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Instabilities in alpine permafrost: strength and stiffness in a warming regime

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Foreword

Global climate change is contributing to hazards to infrastructure in cold regions, as engineers try to quantify uncertainties through a risk-based consideration of sensitivity and consequences, and thereby to mitigate the risks arising from permafrost degradation. A gradually rising Mean Annual Air Temperature, combined with more extreme rainfall conditions and fewer 'freezing degree days', mean that the water phase in soil that has been frozen for many years in the form of permafrost, is likely to thaw and release groundwater into the voids. Since the properties of warm permafrost can change significantly as its temperature rises, climate change can affect not only the thickness of the active layer and the depth of permanently frozen ground, but also the constitutive behaviour of the permafrost layer. This has significance not only for movements and stability in permafrost slopes but also in rock glaciers, which are ice-rich geomorphological landforms. Furthermore, permafrost degradation is causing changes in land surface characteristics and drainage systems, as warming of rock glaciers leads to accelerated creep. Instabilities may also be triggered as the constitutive properties of permafrot change, either in the form of active layer detachments or at depth through the warming permafrost. Catastrophic debris flows may also occur.

Dr Yamamoto has conducted a fundamental and highly innovative experimental investigation into the effect of time and temperature on the creep and shear strength properties of analogue alpine permafrost, under a range of stress conditions that would be experienced in different locations of a rock glacier. She has developed new equipment to maintain the temperature in the frozen soil specimens at ±0.03°C in the previously unexplored range between 0 and -0.5°C, and to record acoustic emissions during creep and shearing. Furthermore, she has carried out novel micromechanical investigations into the changes occurring in the solid, ice, air and unfrozen water mixture as a result of shearing. The results of the laboratory tests have been used to provide a deeper insight, not only into the constitutive behaviour of frozen soils, but also a greater qualitative understanding of the geotechnical performance of rock glaciers under warming conditions.

In addition, she has extended an existing mechanical constitutive model for soils that includes both soil creep and shear behaviour to develop a semi-coupled Thermal-Hydro-Mechanical (THM) constitutive model. The model, when implemented in a finite element package, allows the laboratory element test data to be predicted, which also validates key aspects of her model rather well. This represents a significant step towards achieving quantitative predictions of the influence of temperature variation on the performance of rock glaciers.

Dr Yuko Yamamoto has made original and significant discoveries about the thermo-mechanical response of frozen soils under a range of stress path tests, by developing and using a range of state-of-the-art experimental techniques and combining these with powerful analytical and numerical methods to interpret and model behaviour of permafrost soils. Her research paves the way for future work that will lead to quantitative modelling of geomorphological process in permafrost landforms, such as the creep and stability of rock glaciers.

Prof. Dr. Sarah M. Springman CBE FREng

Acknowledgements

I would like to express my sincere gratitude to my supervisor Prof. Sarah Springman (Institute for Geotechnical Engineering IGT – ETH Zurich) for giving me the great opportunity to work on such an interesting research topic; for her guidance, encouragement, continuous support and constructive discussions throughout this research project. I learned many things from her, and they will stay with me for the rest of my life.

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I wish to express my heartfelt thanks to Dr. Lukas Arenson for all his helpful advice and the discussions we had in course of the research, based on his expertise in permafrost engineering and conducting triaxial testing on frozen soil specimens, using the same triaxial testing apparatus in IGT.

My sincere thanks are directed to Dr. Martin Schneebeli and Dr. Dénes Szabó from Institute for Snow and Avalanche Research SLF in Davos, for kindly allowing me to use their microCT device, for their support in conducting the scans, and for their advice on analysing the image data for the microstructural investigation.

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The information about the state of alpine permafrost in Switzerland was important for me in planning an effective laboratory test programme for this research. I am grateful to the network of Permafrost Monitoring Switzerland (PERMOS) for interesting discussions in their meetings, and especially to Dr. Isabelle Gärtner-Roer for her input regarding the kinematics of rock glaciers.

Special thanks go to the team of workshop and electronic staff at IGT. Adrian Zweidler designed the modifications to the existing triaxial testing apparatus, and Heinz Buschor and Alfred Ehrbar constructed the apparatus with great care. Ernst Bleiker checked the electrical setup of every laboratory testing apparatus to run the tests. Their work was essential for the successful laboratory testing in this research. I also appreciate the assistance of the laboratory team of IGT: Ralf Herzog, Marco Sperl and Anita Abt, for their contribution and advice in running the laboratory tests. I am grateful to Tomas Jaggi from the Institute of Structural Engineering, ETH, and Heinz Richner from the Institute of Structural Engineering, ETH, for providing the cutting machine for the preparation of frozen soil specimens. I would also like to thank Dr. Michael Plötze from the clay mineralogy group of IGT for his contribution to the mineralogical laboratory investigations. Dr. Erich Pimentel from IGT kindly offered me a Non-

Steady-State Probe for the measurement of thermal conductivity of frozen soil samples. I appreciate his support and advice.

