SLOPE INSTABILITY IN TROPICAL SOILS: A PRIMER

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Introduction

Much has been said about the various conditions and factors that contributed to the tragic Taman Hillview landslide of 20 November, by both "experts" and non-experts.

However, the writer believes that many of the comments made, including those made by some experts, are about the different component factors that make up the problem (the topography, geology and geomorphology of the area, the rainfall, the water in the ground, the soil, erosion, the development and the control of the development). It appears that each expert is eager to talk about how factors within his area of expertise had contributed to the collapse of the slope. Each contributes a piece of the whole jigsaw puzzle, but no one has clearly synthesized all the components and addressed the fundamental mechanics of the phenomenon, which I believe is an essential first step in the process of dealing with the problem if we are not to jump to the wrong conclusions and end up spending much public money for the wrong reasons. It is essential that the public and policy makers understand how rainfall-induced landslips (the writer has used the British terminology "landslip" interchangeably with "landslide" in this article) take place so that decisions are made with a clear logic and when difficult decisions have to be made, there is understanding of the rationale and hopefully there will be acceptance of the decisions. We should avoid going into a panic and make *ad hoc* decisions to jump into activities, studies or projects without first having a clear understanding of the physics of the problem. Even studies and research activities have to be designed and for such a design to be done well, it is essential that the fundamentals are first understood by the people who will participate in the research, by the funders and by the people who are supposed to benefit or be affected by the findings of the research. In this article, the writer attempts to provide a condensed and simplified overview of the phenomenon of rain-induced landslips in tropical residual soils and offers suggestions on the way forward in dealing with the problem in this country.

The Soil and the Knowledge Base

The knowledge base of many practising geotechnical experts in this country and indeed in most countries around the world, with perhaps the exception of Hong Kong, is derived largely from the theories and engineering mechanics of "well-behaved", usually saturated, sedimentary soils such as clays, sands and silts formed by gradual deposition over a very long period of time by rivers, oceans, lakes, glaciers, wind and volcanic eruptions. This sort of materials is generally (with some exceptions) found in the coastal plains and alluvial flood plains in this country or in areas where there has been tectonic uplift of these plains in the geological past. In places where the soils were not formed by sedimentary deposition, but instead by the *in-situ* decomposition or weathering of rock bodies, these soils are known as residual soils or decomposed rock. Weathering of rocks occurs relatively quickly in the hot and wet tropics and the depth of weathered rock can exceed 100m. The body of knowledge on such residual soils is unfortunately far less developed than that for sedimentary soils, simply because residual soils are not predominant in the developed temperate countries where the disciplines of soil mechanics and geotechnical engineering developed and were advanced rapidly through research and practice.

The soils in the area where the Taman Hillview and the Highland Towers landslides occurred are made up of residual granite at various stages of decomposition overlying the parent granite rock mass. The thickness of this weathered mass above the parent rock mass can be very large, is also variable and is usually interspersed with numerous granite boulders of various sizes.

The fabric of the weathered granite varies with the degree of weathering, and the degree of weathering is highest at the surface, where the granite has usually decomposed completely into soil and the original fabric of the parent rock is unrecognizable. Even at greater depths where the decomposition is not as advanced, the material is made up of an agglomeration of particles of various sizes and the mass physically behaves like a soil, only with physical properties that differ considerably from the upper zones. In general, particle sizes are finer and porosities lower nearer the surface. A typical profile of a weathered granite column is illustrated in Figure 1.

The Strength of Soils and How Water Affects It

The strength of soil masses is almost purely frictional in nature. The strength of a soil is its resistance to shearing, and this resistance is derived from the frictional resistance provided by the soil particles when they are in turn pressed together. The larger the pressures or stresses pressing the particles together, the higher is the frictional resistance to shearing. The pressures that can press the particles together are those applied by the weight of the soil mass itself or by external loads applied to the soil mass, although the weight of the same soil mass and the external loads also at the same time apply shearing forces that try to destabilize the mass.

Water in soils can have a negative or positive effect. When a soil mass is saturated or completely inundated with water, the positive water pressures in the soil, called pore pressures, will reduce the pressures that can reach the soil skeleton. Thus the pressures that work to press the soil particles together are reduced by the pore pressure, thereby reducing the interparticle contact forces. The pressure that is available to act on the soil skeleton at any point is thus the total pressure applied to a soil element less the pore water pressure at that point and is called the "effective stress". The reduction in the "effective stresses" acting on the soil mass due to positive pore water pressures in a saturated soil mass will reduce its shear strength. The pore water pressure at any point under hydrostatic (no flow) conditions is simply the pressure due to the weight of the water above that point and is equal to the density of the water times the depth of water above that point.

But what if the soil is not saturated? Then the pore pressures in the unsaturated soil mass are negative, i.e. there is suction in the soil which actually increases the shear strength of the soil mass. The suction increases the effective pressures that press the soil particles together and as explained earlier, the higher these pressures are, the higher is the shearing resistance of the soil mass.

Positive and negative pore pressures in soils and their effects on soil shear strength are illustrated in Figure 2.

Thus, it can be seen that while water cannot take shear, it can affect the shear strength of soils by reducing (in the case of positive pore pressures) or increasing (in the case of negative pore pressures) the effective stresses that act within a soil mass. To put it in another way, positive pore pressures have a negative effect on soil strength while negative pore pressures have a positive effect on soil strength.

Soils that lie over a relatively impermeable rock deposit usually contain a water table or phreatic surface. It is the surface of the groundwater that flows by gravity within the soil mass through the pores of the soil without moving the skeleton of the soil mass, which is a porous medium. Below the water table, the soil is saturated and the pore pressures are positive. Above the phreatic surface, there is a small zone that is saturated by capillarity rise of water, but this water does not flow like the water below the phreatic surface. Above the phreatic surface, the pore pressures become increasingly negative (in other words the soil suction increases) as we move upwards closer to the surface.

During dry weather, evaporation also takes place, drawing water out from the soil surface into the atmosphere, increasing the soil suction. If the soil surface is vegetated, transpiration also takes place, adding further suction and thus benefiting the soil mass further in terms of strength.

Figure 3 illustrates the different phases of influence of water in a soil body.

The Stability of Slopes

When the ground surface is sloping, to put it simply, the tendency is for it to try to meet the wish of gravity and find a flat position. When this happens, the slope “fails” or collapses, usually although not always, along a spoon-shaped surface of least resistance within the slope mass. This tendency to collapse is resisted by the shearing resistance of the soil mass making up the slope and if conditions arise such that the shearing resistance is reduced to less than the forces trying to push it to a flat position, the slope collapses. The configuration of a typical landslip and the driving and restraining forces are illustrated in Figure 4. Many methods are available to geotechnical engineers for determining whether the shearing resistance of a sloping soil mass is sufficient to overcome the destabilizing forces due to the weight of the slope itself and any external loads that may be applied to the slope. Slope failures or landslips can occur even in slopes that are relatively dry, but in most cases water plays a major role in the instability of slopes.

