Geotechnical approaches to climate change adaptation

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Abstract

Several signs indicate an ongoing global warming and scenarios show that the warming will continue. According to climate change scenarios the annual temperature in Sweden will increase by 2.5–4.5°C in the next century. In most of Sweden the annual precipitation will increase by 5–30% in the next century. The expected sea level increase is ca 1–2 mm/year. In the south of Sweden this will result in an increased coastal sea level of approximately 0.5 m in less than 100 years. Erosion along coastal areas will increase due to changes in the sea water level, storm-waves and by wind itself. Erosion in open watercourse areas will increase due to increased water flows.

Rough calculations have been done, as a first estimate, of the impact of increased precipitation on hillside slide risks. Reduced safety, for all types of hillsides included in this investigation, is to be expected. Additional risks such as the higher frequency of mudflows due to increased precipitation are expected.

Along rivers there is often industrial activity and contaminated ground due to historical industrial activities. Increased ground water levels will make many of the soil pollutants more movable and possibly more biologically available. The leaching of eutrophic species from farming will increase due to increased water flows, especially under heavy rainfalls. An important influence of the increased precipitation is the leaching conditions of landfills. Simplistic predictions show that the percolation and thereby the leaching of pollutants will increase.
Keywords: climate change, Sweden, increase in precipitation, erosion, slope stability, risks.

1 Introduction

Several signs indicate an ongoing global warming and most likely the main cause is anthropogenic emissions of green house gases, e.g. [1–3]. Global

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scenarios show that the warming will continue at least the nearest 50 to 100 years, e.g. [1, 4]. According to climate change scenarios the temperature increase will be most pronounced in the arctic area and areas of cool temperate climate [1, 4]. Based on global climate change scenarios, ECHAM4/OPYC3 and SRES B2 IPCC emission scenario, climate change in Sweden until 2100 has been simulated by RCA3 at Rossby Centre [4]. According to those scenarios the annual temperature n Sweden will increase by 2.5–4.5°C the nearest century. The change will be most pronounced in winter with shorter periods of snow and ice as well as shorter periods with frost in the ground. The climate borders will move north. In most of Sweden the annual precipitation will increase by 5-30% the nearest century. In the Southeast, however, the annual precipitation will not change, or even on yearly average decrease compared with today. In all of Sweden, more extremes are to be expected, i.e. more frequent storms and more heavy rainfall, e.g. [1, 4].

There are well-known correlations between geotechnical conditions and climate, but there are, to our knowledge, no studies where for example the relationship between slope stability (landslides and avalanches) and the influence of increase in precipitation or more extreme rain fall is quantitatively described for Northern European conditions. In Sweden, SGI has just initiated a study to investigate if the climate change will lead to an increase in natural hazards and accidents such as erosion and landslides and it may significantly affect the mobility and movement pattern of contaminants in soil and groundwater. The study is based on literature survey and some rough predictions. The results have been presented in Hultén et al. [5], Rankka and Rydell [6], Nilsson et al. [7], to the Swedish Government [8, 9] and a summary is presented here.

2 Impact on erosion and inundation, landslides and contaminated soil

2.1 Erosion and inundation

In Europe the frequency of inundation and flooding has increased the last years, e.g. [2, 3]. This has also been observed in Sweden. SGI has noticed the increase by an increased demand of acute expertise in connection with heavy rain episodes. During 2000 and 2004 nine acute actions where taken, while during 1996–1999, there where two or possibly three corresponding occasions.

Increase in precipitation will cause increased water flow, run off and increased ground water levels. Increased water flow of ground water and increased run off may cause erosion in watercourse areas. Most sensitive are steep sand and silt slopes and the probability of erosion is increased if the rain follows a draught period. Estimates, based on the regional climate change scenarios, show that there will be increased water flows especially in autumn and winter, while the spring water flows will be reduced apart from the very north of Sweden [10]. The erosion may be compensated by increased vegetation.

