonomous pressure state variable strategy might be more engaging from a useful designing angle, since it permits greater adaptability as far as describing the shear strength nonlinear conduct relating to a scope of stress courses (Fredlund and Rahardjo, 1993; Fredlund et al., 2012).

2.1.2 Properties of drained Soil

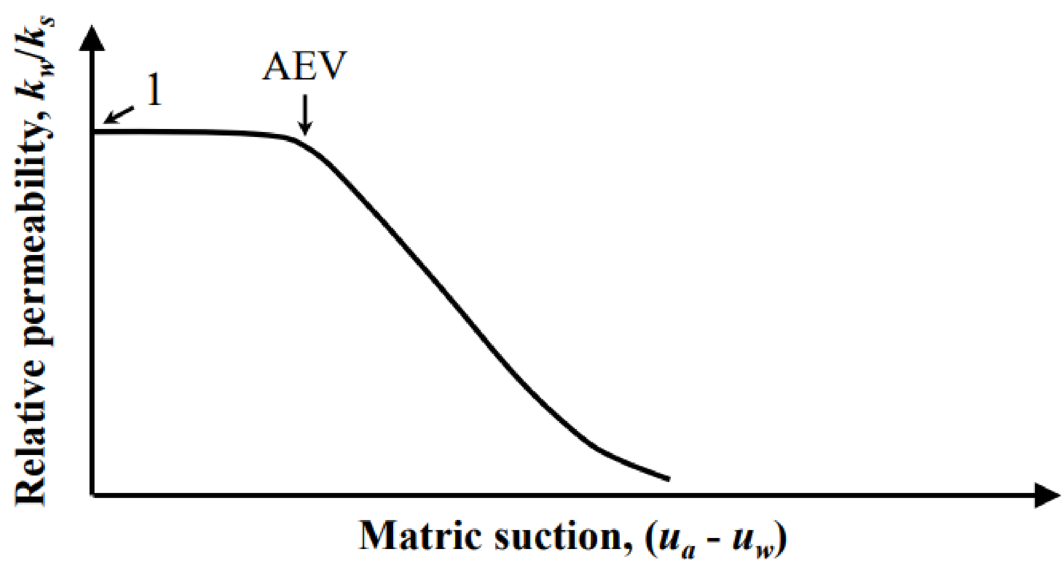
water in an undrained environment not set in stone by the soil attractions (Leong and Rahardjo, 1997). The dirt water trademark bend (SWCC), as displayed in Figure 2.3(a), makes sense of the connection between water content and pull when the attractions is not exactly the air-passage esteem (AEV), the dirt is completely soaked. Water can be effectively cleared by expanding the pull between the AEV and the lingering attractions. Water can barely be separated over the leftover attractions with ensuing expansions in pull.

Since water is course through the constant water channels, the coefficient of penetrability in the water stage is comparable to the dirt's water content (Leong and Rahardjo, 1997) When the attractions are underneath the AEV, the dirt porousness (kw) approaches the soaked porousness (ks), as displayed in

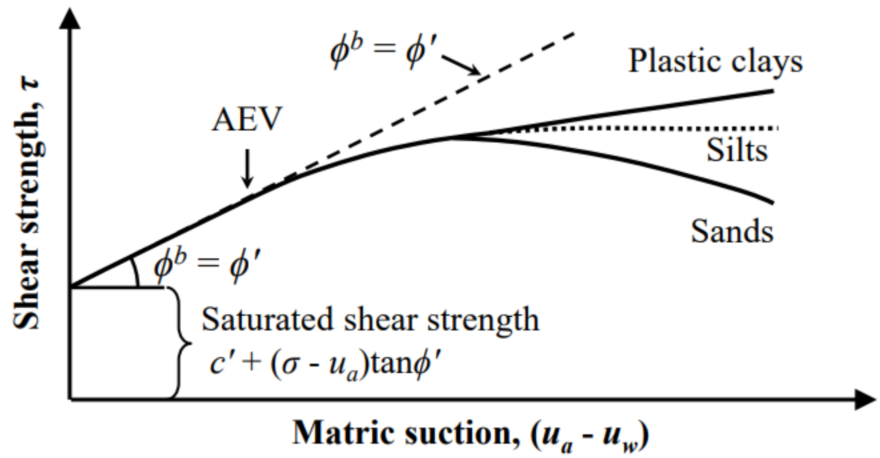
Figure 2.3(b). Whenever the AEV is surpassed, air enters the void, decreases water penetrability altogether and at high attractions, water porousness ought to be exceptionally low.



(a) characteristic of soil water curve (SWCC)



(b) Permeability function



(c) Undrained shear strength of soil

Figure 2.3 SWCC, perviousness function and undrained shear strength [(a) and (b) are changed from Fredlund et al. (1994), (c) is changed from Gan and Fredlund (1996)]

2.2 Review of Slope Failure Caused by Rain

Slope failure induced rainfall have been seen during or soon after times of outrageous or ceaseless weighty downpour. In tropical or subtropical environments, these incline disappointments most typically occur on regular slants in a material, including remaining and soils found in rivers and streams. Cut inclines and slope banks may likewise be defenseless to this kind of slant disappointment, as indicated by some field research. (e.g., Harp et al. 1996; Baum and Chleborad 1999). As per field research, these slant disappointments are regularly short in size and include shallow sliding. (Under 2 m profound) on steep soil inclines of 30 to 50 degrees over the groundwater table (Anderson and Thallapally 1996; Rahardjo 1999; Baum and Chleborad 1999; Johnson and Sitar 1990;). In spite of their little volume, these fiascos guarantee innumerable lives and make huge financial harm in different areas of the planet consistently.

(1) There were two kinds of failures: surface retrogressive failure and slide failure, were noticed. Rainfall water and layer of sand thickness both had a significant impact on slope failure. When the relative density D_r was low and the rainfall concentration, I was high, surface slide defeat occurred, but retrogressive failure happened when D_r was big and I was low.

(2) During the first failure process, some aspects were observed. As the seepage surface developed and climbed up, the soil containing the rainfall flowed out (flow slide) at the toes of slope until the first fracture appeared. When the first failure occurred diminished at the time t_{ff} with increase in rainfall intensity. Reduced effective strains at the slope toes may be the cause of the first failures.

(3) In the case of a surface slide failure, the underlying failure was followed by a big and slight failure. sort of collapse is caused mostly by shear strength reductions induced by saturation of all layer of sand. In the retrogressive failure, little consecutive failure happened after the underlying failure. Since the districts where failure happened were basically the same as those where expanded pore water pressure was estimated, this type of disappointment could be principally brought about by decreased viable anxieties.

(4) Failure classes were concurring with the dislodging designs. The relocations in the surface slide disappointment happened along the slant, and the removals were seen inside the sand layer. In the interim, as opposed to the surface slide disappointment, even relocations were more unmistakable and restricted inside a more modest region in the retrogressive disappointment.

(5) The PWP measurements climbed to positive values when rainfall gathered along the slope toes. There was no drainage of rainfall from the slopes' surfaces before to the failures. To keep the inclines stable, it is vital to deplete the water which is gathered at the slope toes.

2.2.1 Rainfall-Induced Slope Failure Procedure

Failure of slope owing to rainfall has become more common in Uttarakhand during the rainy season, resulting in the deaths of many people and major damage to existing infrastructure and regional culture. Basically, slope failure is mainly cause by the rainfall

- The weight of the soil mass increasing
- With increasing content of water, the unsaturated soil suction decreases
- rise in level of groundwater

The procedure of rainfall is depicted in Figure 2.4 increase in water content in unsaturated soil causes deform of soil mass followed by incline slope after precipitation, as seen in this diagram. The figure also shows how a rise in the level of ground water can create slope distortion and eventually lead to deep slope failure. therefore, the mechanical properties of unsoaked soils must thoroughly investigated in order to understand how rainfall causes slope failure.

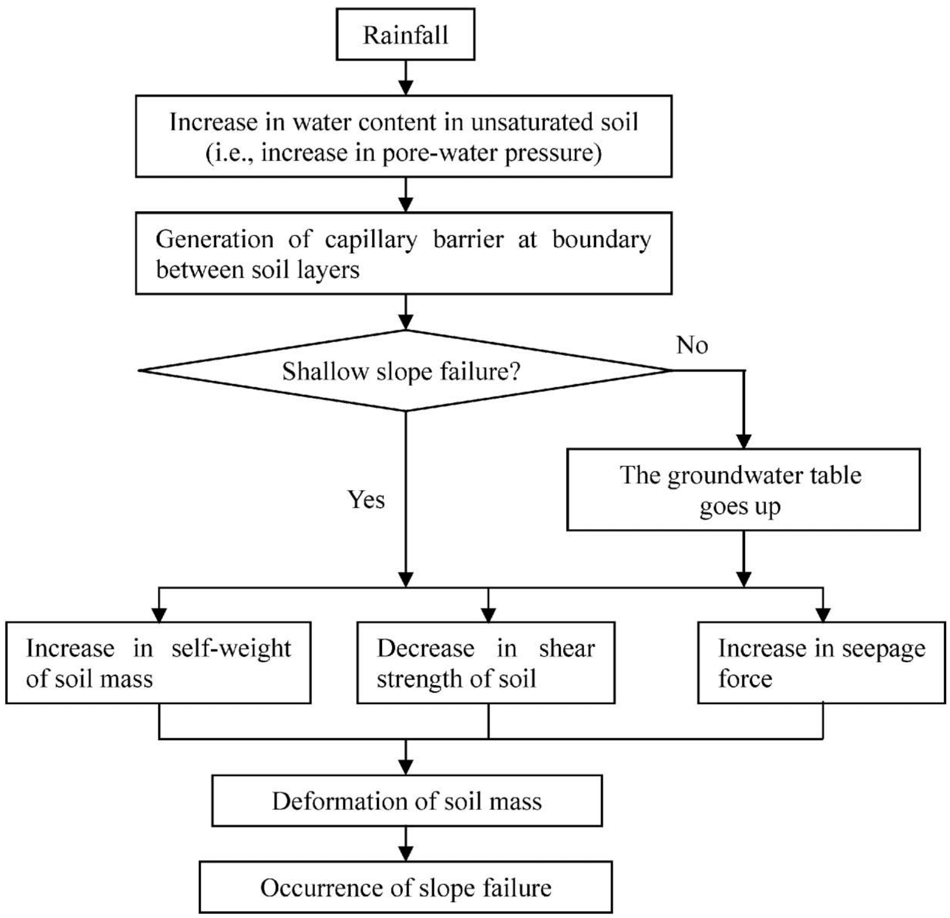


Figure 2.4 Procedure of Rainfall Induced Slope failure

rainwater incited incline failure is viewed as initiated via pore water tension changes and leakage powers (Zhu and Anderson, 1998; Gerscovich et al., 2006.). For rainwater incited incline failure, two separate failure processes have been recognized and examined (Collins and Znidarcic, 2004). In the main system, Positive tensions develop essentially in a low right on target the incline or with the dirt interface. Developments on the surface sliding reason liquefaction, bringing about fast developments, broadened run-out distance, and ultimately liquefaction of the oscillating mass fully (Wang and Sassa, 2001). A persistent shear pressure course can be utilized to portray the in-situ pressure way (Anderson and Sitar, 1995). The dirt is unsaturated in the subsequent component, and failure of slope caused basically by rainfall invasion and a deficiency of shear strength of soil as soil attractions are decreased and disseminated (Fredlund and Rahardjo, 1993; Fourie et al., 1999;).

Cascini et al. (2010) characterized had partitioned precipitation actuated slant disappointment in view of the phases of failure the arrangement of a ceaseless the entire shear surface the whole mass of soil is characterized as the disappointment level. The fast creation of gigantic plastic strains and the subsequent abrupt speed increase of the bombed soil mass portray the post-disappointment stage. Precipitation instigated incline disappointment are described as slide, slide to stream (slides that change into streams), or flow slide in view of the speed increase of the bombed mass. as per Cascini et al., the possible quick speed increase of the bombed mass in the post-disappointment level, is an after effect of slant flimsiness process, subsequently disappointment and post-disappointment stages ought to be concentrated freely. Most of this work will be dedicated to a survey of appropriate investigations on incline shakiness in the disappointment stage; investigation of slants in the post-disappointment stage will be dealt with just momentarily.

2.2.2 Infiltration analysis

Infiltration is the main consideration in the unsteadiness of inclines during blustery climate. Most evaluations address the impact of seepage on incline slope by figuring the variable of factor of safety or basic critical depth for a limitless slope subject to drainage lined up with the slant surface. This technique for study accepts that an immersed consistent state stream is happening at a particular profundity. The phreatic surface ascents match with the incline surface, and the slant is completely soaked, (Collins and Znidarcic, 2004). For such immersed inclines, extra infiltration is beyond the realm of possibility, and precipitation will significantly affect slant security.

The impact of rainfall at the slant surface will be different for inclines that are initially unsaturated. As entering water streams downwards into the dirt, the pore water pressure design that structures will be a transitory cycle. Soil pulls, and consequently the pore pressure of water profile, impact shear strength of soil. The development of the pore pressure of water profile will likewise impact advancement of leakage powers in the incline.

2.2.3 Mathematical Seepage and Slope Stability Analysis

Rainwater infiltrate alters the pore pressure of water circulate in soil, altering the soil's stress state and potentially causing slope instability. Infiltration and stability of slope analyses and performed in either a way of coupled and uncoupled. Pore tensions, stress, and distortion are undeniably tackled independently in an "uncoupled" technique. Pore tensions, stress, and distortion all solved simultaneously in a "coupled" analysis (Fredlund et al., 2012). While changes in Pore tensions, stress, and distortion are all intimately related, the analysis of couple is thought to be high rigorous or accurate. A coupled analysis, on the other hand, has a far more sophisticated and computationally costly formulation than an analysis of uncoupled. As a result, the analysis of uncoupled is more extensively used for slope stability problems because it is not difficult to address and more exact (Fredlund et al., 2012)

2.2.3.1 Mathematical Seepage Analysis

The regulating conditions of two-dimensional flow movement across unsaturated soil can be formed as follows, as according Darcy's control and stream coherence. (Richards, 1931):

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right) = -\partial_{\frac{\theta\omega}{\partial t}} \qquad (2.7)$$

where permeability of coefficient in the x direction is k_x, permeability of water coefficient in the y direction is k_y, h is the head pressure, and θ_w is the vol water content The k_x, k_y, θ_w are all function of h non linear

Penetrability function [k_x (h), k_y (h)] and soil-water trademark curve [θ_w (h)] of the soil should be known to tackle the incomplete differential condition [Eq. (2.7)] For unsaturated soil, Fredlund and Morgenstern (1976) proposed the accompanying water stage constitutive relationship:

$$d\theta_w = m_1^w d(\sigma - u_a) + m_2^w \, d(u_a - u_w) \quad (2.8)$$

where normal stress is σ, pore pressure air is u_a, $m_1^w$is the slope of water volume versus $\sigma - u_a$relationship whenever $d(u_a - u_w)$ is zero, and m_2^w is the incline of the water deposit coefficient, which is the slant of the water volume versus $(u_a - u_w)$ accord $d(\sigma - u_a)$ is zero. The seepage analysis becomes "uncoupled" in the event that the complete pressure is viewed as steady and the pore-gaseous pressure is thought to be climatic, then, at that point, Eq. (2.8) is decreased to:

$$d\theta_w = m_2^w d(-u_w) \quad (2.9)$$

Subbing Eq. (2.9) into Eq. (2.7) would prompt

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right) = m_2^w \rho_w g \frac{\partial h}{dt} \quad (2.10)$$

where ρ_w denotes water density and g denotes gravitational acceleration. Numerical software (such as SEEP/W) can easily solve Equation (2.10). Fredlund et al.