As will be seen later, the problem that we engineers often face is not in the analysis techniques, but in deciding what properties to use for the soil, what pore pressures to use, how to model and predict suction and the way it diminishes with rainfall infiltration or other environmental phenomena, how it is recovered upon cessation of rain, how vegetation enhances soil strength by maintaining suction and by providing root reinforcement, how to completely model the groundwater regime and the rise and fall of the phreatic surface and how to integrate the incomplete knowledge of an area's geology, geomorphology, hydrology, hydrogeology, engineering properties and future development plans.

Most natural slopes in residual soils in this country are stable only because of the soil suction that exists within the soil masses making up those slopes. Take away the soil suction and there will be thousands of slope failures all over the country. Engineers analyzing natural slopes or even man-made slopes that are still standing often find that the slopes should have failed on the basis of the shear strength parameters obtained from field or laboratory tests. In reality, such an inconsistent result, where the slope appears to defy theoretical prediction, is obtained because the suction has been ignored completely and thus the actual shear strengths of the soils that exist in the slopes have been seriously underestimated. For the purpose of designing new slopes, where the conservatism is necessary due to the inability to reliably predict how the suction will respond to various factors, ignoring the suction is mostly justifiable. However, in predicting the actual behaviour of slopes, everything has to be taken into account. In most cases, the soil suction is there because of partial saturation, vegetation and the topography and geological profile that do not cause the water table to rise and the suction to be lowered sufficiently, even during heavy rains. The slopes remain stable for as long as the natural conditions fail to achieve a potent combination that reduces the shearing resistance of the slope mass to a level below the destabilizing forces, as illustrated in Figure 5. It is doubtful that they will remain stable forever; external conditions can change naturally and the internal structure of the soil mass itself will change due to weathering and leaching. Indeed, slope failures occur naturally as a geomorphological process. It is when man comes along and either gets in the way of natural slope failures or makes changes to the naturally occurring conditions, thereby accelerating the failure, that tragedy strikes.

The Effects of Rain

Having understood the importance of suction in enhancing the strength and thus maintaining the stability of slopes in unsaturated residual soils, it is not difficult to see how rainfall can affect the stability of such slopes.

As rain falls on the surface of a slope and on the surfaces uphill of and around the slope, some of the water infiltrates into the ground and some flows down the slope face as surface runoff. How much infiltration takes place depends on factors such as the topography, the surface cover, the surface drainage, the degree of saturation already in place and the porosity of the ground. As rain water infiltrates a slope, it increases the moisture content, causing a lowering of the suction, i.e. making the pore pressures less negative and hence lowering the shear strengths of the soil. In addition, sufficient rainfall and infiltration uphill of a slope can raise the water table in the slope. A rise in the water table by itself, even if there is no direct infiltration into the slope from above, reduces the thickness of the unsaturated zone (see Figure 6) and also reduces the values of suction in the unsaturated zone, again resulting in a general lowering of the shear strength of the soil mass making up the slope. Furthermore, the wetting of the soil mass makes it heavier, causing the destabilizing forces to increase. If the rainfall intensity and duration is such that the reductions in shear strength cause the increasing destabilizing forces to overcome the diminishing shear resistance of the soil mass, collapse occurs. If the rain does not last long enough or is not intense enough, the shearing resistance does not fall sufficiently to be lower than that required to resist the destabilizing forces and the slope remains stable. In fact, as soon as the rain stops, some recovery of the suction takes place, provided the uphill infiltration does not keep raising the water table in the slope.

In some slopes, the condition of a perched water table occurs. This is where there is a relatively impermeable layer or lens of soil within the slope mass above the water table, as illustrated in Figure 7. When this condition exists, the risks are higher.

Other factors such as clearing of vegetation also reduces suction in the ground below by reducing the effects of transpiration, but in the final analysis, infiltration of water is required to cause the suction to be destroyed.

Why, then, do most engineers ignore suction if it plays such an important role in giving stability to slopes? The answer is because suction is affected by so many factors and varies considerably within the slope and over time. Modelling the suction response is extremely complicated mathematically and determining the input parameters is equally challenging. Many engineers feel that the methods of stability analysis that take into account suction and its response to the factors that affect it within the slope and over time are not sufficiently reliable for them to use as tools for the design of slopes; therefore they mostly take the conservative approach and ignore the suction completely. However, this is not a satisfactory state of affairs, because by doing so, they are forced to reconcile the fact that many slopes that their analyses show as unstable are standing. More importantly, we do not want to declare as unsafe slopes that are obviously standing and can remain standing if the suction within the slopes can be maintained.

Some Misconceptions

It is best that some fundamental misconceptions are clarified so that in the course of dealing with the trauma and emotions that are now prevailing, we do not make statements that are scientifically incorrect. Some of these misconceptions are outlined below:

- **Misconception: That owners of houses or buildings built on "strong" foundations need not worry.** If a slope uphill of the building collapses, the collapsed mass will have considerable energy and with the lubrication provided by the water within, the whole collapsed mass will flow and smash against buildings in its path with a horizontal force that the foundations, walls and frame have not been designed to resist. Most building foundations and frames have been designed to withstand vertical loads, not horizontal loads. If a building is on a slope, it matters little whether the building is on piles; if the slope collapses, the piles and of course the building will be dragged along with the slide mass.
- **Misconception: That surface drainage alone is sufficient to prevent slopes from collapsing.** While good surface drainage definitely reduces the proportion of rainfall that infiltrates into the ground, these surface drains must be located at the right places, be free of cracks and be well-maintained. Cracked or overflowing drains on a slope or uphill of a slope can cause concentrated infiltration, erosion and form gullies that can in fact trigger slope failures.
- **Misconception: That structural solutions like retaining walls will prevent slope failures.** In most cases, if they are properly designed and maintained, they do the job of preventing localized slope failures and in doing so they prevent the development of progressively larger slope failures. But there are many cases of obviously thin and inadequate retaining walls of the rubble-and-mortar type that have no chance of retaining the earth behind them if the soil is saturated. Such a wall stays stable only because of the suction of the soil behind it. It will stand if there is sufficient drainage to remove the water that tries to build up behind it such that the water behind it never reaches a level that can destabilize the wall by reducing the suction and causing the earth and water to exert positive pressures on the wall.
- **Misconception: That there must be underground streams for danger to exist.** As explained earlier, soil is a porous medium which water can infiltrate and through which water can flow, albeit at rates that are very slow compared to the flow over the surface. It is not necessary for underground streams to exist for the pore pressures in the slope to rise and destabilize the slope. In fact, a stable underground stream will do good to the slope by becoming a conduit into which rain water that infiltrates the slope can flow into, thereby preventing saturation of the slope and preventing a rise in the ground water table. As will be explained later, it is even desirable to install artificial conduits into the body of the slope to drain water out of the slope.
- **Misconception: That erosion and landslips are the same thing.** Both are geomorphological processes. However, a landslip is a transitional "mass-wasting" process where the sole driving force is gravity, while erosion is a transportational process that involves the gradual removal of small masses of earth by water or wind. Mass wasting bridges the gap between weathering, which occurs in place and erosion which requires a medium of transport. Landslips can occur even when there is no water (they even occur on the surface of the moon). Even small landslips are distinguishable from erosion by the spoon-shaped or wedge-shaped scars they leave behind. While erosion can