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Contents

Kurzfassung

Alpiner Permafrost existiert in den höher gelegenen Gegenden der niederen Breitengrade, wie z.B. den Schweizer Alpen. Die beschleunigte Klimaveränderung, welche sich in den alpinen Regionen unter anderem durch eine jährliche steigende, durchschnittliche Lufttemperatur und das Auftreten von Extremniederschlägen äussert, führt in diesen Regionen oft zu Permafrostdegradation. Blockgletscher sind geomorphologisch gesehen spezielle Arten von alpinem Permafrost und zeichnen sich durch ihre inhomogene Struktur sowie die hangabwärts gerichteten Kriechbewegungen aus. Die Temperaturerwärmung bewirkt eine beschleunigte Kriechbewegung von Blockgletschern, aufgrund einer Zunahme des ungefrorenen Wassers und der höheren Verformbarkeit des Eises. In den letzten Jahrzehnten wurde in mehreren Blockgletschern in der Schweiz eine Entwicklung von sogenannten Vertiefungsspalten beobachtet. Die Veränderungen der Oberflächeneigenschaften und der Entwässerungssysteme bei Blockgletschern können bei diesen zu Hanginstabilitäten führen.

Das Hauptziel dieser Arbeit ist es, die Festigkeit und Steifigkeit des gefrorenen Bodenmaterials in Blockgletschern zu charakterisieren. Zu diesem Zweck wurde das geotechnische Verhalten von warmem alpinem Permafrost, wie beispielweise der Kriechprozess oder das Bruchverhalten, durch triaxiale Spannungspfadversuche mit einem neuartigen Messsystem, basierend auf Schallemissionsmessungen und der Ermittlung der volumetrischen Änderungen der künstlich gefrorenen Bodenproben, untersucht. Die gewählten Spannungspfade reflektierten die Spannungsbedingungen bezüglich Kompression und Extension in den Blockgletschern unter bzw. neben den Vertiefungsspalten. Die Versuchsbedingungen wurden so gewählt, um Parameterstudien im Hinblick auf den volumetrischen Eisgehalt, die Lastbedingungen (Dehnungsrate/Spannungsrate) und die Temperaturen durchführen zu können.

Die Analyse der axialen Kompressionsversuche ergab qualitative und quantitative Angaben über die Festigkeit und die Kriechraten bei einer Temperatur nahe dem Auftaupunkt. Das volumetrische Verhalten der gefrorenen Bodenproben zeigte sowohl Kontraktion als auch Dilatation, abhängig von der Temperatur, der Verformungsgeschwindigkeit und des volumetrischen Eisgehaltes der Proben. Die mobilisierte Deviatorspannung der triaxialen Spannungspfadversuche war abhängig von der Temperatur; d.h. eine Erhöhung der Temperatur führte zu einer Abnahme der residualen Deviatorspannung. Der Vergleich zwischen der residualen Deviatorspannung verschiedener Spannungspfadversuche zeigte, dass die axiale Extension die geringste Deviatorspannung mobilisiert.

Ergänzend zu den triaxialen Spannungspfadversuchen wurde an quaderförmigen, künstlich gefrorenen Bodenproben der Widerstand gegen Rissbildung und Rissausbreitung mittels Balkenbiegeversuchen und unter Zuhilfenahme des akustischen Emissionsmesssystems untersucht. Dabei wurden die Bruchzähigkeit und die Festigkeit beurteilt. Die Ergebnisse zeigten, dass gefrorene Böden mit niedrigem Eisgehalt und Temperaturen nahe dem Auftaupunkt anfälliger für die Entstehung und Ausbreitung von Rissen sein können als jene mit höherem Eisgehalt. Grosse Risse wurden durch die dichte Packung der Bodenkörner eingedämmt, wodurch ein duktiles Verhalten erreicht wurde.

Die Auswertung der an den künstlich gefrorenen Bodenproben durchgeführten Laborversuche deutete an, dass die Entwicklung der tiefen Spalten in den Blockgletschern durch differenzielles Kriechen und thermische Degradationraten auftritt und dass die Deformationsrate das Potenzial aufweist, um zu Instabilitäten beim Blockgletscher zu führen. Die grössten Verformungen können unterhalb der Spalten verursacht werden und führen einerseits zu einer Vertiefung der Spalte mit der Initiierung eines Bruchs, andererseits auch zur Ausweitung der Spalte. Wobei letzterer Mechanismus bei Blockgletschern ohne weitere thermische Degradation eher unwahrscheinlich ist, da die entsprechenden Spannungen nicht erreicht werden.

Das Verhalten von zylindrischen gefrorenen Bodenproben unter triaxialem Spannungspfadeinfluss wurde mittels Finite-Elemente-Simulationen untersucht. Das zeitabhängige Verhalten des gefrorenen Bodens wurde unter Berücksichtigung der thermisch-hydraulisch-mechanischen Wechselwirkungen mit den experimentell gewonnenen Daten validiert. Ein elastisch-visko-plastisches Stoffgesetz („Soft Soil Creep“-Modell; Vermeer & Neher, 1999), ursprünglich entwickelt für das Kriechverhalten von ungefrorenem Ton, wurde als Basis gewählt, um das Kriechverhalten und Scherversagen vom gefrorenen Boden zu modellieren. Die hydro-mechanische Kopplung wurde leicht modifiziert, um das Verhalten von gefrorenem Boden darzustellen und wurde weiter mit einer empirischen Beziehung zur Modellierung des thermischen Einflusses auf die Kohäsion gekoppelt. Der Vergleich der Simulationsergebnisse mit den experimentell gewonnenen Daten zeigte, dass das semi-gekoppelte Modell die wichtigsten Aspekte der temperaturabhängigen Spannungs-Dehnungs-Beziehung für den gefrorenen Boden in kleinem Massstab erfolgreich simulieren konnte.