Erosion along coastal areas may be caused by changes in the sea water level, storm-waves and by wind it self. Situations with high water levels and strong winds are the most erosion sensitive. According to climate scenarios the sea level, the intensity of precipitation and the number of storm occasions, as the wind speed during those, will increase. The expected sea level increase is ca 1–2 mm/year [11]. In the south of Sweden this will result in an increased coastal sea level of approximately 0.5 m in less than 100 years [12]. Due to the parallel ongoing land lift the sea level increase will gradually be reduced going north and there will be no net effect by the north coast of the Baltic Sea.

The water level increase in the coastal southern parts of Sweden will result in material movements to deeper waters from the coastline. Rough calculations for Falsterbonäset, located at the very south coastline (i.e. the southwester corner) of Sweden, using Bruuns law have shown that a sea level increase of 0.5 m will result in a coastal inland movement of 50 m with local variations [13]. Occasions with a temporary coastal sea level rise of +1.0 m occurs approximately every 4th year and of +1.5 m occurs approximately every 60 year based on todays and previous climate. Assuming a sea level increase of 0.5 m, [13], due to climate change the temporary increase of +1.5 m compared to today instead may occur every 4th year and +2.0 m every 60 year. An analysis conducted for the Falsterbonäset peninsula by Blomgren and Hansson [14] show that at a temporary increase of +1.5 m and +2.0 m will result in that of the built up area 18% and 42% respectively will be flooded, Figure 1.

A B C

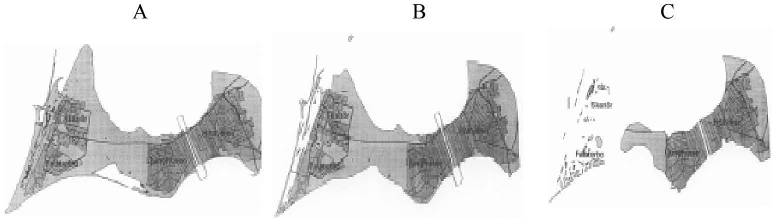

Figure 1: Falsterbonäset, from Hansson and Larson [13]. A: Normal sea level, today's climate. B: Sea level increase +1.0 m above normal sea level today. C: Sea level increase +2.0 m above normal sea level today.

Further, more detailed, risk assessment of erosion need an increased understanding based on new research to be able to develop models and other tools and methods for quantitative estimates of erosion under various conditions including geological, hydrological and climatogological factors. Up to now the most pronounced erosion areas are the south coastal areas and based on today's knowledge there is a potential risk for increased erosion in most parts of Sweden.

2.2 Slope stability

The hillside stability, i.e. the measure of the margin to when the hillside can be regarded as safe towards landslides, depends on the slope and the soil properties. The soil properties depend on the grain size, the water content, and the ion concentrations in the pore water and the pore gases. The relationship between the total soil stress, σ_0, the stress carried by the soil skeleton, σ'_0 (effective stress), and the pore water pressure, u, is described by below equation (1).

$$\sigma_o = \sigma'_o + u \qquad (1)$$

The shear strength of the soil is by traditions split in drained shear strength and undrained shear strength. When the shear strain deformation is that fast that there is not time for water to disappear prior fracture it is mentioned undrained fracture and undrained shear strength. The undrained shear strength in fine soils, cohesive soils, is considered to be constant and independent on the effective stress. The undrained shear strength normally is the dimensioning parameter in hillsides of cohesive soils. When the shear strain deformation is slow and the pore pressure changes will be compensated and equalised prior fracture, it is mentioned drained fracture and drained shear strength. The drained shear strength is the dimensioning parameter in non-cohesive soil and for the long-term stability also in hillsides of cohesive soils. The drained shear strength, τfd, depends on the effective stress, σ'_o, the angle of friction, φ', and a parameter denoted the cohesive intercept, c', as given in equation (2).

$$\tau fd = c' + \sigma'_o \cdot \tan \varphi' \qquad (2)$$

According to the relations described by equation (1) and (2), an increase in the water content will result in a decrease in the stress carried by the soil skeleton due to reduced particle contact pressure within the soil. The drained shear strength thereby is reduced and the stability of the soil may decrease [15].

