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Impact of climate change on natural ground and geoconstructions from a geotechnical point of view

L'effet du changement climatique pour sol naturel est pour géostructures

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ABSTRACT: Climate change is expected to have serious implications for much of the infrastructure and built environment. Spatial planning needs to take greater account of changes in ground conditions and the suitability of the ground for construction. To address these challenges, the Swedish Geotechnical Institute (SGI) drew up an Action Plan for Sustainable Ground Construction (SGI, 2017) to provide a basis for a series of tangible measures, future discussions, and inter-agency collaboration within the geoconstruction sector. The Action Plan is based on a dialogue with some 200 stakeholders from more than 70 organisations, and it highlights what needs to be achieved, how it can be achieved, and suggestions about who can assume responsibility. However, working on the Action Plan also revealed a need for a more detailed description, based on future climate scenarios, of how different geoconstructions are affected geotechnically by climate loads.

This paper presents the results of a synthesis report, including climate change in Sweden, which covers temperature, precipitation and wind changes. These climate parameters indicate that natural ground and geoconstructions are increasingly exposed to shifting load levels due to changes in groundwater level, water flow, drought, snow cover, and frost conditions. This paper presents current knowledge about future climate loads and how natural ground, substructures, superstructures, dewatering plants, ground reinforcement, support structures, and foundations could be affected. It also highlights the current lack of knowledge and proposes suggestions for future research and development.

RÉSUMÉ: Le changement climatique devrait avoir de graves conséquences pour de grands secteurs de l'infrastructure et de l'environnement bâti. La planification spatiale doit prendre davantage en compte les modifications du sol et sa durabilité pour la construction. Cet article présente les résultats d'un rapport de synthèse y compris les changements climatiques en Suède, ce qui implique des changements de température, de précipitations et de vent. Ces paramètres climatiques impliquent que les sols naturels et les géconstructions sont de plus en plus exposés à des niveaux de charge changeants dus aux changements du niveau des eaux souterraines, aux changements dans l'écoulement des eaux, aux changements de sécheresse, à la couverture de neige et l'action du gel. Le document présente des nouvelles connaissances sur des futures charges climatiques et sur la manière dont le sol naturel, les sous-structures et les superstructures, les instalations d'assèchement, le renforcement du sol, les structures de support et les fondations sont affectés. Il dévoile également un manque de connaissances et propose des suggestions de recherche et de développement.

Keywords: Geoconstruction; climate change; climate load; slope; foundation; substructure

1 INTRODUCTION

In Sweden, climate change is expected to result in a change in mean temperature, precipitation and water outflow. It will be necessary to adapt society in different ways to the changes that are taking place: from large-scale relocations to a variety of technical solutions and ground reinforcement measures designed to prevent damage and accidents from occurring.

Climate change will also affect ground conditions and will subsequently result in a change in the impact of climate loads on geoconstructions. A geoconstruction is defined as a supporting or bearing construction that consists of soil or rock or is dependent on the surrounding soil or rock. Geoconstructions could include ground substructures and superstructures, dewatering plants, support structures, spread footing, and pile foundations. Climate loads include water level, stream flow, wind, pore pressure, temperature, and snow cover.

The purpose of the work described here (Lundström et al. 2018) was to:

- Present factors that contribute to climate loads that are relevant to natural ground and geoconstructions and how they are expected to change
- Present ways in which climate loads are described in current regulations
- List the ways in which climate loads impact on natural ground and geoconstructions
- Describe the need for further knowledge and research, focusing on the design of geoconstructions and with the ultimate aim of evaluating the consequences for existing geoconstructions

The content of this work is derived from and concretised using the Action Plan for Sustainable Ground Construction (SGI, 2017).

2 CLIMATE SCENARIOS AND CLIMATE LOADS

This paper includes a presentation of the results from climate scenario RCP 8.5, as they are considered to be related to current trends in greenhouse gas emission measurement (SMHI, 2017). The climate parameters presented are temperature, precipitation, wind, and snow cover. The changes are presented mostly as percentages by comparing the calculated scenarios for 2071-2098 to the measured results for 1961-1990.

2.1 Temperature

It is estimated that the average annual temperature through to 2071-2098 will rise for the whole country. The rise will vary from 3ºC in the south to 6ºC in the north compared to 1961-1990, see Figure 1.