Diese Arbeit trägt mittels experimenteller und numerischer Untersuchungen, unter Berücksichtigung der Zeit und Temperatur bei spezifischen Spannungspfaden, dazu bei, die Veränderungen des geotechnischen Verhaltens von alpinem Permafrost besser zu verstehen. Nichtsdestotrotz sind weitere Untersuchungen notwendig, um die langfristige Blockgletscherstabilität unter dem Einfluss des Klimawandels zu beurteilen.

Abstract

Alpine permafrost exists at high altitude at lower latitudes, such as in the Swiss Alps. Accelerating climate change, including rising mean annual air temperature and extreme rainfall conditions in alpine regions induces permafrost degradation. Rock glaciers are special geomorphological features in alpine permafrost and are characterised by their inhomogeneous internal structure and downslope movement due to creep in the permafrost. The warming of permafrost causes accelerated creep of rock glaciers, due to increased unfrozen water content and higher deformability of the ice phase. Recently, the development of deepening depressions has been observed in several rock glaciers in Switzerland, and the changes in land surface characteristics and drainage systems may initiate slope instabilities in rock glaciers.

The main aim of this thesis is to characterise the strength and stiffness of alpine frozen soil in rock glaciers. To this end, the geotechnical response, such as creep and failure of frozen soil was investigated through a triaxial stress path testing programme with novel measurement systems for detecting acoustic emissions and measuring volumetric change. Artificially frozen soil specimens were prepared to be analogous to alpine permafrost. The stress paths chosen reflected stress conditions, in compression or extension, under, or beside, deepening depressions in rock glaciers. Test conditions were selected to examine the parameters of volumetric ice content, loading conditions (strain rate/stress rate) and temperatures.

The analysis of triaxial stress path tests in axial compression provided qualitative and quantitative data on strength and creep rates at temperatures close to the thawing point. The volumetric behaviour of the frozen soil specimens demonstrated both contraction and dilation depending on the temperature, strain rate and volumetric ice content of the specimens. The deviatoric stress mobilised in the stress path tests was dependent on the temperature: an increase in temperature resulted in a decrease in residual deviatoric stress. A comparison between the residual deviatoric stresses obtained from the different stress path tests indicated that the value mobilised under the axial extension stress path was the lowest.

In addition to the triaxial stress path tests, the resistance to crack initiation and propagation was investigated through a beam bending test programme on rectangular artificially frozen soil specimens, using the acoustic emission measurement system. The fracture toughness and tensile strength were assessed. The results implied that the frozen soil with low volumetric ice content might be more susceptible to the initiation and propagation of cracks than soil with higher volumetric ice content, at temperatures close to the thawing point. Large cracks were constrained by the dense packing of soil grains, thus a ductile response was obtained.

The evaluation of laboratory tests on artificially frozen soil specimens implied that the development of deep depressions in rock glaciers, occurs through differential creep and thermal degradation, and that the rate of deformation has the potential to lead to instabilities in rock glaciers. The largest deformations might be caused under depressions. This may promote the deepening of depressions together with the initiation of failure through the base of the depression or the propagation of a tension crack on the surface. The latter mechanism is,

however, unlikely to occur in the stress conditions generally pertaining to rock glaciers without further thermal degradation.

Preliminary finite element simulations were conducted to investigate the response of cylindrical frozen soil specimens under triaxial stress paths. The time-dependent behaviour of alpine frozen soil was coupled with the thermal-hydraulic-mechanical interactions and was validated against the experimental data. An elastic-visco-plastic model (Soft Soil Creep model; Vermeer & Neher, 1999), originally developed for the creep behaviour of unfrozen clay, was chosen as a framework to combine the creep response and shear failure of frozen soil. The hydro-mechanical coupling was slightly modified to represent the response of frozen soil, and was further coupled with an empirical relationship to model the thermal effects on cohesion. A comparison of the simulation results with the experimental data demonstrated that the semi-coupled model was successful in simulating the most important aspects of the temperature-dependent stress-strain relationship for the frozen soil behaviour that was measured at the element scale.

This thesis contributes to an understanding of the variations in geotechnical response of alpine permafrost, by investigating the behaviour of artificially frozen soil specimens experimentally and numerically with time and temperature under specific stress paths. However, further investigations are necessary to assess the long-term stability of rock glaciers affected by climate change.

1 Introduction

1.1 Motivation

Progression of climate change in cryogenic regions is more pronounced than the global average (Haeberli & Hohmann, 2008). The rising mean annual air temperature and extreme rainfall conditions cause permafrost degradation per se. Therefore, increasing priority has been given to establishing the expected impact of climate change in cryogenic regions in the past few decades.