The writing contains pore-water pressure profiles under precipitation penetration for different soil types and precipitation circumstances (e.g., Zhang et al., 2004; Lee et al., 2009). Figure 2.5 shows a schematic portrayal of commonplace pore water pressure designs under precipitation penetration. Figure 2.5(a) portrays the consistent state pore-water pressure profile. The slope of pore-water tension in consistent state, as per Kisch (1959), can be composed as:

$$\frac{du_w}{dy} = \gamma w \left(\frac{1}{k_s} - 1\right) \quad (2.11)$$

where I is the penetration rate, k_s is the soil-soaked porousness, and w is the water's unit weight. The pore-water pressure is hydrostatic when I = 0. Pore-water pressure ascend as I/k_s rise. When I/k_s= 1, the strain dispersion bend swings to one side and approaches zero. All through the pore-water pressure is in a transient condition among beginning and stable stages during precipitation penetration.

Figures 2.5(b), (c), (d), and (e) show Matric pull can be utilized for a blustery occasion with I/ks. Even assuming that the precipitation goes on for quite a while and the porewater pressure moves toward the consistent state [Figures 2.5(b) and (c)], the porewater strain will constantly be kept up with somewhat.

Matric suction might in any case be kept up with for a precipitation occasion with I/k_s1 [Figures 2.5(d) and (e and how much leftover matric not set in stone by the precipitation highlights and soil water powered boundaries (Zhang et al., 2004).

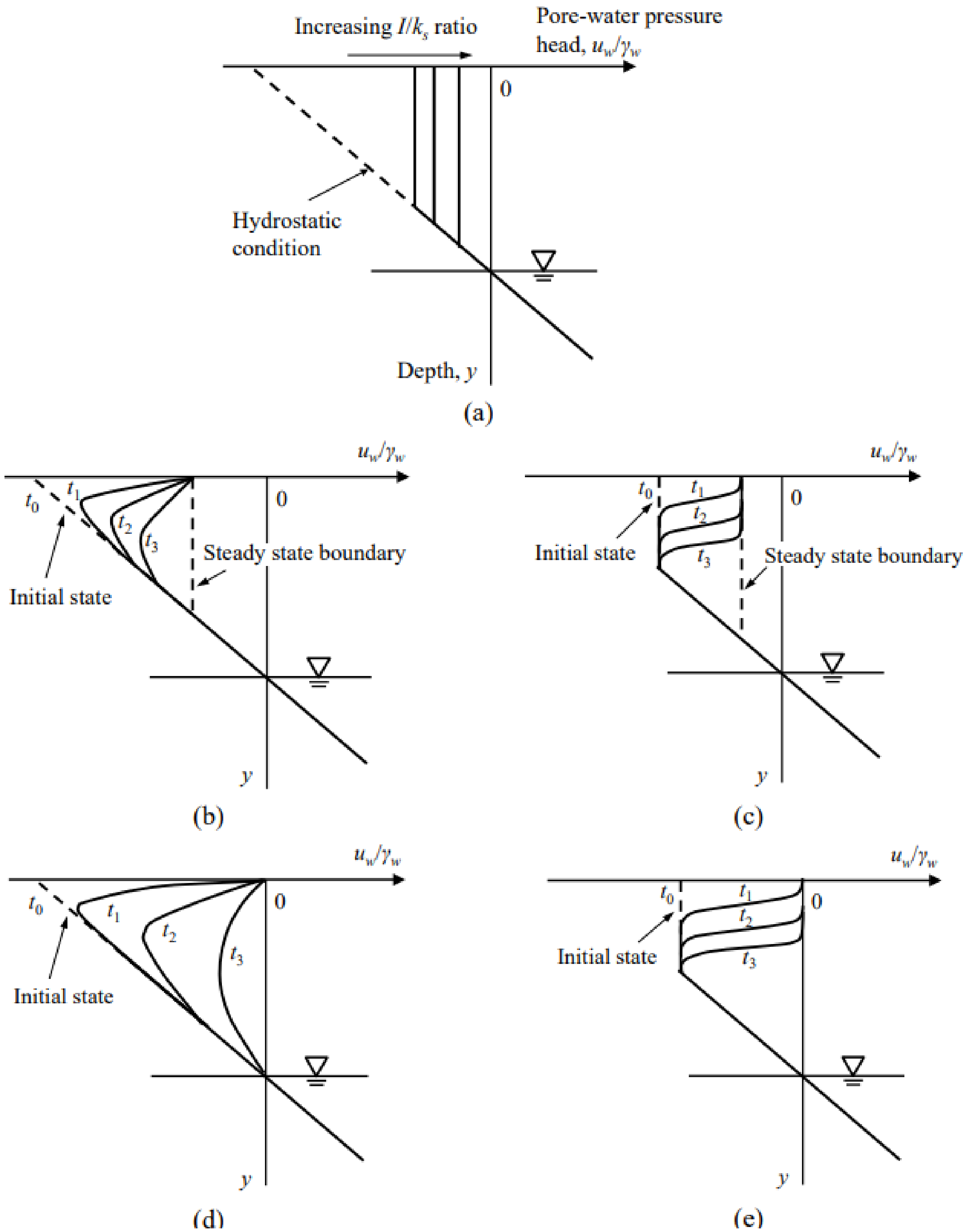


Figure 2.5 Typical pore-water pressure profiles in an unsaturated soil incline with different ground surface transitions: (a) consistent state condition; (b) transient condition, $I/k_s < 1$; $I/k_s \geq 1$ (from Zhang et al., 2011)

Figure 2.6 shows Rahardjo et al. (1995)'s Under rainfall infiltration pore pressure of water profiles in an undrained residual soil slope were predicted. Profile (a) display smooth wetting front that is common soils with fine grains (Zhang et al., 2004; Lee et al., 2009). A moist soil. is represented by profile (b), which is more common soils with coarse grains (Zhang et al., 2004; Lee et al., 2009). A water table that is perched is seen in profile c, which is common in soils that have a porous layer just above wet front and a layer below it that is less permeable (Cho, 2009).

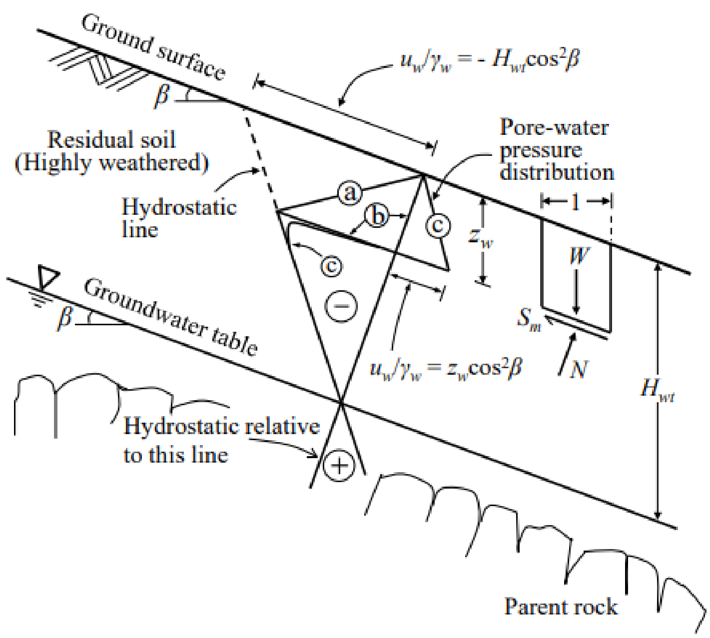


Figure 2.6 Various pore pressure of water profiles inside an undrained residual soil slope during rainfall infiltration (a, b, and c) (from Rahardjo et al., 1995)

2.2.3.2 Limit Equilibrium Analysis

A slope stability analysis can easily incorporate the pressures of pore-water obtained based on a temporary seepage investigation. Limit equilibrium approaches that method of vertically slicing a failure mass, as shown in Figure 2.7, has been widely used to test the stability of moist and undrained soil slopes.

Usually limit equilibrium methods can be simply adjusted for unsaturated slopes of soil applying the [Eq. (2.5)] the enlarged Mohr-Coulomb failure criterion The following are the safety parameters in moment equilibrium (Fm) and force equilibrium (Ff) (Fredlund and Rahardjo, 1993):

$$F_M = \frac{\sum[c' \Delta l R + \left(N - uw\Delta l \frac{\tan \phi^b}{\tan \phi'}\right) R \tan \phi']}{\sum w_x}_x \qquad (2.12)$$

$$F_M = \frac{\sum[c' \Delta l cos\Theta + \left(N - uw\Delta l \frac{\tan \phi^b}{\tan \phi'}\right) cos\Theta \tan \phi']}{\sum N sin\Theta}_x \qquad (2.13)$$

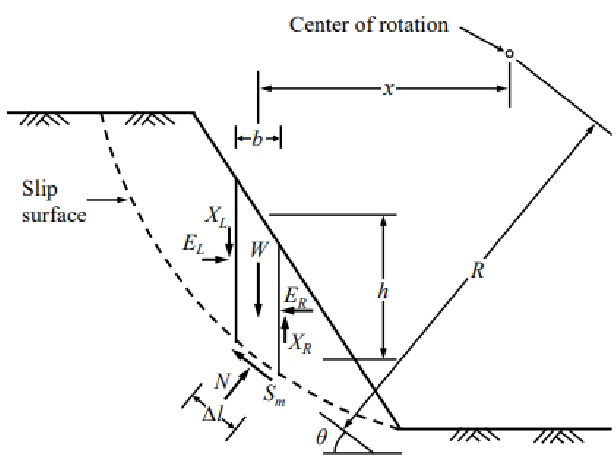


Figure 2.7 Forces operating on circular slip surface slope through a sliding mass (modified from Fredlund and Rahardjo, 1993)

Although limit equilibrium analysis produces adequate design results in most cases, it has been criticised for lacking a theoretically sound foundation (Yu et al., 1998; Chen, 1975; Miller and Hamilton, 1989; Michalowski, 1995);.(1) The soil yield requirement may be violated by forces occurring all across slip surface and forces acting between slices., resulting in a statically admissible field of stress in the failure mass; and (2) In this work, a stress-strain relationship is ignored, leading in a kinematically acceptable slip surface.

Limit equilibrium analysis, according to Lu et al. (2012), works fairly well when rotational fail is the primary failure mode; but, if translational fail is more important, limit state analysis fail to detect likely slip surface is shallow.

Commercial software versions SEEP/W and SLOPE/W are commonly used for integrated transient seep age and slope stability analysis (Gasmo et al., 2000; Tsaparas et al., 2002; Huat et al., 2006; Rahardjo et al., 2007, 2010; Cascini et al., 2010; Rahimi et al., 2011)

The transient pore-water pressure (u_w) during rainfall infiltration is determined using SEEP/W, and the pore-water pressure is then transferred to SLOPE/W for slope stability analysis [Eqs. (2.12) and/or (2.13)].

CHAPTER 3 – STUDY AREA

3.1 Area

The site of the project is referred as as Bhikiyasain - Deghat - Bungidhar - Mehal Chauri – Bachuaban – Chaukhutiya motor road section of SH-33. Project lies in Almora, districts of Uttrakhand.

The road alignment is marked on Google earth as shown in Fig 3.1. below:

Figure 3.1: Road alignment marked on Google earth

3.2 Climate

The monsoons have a big impact on Almora's climate, which is completely mountainous. It has a climate that is mild. Summers are hot in the mornings but cool in the nights. Summer temperatures typically range from 15 to 30 degrees Celsius. Cold winters and light during the day, but bitterly cold at night, with temperatures dropping below 0 degrees. The monsoon season typically begins in July and lasts until September.

3.3 General geology

The studied area is part of the Lesser Himalaya's physiographic-cum-geological unit. The Main Central Thrust (MCT) separates it from the Greater Himalaya in the north. In the south, Krol or Main Boundary Thrust (MBT) defines the boundary. The pre-Cambrian and Palaeozoic sedimentary with granite injected metamorphic are seen in the progression of three thrusting layers or nappes between all these two regional planes of separation Each tectonic unit of the Lesser Himalaya is defined by its individual lithology, structural setting, rock deformation, and geomorphic features, and is sandwiched between these two well-defined structural limits, i.e., MBT (south) and MCT (north).

3.4 Seismicity

The Bureau of Indian Standards revised India's seismic hazard map in 2000. (BIS). The road alignment of Bhikiyasain–Deghat – Bungidhar – Mehal Chauri – Bachhuaban–Chaukhutiya motor road section of SH-33 lies in Zone IV. In these places, the greatest intensity expected is about MSK VII.

3.5 Liquefaction

Under saturated conditions, liquefaction is the abrupt loss of shear strength of loose fine-grained sands caused by earthquake-induced vibration. Seed & Idriss (1983 – 1985) suggested a simpler approach for assessing the liquefaction potential of foundation stratum based on SPT data and peak ground acceleration predicted to occur at the site. The cyclic shear stress that a Design Basis Earthquake (DBE) is likely to create in the foundation strata is initially assessed using this method. SPT data and empirical relationships are used to predict the next threshold cycle shear stress that will trigger liquefaction. Finally, the foundation strata's liquefaction susceptibility is estimated by comparing these two stresses.

CHAPTER 4 – METHODOLOGY AND MATERIAL PROPERTIES

4.1 Overview

This chapter introduces & discusses software tools and approaches that will be used in this thesis and describe the properties of soil.

4.2 MATERIAL PROPERTIES

4.2.1 Sand parameters

Sand includes drain qualities such as unit weight of soil, cohesiveness, and internal friction angle. Table 1 lists the properties of sand.

L1 Input parameters for the software simulations. (Table 4.1)

Type of Soil	Symbol	Units	Property	Assumed values
SILTY SAND	τ	kN/m³	Soil's Total Unit Weight	18.27
	C	kN/m²	Cohesion of soil	25.80
	ϕ	°	Angle of internal friction	34.78

L2 Input parameters for the software simulations. (Table 4.2)

Type of Soil	Symbol	Units	Property	Assumed values
SILTY SAND	τ	kN/m³	Soil's Total Unit Weight	19.60
	C	kN/m²	Cohesion of soil	27
	ϕ	°	Angle of internal friction	36.75

L3 Input parameters for the software simulations. (Table 4.3)

Type of Soil	Symbol	Units	Property	Assumed values
SILTY SAND	τ	kN/m³	Soil's Total Unit Weight	17.80
	C	kN/m²	Cohesion of soil	29.80
	ϕ	°	Angle of internal friction	26.23

L4 Input parameters for software simulations. (Table 4.4)

Type of Soil	Symbol	Units	Property	Assumed values
SILTY SAND	τ	kN/m³	Soil's Total Unit Weight	19.50
	C	kN/m²	Cohesion of soil	19.40
	ϕ	°	Angle of internal friction	35.09

4.3 Geo Studio Software

To estimate the stability of slope stability subjected to rainfall, two analyses are performed. The pore water distributions were determined using seepage analysis, and also the results were utilized to calculate the slope safety factor to assess stability of the slope. Both experiments were conducted using commercially accessible software, SEEP/W and SLOPE/W. (GEOSTUDIO 2007).

