IMPACT OF GLOBAL WARMING ON STABILITY OF NATURAL SLOPES

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RÉSUMÉ
Le réchauffement climatique exerce un impact croissant sur plusieurs facteurs reliés directement à la stabilité des pentes, déclenchant des glissements de terrain et causant de graves impacts sur l'environnement naturel et le développement humain. Plusieurs facteurs sont analysés pour évaluer leur importance. Ceux-ci comprennent la perte de la végétation, avec son renforcement grâce aux racines, l'augmentation des précipitations engendrant des nappes phréatiques plus élevées et une diminution de la succion dans les sols, des niveaux d'inondations plus élevés provoquant l'érosion des matériaux stabilisateurs au pied des pentes, le dégel du permafrost résultant en un sol saturé et instable, et des températures de sol plus élevées causant une perméabilité accrue du sol. Les analyses confirment que ces changements ont un impact important sur la stabilité des pentes. Basé sur ces résultats, certains types de pentes très vulnérables aux instabilités résultant des changements climatiques sont identifiés. Pour des problèmes à grande échelle causés par le réchauffement climatique, les méthodes traditionnelles reliées à des sites précis peuvent s'avérer inappropriées. Plusieurs autres approches sont présentées.

ABSTRACT
Global warming has an increasing impact on many factors that relate directly to the stability of natural slopes, triggering landslides and causing severe impacts on both the natural environment and human development. Several such factors are analyzed to assess their significance. These include loss of vegetation with its root reinforcement, increased precipitation causing higher water tables and loss of soil suction, higher flood flows causing erosion of stabilizing materials at the toe of slopes, thawing of permafrost resulting in unstable saturated ground, and higher ground temperatures causing increased soil permeability. Analyses confirm that these changes have a significant effect on the stability of slopes. Based on these results, types of slopes that are highly vulnerable to instability as a result of climate change are identified. For such large scale slope problems caused by climate change, traditional site specific solutions may not be appropriate. Several alternative approaches are noted.

1. INTRODUCTION

Global warming and climate change have been a major issue during the last two decades. Many environmental changes have been occurring due to global warming caused by greenhouse gases. These include an increase in temperature and changes in precipitation patterns. Associated with these are dramatic changes in the frequency and magnitude of storms together with the associated changes in surface and ground water regimes. These are having an increasing impact on natural hazards, namely flooding and landslides.

Landslides have a very high impact on the socio-economic factors of many countries (Brabb & Harrod 1989). The total cost associated with slope movements in the world has exceeded 20 billion US$ per year (Leroueil 2000). Human casualties related to landslides are also enormous, with an estimated 110,000 casualties in China alone in the 20th century (Li, 1989). Schuster (1996) also notes that landslide activity is increasing due to continued deforestation, increased urbanization and development in landslide prone areas as well as increased regional precipitation caused by changing climate patterns.

This paper will discuss the impact of global warming on stability of natural slopes. This will assist in assessing the degree of increase in risk to the environment, to identify landslide prone land with increasing risk, and to develop new large-scale solutions that can be economically applied to such terrain.

2. GLOBAL WARMING

Due to an increase in greenhouse gases the global temperature has been rising during the last few decades. Global warming is predicted, by climatic modelers, to increase the average temperature at the earth surface 1.5 to 4.5°C by the middle of this century (Boyle and Ardill 1989). This rate of warming would be between 0.3 and 0.8°C per decade with greater increases towards the pole of up to 8°C, with an average at mid latitudes and the least in tropical regions (as little as 0.1°C). Therefore, irrespective of the resulting changing in global weather patterns, continents in the far north (e.g. Canada, Greenland, Russia) will be much more affected than other parts of the world. It is predicted that there will be greater warming impacts in the winter than in the summer. Past trends of temperature for various part of the world are shown in Figures 1 and 2.

Due to global warming, there will be many inter-related changes to the weather. There will be more droughts, heat waves, storms and floods. Vegetation systems will also be changed. Changes in the amount and distribution of ice, permafrost, snow, water and vegetation may modify the

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environment. This global climate change will affect the lifestyle of human beings, our infrastructure and our natural environment. The stability of natural slopes and the associated risk will be very much affected by global warming due to the reasons explained in the foregoing sections.