sometimes trigger landslips, or can make it easier for rainfall to infiltrate into a slope, erosion is not a prerequisite for a landslip to occur.

- **Misconception: Soil tests will determine whether a slope is stable.** There are hundreds of soil tests. Each type of soil test will determine a set of properties of the soil that can be used by engineers in their analyses of soil slopes. Some tests are simply for identifying and classifying the soil, some tests are to determine the shear strength under different conditions, some tests are to determine how compressible the soil is, some tests are for determining how permeable the soil is, etc. Some tests are done in the laboratory on samples obtained from boreholes; the degree of disturbance on these samples during sampling and transportation in turn affect the test results. Some tests are done in place either in a borehole, on the ground or by inserting an instrument into the ground and making the desired measurements. In many cases, the test results themselves have to be interpreted by using empirical correlations established elsewhere (often based on research done in other countries on different soils). The results of soil tests are used by engineers for their analyses. What the public should know is that soil mechanics and geotechnical engineering are not exact sciences and they should be accepted as such. The properties of soils, in particular residual soils, are so variable that much judgement is required to select appropriate parameters for different applications. In addition, the conditions that exist below the ground surface can only be investigated at discrete points and the rest is deduced using knowledge of the local geology, past experience and logical interpolation and extrapolation. No two engineers will independently make the same assumptions about the subsurface conditions and soil properties. No two engineers will independently order the same set of investigation techniques or the same soil tests. Geotechnical modeling is not perfect, with many limitations and assumptions that have to be made simply because the state of knowledge is not complete. Our calculations and estimates are only as accurate as the accuracy and appropriateness of the parameters that are used by the person carrying out those calculations and this in turn depends ultimately on his or her geotechnical experience and judgement in selecting the parameters and the means by which those parameters are obtained for him to select from.

Getting Organized

Could the authorities have prevented these landslides? There are situations where the authorities could have done more to establish more stringent rules for hillside development, for rehabilitating abandoned projects and for inspecting and maintaining clogged drains and weepholes that form part of the public infrastructure. But if we take a larger view at whole areas where hillside developments are taking place, it is obvious that not everything is within the control of the authorities. As explained above, many slope failures are part of the natural geomorphological process; it so happens that man was there in the way. Should the authorities be made responsible for identifying every possible location where there is potential slope instability? If this is the case, the whole of the area flanking Jalan Hulu Klang and many other areas nationwide should be declared unsafe because every slope there is potentially unstable. Is this what the public wants? True, the authorities should have commenced a well designed study and produced and enforced more stringent guidelines after earlier events like the Highland Towers tragedy of 1993. Or the authorities could have emulated Hong Kong and established a similar organization like its Geotechnical Engineering Office which, besides carrying out studies and research, produces guidelines, set up a landslip warning system and educates the public and creates awareness on slope safety and maintenance. But even then, all that can be done is to identify and reduce the risks, not to completely prevent these landslides from taking place.

The most effective long-term solution is to begin to understand the problem and to take immediate measures to set up a dedicated organization that has authority over hillside development for the whole country and not just within each local authority. The last thing we want is for each municipal council to have its own hillside development control unit, each with its own research activities, guidelines, procedures, systems, experts and budgets. Where should this central agency be parked? The writer believes that the most appropriate department to park this under is the Department of Land and Mines, because this is a matter involving the land, its topography, its geology, its properties and its stability. As will be seen later, the land ownership issue is also crucial in carrying out investigations, instrumentation and in implementing rectification solutions.

Having established this central agency, it should be mandated by federal legislation and be allocated sufficient funds to carry out investigations , studies and research on anything to do with hillside development and slope safety, to issue guidelines and standards, to approve hillside development, to monitor slopes and enforce its guidelines, to put in place a slope safety management and warning system, to rectify unsafe slopes, to recommend evacuations if this is the only safe option, to educate and create awareness among developers, administrators and the general public, to identify potentially unsafe slopes and make the list of such unsafe slopes available to the public and to generally reduce the risk of life-threatening landslips in the country. We do not have to start from scratch. Much can be learnt from the Hong Kong experience and how its Geotechnical Engineering Office has reduced the risk of landslides to about 50% of what existed in 1977 when it was set up (initially as the Geotechnical Control Office) following the hundreds of landslides that occurred on 25 August 1976 as a result of 416mm of rainfall, killing or injuring 57 people. Let us take stock of what the current state of knowledge and practice is in this country and compare it and learn from Hong Kong, a colony that has achieved so much in this area , not overnight but through painstaking research and development efforts over the last 24 years. The key to this whole exercise comprises patience, stamina, commitment and perseverance.

Designing the Research

As the writer explained earlier, the investigations, studies and research that need to be conducted must be designed to be effective. They must be based on an understanding of the physics of the problem and a systematic approach to determine as accurately as possible the parameters involved, how they affect the phenomenon, how they behave under different conditions, how they are interrelated and how they can be used to make slopes safer. It is obvious that the factors involved are the topography, the geology, the rainfall, the soil, the suction, the water table and subsurface flow, the vegetation, the evaporation, the surface drainage, the surface condition and any subsurface drainage. The objective is to develop a more realistic and advanced model for simulating actual conditions in slopes before, during and after rainfall and for predicting the stability of slopes in various types of soils in their "dry" state and upon being subjected to rainfall of specified intensities and durations, so that potentially risky slopes can be identified and appropriate actions taken. The appropriate actions may involve simply abandoning the slope and evacuating the affected population or instrumenting the slopes to provide a warning system or designing measures to rectify the slopes to make them safe, usually together with instrumentation.

The subjectivity in geotechnical engineering will always be there, but with more sophisticated models, more systematic data and continuous calibration with actual cases, it is hoped that the band of subjectivity will keep narrowing and more consistent and reliable results will be obtained.