GeoStudio 2007 is a software program that allows you to analyses geotechnical models. Computational simulation of nonlinear models is used in geotechnical applications to determine the behavior of soil parameters over time. A method for estimating hydraulic and nonhydraulic water pressure is essential since land has numerous phases. Soil modelling is required for many activities that involve geotechnical simulation of soil structure and reactivity. GeoStudio 2007 is divided into sections, each of which depicts a different form of geotechnical structure.

In this study, the SEEP/W and SLOPE/W models were employed to assess slope stability. SEEP/ W was used to determine the pore-water pressure. The slope safety a priority for the slopes in consideration were then determined using the SLOPE/W analysis (Geoslope International, 2012a, b). For water flow through two-dimensional unsaturated soil elements, the following controlling equation was proposed by Richards (1931; Fredlund and Rahardjo, 1993):

$$\frac{\partial}{\partial x}\left(k_x(H)\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y(H)\frac{\partial h}{\partial y}\right)+Q=-\partial_{\frac{\theta\omega}{\partial t}} \qquad (4.1)$$

Where k_x and k_y are hydaulic driven conductivity in the x and y course, H is the complete hydraulic driven head, Q is the applied limit transition, and θ is the volumetric water content. The contrast between the stream entering and leaving an essential volume at a given time is identical to the adjustment of the dirt framework's stockpiling, as displayed in Equation 4.1

(Fredlund and Rahardjo, 1993): The condition for the progression of water in the dirt used in SEEP/W to evaluate two-layered transient and leakage is:

$$m_{\omega}^{2}\gamma w\frac{\partial h_{\omega}}{\partial t}=\frac{\partial}{\partial x}\left(-k_{wx}\frac{\partial h_{\omega}}{\partial x}\right)+\frac{\partial}{\partial y}\left(-k_{wy}\frac{\partial h_{\omega}}{\partial y}\right)+q \quad (4.2)$$

where m_{ω}^{2} is the soil-water slant, w is the unit weight of water, h_{ω} is the hydraulic head or total head, t is time, k_{wx} and k_{wy} are permeability coefficients with regard to water and the amount of matric suction in the x and y directions, respectively, and q is the applied flux at the boundary.

According to our research, the GEOSTUDIO geotechnical product portfolio includes SLOPE/W and SEEP/W. Both on upstream and downstream sides of the dam, SLOPE/W can analyse both simple and complex issues such as shape, soil density, pore water pressure, analytical techniques, and loading scenarios such as steady flow seepage and rapid or sudden drawdown.

The Morgenstern-Price Procedure (M-PM), which is utilized in SLOPE/W to evaluate the model with all four cases in order to determine the safety factor, is the most widely used limit equilibrium (LE) based approach.

SLOPE/W is expressed as follows of force and moment equilibrium to produce a factor of safety equations.

Morgenstern – Price approach is used to determine moment and force equilibrium (1965). The SEEP/W tool is being used to evaluate groundwater seepage and find problems with excessive pore pressure dissipation inside porous materials like rock and soil.

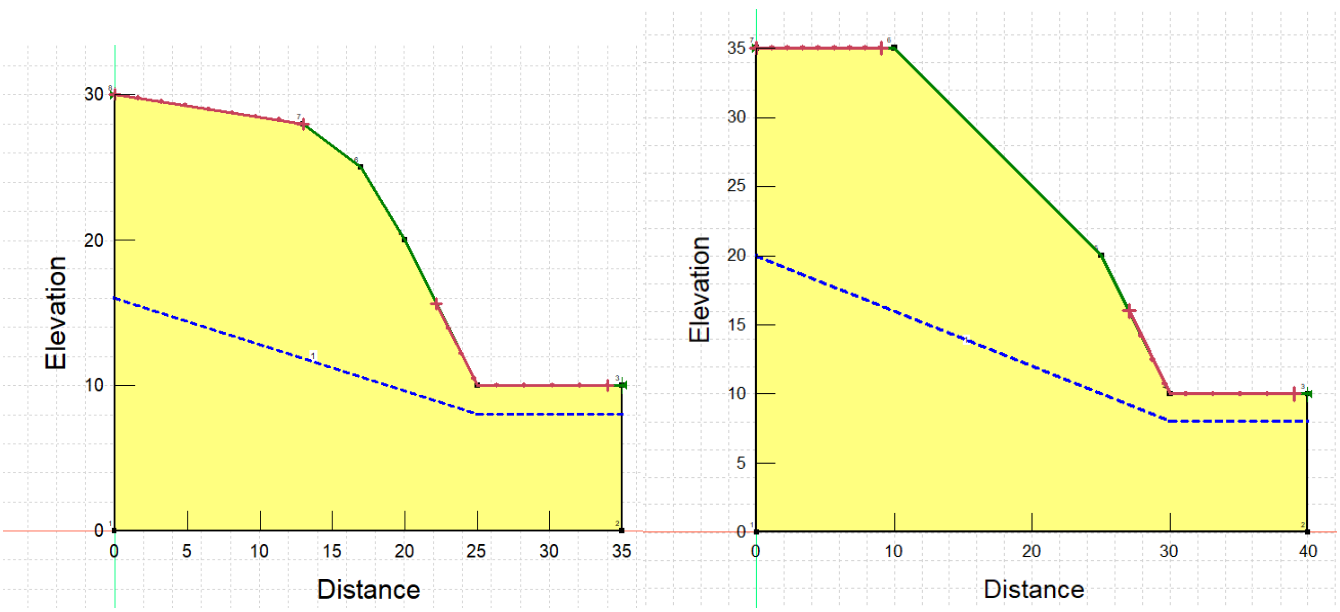
4.3.2 Design factor of safety (FOS)

When the FOS is less than 1.0, the slope is said to be unstable. If FOS have been a deterministic parameter, a slope with a value close to 1.0 would be characterized as stable. The final value has a degree of error due to the uncertainties inherent in the FOS calculation (analysis method, physical and mechanical properties of the ground, ground shape, seismic load, and others). A probabilistic study is necessary to establish a sampling error for the FOS.

4.4 Geometry of soil slopes

The dimension of the slope is mentioned in the table below, and the slope is displayed in Fig.4.4.1. The surface was specified as a flux barrier receiving rainwater infiltration. The total head was used to determine the left and right vertical borders below the ground water table.

Slope Identification	Elevation	Distance
L1	35	40
L2	30	35
L3	30	30
L4	25	35



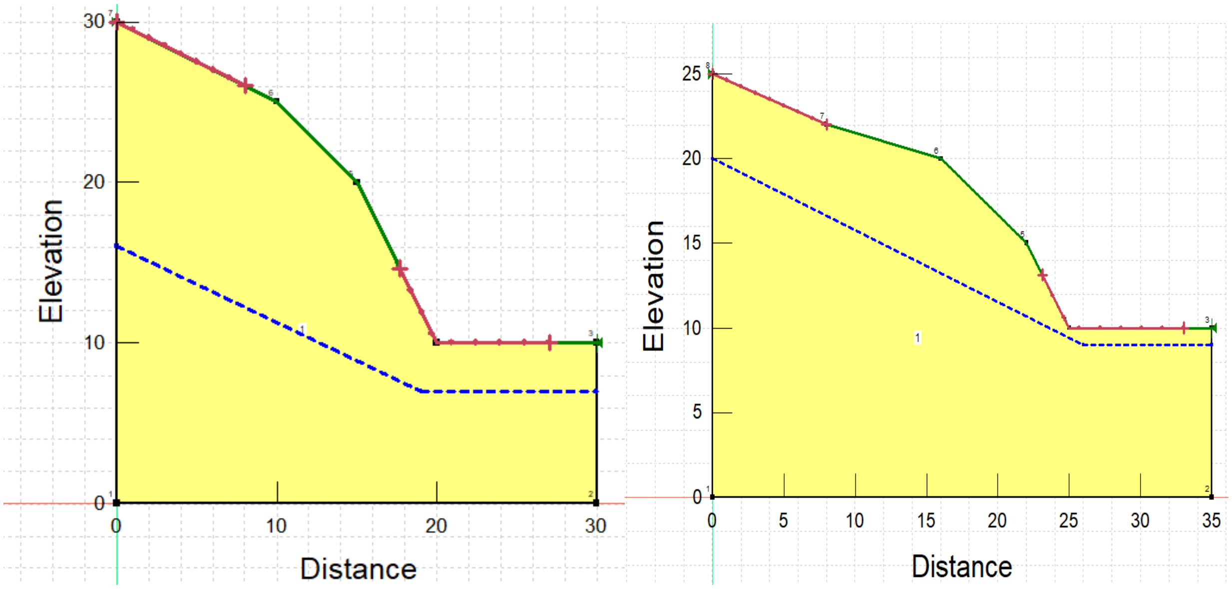


Figure 4.1 shows different dimension slopes to analyses slope stability

CHAPTER 5 – RESULTS AND DISCUSSION

5.1 Rainfall infiltration impact on slopes

A silty sand soil layer was used to represent four slope conditions. The pore water pressure distribution and factor of safety were measured at various at different time interval on the year's maximum rainfall. In the time interval of rainfall, the maximum day rainfall is considered from the 5 years of rainfall data.

5.2 Rainfall intensity and factor of safety for L1 Slope (Table 5.1)

Slope Identification	Maximum rainfall data	Rainfall (mm)	Number of wet days	FOS in dry condition	FOS in wet condition
L1	1997-2001	99.60	1	1.220	1.203
	2002-2006	163.40	1	1.220	1.180
	2007-2011	152.2	1	1.220	1.185
	2011	548.8	26	1.220	1.085

For maximum rainfall data 1997-2001

- In figure 5.1, the slope is considered at the location of Uttarakhand Almora, and the safety factor is 1.220 computed by slope/w method using GeoStudio software before the rainfall impact

- consider the maximum rainfall intensity of 99.60 mm of one day and compute the seepage of slope using seep/w method using GeoStudio software, as shown in figure 5.2.

- In figure 5.3 the effect of rainfall on slope has been observed, with the safety factor falling by 1.203, and the factor of safety is then determined using the slope/w method and GeoStudio software.

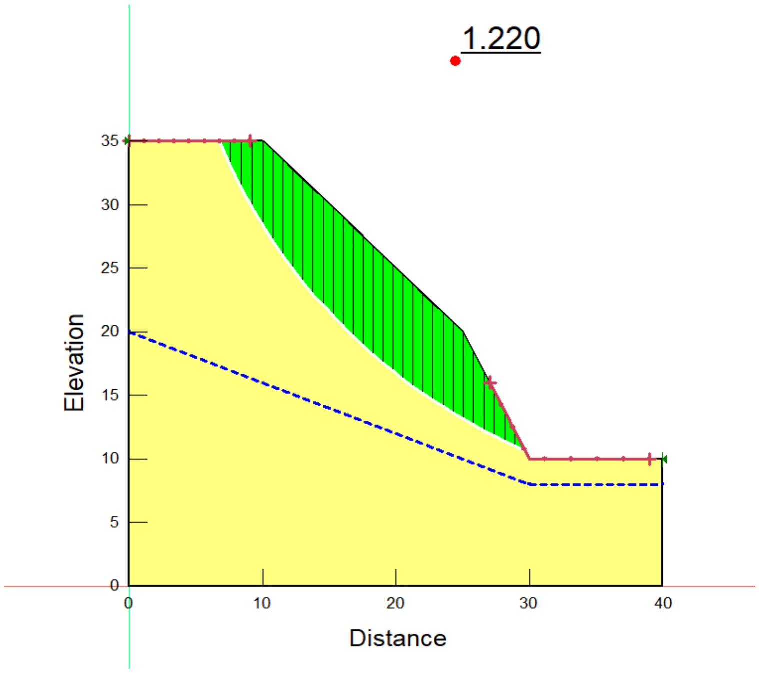


Fig. 5.1 shows the factor of safety in dry condition

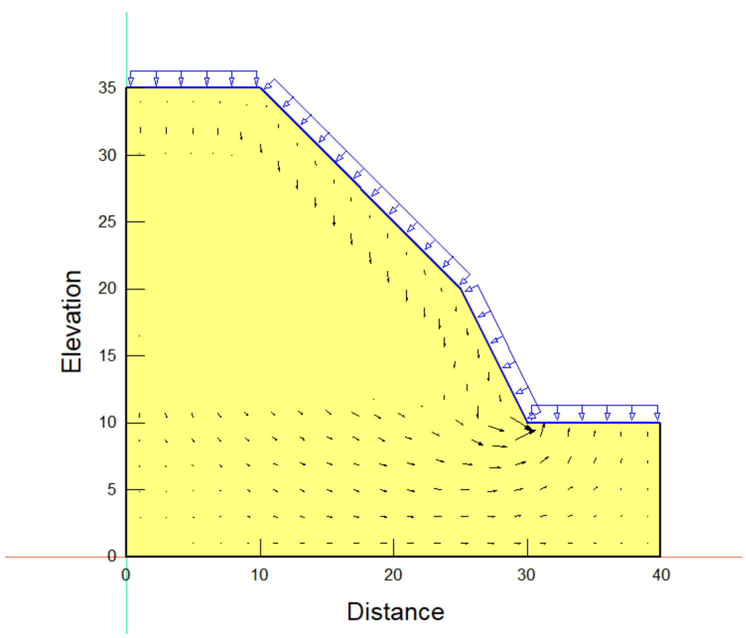


Fig. 5.2 shows the seepage analysis

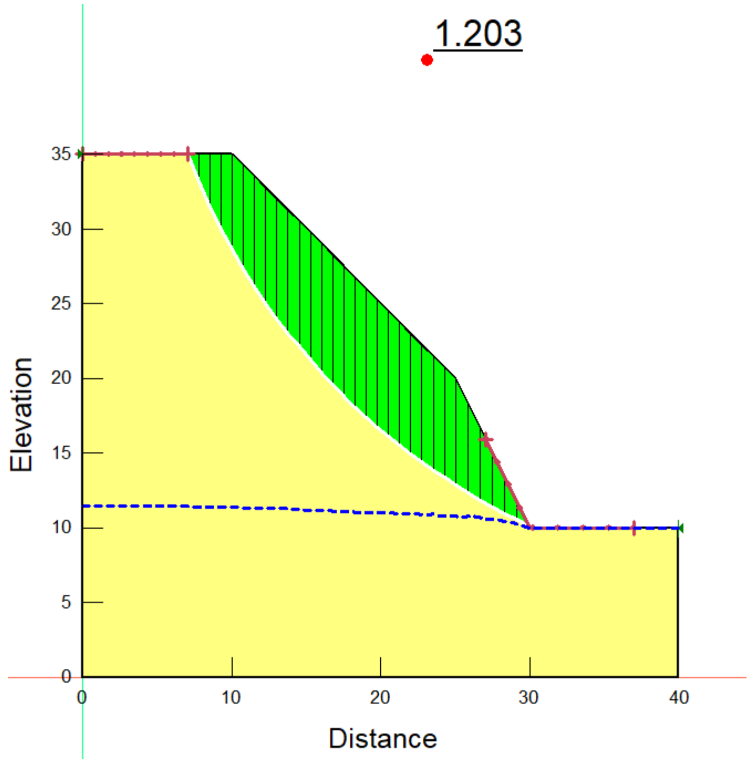


Fig. 5.3 factor of safety after rainfall infiltration

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For maximum rainfall data 2002-2006

- In figure 5.1, the slope is considered at the location of Uttarakhand Almora, and the safety factor is 1.220 computed by slope/w method using GeoStudio software before the rainfall impact

- consider the maximum rainfall intensity of 163.40 mm of one day and compute the seepage of slope using seep/w method using GeoStudio software, as shown in figure 5.4.