These changes will be most significant during the winter. The maximum daily temperature will increase nationwide and throughout the seasons. The increase will be 0-5°C in large parts of the country.

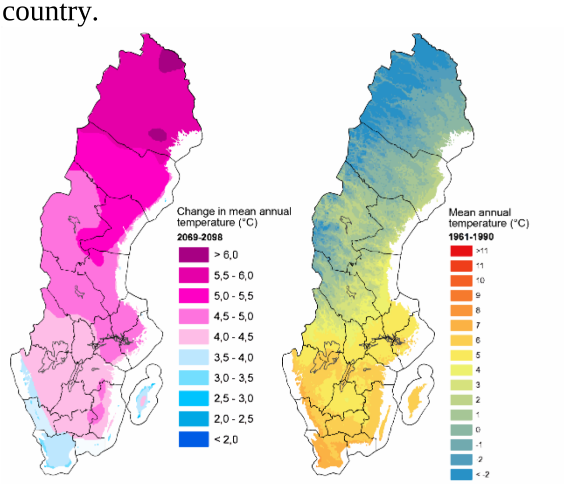

Figure 1. Change in the mean annual temperature (ºC) for the period 2016-2098 compared to 1961-1990. (From Sjökvist et al. 2015. Adapted by SGI).

2.2 Precipitation

It is estimated that annual precipitation for the whole country will increase by 10-45% through to 2069-2098 compared to 1961-1990. The largest increase, 30-35%, will be in northern Sweden, see Figure 2.

For most of the country, the maximum daily precipitation over a one-year period is expected to rise by 20-30% through to 2017-2100.

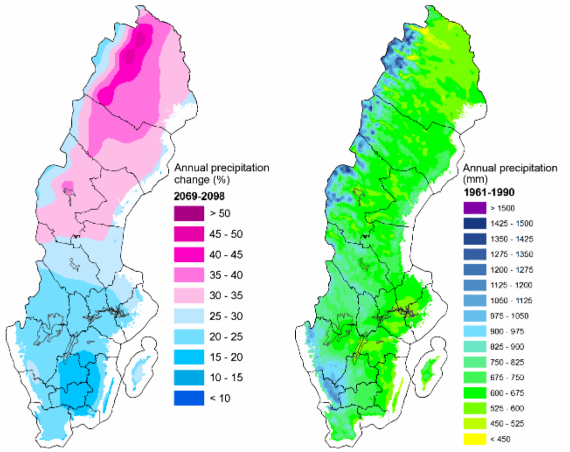

Figure 2. Change in annual precipitation (%) for the period 2069-2098 compared to 1961-1990. (From Sjökvist et al. 2015. Adapted by SGI).

There will be a nationwide increase in the number of days with heavy precipitation (10 mm or more) through to 2069-2098.

Dry periods, i.e. the number of days per year without precipitation, are expected to decrease by 2-6 days through to 2071-2100.

2.3 Water level

There is no analysis covering the whole of Sweden that shows how water levels in the rivers will change (Sjökvist 2017). In the case of regulated rivers, the water level depends on natural conditions and water management regulations.

The sea level depends on postglacial land uplift. The uplift varies from 8 mm per year along the northern coast, down to almost 0 mm per year in the south. Climate change will lead to a more rapid rise in sea level. If land uplift is taken into account, the rise in sea level in 100 years' time will vary – from 0.1-0.2 m along the northern coast to 0.8-1.0 m in the south (Eklund et al. 2015).

Changes in the water level in lakes through to 2100 have been calculated for the three largest lakes in Sweden: Vänern, Vättern and Hjälmaren (Eklund et al. 2017c). It has been calculated that low water levels in these lakes will be more common. For Vänern, the maximum water level will rise by about 0.3 m and high water levels will be more frequent.

2.4 Stream flow

It is estimated that through to 2069-2098, 100-year stream flows will increase by 15-35% in southern Sweden, along the southern coast of northern Sweden, and in the northwest. The northwestern parts of central Sweden, the northern inland area, and the northernmost coastal area normally have the highest stream flows in the spring due to snow melt. An expected decrease in stream flows in these areas during the spring will result in 100-year stream flows falling by 10-35%.