Precipitation influences the ground water level. A recent study by the Swedish Geological Survey (SGU) [16] was conducted at three SGU stations in the Gothenburg region: Station 52:8 Kungsbacka (closed aquifer, moraine), 53:11 Kungälv (closed aquifer, clay), 54:10 Lerum (open aquifer, moraine). The stations have been running since 1971. During 1998–2002, the precipitation during September to April was 40% higher than normal. According to this SGU investigation the 40% precipitation increase resulted in groundwater level increases of 0–0.9 m varying between the stations. The groundwater variation has a direct impact on the pore pressure fluctuations. There are, to our knowledge, no studies quantitatively showing the relations between precipitation and risks for slides under geological conditions as in Scandinavia. There is, however, large uncertainty to what extent and the impact time scale of different types of rainfalls in different soils. There are some studies which have shown that the longer continuos precipitation period the larger the risk for land slides and the lower the soil permeability the longer time before the impact on the soil stability may be observed [17].

Here some first attempts to investigate possible impact of increased precipitation on slope stability have been investigated. The investigation is based on tests and sensitivity analysis using methods developed for previous and present climatological conditions. The investigation is further based on a scenario where the groundwater level may rise 1 m due to increased precipitation. According to the study by SGU this may be realistic for a precipitation increase $\geq$ 40%, which also may occur under present climatological conditions [16]. The assumption has been tested for different conditions described in Table 1 and Figure 2.

The hillside slope stability depends on several factors. These are factors such as the height of the hillside, the slope, the load and the strength of the soil, the groundwater level, and the pore pressures. Also other factors such as any loads and stress from buildings or other constructions, erosion by the base of the hillside and the water level in an adjacent watercourse such as a river.

To describe the slope stability a safety factor is used. The safety factor F, is defined as the ratio between the shear strength on average along an assumed gliding surface, τ_f, and corresponding mobilised shear strength, τ_{mob}, equation (3).

$$F = \tau_f / \tau_{mob} \tag{3}$$

A hillside where the safety factor is > 1 is considered save regarding landslides. The larger the value of F the safer the hillside, and the larger the margin to when the slope is regarded high possibility for slides to occur. A hillside with a safety factor ≤1 is considered not to be stable, i.e. the possibility for a landslide to occur is large.

2.2.1 Results of calculated slope stability

The changes in safety factors for the different case studies, due to the changes described in Table 1, are shown in Table 2. As can be seen from Table 2 increased precipitation will lead to a reduced calculated safety factor for all types of hillsides in this investigation.

In addition to the calculations of safety factors conducted here, showing increased possibilities or lower margins for slides to occur, there are additional risks connected with increased precipitation in valleys and river areas. Among those are higher frequency of mudflows are to be expected due to the increase in precipitation and water flows. Also in quick clay areas, and where erosion and slides are likely to increase due to climate change, the extension and consequences will be even larger than obvious from calculated safety factor and the initial slide itself, e.g. [18, 19, 20]. Quick clay is a soil that behaves like a liquid after disturbance, and it is common in the western parts of Sweden. In those areas prevention of inundation, erosion and landslides is of great importance.

2.3 Contaminated soil

Along rivers and other open watercourses there are often industrial activity and contaminated ground due to historical industrial activities. Climatic changes may cause a changed behaviour of the pollutants. Temperature and hydrological changes may alter the vegetation and the biological and chemical processes in the soil. Increased ground water levels and increased water flows as well as the increased risks of natural hazards such as inundation and landslides may result in the pollutants becoming more biologically available and also reach larger areas. Increased ground water levels, either during longer periods due to general precipitation increase or occasionally due to heavy rainfall, will make many of the soil pollutants more movable and possibly more biologically available. The leaching of eutrophic species from farming will increase due to increased water flows, especially under heavy rainfalls.

Table 1: Case studies to investigate possible impacts of increased precipitation in Sweden.