- In figure 5.5 the effect of rainfall on slope has been observed, with the safety factor falling by 1.180, and the factor of safety is then determined using the slope/w method and GeoStudio software

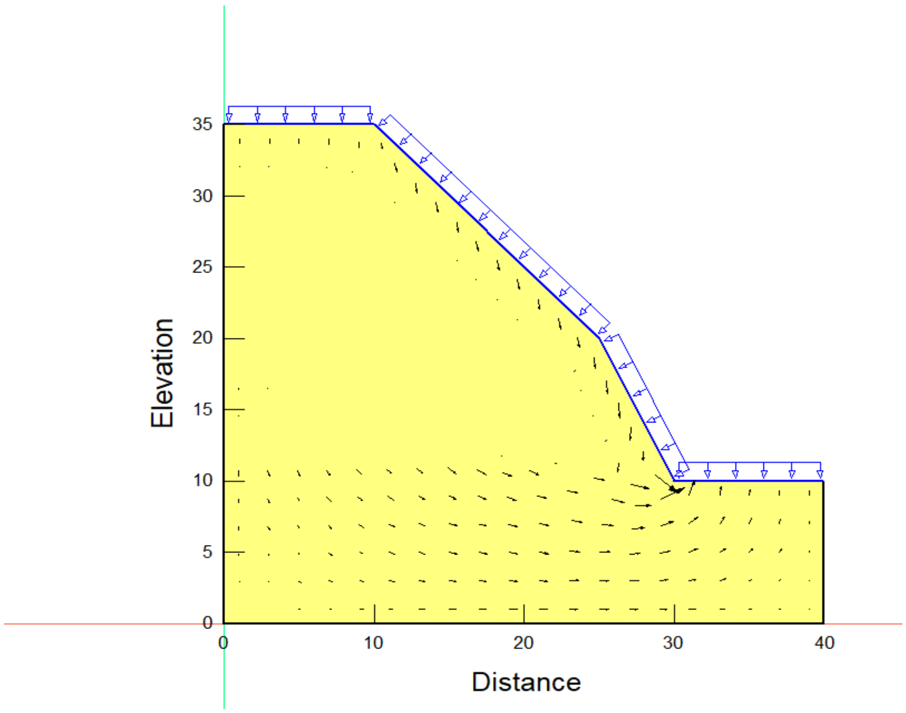

Fig. 5.4 shows the seepage analysis

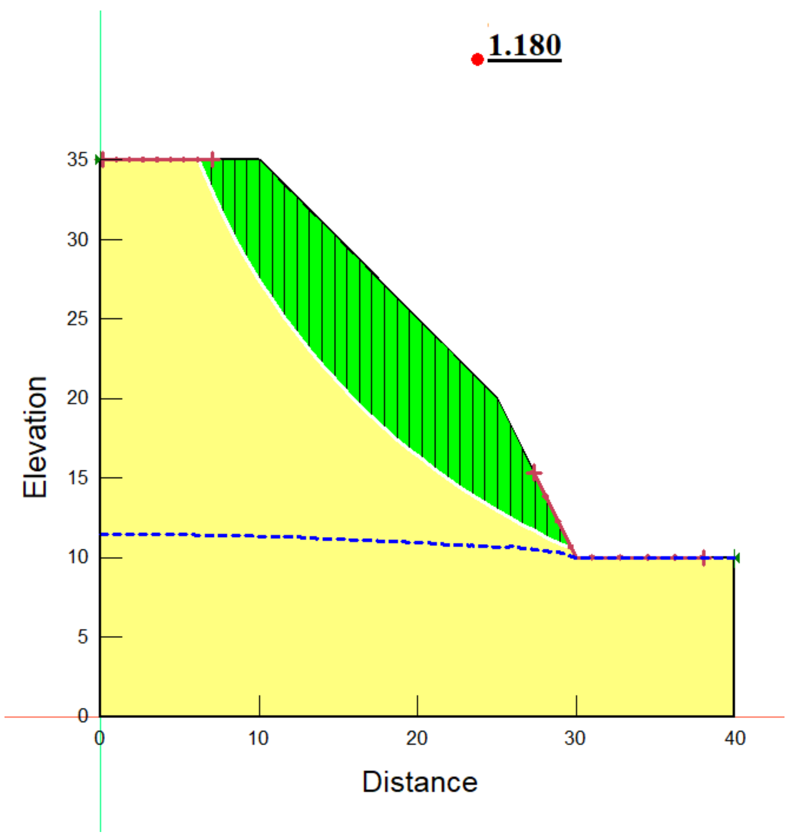

Fig. 5.5 factor of safety after rainfall infiltration

For maximum rainfall data 2007-2011

- In figure 5.1, the slope is considered at the location of Uttarakhand Almora, and the safety factor is 1.220 computed by slope/w method using GeoStudio software before the rainfall impact

- consider the maximum rainfall intensity of 152.20 mm of one day and compute the seepage of slope using seep/w method using GeoStudio software, as shown in figure 5.6.

- In figure 5.7 the effect of rainfall on slope has been observed, with the safety factor falling by 1.185, and the factor of safety is then determined using the slope/w method and GeoStudio software

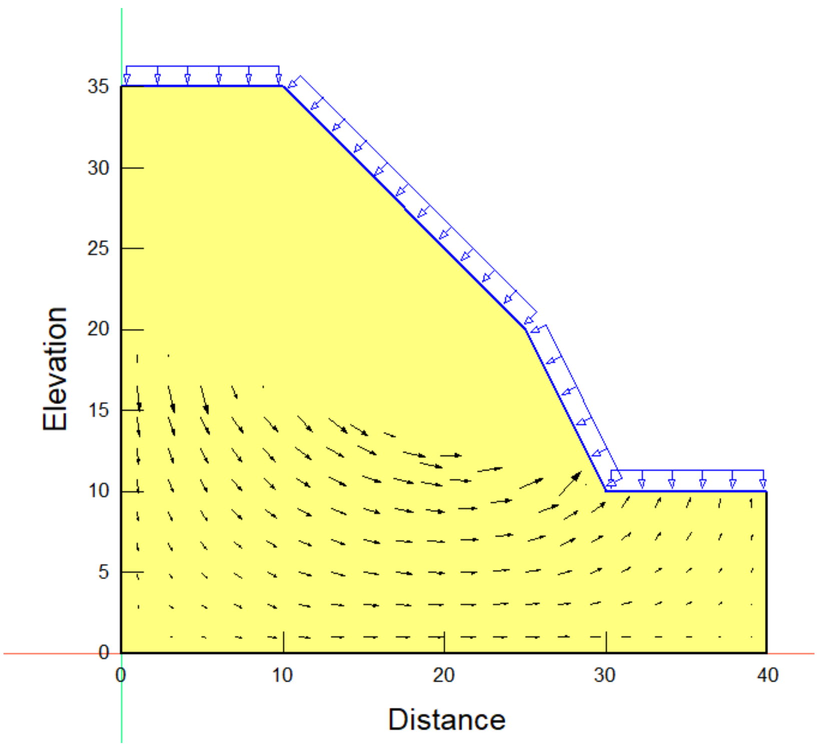

Fig. 5.6 shows the seepage analysis

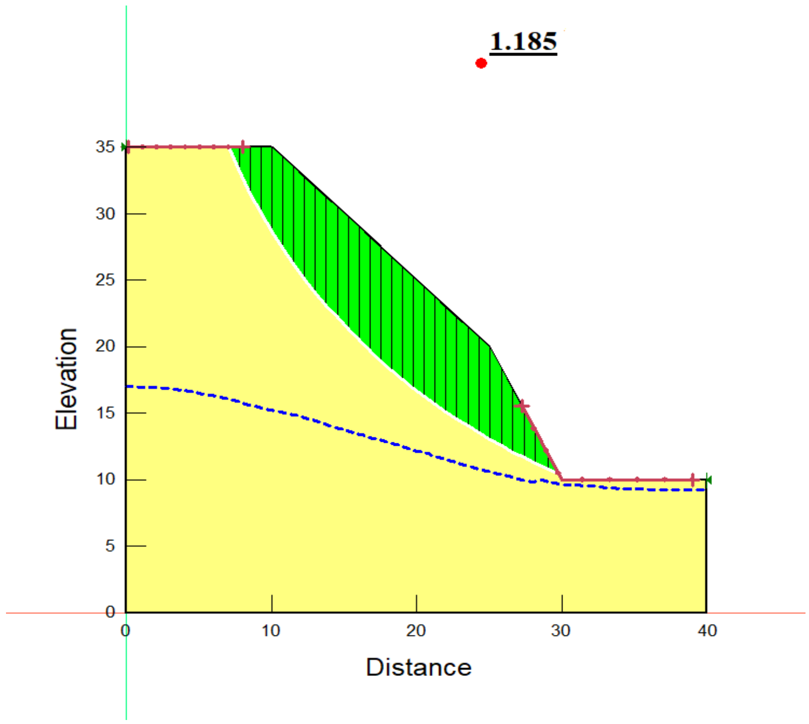

Fig. 5.7 factor of safety after rainfall infiltration

For monthly maximum rainfall data 2011

- In figure 5.1, the slope is considered at the location of Uttarakhand Almora, and the safety factor is 1.220 computed by slope/w method using GeoStudio software before the rainfall impact
- consider the rainfall intensity of 548.80 mm of 26 days and compute the seepage of slope using seep/w method using GeoStudio software, as shown in figure 5.8.
- In figure 5.9 the effect of rainfall on slope has been observed, with the safety factor falling by 1.085, and the factor of safety is then determined using the slope/w method and GeoStudio software

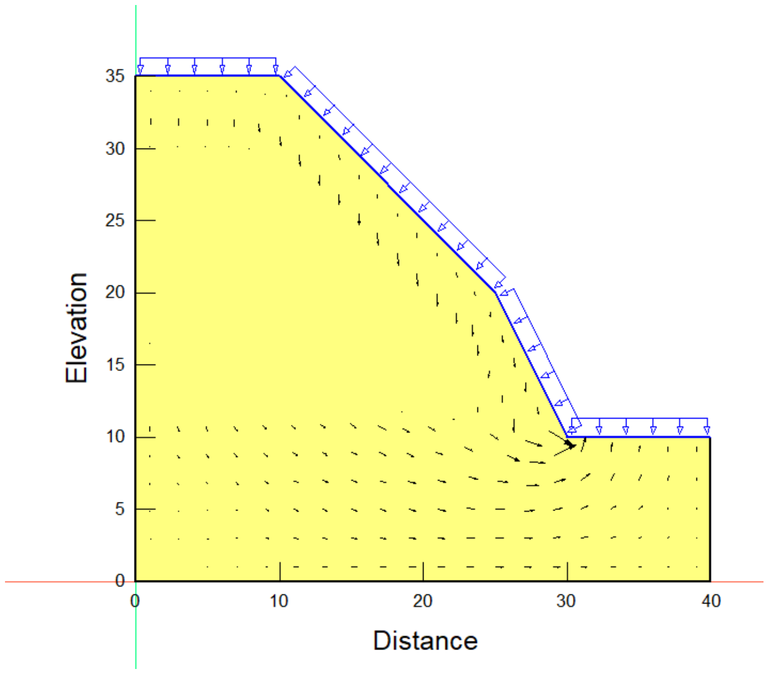

Fig 5.8 shows the seepage analysis

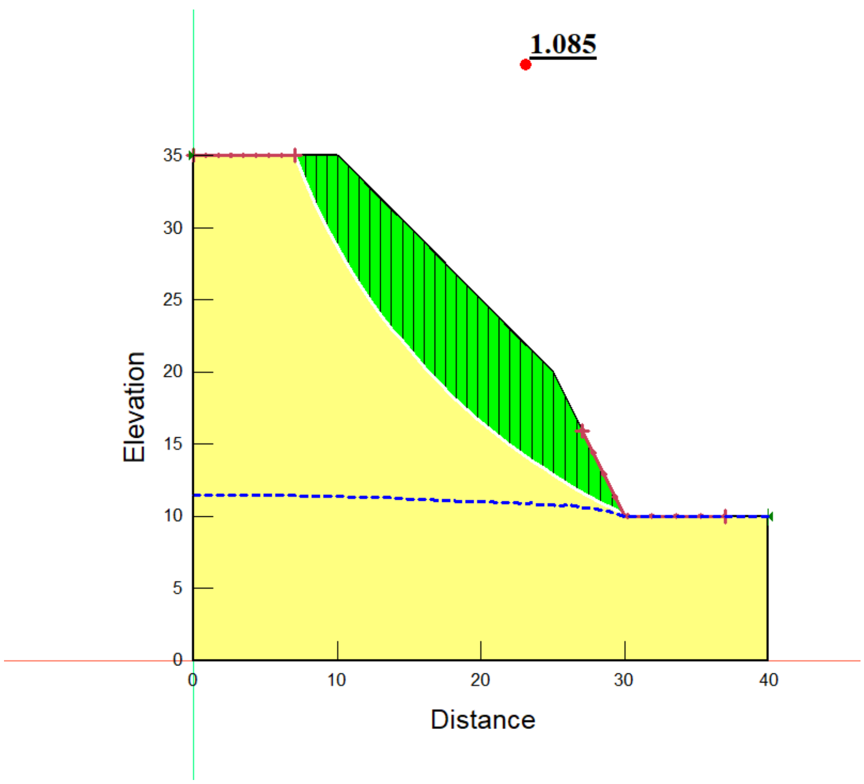

Fig 5.9 factor of safety after rainfall infiltration

5.3 Rainfall intensity and factor of safety for L2 Slope (Table 5.2)

Slope Identification	Maximum rainfall data	Rainfall (mm)	Number of wet days	FOS in dry condition	FOS in wet condition
L2	1997-2001	99.60	1	1.262	1.245
	2002-2006	163.40	1	1.262	1.175
	2007-2011	152.2	1	1.262	1.180
	2011	548.8	26	1.262	1.117

For maximum rainfall data 1997-2001

- In figure 6.0, the slope is considered at the location of Uttarakhand Almora, and the safety factor is 1.262 computed by slope/w method using GeoStudio software before the rainfall impact

- consider the rainfall intensity of 99.60 mm of 1 day and compute the seepage of slope using seep/w method using GeoStudio software, as shown in figure 6.1.