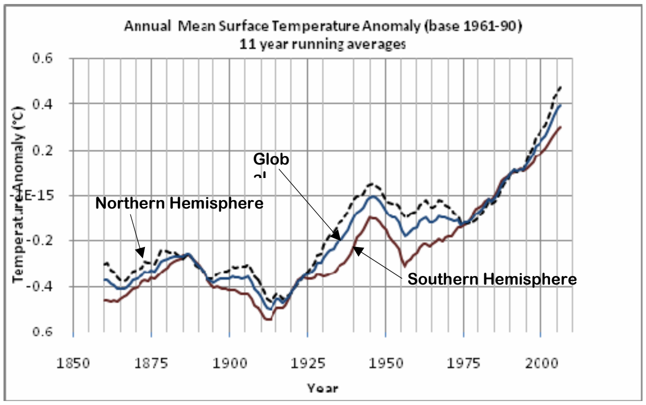

Figure 1. Annual Mean Surface Temperature Anomaly (Australian Government Bureau of Meteorology, 2007).

3. STABILITY OF NATURAL SLOPES

Firstly, in order to visualize the effects of environmental change on the stability of a slope, the mechanism and factors controlling slope stability will be discussed.

The factor of safety (FOS) against the instability of a specific slope can be deterministically calculated by limit equilibrium, namely the minimum ratio of available resisting force or moment to the driving force or moment for all possible slide surfaces. Other analysis methods include deformation and probabilistic analyses, generally considered more applicable to site specific conditions rather than large areas of similar terrain. As a generic analysis, a discrete section of slope can also be analyzed in terms of a failure plane parallel to the face of the slope (Lowe 1976). This simplified analysis is directly applicable to infinitely long slopes where potentially the failure mode is a relatively shallow translational slip and end effects become negligible. The foregoing discussion will first assess slopes based on this simplified analysis. Secondly, to assess deeper failure modes, circular failures will also be investigated using well established limit equilibrium analytical methods. The available strengths mobilized during the displacement of soil elements, can be defined in terms of an apparent cohesion and a drained internal friction angle. This discussion will focus on drained strength parameters rather than short term undrained parameters. These are directly applicable to the long term strength of the soil. Three dimensional effects (Duncan 1999, Bo 2004) and plain strain effects and effects due to variation of mode of failure along the slip (Bo 2004) on the FOS is beyond the scope of this study, given that these are normally a small effect.

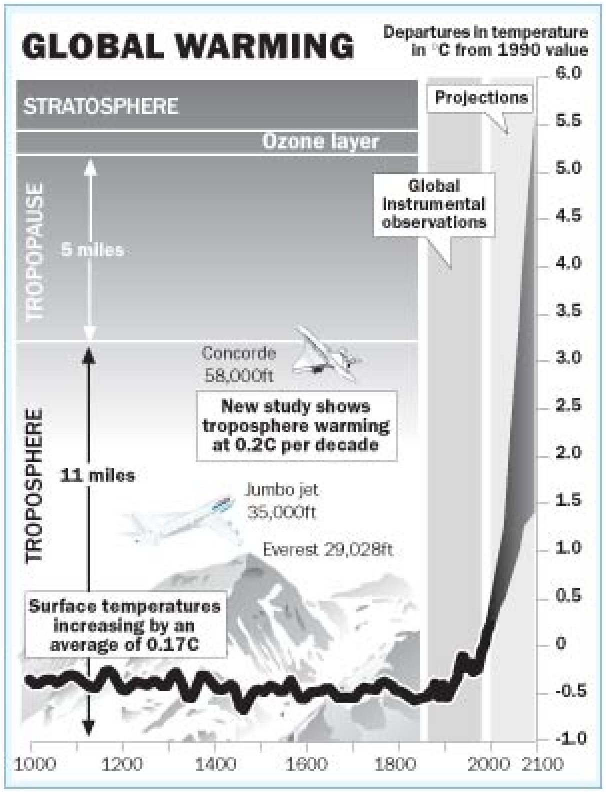

Figure 2. Effects of Global Warming (Henderson, 2004).