Alpine permafrost exists at high altitudes and at lower latitudes than at the poles, such as in the Swiss Alps, and contains ice alone or an ice-water-air-soil mixture. It is particularly susceptible to climate change. The “Organe consultatif sur les Changements Climatiques” (OcCC, 2007) reports an temperature increase on the southern side of the Alps of approximately 1.0°C during the 20th century, which is more than global average of 0.6°C reported by the Intergovernmental Panel on Climate Change (IPCC, 2001). In addition, the average winter precipitation in the northern and western Alps has been increased by 20 – 30%. Accelerated climate change is predicted by the OcCC (2007) till 2050 that temperatures will increase with respect to 1990 by 1.8°C in winter and 2.8°C in summer on both the north and south of the Alps (Figure 1.2), and the 0°C-isotherm will rise during winter by about 360 m (Haeberli & Hohmann, 2008). Moreover, the precipitation will increase by approximately 10% in winter and decrease by about 20% in summer (Figure 1.2, OcCC, 2007; Haeberli & Hohmann, 2008).

The release of groundwater due to melting into the slope was found to be critical to the slope stability of alpine permafrost, since the shear resistance of the soil decreases due to an increase of the pore water pressure (Davies et al., 2000, 2001). Moreover, ice becomes more deformable as temperatures increase to the thawing point (Morgenstern et al., 1980), which results in accelerated downslope motions in the alpine permafrost (Ikeda et al., 2008). The accelerated land motions of warming alpine permafrost, and transitions into wholesale degradation of the permafrost lead to changes in behaviour and potential risks for initiation of landslide and debris flows, which could impact on infrastructure and population in mountainous areas (Springman et al., 2011).

For instance, Crosta et al. (2004) reported on the landslides at Val Pola in northern Italy in 1987, in which the exceptionally high rainfall accompanied by thawing of ice due to relatively high altitude of the 0 degree isotherm caused a large debris flow (estimated volume 34 – 43 Mm^3). Krysiecki et al. (2008) described the sudden failure of the lower part of the Bérard rock glacier in 2006, most probably triggered in warm permafrost by uplift seepage pressures, which subsequently caused a debris flow. Frauenfelder et al. (2003) and Kääb et al. (2007) mentioned that the rock glacier surface speed seems to increase exponentially with the mean annual air temperature increase. Photogrammetric analysis conducted by Roer et al. (2008) indicated that compression and extension zones have formed, which have led to the development of deepening depressions in several rock glaciers.