- In figure 6.2 the effect of rainfall on slope has been observed, with the safety factor falling by 1.245, and the factor of safety is then determined using the slope/w method and GeoStudio software

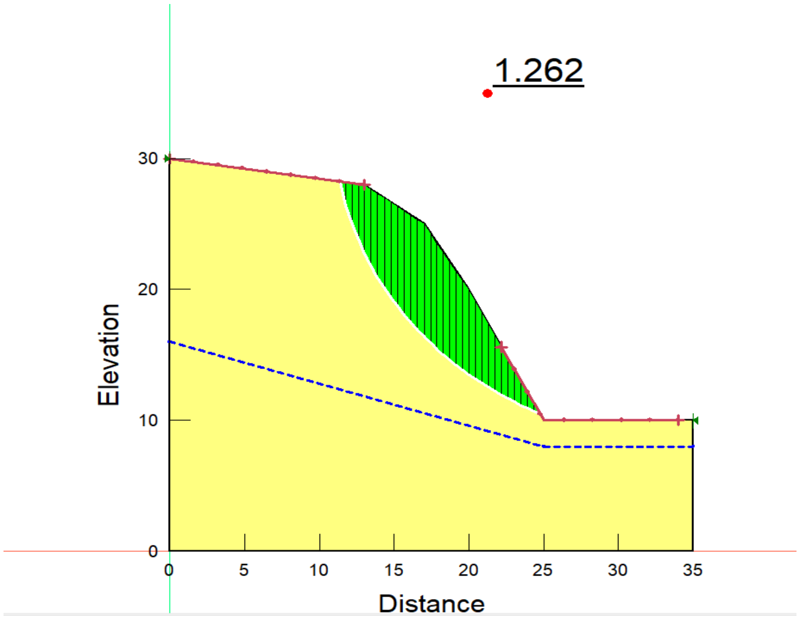

Fig 6.0 shows the factor of safety in dry condition

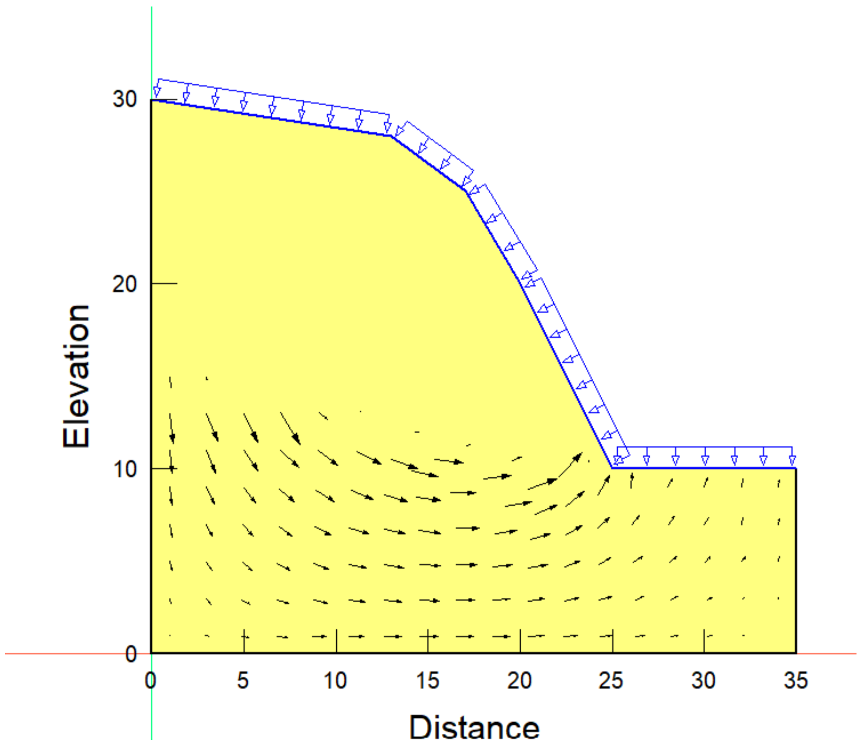

Fig 6.1 shows the seepage analysis

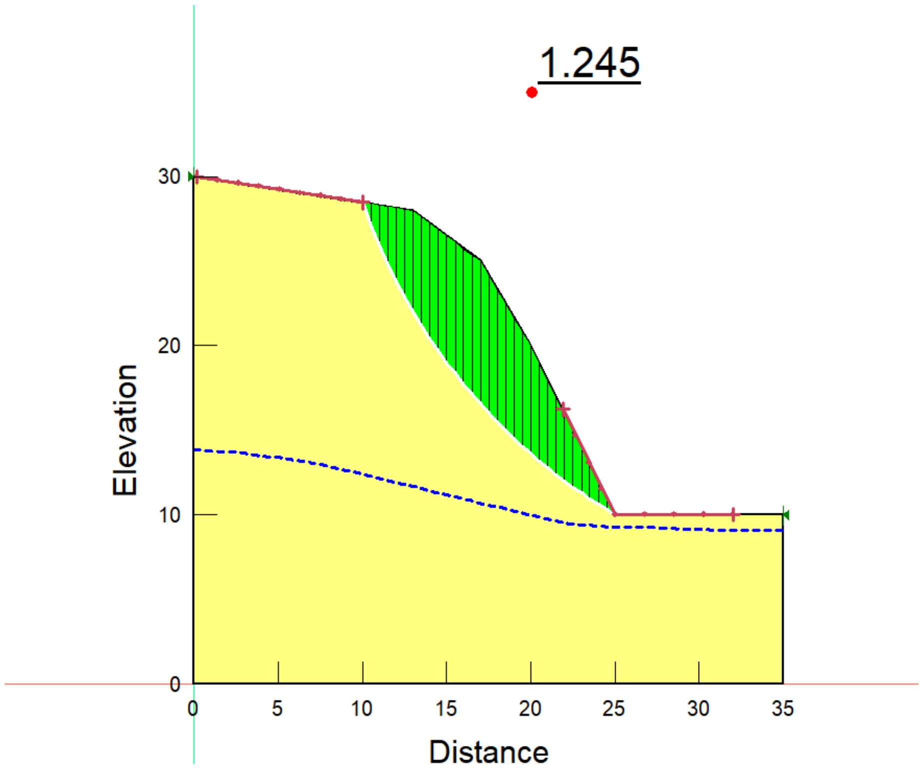

Fig 6.2 factor of safety after rainfall infiltration

For maximum rainfall data 2002-2006

- In figure 6.0, the slope is considered at the location of Uttarakhand Almora, and the safety factor is 1.262 computed by slope/w method using GeoStudio software before the rainfall impact
- consider the rainfall intensity of 163.40 mm of 1 day and compute the seepage of slope using seep/w method using GeoStudio software, as shown in figure 6.3.
- In figure 6.4 the effect of rainfall on slope has been observed, with the safety factor falling by 1.175, and the factor of safety is then determined using the slope/w method and GeoStudio software

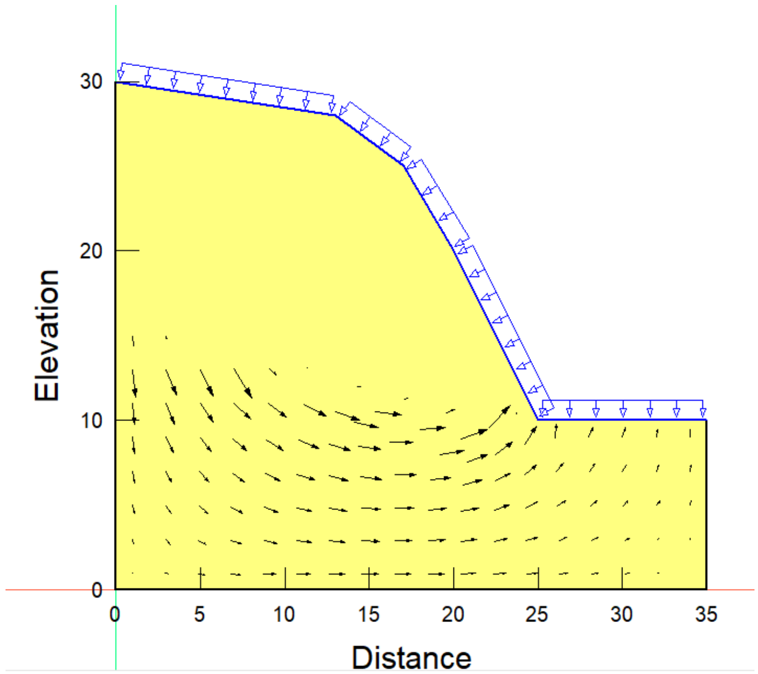

Fig 6.3 shows the seepage analysis

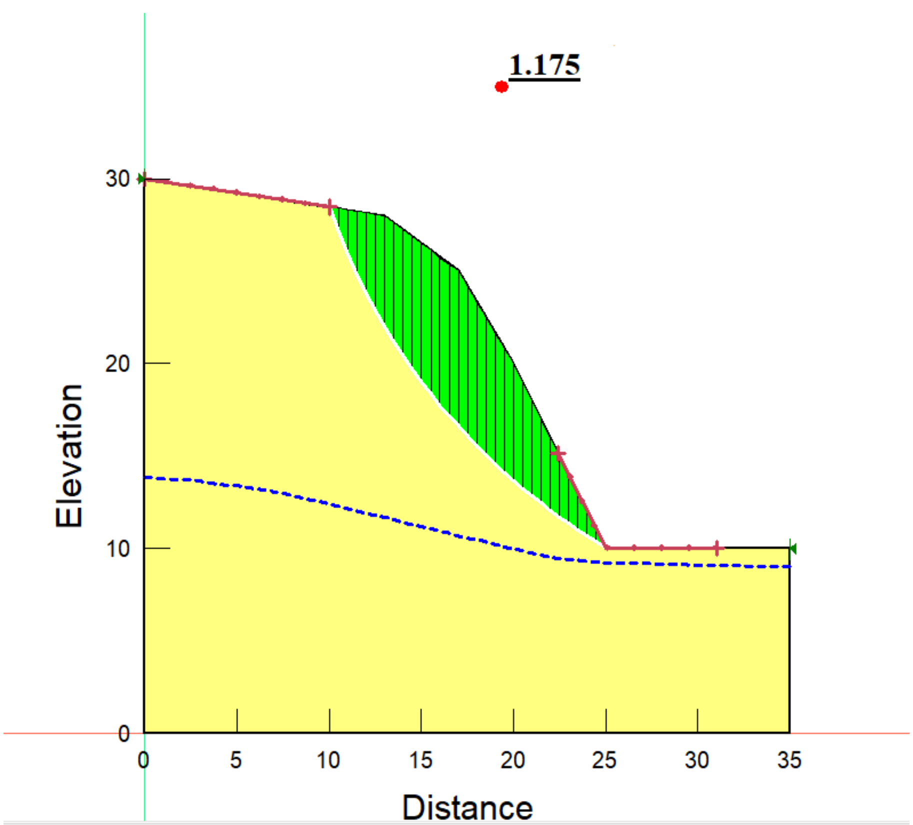

Fig 6.4 safety factor after rainfall infiltration

For maximum rainfall data 2007-2011

- In figure 6.0, the slope is considered at the location of Uttrakhand Almora, and the safety factor is 1.262 computed by slope/w method using GeoStudio software before the rainfall impact
- consider the rainfall intensity of 152.20 mm of 1 day and compute the seepage of slope using seep/w method using GeoStudio software, as shown in figure 6.5
- In figure 6.6 the effect of rainfall on slope has been observed, with the safety factor falling by 1.180, and the factor of safety is then determined using the slope/w method and GeoStudio software

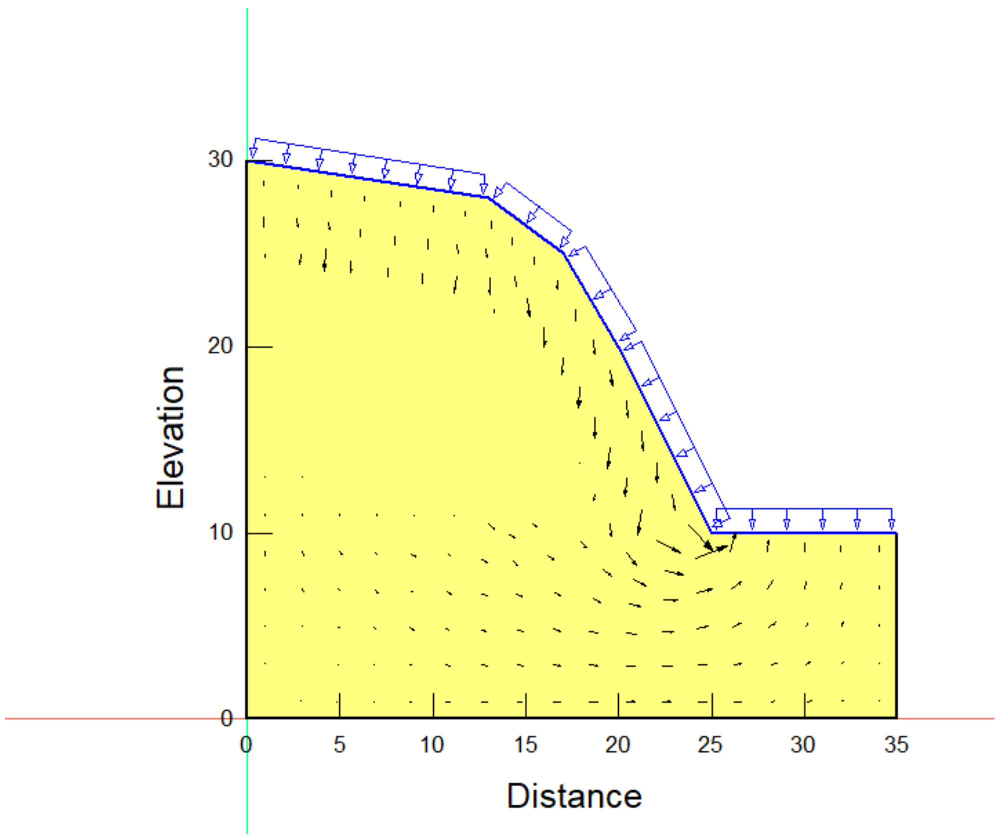

Fig 6.5 shows the seepage analysis

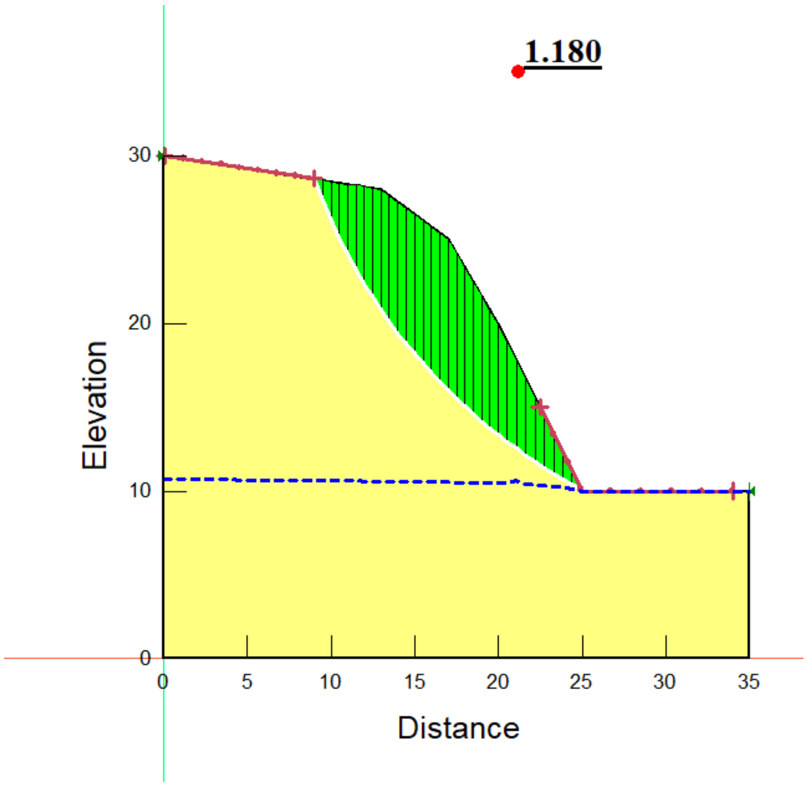

Fig 6.6 safety factor after rainfall infiltration

For monthly maximum rainfall data 2011

- In figure 6.0, the slope is considered at the location of Uttarakhand Almora, and the safety factor is 1.262 computed by slope/w method using GeoStudio software before the rainfall impact
- consider the rainfall intensity of 548.80 mm of 26 days and compute the seepage of slope using seep/w method using GeoStudio software, as shown in figure 6.7
- In figure 6.8 the effect of rainfall on slope has been observed, with the safety factor falling by 1.117, and the factor of safety is then determined using the slope/w method and GeoStudio software