For a natural soil slope unaffected by active erosion, where the soil is above the water table without soil suction or other cohesion effects, it is well established that the long term slope angle follows the natural angle of repose of the soil (e.g. Cornforth 2005, Cruden et. al. 1989). For such a case, the FOS of an infinite slope is given by Kaniraj (1988) and Bo & Choa (2004):

$$FOS = \frac{\tan \Phi'}{\tan i} \qquad [1]$$

where i is the slope angle (from the horizontal) and Φ' is the drained internal friction angle of the non-cohesive soil.

However when seepage forces are involved the FOS is reduced to the following equation for a saturated soil with seepage parallel to the slope (Taylor 1948):

$$FOS = \frac{\gamma_b (\tan \Phi')}{\gamma_{sat} \tan i} \qquad [2]$$

where γ_b is the submerged unit weight and γ_{sat} is the bulk unit weight.

Therefore with the submerged soil unit weight approximately half of its bulk unit weight, the FOS for a saturated slope is reduced by approximately half.

These equations, however, only hold true for recently formed slopes which lack cohesion. In reality, most natural soil has an apparent cohesion. Cohesion is typically caused through cementation or aging effects.

For a slope formed with soil having a cohesive component soil the FOS increases due to the cohesion:

$$\mathrm{FOS} = \frac{\tan \Phi'}{\tan i} + B\,(c'/\gamma H) \qquad [3]$$

where the parameter B ranges between 1 and 6 depending upon the slope ratio, c' is the apparent cohesion, γ is the bulk unit weight of the soil and H is the thickness of the sliding mass. However, in the long term, for example as a result of desiccation, stress relief or seasonal frost effects, many soils lose their cohesion and the FOS equation goes back to Equation 1.

When seepage forces are involved further below the slope surface, then the FOS of a slope with cohesion is reduced by a lesser degree to the following equation for seepage parallel to the slope:

$$\mathrm{FOS} = A\,\frac{\tan \Phi'}{\tan i} + B\,(c'/\gamma H) \qquad [4]$$

where A ranges between 0 to 1 depending upon r_u values and the slope ratio, and where r_u is the pore pressure ratio, a measure of the water table height within the slope.

An apparent cohesion can also result from soil (matric) suction. The latter applies to unsaturated soil, and varies with its degree of saturation and the magnitude of the suction. Soil suction therefore provides additional strength, explaining why natural slopes appear stable even when the FOS calculated without an allowance for soil suction is less than unity. However, this additional strength is lost if the soil saturates, for example, during heavy rain. When soil suction is involved as a result of a partially saturated soil, the FOS increases following the equation below by Fredlund and Rahardjo (1993):

$$\mathrm{FOS} = \frac{\tan i}{\tan \Phi'} + B\,(c/\gamma H) \qquad [5]$$

where c is the total cohesion which has two components; the apparent cohesion c' and the matric suction parameter $(u_a\text{-}u_w)\tan\Phi_b$. In this case u_a is pore air pressure, u_w is pore water pressure and Φ^b is the angle of friction with respect to changes in matric suction.

However, when saturation of the soil occurs, the matric suction disappears and the FOS equation goes back to Equation 1 or 4.

When natural soil slopes have vegetation cover, the roots serve as reinforcement and the FOS again increases.

$$\mathrm{FOS} = \frac{(\text{available strength from soil + reinforcement})}{\text{required strength}} \qquad [6]$$

Mathematically this becomes:

$$\mathrm{FOS} = \frac{\tan i}{\tan \Phi'} + B\,(c_1/\gamma H) \qquad [7]$$

where c_1 consists of strength as a result of both soil cohesion and root reinforcement.

The soil cohesion within the root zone is usually nonexistent due to weathering effects. The remaining cohesion as a result of root reinforcement can be lost if the vegetation dies.