The expertise that will be required is now obvious: geologists, meteorologists, geotechnical engineers, geophycisists, soil scientists, surveyors, remote sensing specialists, botanists, hydrologists, hydrogeologists, drainage engineers, mathematicians, instrumentation engineers and computer programmers to do the research and modeling, engineers to design rectification measures and contractors to install those rectification measures.

In addition to the above, the Department of Land and Mines and the state land offices will play an important role in implementing whatever solutions, because land will have to be acquired or land owners will need to be asked to cooperate in allowing access through and for investigation and instrumentation to be done on their land. Some of the solutions may require surface and subsurface drains and stabilizing structures to pass on or under land belonging to many owners. If existing laws are inadequate to ensure cooperation ad compliance, new laws will have to be drafted for parliament to consider.

How this research effort might be planned is illustrated by the example shown in Figure 8.

Immediate Rectification Measures

The question that begs an answer is, "Are there any immediate solutions that can be implemented to stabilize some of the slopes that are believed to be of high risk?"

The writer believes there are and will discuss one of these below, but it must be recognized that this is an emergency solution that is proposed without the benefit of a full investigation. This approach, while appropriate for emergencies, is not the usual one that should be adopted in deciding how to rectify unstable slopes in general. The method of stabilization may be appropriate, but the decision to adopt it should really be based on thorough investigations and analyses.

As was explained at length earlier, the main contributing factor to the loss of strength of soils within a slope mass is the increase of pore pressure or loss of suction within the slope. Suction is lost due to the increase in moisture content of the soil caused by rainfall infiltration and also due to the rise in the water table. The rise in the water table, besides reducing suction values above it, also increases the pore pressures below it. One obvious and effective way of stabilizing a potentially unstable slope is then to try and lower the water table or at least prevent it from rising. This can be done by installing subsurface drains into the slope.

There are many types of subsurface drains, but where the slopes are high and long and it is not possible or unsafe to construct subsurface drains by cutting into the slope from its surface, an available technique is to use deep horizontal drains (DHDs). DHDs are formed by drilling almost horizontally (usually at a gradient of about 10 percent up) into the slope body and then installing perforated steel or plastic pipes into the drilled hole. For the drains to be effective, they must be long enough to reach well into the slope and be below the suspected water table. In the case where we are installing the horizontal drains without the benefit of a prior investigation, we will have to adopt the concept of progressive design by performance, i.e. we keep modifying the design as we observe how the drains perform. If there is no flow, we keep drilling deeper into the slope. If we find water, we drill slightly deeper to maximize the contact between the drain and the ground we want to drain and we install more drains adjacent to and at levels below the successful drain. The decision making has to be done on site by the relevant exerts involved. The materials coming out of the drill holes are logged and studied; so is the rate of flow of water, because these will help us design better drains and also determine how much water we are able to drain out of the slope. In theory, if we are able to drain out as much water as that which enters the slope by infiltration or flow from behind the slope for a specified rainfall intensity and duration, we will be able to prevent the water table from rising due to that rainfall event and are likely to keep the slope stable, as is illustrated in Figure 9.

Installing these deep horizontal drains into slopes will involve traversing through state and private properties and will need the cooperation of the affected landowners. To enable such solutions to be applied for the long term, it may be necessary to put in place legislation that allows the government to implement such solutions without having to worry about the possible objections of land owners.

Concluding Remarks

The writer has attempted to explain in simple terms the factors affecting the stability of slopes in tropical residual soils such as those found in the Hulu Klang area where a series of catastrophic landslides occurred recently and in the past. The mechanics of slope failures in such soils and the effects of rainfall on the strength and stability of slopes is explained in simple terms. The writer has also attempted to clear some misconceptions that surround the subject and has suggested actions that may be taken to systematically organize the investigative and regulatory machinery. A possible immediate solutions that can be considered for rectifying high-risk slopes is also suggested. It is the writer's hope that this primer will help the public, administrators, policy makers and legislators to gain a more complete understanding of landslides.

As a final note, the writer wishes to reemphasize that while the design of engineering measures to rectify or stabilize unsafe slopes remains a responsibility that is within the domain of qualified professional engineers, the study of slopes and landslides must by necessity be an endeavour that involves contributions from and interaction among many areas of knowledge. No one discipline has the right to claim exclusive dominance and authority over this effort and the issue of slope safety should not be constrained by the boundaries of any particular discipline.

The writer is a Professional Engineer registered with the Board of Engineers, Malaysia and has a PhD in civil engineering specializing in geotechnical engineering. He has more than 24 years' combined experience practising, doing research in and teaching geotechnical engineering and project management and has been involved in the implementation of many large infrastructure projects in Malaysia and abroad. He isChairman and CEO of Macroworks Sdn Bhd, a project management-engineering-construction company he founded in December 2001. He is a member of the Institution of Engineers, Malaysia, the American Society of Civil Engineers, the Construction Institute, USA , Sigma Xi, the Scientific Research Society and is an ASEAN Engineer.

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Seri Kembangan, Selangor
November 2002