Case	Geological conditions	Change in conditions	Slope
1:1	Clay hillside slope above friction soil layer. Common in middle and west Sweden. The hillside slopes towards open water (river).	Change (increase) in groundwater level (1m). The river water level is assumed to increase 0.5 m.	1:3
1:2	Clay hillside slope above friction soil layer. The hillside slopes towards open water (river). Common in middle and west Sweden	Change (increase) in groundwater level (1 m).	1:3
1:3	Clay hillside slope above friction soil layer. The hillside slopes towards open water (river). Common in middle and west Sweden	Change (increase) in groundwater level (1 m). Erosion in the hillside base.	1:3
2:1	Clay hillside slope above friction soil layer. A layer of friction soil is embedded in the clay layer. The hillside slopes towards open water (river). Common in west and middle Sweden	Change (increase) in groundwater level (1 m). The river water level is assumed to increase 0.5 m.	1:3
2:2	Clay hillside slope above friction soil layer. A layer of friction soil is embedded in the clay layer. The hillside slopes towards open water (river). Common in west and middle Sweden	Increase in groundwater level (1 m). The river water level is assumed to increase 0.5 m. Build up of artesian pressure in the friction layer. Common initial state of rain period, prior equalised pressure in the whole soil profile.	1:3
2:3	Clay hillside slope above friction soil layer. A layer of friction soil is embedded in the clay layer. The hillside slopes towards open water (river). Common in west and middle Sweden	Change (increase) in groundwater level (1 m).	1:3
3:1 3:2	Clay hillside slope above friction soil layer. A layer of friction soil is embedded in the clay layer. Common in areas nearby solid rock.	Change (increase) in groundwater level (1 m). With and without build up of artesian pressure in the friction layer.	1:8
4	Hillside of sand and silt above a layer of silt clay. The hillside slopes towards open water (river). Common in north Sweden	Change (increase) in groundwater level (1 m). The river water level is assumed to increase 0.5 m.	1:1.1
5:1	Steep hillside in valley with several layers. See Figure 2, based on Krokvåg, North of Sweden [21, 22].	Change (increase) in groundwater level (1 m). The river water level is assumed to increase 0.5 m.	See Figure 2
5:2	Steep hillside in valley with several layers. See Figure 2, based on Krokvåg, North of Sweden [21, 22].	Increase in groundwater level (1 m). The river water level is assumed to increase 0.5 m. Increased erosion up to 1.0 m by the hillside base.	See Figure 2

An important influence of increased precipitation is the leaching conditions of landfills. The dimensions of the landfills are based on European guidelines. The guidelines are based on acceptable leaching. The landfills in Sweden are constructed according to those guidelines, but based on the climate today. Simplistic calculations have been done for a selection of landfill types in Sweden today. The results from those calculations show that the percolation and thereby the leaching pollutants as well as the evaporation from landfills will increase, and it is possible the percolation will be higher than the European and national guideline values. Further simulations are needed to investigate the size of the problem.

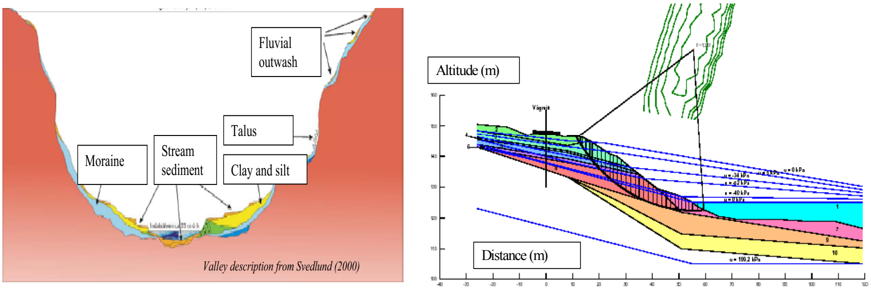

Figure 2: Hillside, North of Sweden, Krokvåg. Top layer silty sand, leaning on silt and clay and the bottom layer is sand silt. This layer order is very common for river valleys in the northern parts of Sweden [22]. The groundwater level today is 2 m below the surface. The pore water pressures are based on measurements [21].

Table 2: Calculated change of slope stability.