4. IMPACT OF GLOBAL WARMING ON STABILITY OF NATURAL SLOPES

Due to global warming, patterns of precipitation and wind, type of vegetation, average temperature and flooding will change. For natural soil slopes, these changes can result in the loss of certain resisting forces available and incur additional driving forces. Natural slopes normally have a FOS marginally above unity, with their slope angles representative of the most severe conditions experienced in the past. Where the climate change effects reduce the FOS, landslides can result (Figure 3). Furthermore, landslide prone terrain becomes more susceptible to non climate change related triggers such as earthquakes.

Figure 3. Landslide at Pic River near Marathon, Ontario.

Examples of climate change impacts on slopes include an infiltration increase causing loss of soil suction, a reduction in effective stress due to rising groundwater levels, a loss of root reinforcement due to changes in the type of vegetation or dying of vegetation, an increase in seepage forces due to frequent and intense storms, an increase in the frequency of rapid drawdown conditions, a reduction of resisting forces due to erosion of the slope toe, an increase in seepage velocity due to an increased groundwater temperature, a reduction of soil cohesion due to increased temperature, and finally vegetation losses as a result of wind changes. These will be discussed in detail in the following sections.

Figure 4. Slope failures along the Kaministiquia River in Thunder Bay, Ontario.

4.1 Impact Due to Change in Patterns of Precipitation

It is foreseen that global warming may cause an increase in precipitation in many areas of the world. This will raise the groundwater level. An increase in the groundwater level would lead to a reduction of the soil's effective stress and an increase in seepage forces and velocities.

Seepage induced slope failures, such as the failures shown in Figure 4, were studied by Budhu and Gobin (1995). Based on their study, an increase in the hydraulic gradient and an increase in the slope of the seepage line could significantly reduce the FOS. An increase in seepage forces will also potentially affect the piping (internal hydraulic erosion) potential of the soil (Tomlinson and Vaid 2000). In addition an increase in infiltration would replace the air voids in the soils with water, and the significant strength obtained from soil suction would be lost.

Rain induced landslides have been studied by several researchers such as Anderson and Sitar (1995). Examples are debris flows in mountainous terrain as well as shallow sliding in granular soil slopes.

Increases in precipitation will also result in a greater water surplus in the catchment areas causing greater flows in water courses and extreme flooding. This causes erosion at the toe of natural slopes in the floodplains of streams or river banks. This process can trigger a landslide due to reduction of the toe resistance. These fluctuations can also create frequent occurrences of rapid drawdown conditions in front of slopes which are well known to trigger instability to natural slopes. Surface erosion can also occur, removing vegetation and increasing runoff infiltration.

Another impact of a rising water table is that it can render a zone of loose soil within or below a slope susceptible to seismic liquefaction. In the event of an earthquake, this can result in a large soil strength loss, triggering a landslide.

4.2 Change in Type of Vegetation

The importance of root reinforcement and hydrology on slope stability has been studied by Van Beek et.al (2005), Watson et.al (1999), Bransby et.al (2006) and Roering et.al (2003).

Vegetation significantly affects the stability of natural slopes.

- Roots of the vegetation provide some degree of reinforcement strength, especially to the superficial soil.
- As tree roots uptake water, soil suction in the soil, beneficial to stability, is maintained or increased in the near surface soils (Indraratna et.al. 2006).
- Roots can be lost due to dying of the vegetation as a result of higher temperatures, or due to removal of the vegetation from increased runoff over the surface.
- High trees which are exposed to the wind transfer the wind forces to the soil and have negative impacts on slope stability.
- Foliage intercepts rainfall, causing absorptive and evaporation losses while increasing the rate of runoff, and thereby reducing infiltration. A loss of vegetation can therefore result in increased infiltration with the associated loss of beneficial shallow soil suction and a detrimental rise in the groundwater table.
- Roots bind the soil particles reducing their susceptibility to erosion. A loss of vegetation therefore contributes towards shallow erosion with the associated increases in water infiltration.
- The weight of the trees on a steep slope, if soil suction and root effects are lost, has a detrimental impact on stability.
- Changes in vegetation can either reduce or increase the near surface permeability of the soils. An increase in soil permeability would facilitate seepage flow parallel to the slope and reduce the FOS of the slope (Greenway 1987). Effects of soil permeability on the stability of homogeneous slopes have been extensively described by Pradel and Raad (1993).