2.5 Water pressure, stream flow, stream velocity, stream pressure, ice pressure

The impact of temperature, precipitation, evaporation and wind on climate is reflected in the form of stream flow, water level, and wave force. More rapid stream flow will result in a higher stream velocity in the parts of a river where inundation cannot occur. This will lead to a rise in stream pressure. More rapid stream flow may also result in a rise in the water level in streams and rivers.

With an increase in low stream flow frequency, the lowest water level could fall even further. This applies most to unregulated rivers.

There is currently no forecast of a change in ice thickness.

2.6 Groundwater level, pore pressure and groundwater flow

The Geological Survey of Sweden (SGU) has conducted a study of changes in groundwater levels in open groundwater basins. The study was based on 30 monitoring wells (Vikberg et al. 2015). The results show that higher groundwater levels can be expected in the north of Sweden, while in central and western parts they are expected to remain unchanged. In southern and eastern parts, groundwater levels are expected to fall.

If the groundwater level rises in stratified soils, it can be assumed that groundwater flow will increase. No analyses are currently available of how pore pressure levels will change.

2.7 Zero crossings

A ‘zero crossing’ is defined as the number of days when the temperature is both below and above 0°C. It is estimated that as we approach 2071-2098 the number of zero crossings will increase significantly in central areas and to the north (Strandberg et al. 2014). In contrast, the number in the south will decrease.

2.8 Snow cover

It has been calculated that the number of days with snow cover will fall throughout the whole of the country (Sjökvist et al. 2015). The fall will be most significant along the northern coast, in inland areas, and in the southern part of the northern mountain range (Scandes). The maximum thickness of the snow cover will fall throughout most of the country with the exception of the northern part of the Scandes. Consequently, the snow load will probably also fall. Changes in humidity could affect the density of the snow cover and with that the snow load.

3 HOW CLIMATE LOADS ARE TAKEN INTO CONSIDERATION IN CURRENT GEOTECHNICAL REGULATIONS

When designing geoconstructions, climate loads such as snow load, wind load and water pressure, must be taken into consideration. The designs must take account of the “ultimate limit state” (ULS) and the “serviceability limit state” (SLS) according to Eurocodes. For certain climate loads, i.e. surface water and groundwater pressure, there is no exact value. Measurements and statistical analyses must be carried out to determine these parameters. Climate parameters include precipitation, temperature and wind. According to norm SS-EN 1990, loads must be classified according to their duration. With the exception of surface water and groundwater, climate loads are considered to be variable. Free water and groundwater can be regarded as being permanent, variable, or a combination. In SS-EN 1990, characteristic values are obtained using a probability of 0.02 (recurrence interval of 50 years). The characteristic values are obtained from measurement of e.g. precipitation, stream flow, and water level at more than 150 locations throughout the country. Examples of normative documents and design values for different climate loads are given below.

3.1 Water level and stream flow

Water level and stream flow are not described in Eurocodes or in the Swedish National Board of Housing Building and Planning (SNBHBP) construction rules and regulations in any detail other than stating that they must be taken into consideration (SNBHBP, 2016). The Swedish Transport Administration (STA) has formulated a number of rules regarding climate parameters. These are included in design documents for roads, railways and bridges. The parameters must be calculated with maximum and minimum values with a recurrence interval of 50-200 years (depending on the parameter) and are based on statistical data.

To facilitate the design of erosion protection in streams and rivers, recommendations are provided by SRA (SRA 1987) and the Commission on Slope Stability (Commission on Slope Stability 1995). In the case of protection against coastal erosion, the recommendations issued by the US Army Corps of Engineers are used (US Army Corps of Engineers 1989).

Design rules and recommendations with due account taken of climate change have not yet been developed for road and bridge design. In the case of dewatering plants, a climate factor of 1.2-1.25 is given.

3.2 Groundwater level and pore pressure

With regard to groundwater level and pore pressure, there are no rules in Eurocodes other than that groundwater parameters must be taken into consideration, and that characteristic values must be measured or estimated at the upper and lower levels. No further rules have been issued by SNBHBP.

According to the SRA regulations (SRA 2013, 2014) groundwater level and pore pressure forecasts must be based on observation points for each specific project. These values are then compared with values from nearby reference wells, provided by SGU with long measurement series, to obtain the 50-year value for that point.

There are no indications in any of these normative documents of how changes in groundwater level and pore pressure caused by future climate change must be taken into consideration.