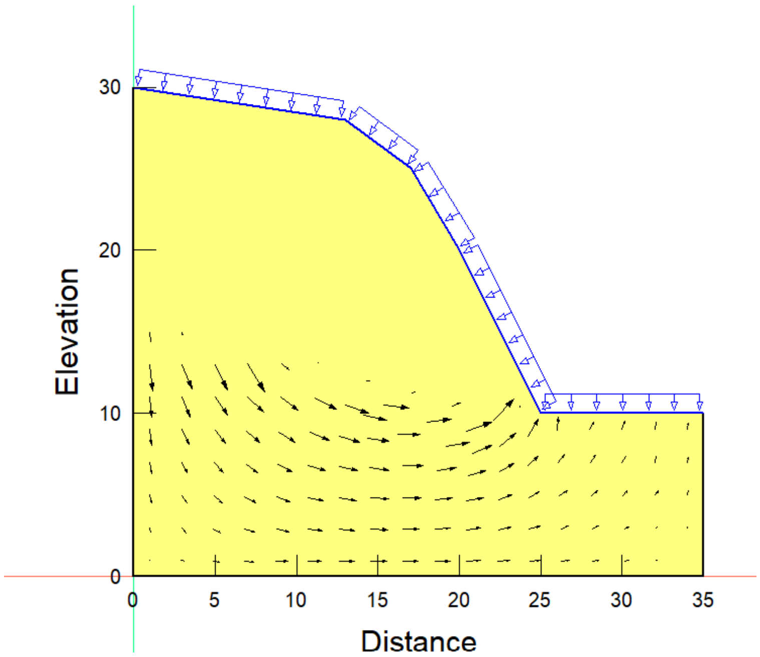

Fig 6.7 shows the seepage analysis

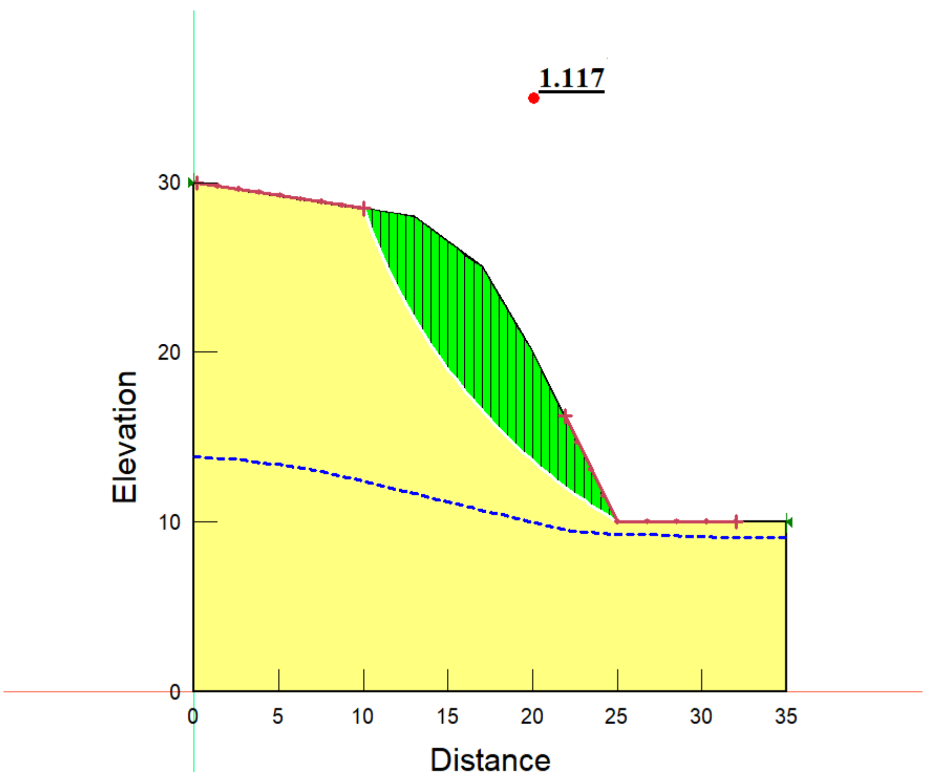

Fig 6.8 factor of safety after rainfall infiltration

5.4 Rainfall intensity and factor of safety for L3 Slope (Table 5.4)

Slope Identification	Maximum rainfall data	Rainfall (mm)	Number of wet days	FOS in dry condition	FOS in wet condition
L3	1997-2001	99.60	1	1.227	1.220
	2002-2006	163.40	1	1.227	1.113
	2007-2011	152.2	1	1.227	1.116
	2011	548.8	26	1.227	0.946

For maximum rainfall data 1997-2001

- In figure 6.9, the slope is considered at the location of Uttarakhand Almora, and the safety factor is 1.227 computed by slope/w method using GeoStudio software before the rainfall impact
- consider the rainfall intensity of 99.60 mm of 1 day and compute the seepage of slope using seep/w method using GeoStudio software, as shown in figure 7.0
- In figure 7.1 the effect of rainfall on slope has been observed, with the safety factor falling by 1.220, and the factor of safety is then determined using the slope/w method and GeoStudio software

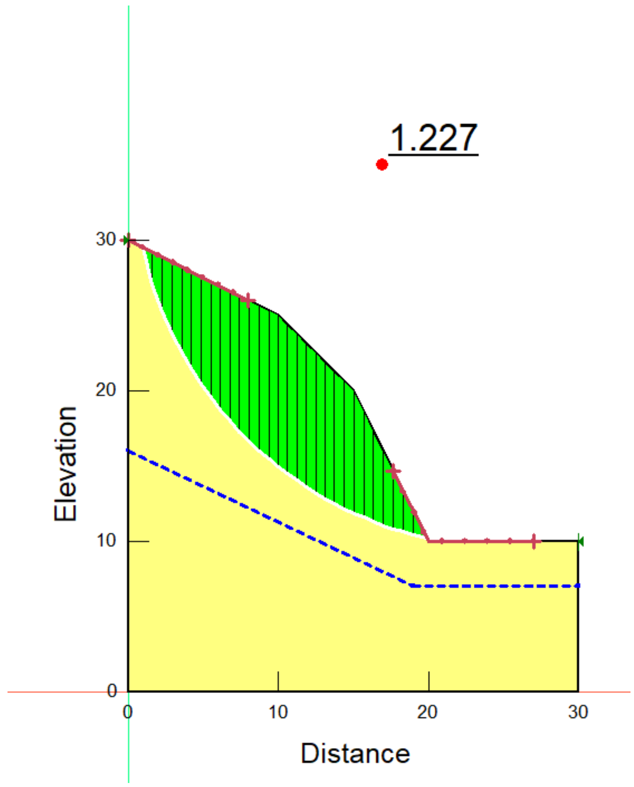

Fig 6.9 shows the factor of safety in dry condition

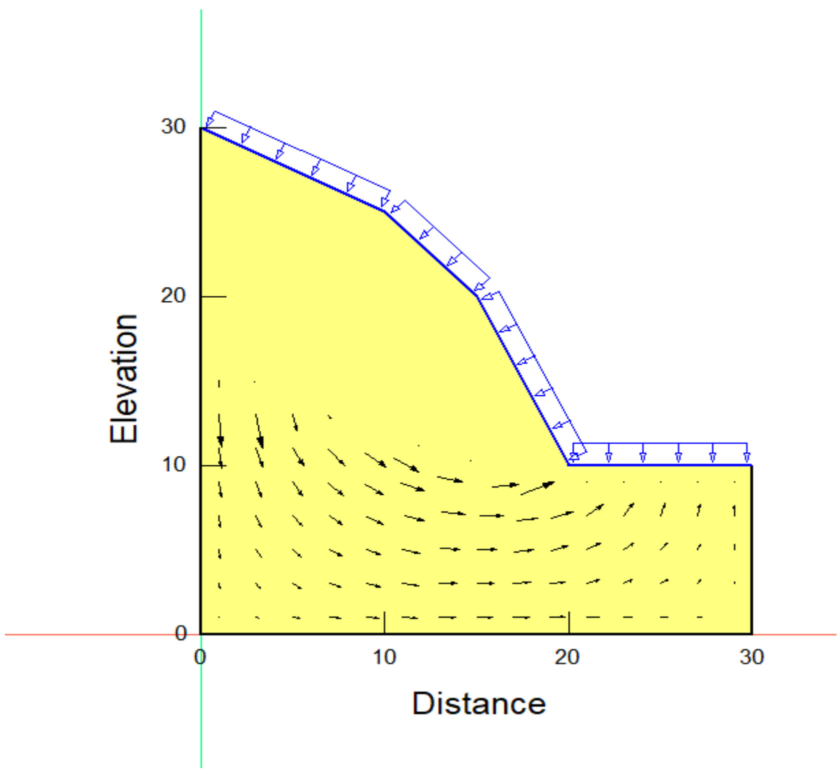

Fig 7.0 shows the seepage analysis

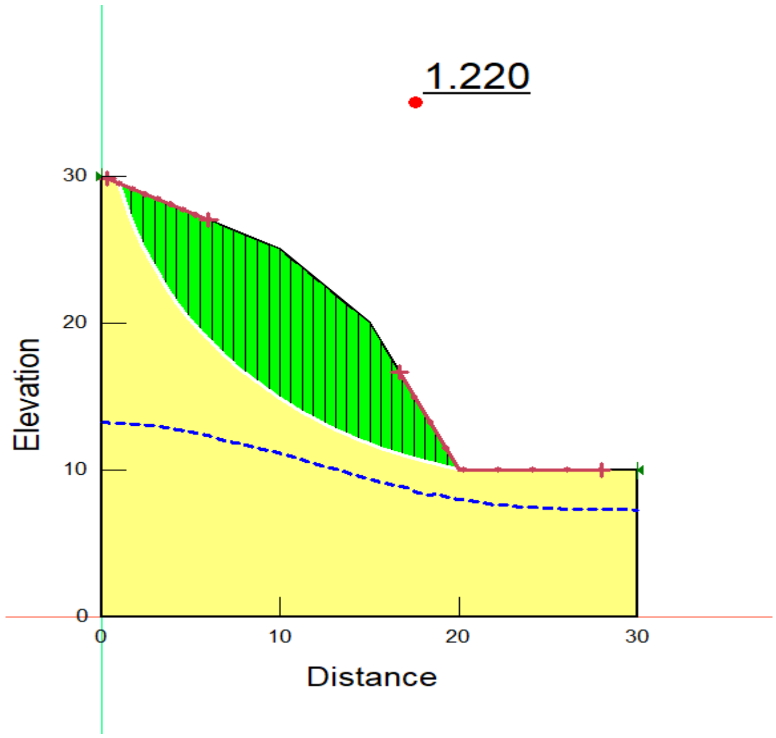

Fig 7.1 factor of safety after rainfall infiltration

For maximum rainfall data 2002-2006

- In figure 6.9, the slope is considered at the location of Uttarakhand Almora, and the safety factor is 1.227 computed by slope/w method using GeoStudio software before the rainfall impact
- consider the rainfall intensity of 163.40 mm of 1 day and compute the seepage of slope using seep/w method using GeoStudio software, as shown in figure 7.2
- In figure 7.3 the effect of rainfall on slope has been observed, with the safety factor falling by 1.113, and the factor of safety is then determined using the slope/w method and GeoStudio software

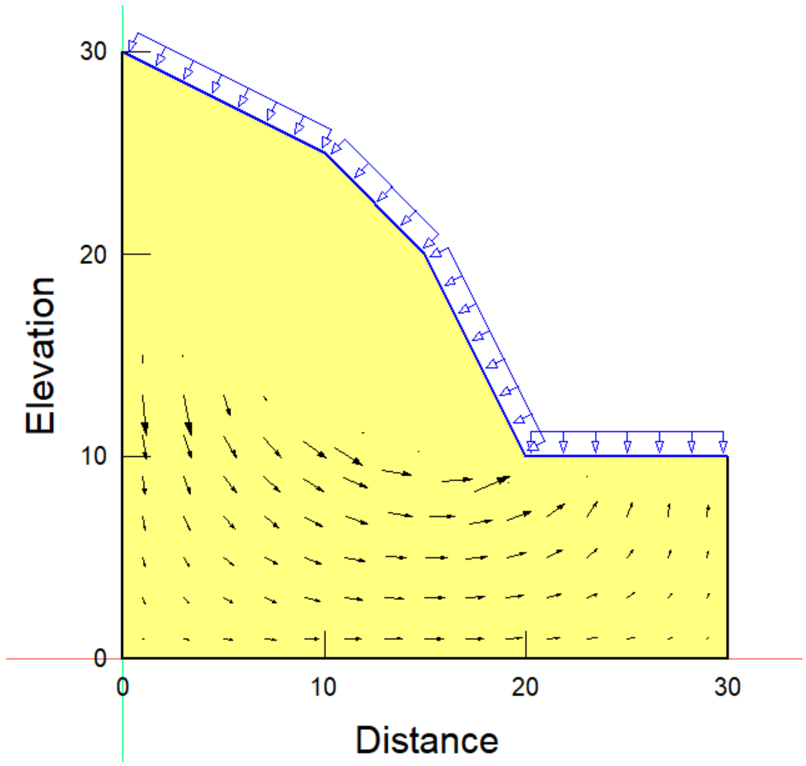

Fig 7.2 shows the seepage analysis

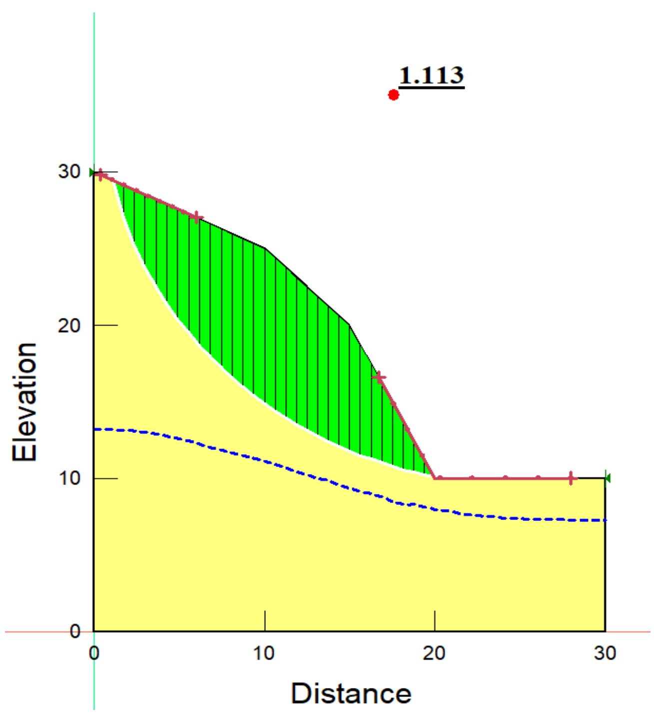

Fig 7.3 factor of safety after rainfall infiltration

For maximum rainfall data 2007-2011

- In figure 6.9, the slope is considered at the location of Uttarakhand Almora, and the safety factor is 1.227 computed by slope/w method using GeoStudio software before the rainfall impact