In general, vegetation has more positive effects than negative. Loosing vegetation increases the risk of instability of a natural slope, particularly for shallow translational failures less than 3 m deep. Changes in the type of vegetation due to increases in precipitation, for example from low rise trees to high stem trees, can also negatively affect the stability due to increase in weight.

4.3 Change in Temperature

Temperature changes can affect the stability of a slope in several ways. Firstly, changes in temperature can cause changes in vegetation cover, for example previously healthy vegetation can die. These impacts essentially cause the same effects as those discussed above as a result of precipitation changes.

Secondly, temperature also affects groundwater. As the hydraulic conductivity of soil is dependent upon the viscosity of a fluid, seepage velocity would increase due to a rise in temperature. In addition, the groundwater body would experience thermal expansion. This thermal expansion could lead to a rise in groundwater level. Therefore a significant temperature rise will reduce the stability of a natural slope.

Thirdly, increasing the temperature can desiccate the soil. Whereas in some cases the lower moisture content will increase soil strength parameters and beneficial soil suction, it can conversely result in losses of soil cohesion, for example as a result of fissuring of a clay deposit. These fissures or cracks also accelerate infiltration into the slope with the associated loss of FOS.
Finally, warming arctic temperatures affect stability of slopes depending on frozen conditions for stability. As these permafrost slopes thaw, shallow sliding as a result of saturated conditions occur.

4.4 Change in Wind Velocity

Wind effects on slope stability occur in 2 ways. Indirectly, they affect vegetation and therefore slope stability, as outlined above. This is through aggravating drought effects. This can lead to dying vegetation through reduced moisture, and also losses associated with increased fire hazards. The lateral load on trees as a result of high winds from storms is another effect on slope stability when the wind direction is downslope.

4.5 Quantifying the Impacts

The above noted equations were applied to a variety of conditions based first on an infinitely long slope. This is applicable to slopes that experience relatively shallow failures (less than a few metres deep). Secondly, to study the effects of a slope having a defined shape and where deeper failures can occur, a model was also analysed using limit equilibrium slope stability software for circular failure modes.

Analyses were applied to slope angles varying from 30 to 60 degrees. Selected parameters were as follows:

- Friction angle =30^{o}, typical of loose sand and silts as well as low plastic clays
- Cohesion as a result of roots: 1 kPa, representing an average reinforcement effect within the soil.
- Water table: at the level of the slope's toe
- Soil suction: varying from 0 kPa at the water table to -285 kPa at ground surface
- Soil suction friction angle $\Phi^{b} = 15^{o}$

The results of stability analyses for translation failures in an infinitely long slope are summarized in Tables 1 and 2. These confirm that significant reductions in stability, as indicated by reduced FOS values, will occur as a result of loss of vegetation and soil suction, as well as a rising water table.

An analysis was also made of circular failure modes within a generic soil slope having the same soil parameters as above. In this case, an upper zone 2 m thick was allocated as the root zone as well as the zone in which soil suction can be lost due to saturation. The results are also illustrated in Table 2. These likewise confirm significant reductions in FOS as a result of climate change effects.

Table 1. Results of Circular slip analyses.

	Factor of Safety		
	30° Slope	**45° Slope**	**60° Slope**
Base Case	**1.10**	**1.10**	**1.10**
FOS after root loss	**1.10**	**1.10**	**1.10**
FOS after suction loss in upper 2 m	**1.09**	**0.72**	**0.56**
FOS after loss of both roots and suction	**0.96**	**0.56**	**0.43**

Table 2. Effect of Water Table Rise on Stability

		Water Table Level (h/H)		
	FOS	**30° Slope**	**45° Slope**	**60° Slope**
Base Case	**1.10**	**0.70**	**0.00**	**0.00**
Failure	**0.99**	**0.80**	**0.37**	**0.30**
H/h = water table height above toe / slope height				

5. CONCLUSIONS

Undisputed evidence has now confirmed that the global temperature has been increasing during the last few decades due to global warming as a result of increasing greenhouse gases. Climatic conditions predicted from worldwide global warming will involve new precipitation and wind conditions. These will significantly affect the amount and type of vegetation, groundwater levels and surface water levels. All these factors will affect the stability of certain natural slopes due to losses of soil suction, higher groundwater tables, increases in seepage velocities, frequent occurrences of rapid drawdown conditions, losses of soil reinforcement contributed by roots and losses of stabilizing materials through erosion from flooding.