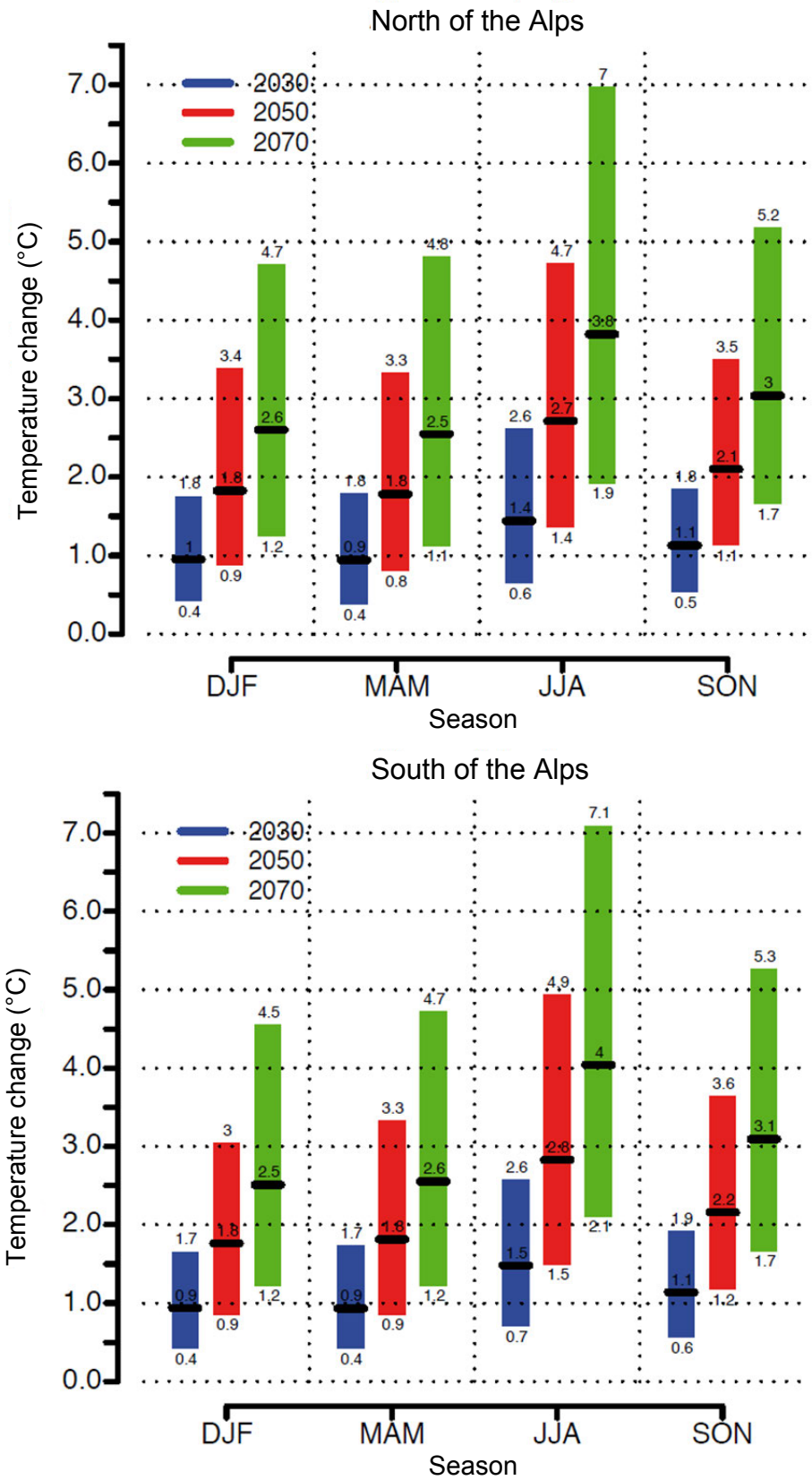

Figure 1.1: Forecast of the seasonal change of average temperature with respect to 1990 for the north and south of the Alps (after OcCC, 2007).

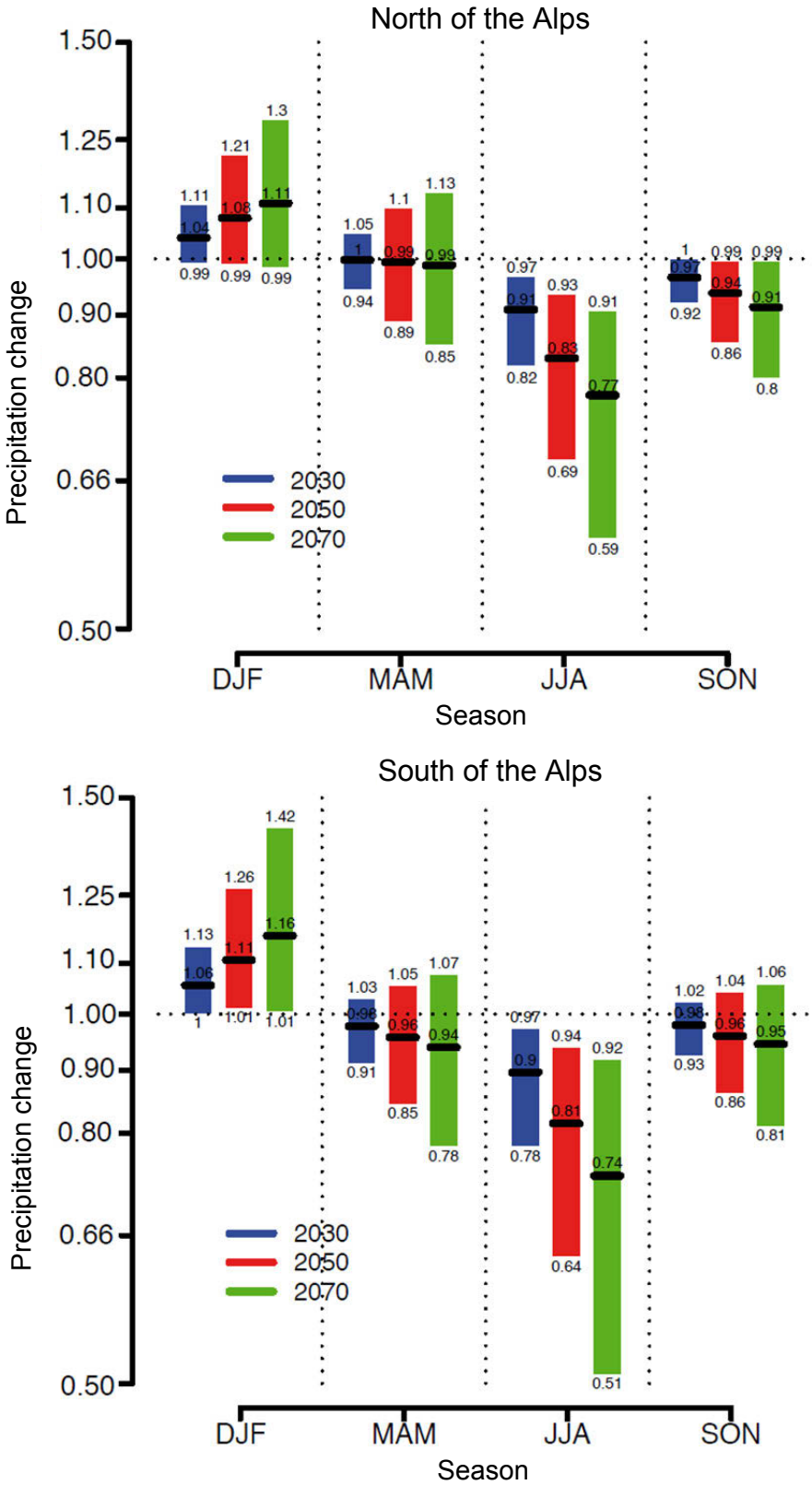

Figure 1.2: Forecast of the relative change of seasonal average precipitation with respect to 1990 for the north and south of the Alps (after OcCC, 2007).