3.3 Zero crossings and snow cover

Roads, railways and buildings are designed with account taken of frost heave and frost depth based on historical observations of freezing degree days. The term ‘freezing degree days’ is defined as the total number of days per winter season the temperature is below 0°C.

In the case of railway design, the design values are provided by the Swedish Rail Administration (2003[1]). In the case of road design, the design values are provided by the Swedish Transport Administration (2011). No advice or instructions are available about how changes in temperature and snow cover should be taken into account in terms of frost heave and frost depth. Neither is there any advice available on how maps showing freezing degree days and climate zones should be updated.

4 EXPECTED IMPACT ON NATURAL GROUND AND GEOCONSTRUCTIONS

Based on climate scenarios through to 2100, the expected impact of changes in climate loads on different geoconstructions is presented below. The descriptions are conceptual as the impact on natural ground and geoconstructions depends on the magnitude of the changes in climate load .

4.1 Natural ground

4.1.1 Flat ground

An increase in annual precipitation and number of days with intense precipitation means that water will accumulate more easily. The possibility of infiltration of a higher volume of water is less in areas with a large proportion of paved surfaces.

4.1.2 Natural and engineered slopes

An increase in annual precipitation and number of days with intense precipitation will lead to increased runoff on slopes. In those places where the vegetation cover is thin or absent, this will lead to intensified erosion in erosion-sensitive soils such as silt and sand. The probability of mudflows and landslides in silt, sand and till will rise.

Greater inflow into streams and rivers will lead to higher stream flow in rivers, which will intensify riverbed and shoreline erosion. This will lead to a greater probability of landslides along watercourses in all types of soil. The biggest increase in inflow is expected in southern

[1] The former Swedish Rail Administration and Swedish Road Administration were replaced in 2010 by the Swedish Transport Administration.

Sweden and along the northern coast. Watercourses in the south will have several days of low water flow, which will reduce the resisting force of water on the slope.

In frost-lifting soils such as silt, an increase in the number of zero crossings in the north will lead to accumulation of shallow water, which will in turn lead to loosening of the upper part of the soil profile. This will result in reduced soil strength and a greater probability of landslides.

A possible increase in frost depth, in combination with an increase in precipitation, may lead to a rise in the number of shallow landslides. Precipitation on partly thawed ground results in saturation in the upper part of the soil, leading to a decrease in effective stresses and a consequent decrease in resistance to movement.

4.1.3 Coastal areas

It is mainly the coastal areas in southern Sweden that will be affected by rising sea levels. The shoreline will be affected by increased erosion and inundations. Along with landslides, these phenomena will affect buildings and infrastructure. Existing erosion protection and flood walls are not designed to cope with rising sea levels, as they have not been built sufficiently high. Erosion protection often takes the form of hard structures that cannot be adapted to changing climate conditions.

4.2 Superstructure and substructure

Higher precipitation levels mean that existing superstructures and substructures built using fine-grained material high up in the structure will have a higher water content. This will also be the case for low-lying roads and railways. A higher water content leads to an increased probability of deformation due to traffic load and damage to surface layers, as well as a growing need for maintenance and dewatering measures.

Embankments consisting of fine-grained material, which are quite common in central and northern parts of Sweden, will be negatively affected by higher surface water and groundwater levels. Higher groundwater levels lead to a reduction in the strength of the natural soil, thus increasing the probability of landslides. In addition, internal erosion (piping) can occur when flowing water transports fine-grained material from the embankment. This could lead to the formation of cavities, followed by land settlement and embankment slides.

For roads, railways and other land facilities located close to watercourses, increased water flow, stream pressure and ice pressure lead to a greater probability of erosion of embankment slopes along the watercourses. Facilities located close to the coast in southern Sweden could be affected by a rise in the sea level, leading to increased erosion and more landslides and inundations.

A rise in temperature and a fall in the number of days with snow cover could lead to a reduction in frost depth, which could in turn lead to a reduction in frost heave. However, the frost depth applied in Swedish railway regulations is dependent on the snow cover, making it difficult to estimate the consequences of a rise in temperature. A combination of reduced snow cover and a rise in the number of zero crossings could also lead to an increase in frost depth and increased loosening of substructure layers high up in the embankment (close to the surface), thus lowering the bearing strength of roads and railways.