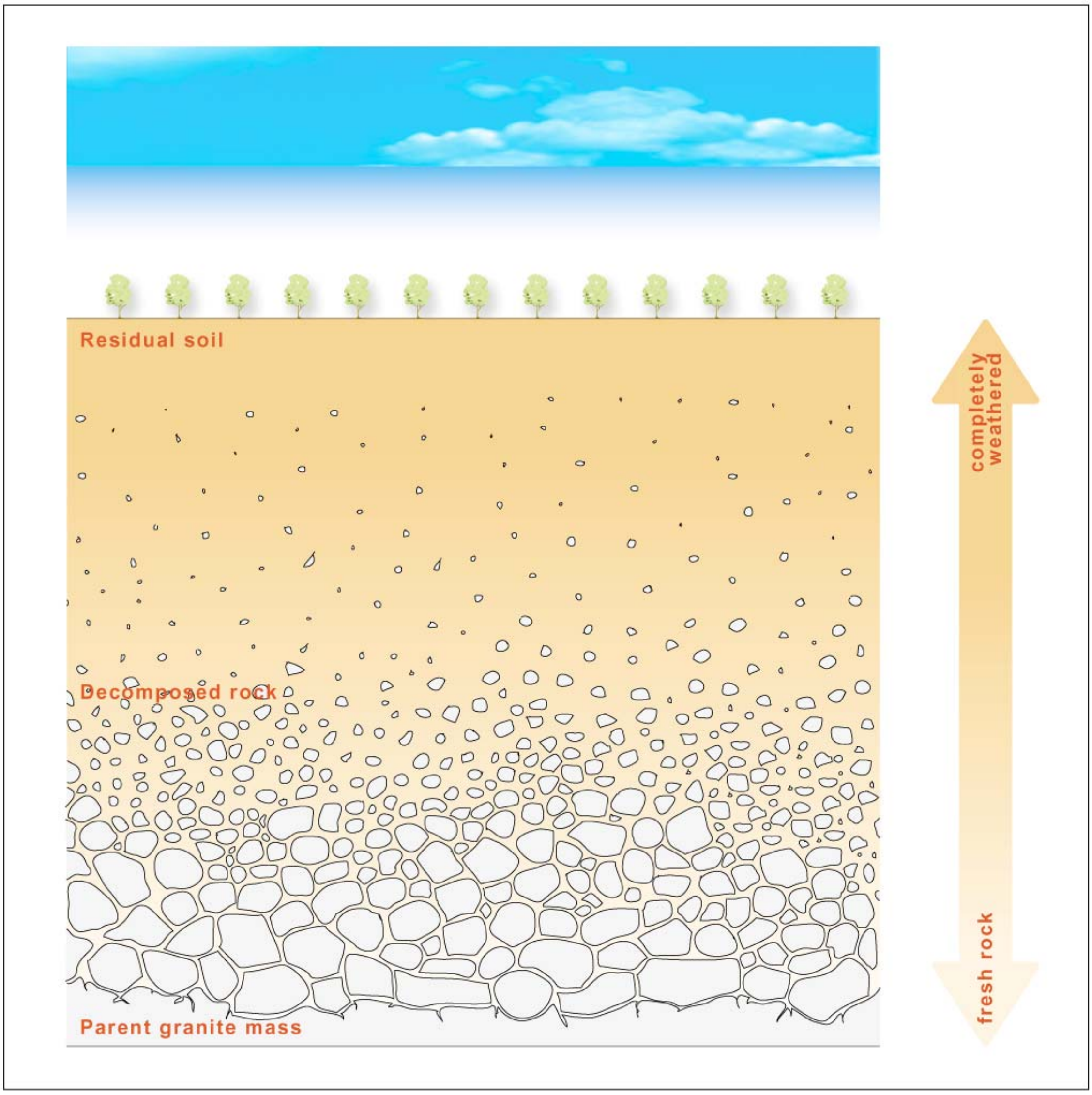

Figure 1 : Profile of a weathered granite column.