These degrading formations, and the associated deformation behaviour, indicate that instabilities could be triggered within rock glaciers due to warming permafrost initiating from the depression zones, in addition to the possibilities of detachments at the front, due to debris flows and landslides (Springman et al., 2011, 2012). Since such slope stability problems have been identified in recent decades, there is a demand to fill the knowledge gap relating to the geotechnical response of alpine permafrost under transient increases in temperature. However, the data on laboratory investigations, which have been conducted on alpine permafrost, are limited in Switzerland, despite encouraging first investigations by Arenson (Arenson, 2002; Arenson et al., 2004; Yasufuku et al., 2003). Moreover, the knowledge of alpine permafrost behaviour in a gradually warming thermal cycle, and the shear strength mobilised under different stress paths experienced by a soil specimen at different zone of a rock glacier, is necessary for the temporal stability analysis of permafrost slopes.

Stability analysis of permafrost slopes exposed to changing climate conditions needs to be conducted by altering the thermal, hydrological and mechanical properties of the permafrost soil simultaneously. This requires a novel coupled thermal-hydro-mechanical (THM) model to simulate the transient conditions in a permafrost environment. Coupled THM response of frozen soil has mainly been investigated for constitutive and numerical modelling at temperatures warmer than 0°C, e.g. for radioactive waste disposal (e.g. Gens et al., 2009). Development of more advanced modelling techniques for the assessment of climate change-induced effects on engineering facilities in regions of permafrost, which can capture essential response modes, is becoming more important (Clarke et al., 2008; Gens, 2010). However, a limited number of THM models has been proposed for specific simulation targets, which may not be suitable to represent the THM interactions in the alpine permafrost environment.

1.2 Objectives of the thesis

Knowledge of the effect of a warming regime close to the thawing point in permafrost soils is necessary to be able to assess the time dependent and failure response of the rock glaciers. Roer et al. (2008) reported that the extension features in rock glaciers are becoming more apparent, therefore the extension stress paths are thought to represent the field case around and below thermally degrading depression zones, i.e. Axial Extension, Lateral Compression and Lateral Extension (Figure 1.3), which are different from conventional Axial Compression stress paths. It can be postulated that tension features or fracture at the surface of the rock glaciers may play a role in possible failure mechanisms as well.

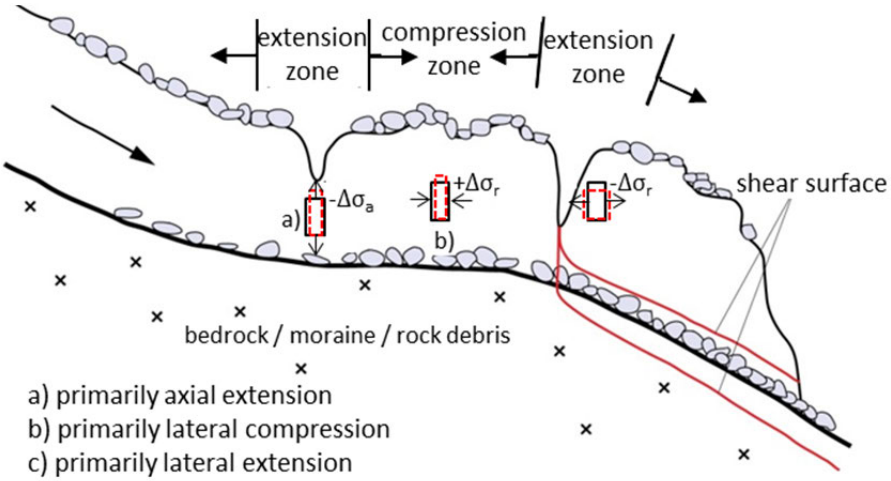

Figure 1.3: Possible zones of extension and compression with shear planes extending from the base of a depression and stress paths experienced by soil elements (Springman et al., 2011).

THM interactions of frozen soil behaviour under transient thermal conditions need to be investigated under controlled boundary conditions. Element tests conducted on the frozen soil specimens in the laboratory can be benchmarked against numerical analyses carried out using a suitable constitutive model and parameters determined to describe the behaviour of alpine permafrost.