Case	Calculated safety factor, F, today.	Calculated safety factor, Fs, due to changed conditions
1:1	1.25	1.22 (i.e. not significant)
1:2	1.25	1.09 (13% reduced risk margin)
1:3	1.25	0.97 (19% reduced risk margin, the hillside can not be regarded safe)
2:1	Top 1:3 Middle 1.27 Base 1.19	0.99 (20% reduced risk margin, the hillside can not be regarded safe)
2:2	Top 1:3 Middle 1.27 Base 1.19	1.2 (8% reduced risk margin) Longer precipitation period will result in increased pressure in the top layer of the soil, thereby further reducing the safety factor.
2:3	Top 1:3 Middle 1.27 Base 1.19	Top 1.03 Slope base 0.8 (30% reduced risk margin, the hillside can not be regarded safe).
3:1 3:2	1.35	1.31 and 1.33 dependent on artesian pressures, but no significant changes. The impact may be more pronounced due to local conditions such as clay type.
4	1.03	0.88 (15% reduced risk margin). The hillside cannot be regarded safe. Increased water flow will cause erosion, which further reduces the safety factor.
5:1	1.21	1.03 The hillside can not be regarded safe
5:2	1.21	0.98 The hillside can not be regarded safe Increased precipitation results in ground water level near the surface. The surface water runoff thereby will increase, which combined with increased flow and percolation in the permeable layers, will cause increased hillside erosion.

3 Main results and discussion

Increased water flow of both surface and ground water, as a consequence of intensive precipitation, may cause erosion in watercourse areas. Most sensitive are steep, sandy and silty slopes, and the probability of erosion is increased if the rain follows a draught period. Increased precipitation and increased ground water level leads to increased risks for landslides.

For all cases investigated here, the safety factor will be reduced due to increased precipitation. The magnitude of the change is larger the more intensive rainfall. The magnitude of the change is also increased if there are large water flows causing erosion by the hillside base. On the other hand, the magnitude of the change is reduced if the water level in the river, or other open water by the bottom of the hillside slope, increases simultaneously as the groundwater level. Hillsides that today can be regarded as safe may not be able to regard as stable in some decades due to increased precipitation. Most sensitive are those hillsides where the safety factor (F) is just above one where only small changes in precipitation F will become <1. Many hillsides have been formed naturally by erosion and other processes and the processes have stopped when the hillside is just on the limit of being stable, i.e. when F≈1. The probability for landslides will increase in many parts of Sweden and according to the results presented here it will increase also in areas where slides are common already today.

The calculated safety factors may increase by up to 30% in some of the cases investigated here. This means that also in built up areas, where the recommended safety factor is 1.35 [23], the safety factor will be near or maybe even less than one under some conditions. In addition, an increase in precipitation by 30% on average may result in occasions with much higher rainfall during shorter periods as more extreme weather situations are to be expected [2–4]. Further studies, local to regional climate scenarios, will be done to investigate the frequency and the type of rainfall that can be expected in Sweden the nearest decades and the nearest century. In case of more extreme rainfalls the risks for erosion and landslides are even higher. The ground evaporation will increase due to increased temperature also this may influence the soil properties in a way that has not been considered here.

The calculations and investigations presented here indicate increased possibilities for erosion and landslides in open watercourse areas in Sweden. By tradition those areas are industrialised and several industries are still active along rivers and other open waters in Sweden. Often the open waters have been used for transportation and today there often run parallel main roads and railways. These areas also are, with Swedish measures, densely populated. Due to the locations of those main communication systems other activities are situated along rivers which are sensitive to erosion and landslides. The expected climatic changes the nearest century may cause increased activities due to the climate change variation over Europe, i.e. south Europe will become much dryer and warmer, e.g. [2, 3]. Increased activities will increase the pressure on infrastructure. There is a large need to make systematic risk assessments and risk management, in Sweden to investigate where there is a demand to reduce the risks for inundation, erosion, landslides and ground pollution the nearest decades. The risks can be reduced by changes in building design, remediation and technical constructions adapted for the new hydrological conditions, land planning and the build up of organisations to handle natural hazard occasions.

Conflicts are expected in areas where there is a need, but limited, draw due to risks of erosion and slides in the lower parts of a watercourse such as a river. According to this first survey of available knowledge, simple simulations and calculations, an increase in flooding, erosion and land slides and mobility of pollutants especially in the more exploit areas is expected [5–7]. To estimate the vulnerability, further studies are needed including several aspects such as quantification of the relations between climatological, geohydrological and geotechnical properties and identification and mapping of risk areas.

In the land planning today the impact of climate change, consequently has to be taken into account in several areas including prevention of natural hazards, planning of brown field areas and dimensioning landfills among others.

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