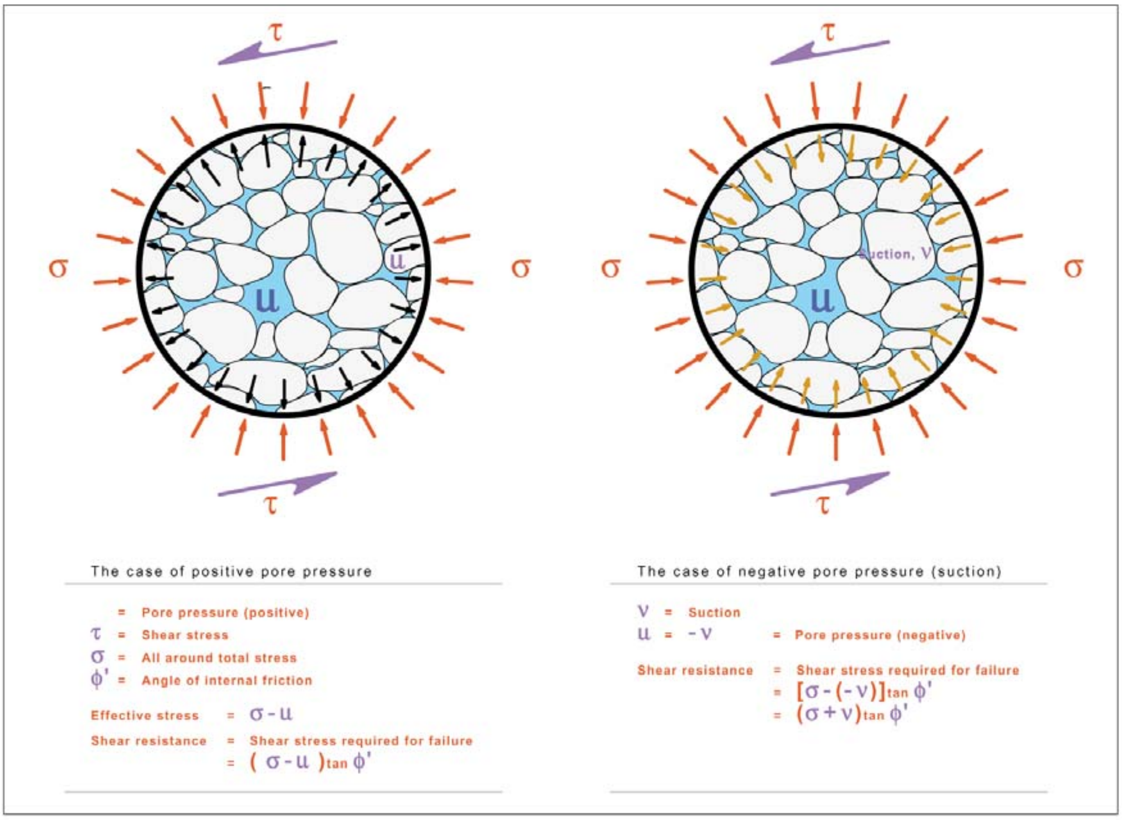

Figure 2 : Positive and negative pore pressure in soils

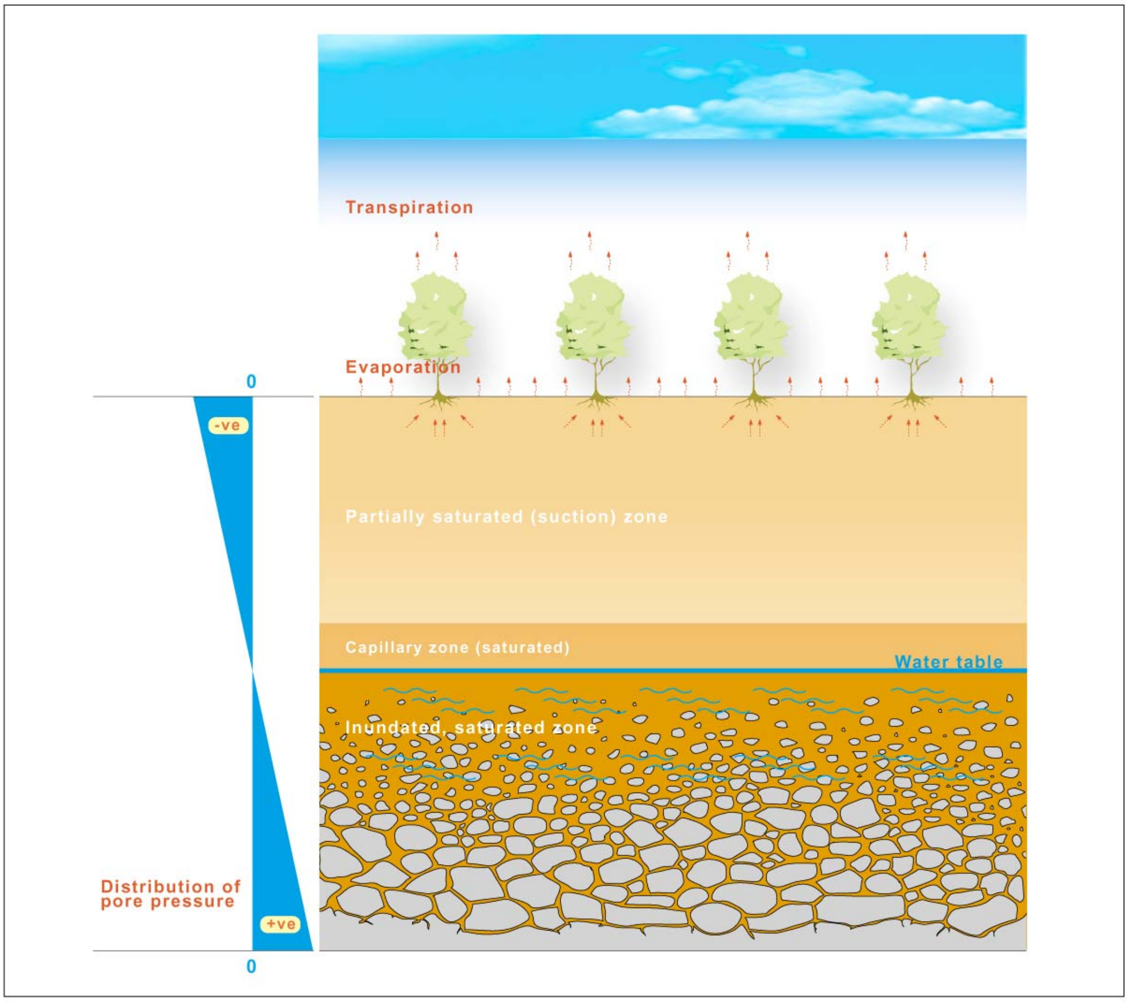

Figure 3 : Phases of saturation in a soil body

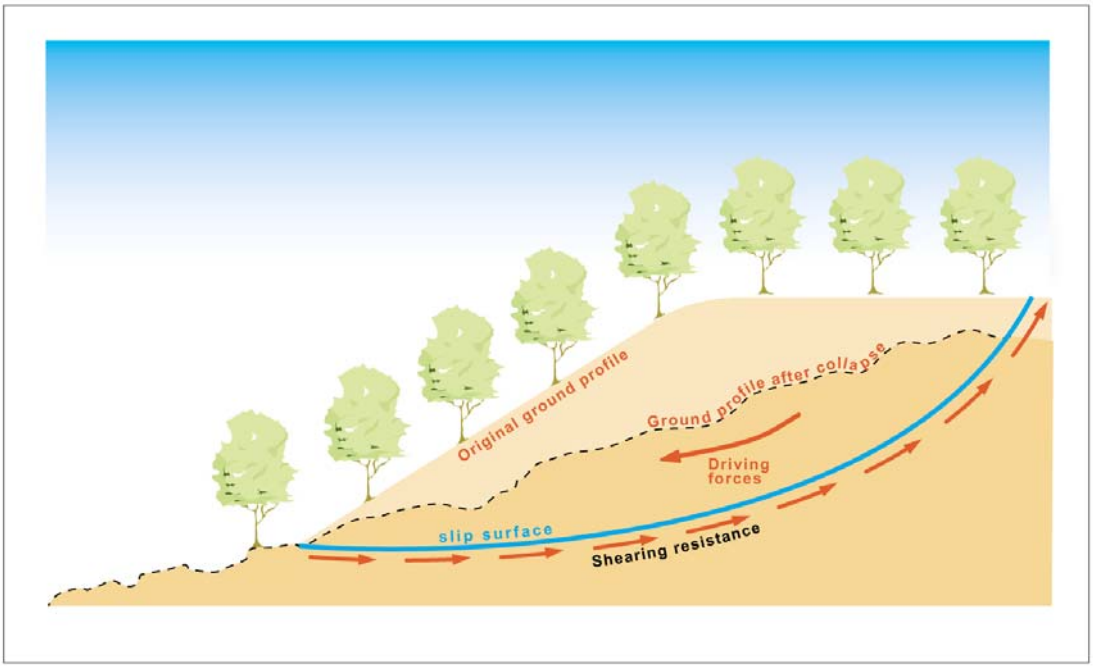