Accordingly, the specific goals for this thesis are set out as follows:

- to characterise the shear strength of alpine frozen soils under different thermal conditions at close to the thawing point and under different stress paths,
- to examine whether these stress paths would have an impact on the mobilised shear strength, and if so, to what degree,
- to observe accelerated creep behaviour with a temperature increase close to the thawing point in Constant Stress Creep tests, representing shear zone behaviour in a creeping rock glacier,
- to obtain knowledge of microstructural effects and deformation mechanism surrounding any zones of tension or shear in frozen soil, and to investigate mechanisms from a microstructural point of view,
- to understand the initiation and propagation of tension cracks in laboratory samples that would contribute to an understanding of fracture mechanics in a rock glacier,
- to determine key parameters that can be used in the THM modelling of frozen soils,
- to test a constitutive model that represents the Thermal-Hydro-Mechanical (THM) interactions of frozen soil, and find a modelling system for replicating and predicting the outcome of laboratory element tests.

1.3 Organisation of the thesis

The thesis consists of seven main chapters with an additional reference section and appendix at the end. The thesis starts with an introduction, which outlines the motivation and objectives of the project.

Chapter 2 presents a review of the literature relevant to this project. The characteristics of alpine permafrost and rock glaciers, such as internal structures, thermal conditions and downslope movements, based on the field investigations are reviewed firstly. Secondly, the mechanical behaviour of frozen soil is summarised, which exhibits both ductile and brittle behaviour due to the existence of ice depending on different parameters. Finally, common constitutive models for creep and failure behaviour of frozen soils are studied, and novel Thermal-Hydro-Mechanical (THM) numerical simulations that have been conducted to date on frozen soils are presented.

Triaxial stress path tests conducted on artificially frozen soil specimens are presented in chapter 3. The specifications of the triaxial testing apparatuses used in this project and the testing procedure are described. Subsequently, the overview and results of four different stress paths tests, i.e. Axial Compression (AC), Axial Extension (AE), Lateral Extension (LE) and Lateral Compression (LC) tests, are presented in sequence. Finally, the representation of alpine permafrost soil by the artificial frozen soil samples prepared in this project is discussed by comparing the results with data from similar experiments on artificial frozen and alpine permafrost specimens obtained from a past research project. In addition, creep parameters for the common constitutive model are determined based on the tests in axial compression, and the mobilised shear strength of the four different stress paths tests are compared.

The laboratory tests, other than the triaxial tests on frozen soil, are presented in Chapter 4. The chapter includes the results of triaxial compression tests on unfrozen soil grains, three- and four-point bending tests, measurement of unfrozen water content using a Time Domain Reflectometry (TDR) probe, measurement of thermal conductivity of frozen soil using a Non-Steady-State Probe (NSSP) and the micromechanical investigation using X-ray microComputed Tomography (microCT).

The results of the laboratory tests presented in chapters 3 and 4 are analysed and interpreted synergistically in chapter 5, taking the “warming” effect on the frozen soils into account.

The triaxial stress path tests modelled in numerical simulations are presented in Chapter 6. Firstly, the formulation of the semi-THM-t model is described, and then the model parameter determination for the constitutive models is shown in detail. Finally, the simulation results of the triaxial tests using the multiphysical simulation software COMSOL are presented.

The main findings of the project are summarised in chapter 7. Moreover, some recommendations for future investigations on instabilities in alpine permafrost are presented.

2 Literature review

2.1 Permafrost

2.1.1 Definition

The term permafrost is defined as soil or rock having temperatures below 0°C over at least two or more years (Brown & Kupsch, 1974), which is only based on the temperature and independent of the existence of the water or ice in the ground. Figure 2.1 Illustrates a maximum and a minimum temperature profile in perennially frozen soil above the depth of zero annual amplitude with a so-called trumpet curve due to its shape and showing the existence of a permafrost layer (Andersland & Ladanyi, 1994). The top layer above the permafrost is called the active layer, which thaws during summer and freezes again during autumn. An unfrozen ground layer lies below the permafrost base. The geothermal gradient corresponds to the heat flow from the earth's interior, which varies from 1°C per 22 m to 1°C per 160 m (Brown et al., 1981). The thickness of the permafrost layer is mainly determined by the mean annual surface temperature (T_m) and local geothermal gradient (Andersland & Ladanyi, 1994).