A review of potential global warming impacts on natural slopes has been carried out. The impacts are significant and will result primarily from effects related indirectly to increasing runoff and infiltration as well as loss of vegetation. With a sound understanding of these mechanisms, landslide prone areas can be assessed with respect to the potential of global warming impacts.

The frequency of landslides is increasing and will continue to increase. There are many natural slopes standing steeper than the angle of repose of the soil. It is the right time for introducing national, regional and global landslide hazard and risk maps (various mapping projects are currently underway, for example Baron et. al. 2007; Quinn et. al. 2007) and assessing the impact on these natural slopes due to global warming. Based on the foregoing analyses, natural slopes that are above/below areas of development or can impact water courses upstream of development, can present an increased risk to impacts from climate change. In particular, the following slopes can generally be considered as high risk:

1. Steep slopes in sandy or silty soil. These are subject to shallow slides during heavy rainfall, also if the vegetation is lost.
2. Slopes in clay soils: If the temperature changes from temperate to arid conditions, these slopes desiccate, increasing the water infiltration and are subject to shallow sliding.
3. Slopes with sparse vegetation: This is an indicator that even small climate changes can result in vegetation loss with the accompanied shallow sliding.
4. Permeable sloping terrain (e.g. sandy soil, weathered bedrock) with uphill areas susceptible to water ponding. Increased precipitation can raise water tables within these slopes, resulting in deep and extensive landslides. This can also reactivate large historic slides.
5. Slopes in silt or clay soil deposited with permeable interbeds. The permeable interbeds are highly susceptible to extensive slides from increased water pressures caused by small changes in uphill infiltration.
6. Slopes susceptible to erosion from a water course at the toe. As stabilizing toe support is lost as a result of higher flows and flood levels, the resulting landslide can temporarily dam a river with disastrous downstream consequences when water breaks through the dam. Furthermore, slopes in some soils (eg. highly sensitive marine clay) can regress for great distances behind the original slope.

Once landslide prone terrain has been mapped, then the potential risks can be assessed, and the need for pre-emptive action assessed.

Due to the extensive impacts of climate change on natural landslide hazards, remedial approaches need to differ radically from historical methods. The latter have generally been developed as localized site specific solutions through careful site characterization and application of civil engineering principals for stabilization (e.g. Cornforth, 2005). Solutions typically include slope flattening, slope drainage, soil replacement, various structural retaining systems and reinforcement. The science has advanced reasonably well so that sites can be stabilized with a high degree of confidence in the prediction of performance. Associated costs are high, but can be justified by the high economic return for investors.

The approach to large scale solutions for new natural hazards as a result of climate change needs to be completely different. Firstly, accurate quantification of sub-surface conditions to the traditional level of accuracy cannot be justified, for example with deep boreholes on a 50 m spacing over many kilometres of mountain slope above or below a rural road or village. Secondly, a heavy civil engineering solution such as slope flattening, tied back retaining walls or sheet piles are too costly. Thirdly, there may well not be any direct short term economic return to justify an investment in a solution. Some recent approaches that have a potential for application to such problems include the following:

- The observational approach based on predetermined setbacks for regressing slopes (e.g. Fabius *et al.*, 2004; Cruden *et al.*. 1989).
- The observational approach based on rapid warning systems applying real time monitoring systems through the use of new ‘high-tech’ technologies (e.g. Baum, 2007)
- Simple ‘low-tech’ and low cost ground reinforcement systems, such as steel inclusions installed rapidly, without drilling or grouting, and that can be applied surgically on an as required basis (e.g. Fabius *et al.*, 2008; Short and Collins, 2006).
- Legislative approaches to strengthen and expand existing restrictions on development in landslide-prone terrain.

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