Figure 4 : A typical landslip and the driving and restraining forces

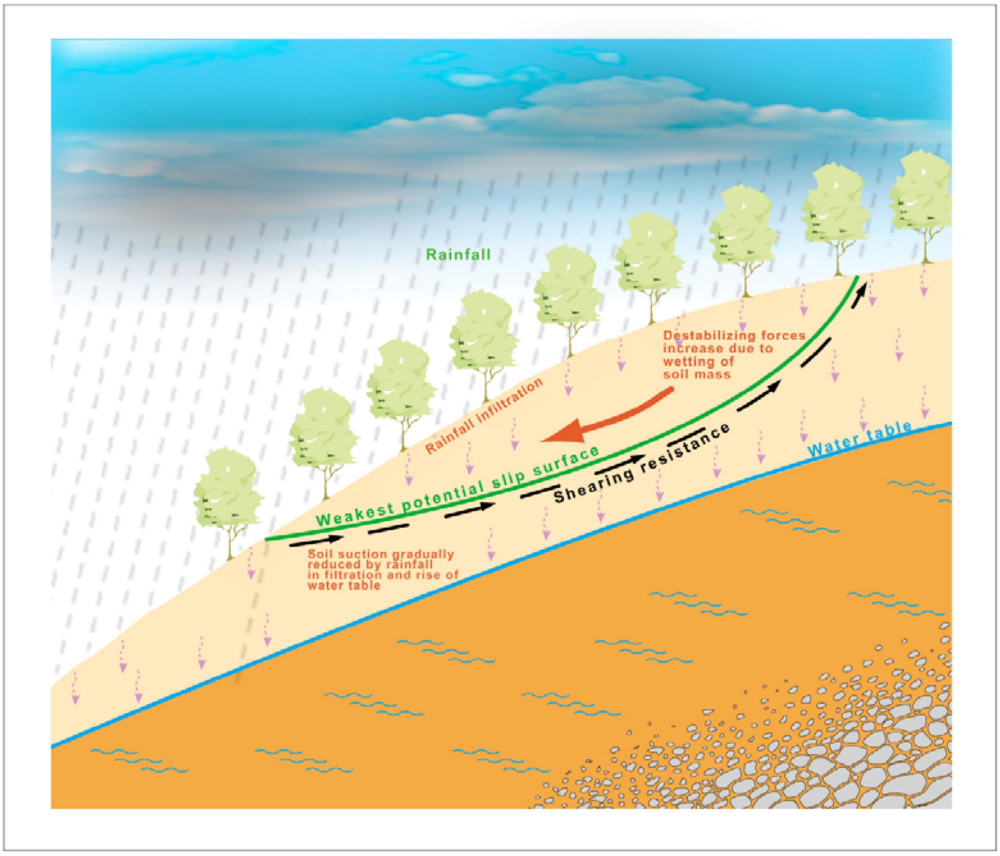

Figure 5 : The basic mechanics of slope stability

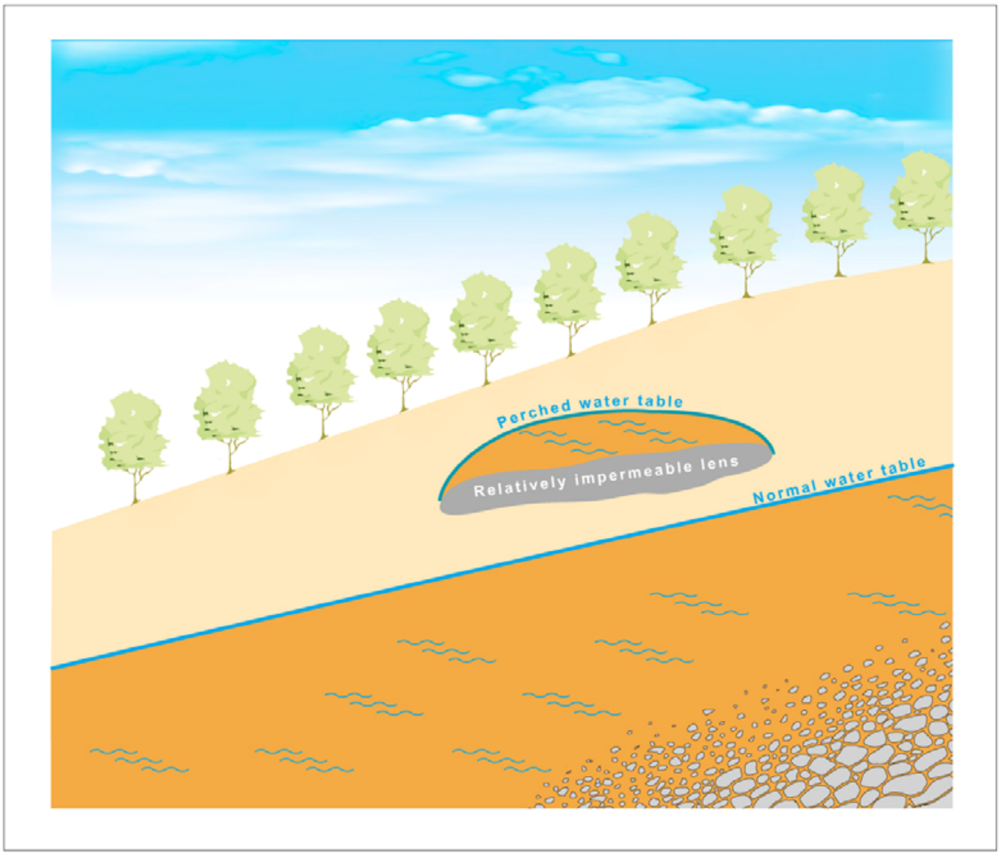

Figure 6 : Perched water table

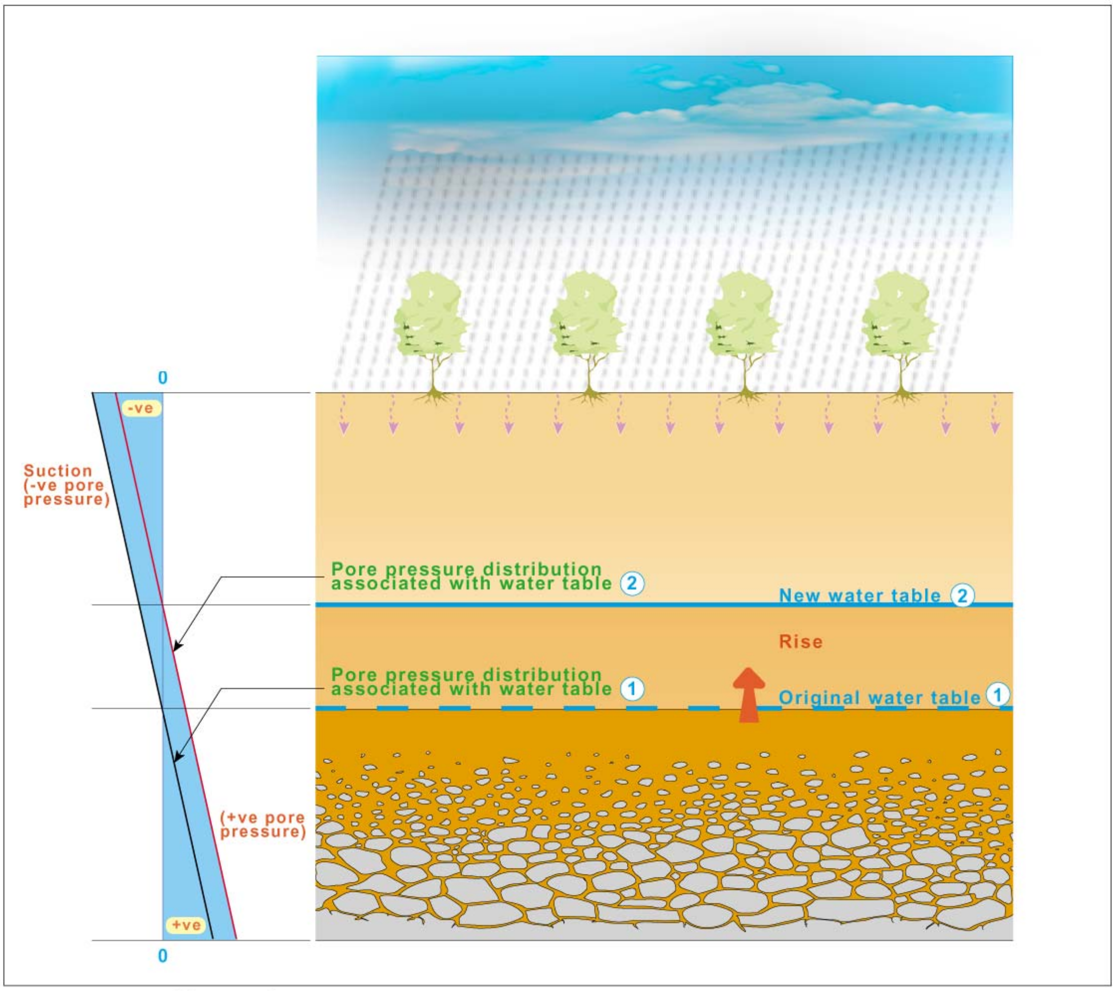