4.3 Culverts, drainage systems and ditches

A rise in precipitation and the number of days with intense precipitation mean that the capacity of culverts would not be sufficient for the water to pass through them. This may lead to washout of culverts and road/railway embankments. Higher water flows upstream may lead to erosion and debris flows that could cause clogging when they reach the culverts. A clogged culvert results in inundations, forcing the water to find new paths.

An increase in precipitation and higher groundwater levels will lead to higher water flows in drainage systems and ditches. The resulting rise in water level in the facility will exert greater pressure on the construction.

4.4 Foundations

4.4.1 General

Higher water levels will affect buildings close to watercourses, lakes and the sea, increasing the probability of leakage into the buildings. This is also the case for concrete tunnels and similar constructions located below the ground surface. Constructions exposed to uplift due to surface water or groundwater will be affected by greater uplift forces in the event of higher surface water and groundwater levels. A higher water flow close to constructions that are in or adjacent to surface water or groundwater will affect erosion around the foundation and increase the probability of construction damage or washout.

4.4.2 Piled foundations

In the case of piled foundations, lower groundwater levels may lead to settlement in the soil around the piles, which would raise the load on the sides of the piles. The safety of the construction would thus be impaired, and for floating piles it would increase the probability of building subsidence. Lower groundwater levels would also increase the probability of wooden piles rotting. Close to constructions built on piles, lower groundwater levels lead to settlement of the surrounding land, which in turn leads to differential settlement in the connections between land and buildings and between pipes and buildings. Lower groundwater levels are expected in south-east Sweden.

4.4.3 Spread footings

Higher groundwater levels lead to a decrease in soil strength, which leads to a reduced margin of safety with regard to the bearing capacity of bridges and buildings founded on spread footings. It is in the north that groundwater levels are expected to rise.

Lower groundwater levels, which are expected in the south-east, could lead to damage to buildings or underground constructions due to subsidence.

4.4.4 Ground reinforcements

The impact of climate change on ground reinforcements is exemplified below by the effects on lightweight fill materials. A rise in annual precipitation and maximum daily precipitation would lead to an increase in the water content of lightweight fill materials, such as lightweight expanded clay and foam glass aggregate. A higher water content could also occur due to higher groundwater and surface water levels.

A higher water content could lead to a greater risk of deformation in the embankment caused by traffic load and damage to the surface layer. The inner stability of the embankment could also be affected.

The probability of uplift of the lightweight fill material would increase due to higher groundwater levels and is most critical for plastic foam.

4.4.5 Support structures

Support structures are affected by a rise in precipitation and a change in water level. It has not been fully determined how groundwater or pore pressure levels would alter due to climate change. With higher precipitation levels, more water will percolate towards the retaining wall or sheet pile wall. It is predicted that the increase in the number of days without snow cover will contribute to this effect.

Retaining walls are generally not waterproof and are therefore built with a drainage system. If the drainage system is insufficient, the pressure exerted by stationary water on the wall would increase. This may lead to unwanted deformation of the wall. Sheet pile walls are generally designed to cope with stationary water pressure. The biggest increase in annual precipitation is expected in northern Sweden.

The increase in the number of zero crossings, mainly in the central areas of the country and further north, may lead to frost heave, which could lead to a brick or concrete retaining wall cracking, resulting in unwanted deformations. Sheet steel pile walls are less sensitive to frost heave.

Higher groundwater levels reduce effective stresses in frictional soils and silts and hence the shear strength of the soil. The stability of the wall may therefore fall below the stability level required for the purpose for which it was originally designed.

More rapid stream flow, stream pressure, wave force and ice pressure will have a negative impact on support structures located within or adjacent to water, and with a subsequent increased risk of damage to constructions.

5 CONCLUSIONS

The review of the expected impact of climate change in Sweden for 2100 – based on scenario RCP 8.5 – on different types of geoconstructions and natural ground, indicates that slopes, superstructures and substructures are the types of geoconstructions where significant impact can be expected.

Knowledge of a change in some of the above-mentioned climate loads is lacking. Generally, it can be said that there is an absence of recommendations about how changes in climate loads can be taken into account. The highest priority should therefore be given to a specification of future climate e loads, partly in relation to the design of new constructions and partly to facilitate evaluation of the consequences for existing constructions.

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