- consider the rainfall intensity of 152.20 mm of 1 day and compute the seepage of slope using seep/w method using GeoStudio software, as shown in figure 7.4

- In figure 7.5 the effect of rainfall on slope has been observed, with the safety factor falling by 1.116, and the factor of safety is then determined using the slope/w method and GeoStudio software

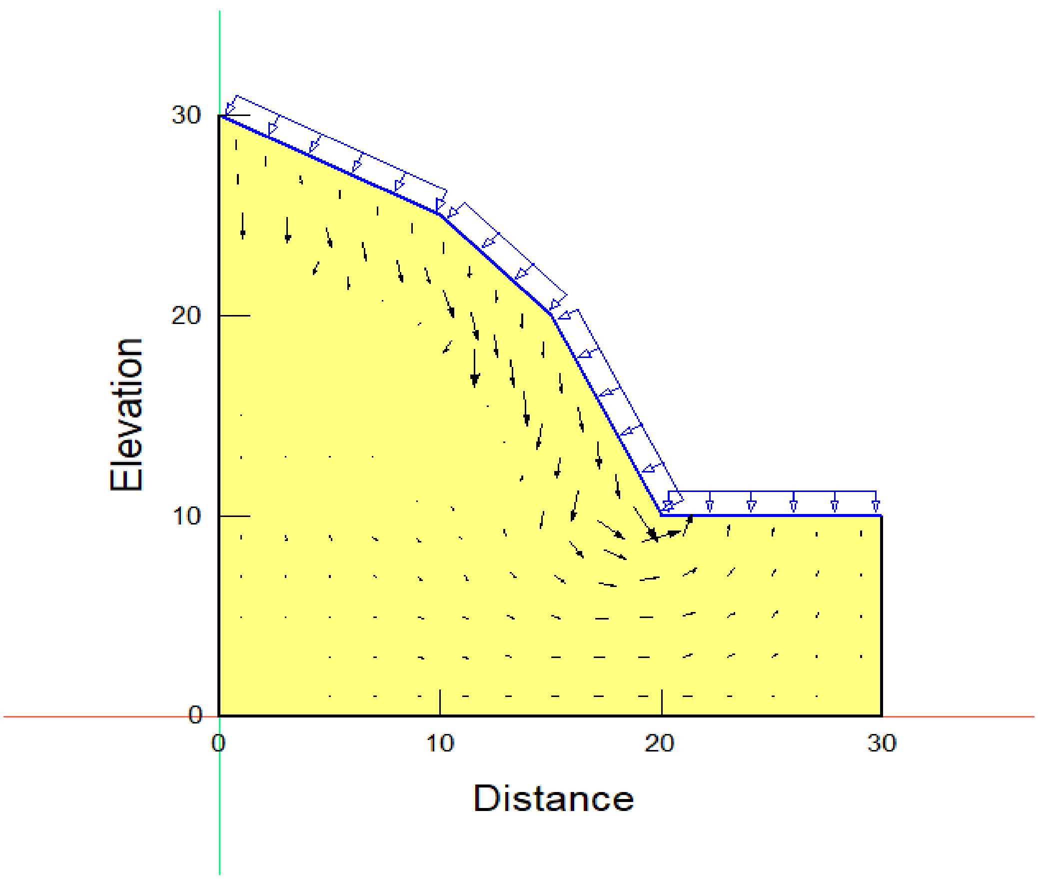

Fig 7.4 shows the seepage analysis

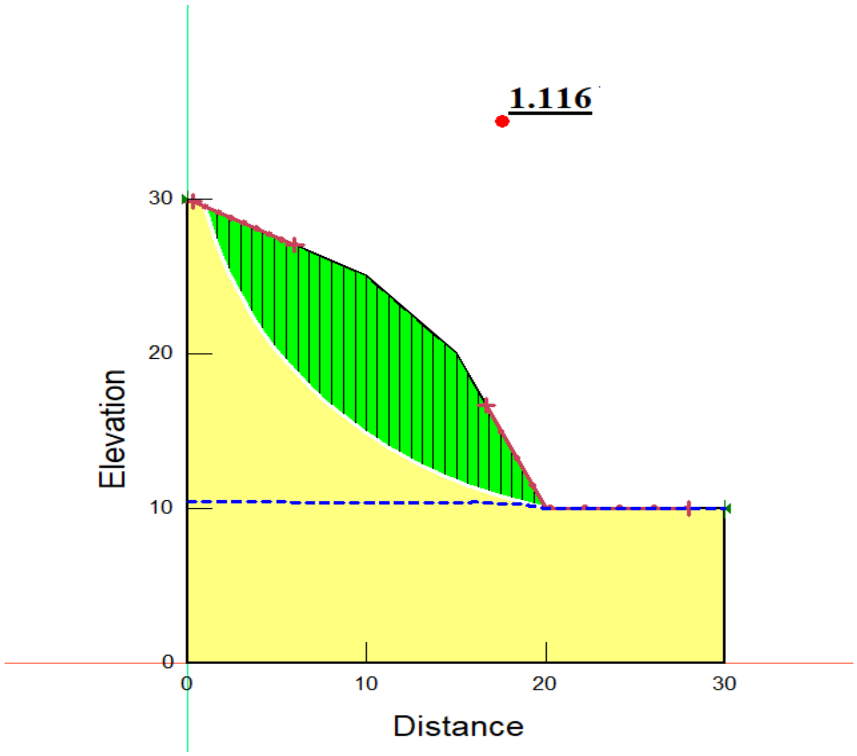

Fig 7.5 factor of safety after rainfall infiltration

For monthly maximum rainfall data 2011

- In figure 6.9, the slope is considered at the location of Uttarakhand Almora, and the safety factor is 1.227 computed by slope/w method using GeoStudio software before the rainfall impact
- consider the rainfall intensity of 548.80 mm of 26 days and compute the seepage of slope using seep/w method using GeoStudio software, as shown in figure 7.6
- In figure 7.7 the effect of rainfall on slope has been observed, with the safety factor falling by 0.946, slope failure is occurred because the FOS is below <1 and the factor of safety is then determined using the slope/w method and GeoStudio software

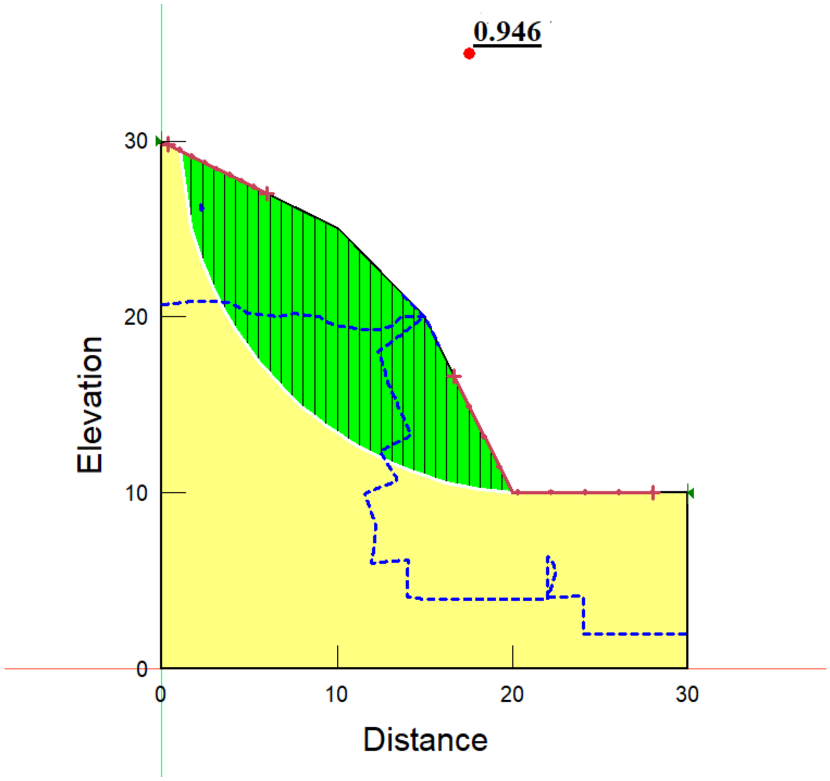

Fig 7.7 factor of safety after rainfall infiltration

5.4 Rainfall intensity and factor of safety for L4 Slope

Slope Identification	Maximum rainfall data	Rainfall (mm)	Number of wet days	FOS in dry condition	FOS in wet condition
L3	1997-2001	99.60	1	1.764	1.734
	2002-2006	163.40	1	1.764	1.650
	2007-2011	152.2	1	1.764	1.674
	2011	548.8	26	1.764	0.967

For maximum rainfall data 1997-2001

- In figure 7.8, the slope is considered at the location of Uttarakhand Almora, and the safety factor is 1.764 computed by slope/w method using GeoStudio software before the rainfall impact

- consider the rainfall intensity of 99.60 mm of 1 day and compute the seepage of slope using seep/w method using GeoStudio software, as shown in figure 7.9

- In figure 7.3 the effect of rainfall on slope has been observed, with the safety factor falling by 1.734, and the factor of safety is then determined using the slope/w method and GeoStudio software