Figure 7 : Effect of rise in water table on soil suction

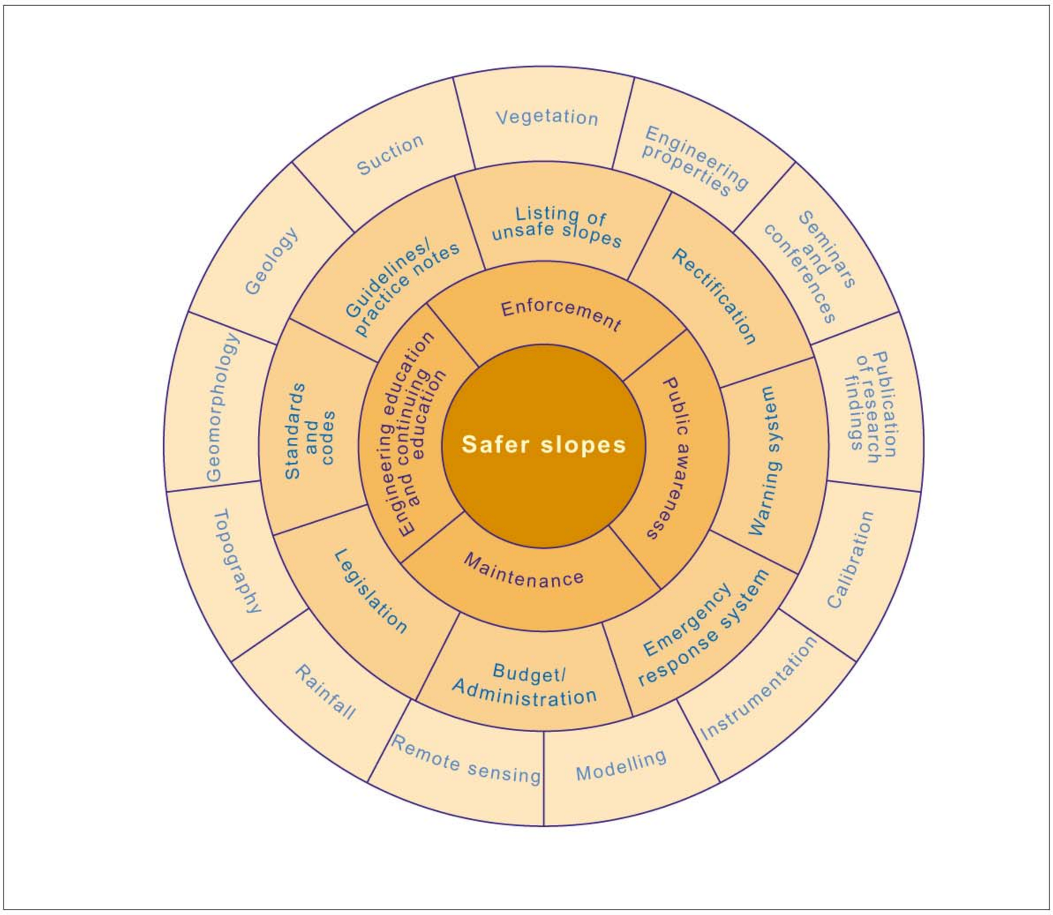

Figure 8 : Design of research to achive safe slopes

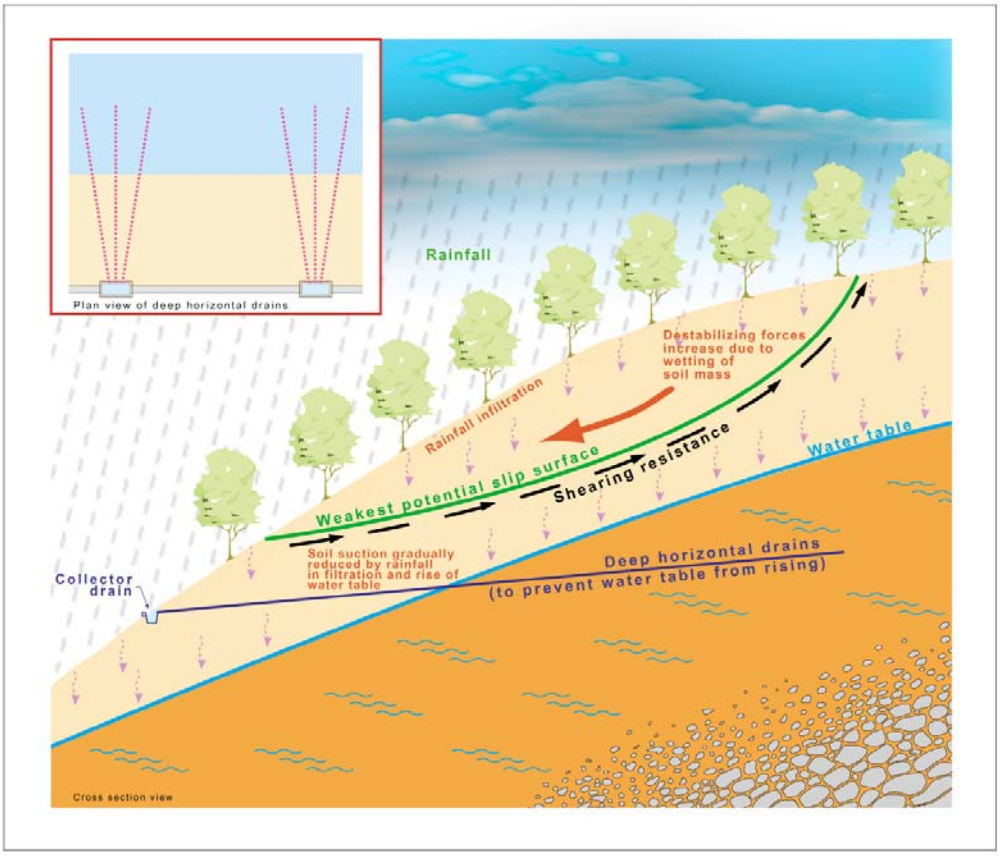

Figure 9 : Deep horizontal drains for maintaining slope stability