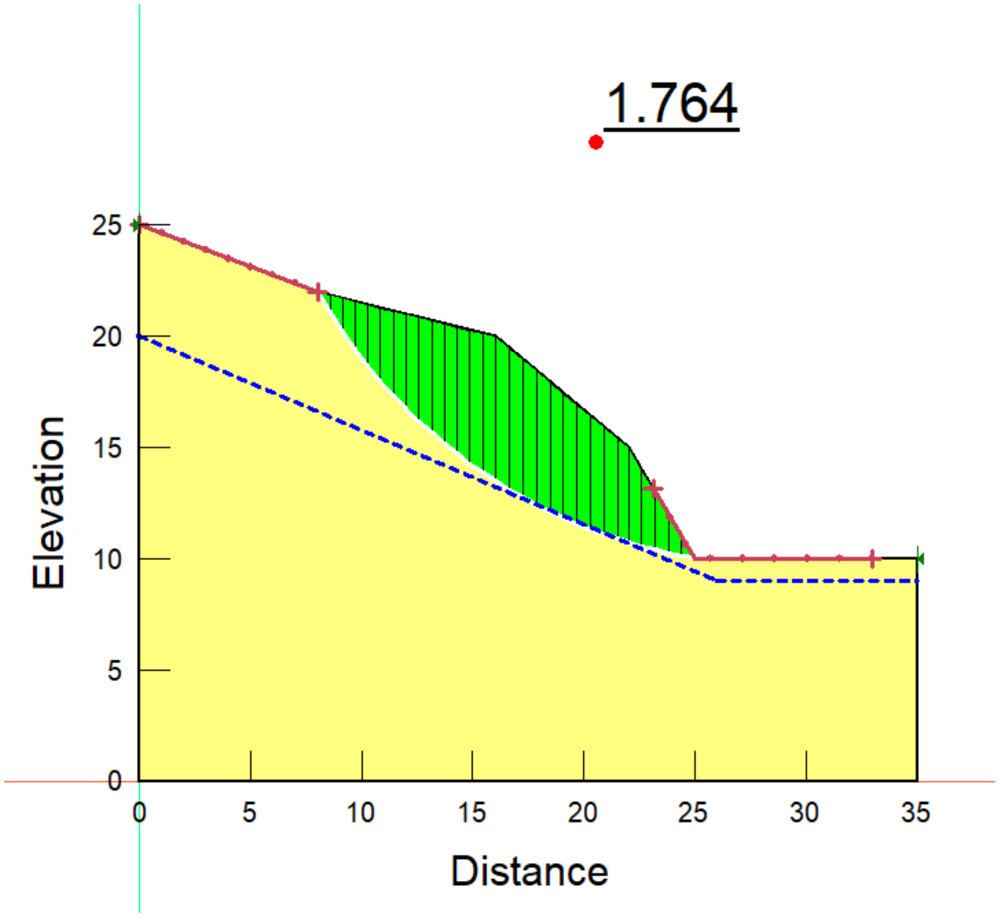

Fig 7.8 shows the factor of safety in dry condition

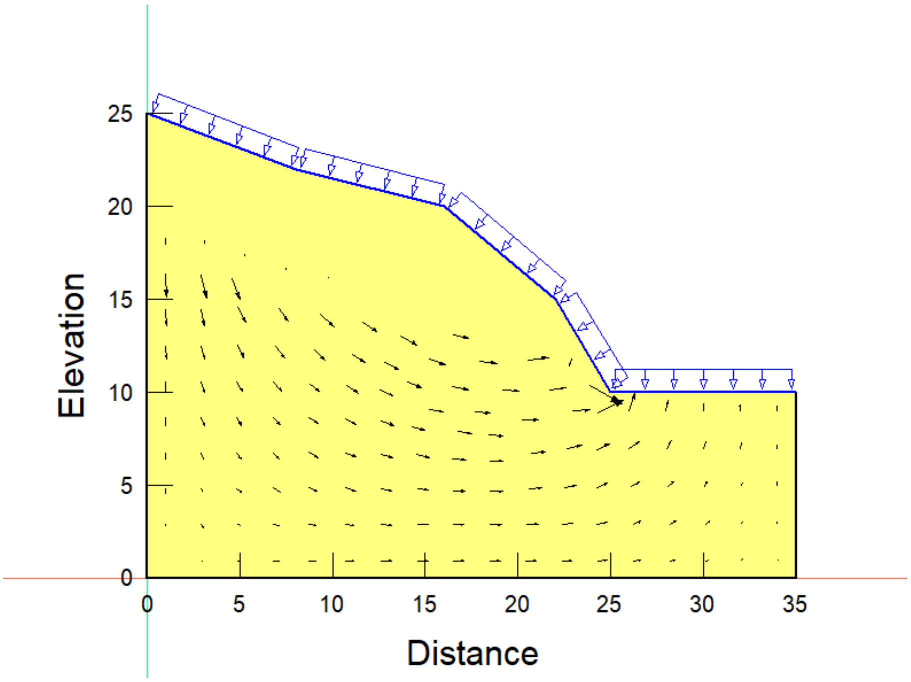

Fig 7.9 shows the seepage analysis

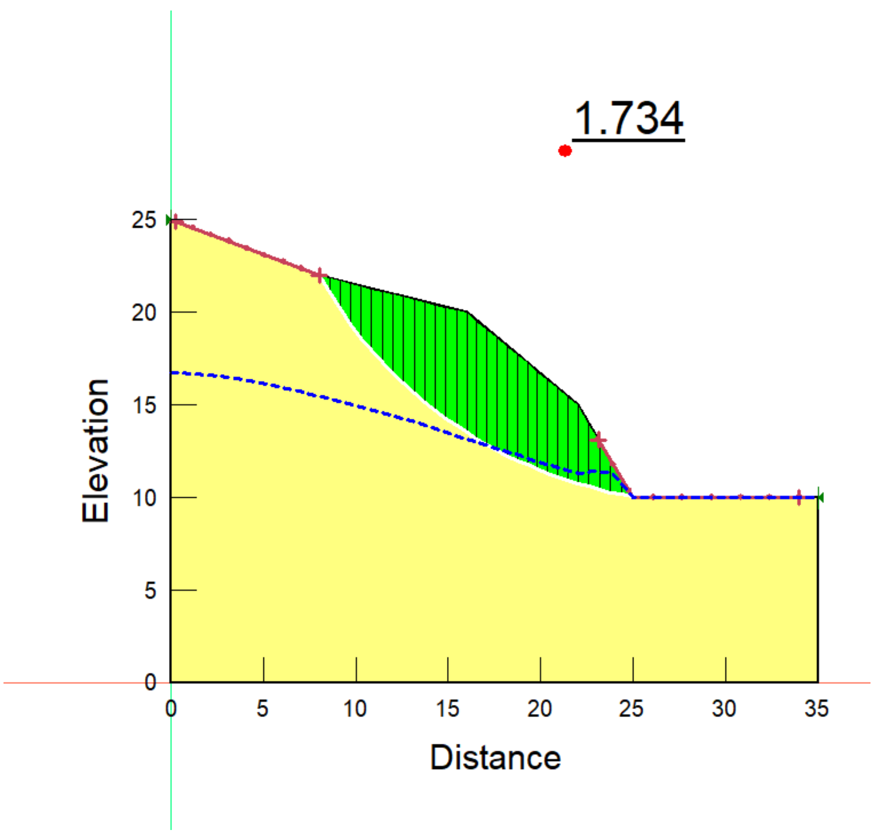

Fig 8.0 factor of safety after rainfall infiltration

For maximum rainfall data 2002-2006

- In figure 7.8, the slope is considered at the location of Uttarakhand Almora, and the safety factor is 1.764 computed by slope/w method using GeoStudio software before the rainfall impact
- consider the rainfall intensity of 163.40 mm of 1 day and compute the seepage of slope using seep/w method using GeoStudio software, as shown in figure 8.1
- In figure 8.2 the effect of rainfall on slope has been observed, with the safety factor falling by 1.650, and the factor of safety is then determined using the slope/w method and GeoStudio software

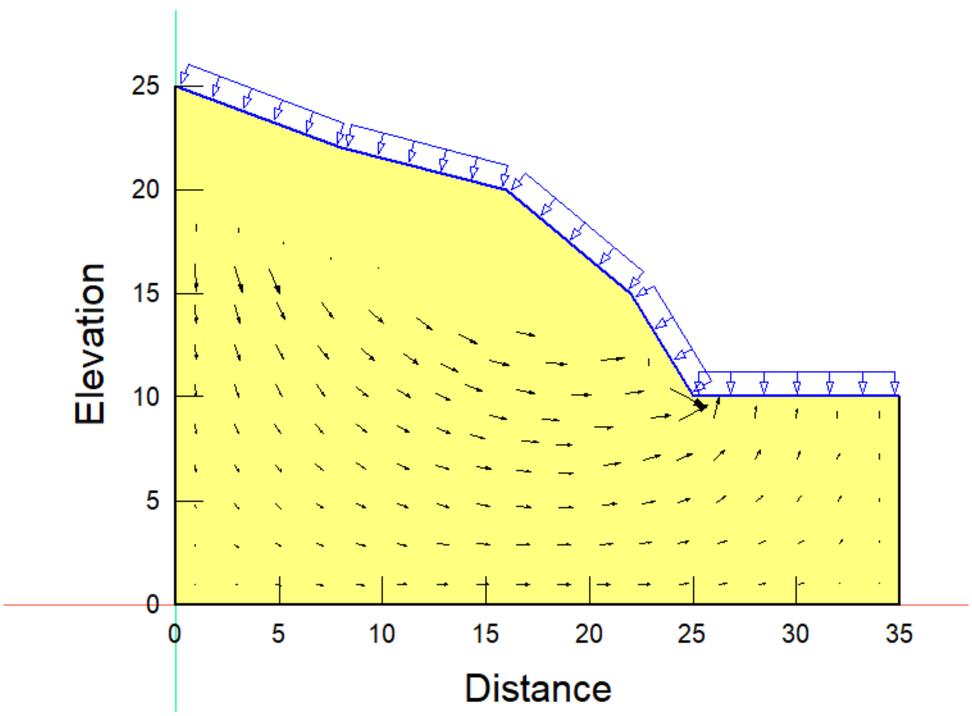

Fig 8.1 safety factor after rainfall infiltration

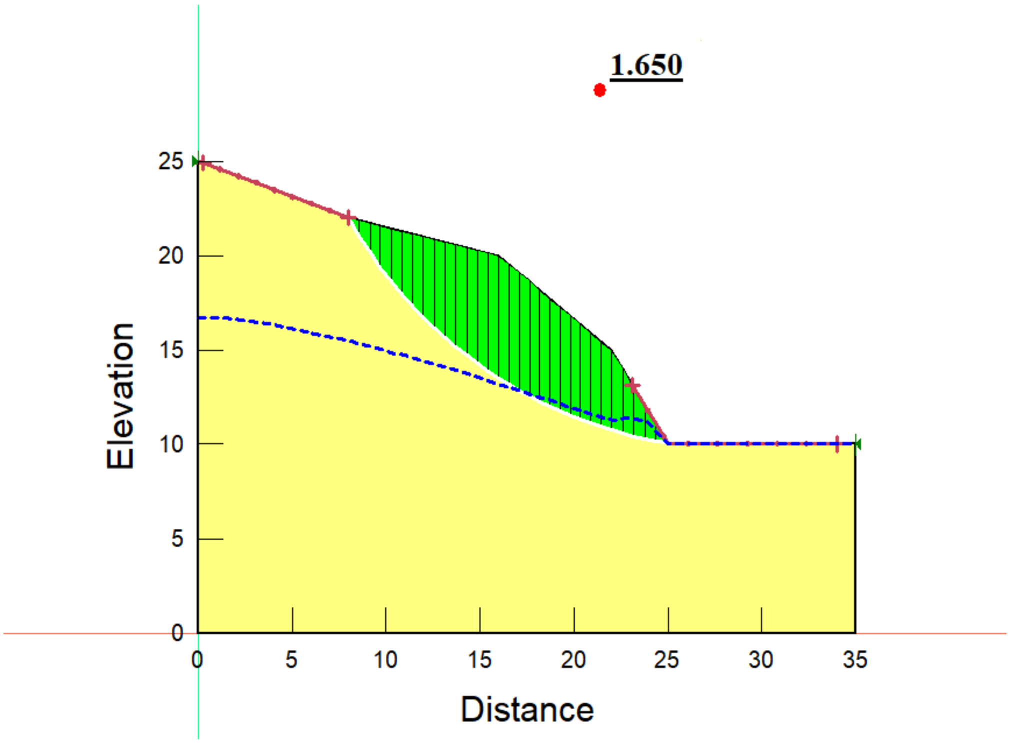

Fig 8.2 factor of safety after rainfall infiltration

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For maximum rainfall data 2007-2011

- In figure 7.8, the slope is considered at the location of Uttarakhand Almora, and the safety factor is 1.764 computed by slope/w method using GeoStudio software before the rainfall impact

- consider the rainfall intensity of 152.20 mm of 1 day and compute the seepage of slope using seep/w method using GeoStudio software, as shown in figure 8.3

- In figure 8.4 the effect of rainfall on slope has been observed, with the safety factor falling by 1.674, and the factor of safety is then determined using the slope/w method and GeoStudio software

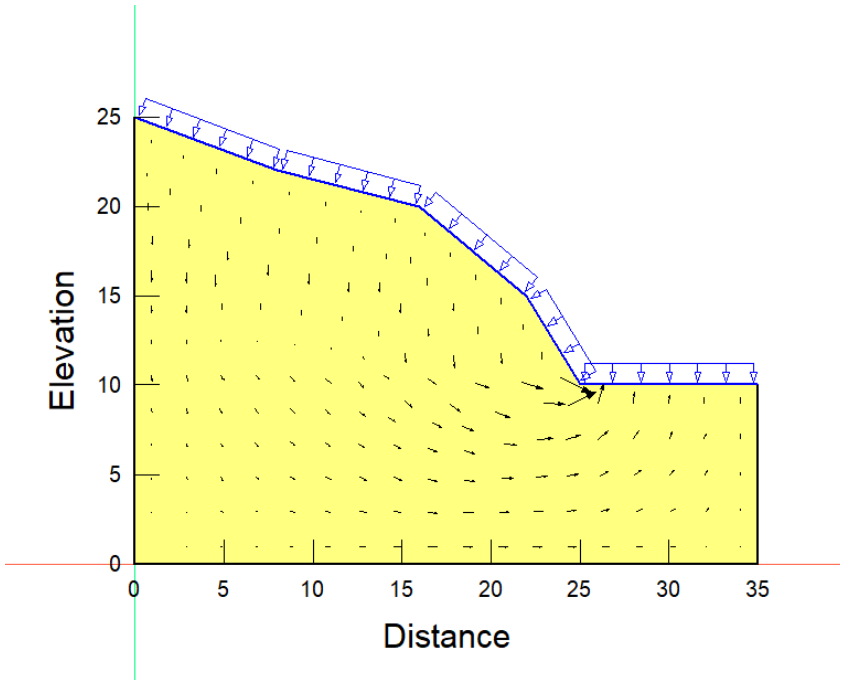

Fig 8.3 shows the seepage analysis

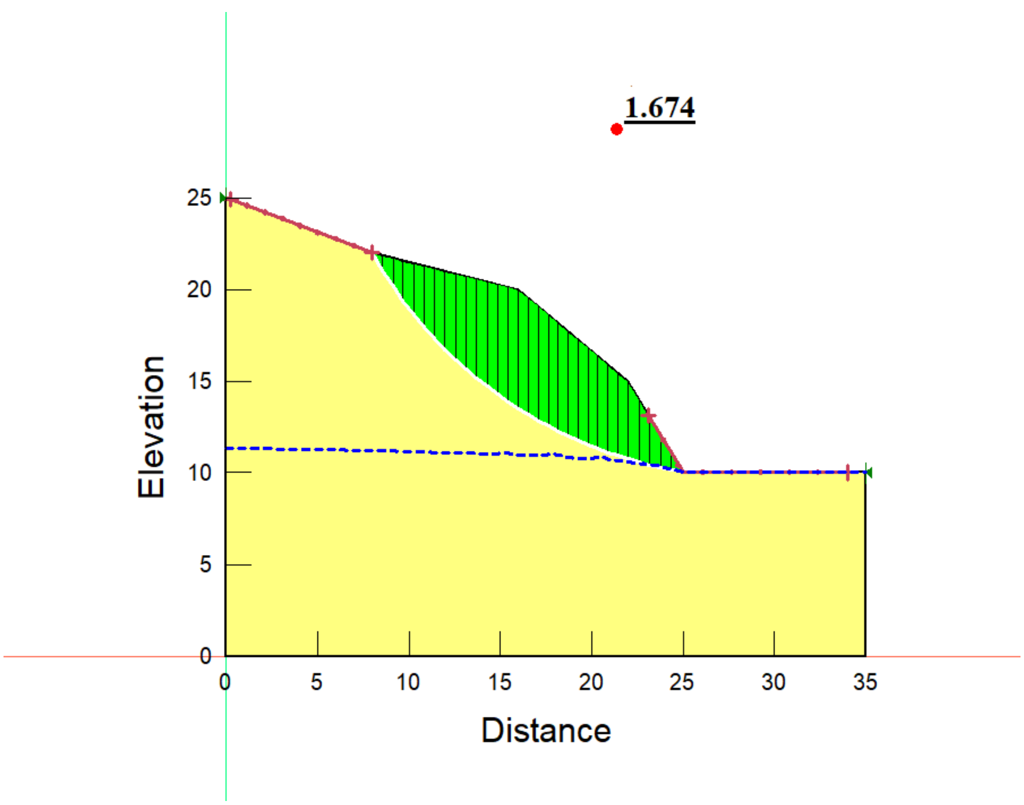

Fig 8.4 factor of safety after rainfall infiltration

For monthly maximum rainfall data 2011

- In figure 7.8, the slope is considered at the location of Uttarakhand Almora, and the safety factor is 1.764 computed by slope/w method using GeoStudio software before the rainfall impact

- consider the rainfall intensity of 548.80 mm of 26 days and compute the seepage of slope using seep/w method using GeoStudio software, as shown in figure 8.5

- In figure 8.6 the effect of rainfall on slope has been observed, with the safety factor falling by 0.967, slope failure is occurred because the FOS is below <1 and the factor of safety is then determined using the slope/w method and GeoStudio software

Fig 8.5 shows the seepage analysis

Fig 8.6 factor of safety after rainfall infiltration

CHAPTER 6 – CONCLUSION

Soil shear strength reduces with rainfall infiltration, slope stability is reduced. The water pressure in the slope during rainfall was calculated by seep/w analyses of rapid flow of water trough unsaturated–saturated soils, as well as the slope stability was assessed using the slope/w with shear strength reduction approach in this thesis. As shown above, the stability of the slope or shear strength of the slope decreases with varied intervals of rainfall infiltration. If the rainfall arrived for a longer duration, the shear strength of the slope decreases more than if the rainfall occurred for a short period of time when rainfall occurs over a short length of time but at a high intensity, the factor of safety is reduced more than when rainfall occurs over a long period of time but at a low intensity.
The results demonstrate varying safety factor at different intervals, as well as slope failure if rainfall is applied for an extended length of time.

The outcomes of the Infinite slope model of rapid flow of water and slope stability lead to the following conclusions:

- The hydraulic features of soil have a significant impact on the steady flow within the slopes and the process of water pressure rise owing to rainfall infiltration, thereby increasing the risk of slope failure.

- The starting volume moisture content had a substantial impact on the water pressure rise pattern, and hence slope stability. The larger the starting volumetric moisture content, the quicker the water pressure rose within the slopes under rainfall, increasing instability within the slope.

- The factors responsible for the slope instability due to rainfall infiltration are the hydraulic features of the soils, rainfall intensity and duration, and soil shear strength parameters of soil.

- For slopes with a relatively high permeability, slope failures may have occurred with shorter duration and greater intensity rainfall.

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