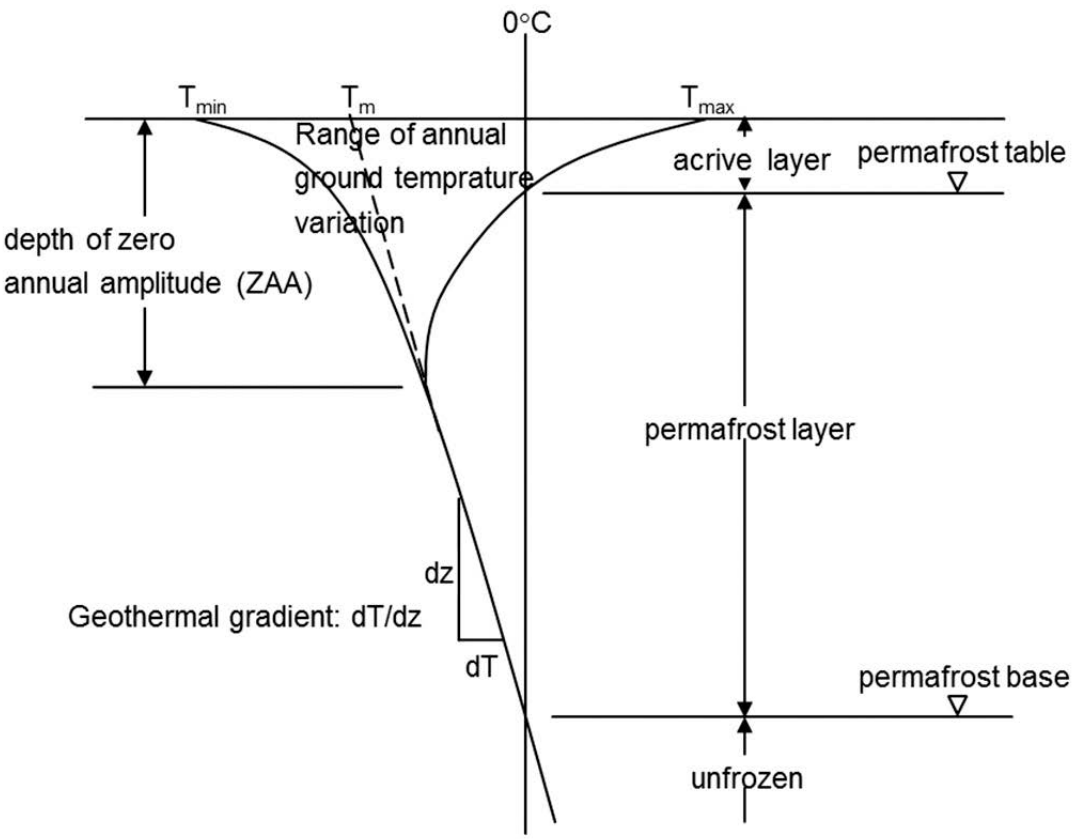

Figure 2.1: Temperature profile in perennially frozen soil (after Andersland & Ladanyi, 1994).

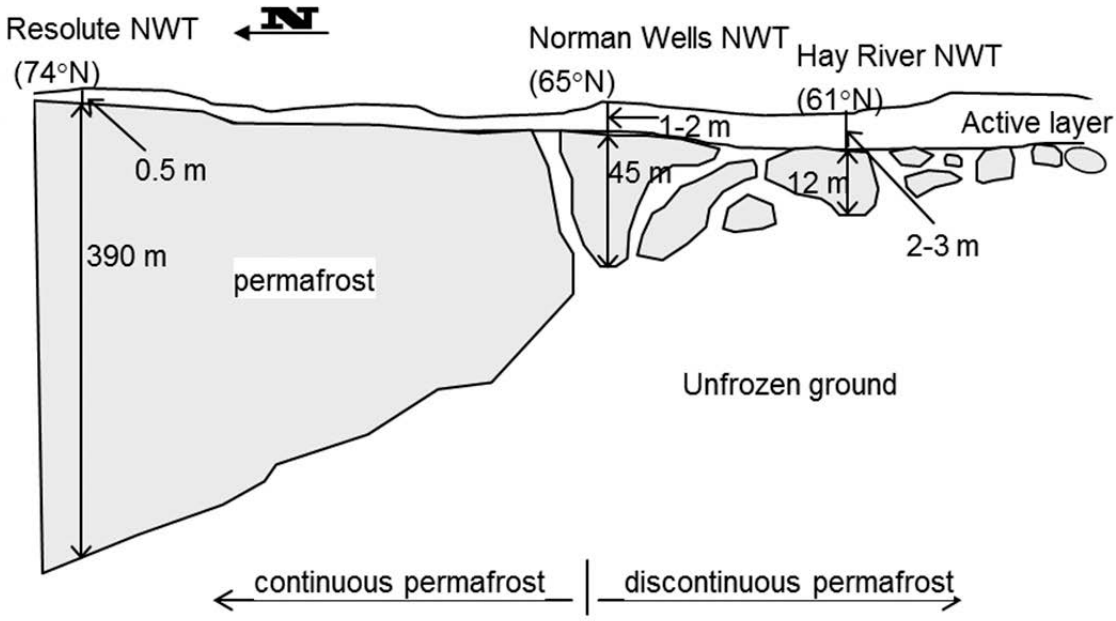

Figure 2.2: Latitudinal profile through the permafrost zone showing increasing depth of active layer with reducing latitude (after Brown et al., 1981).

2.1.2 Distribution

Permafrost is divided into two zones, continuous and discontinuous zone. Continuous permafrost exists everywhere beneath the exposed land surface throughout a geographic regional zone. Areas with continuous permafrost often have permafrost layers of more than 100 metres thick. In contrast, discontinuous permafrost exists in some areas beneath the ground surface throughout a geographic regional zone where other areas are free of permafrost (Brown et al., 1981). The discontinuous permafrost includes sporadic permafrost, according to the basis of percentage of land surface underlain by permafrost: continuous zone, 90 – 100%; discontinuous zone, 50 – 90%; sporadic zone, 10 – 50% (Romanovsky et al., 2002; U.S. Arctic Research Commission, USARC, 2003)

Permafrost exists in a special thermal condition. Its distribution, thickness and temperature depend on the surrounding climate. To determine the location and extent of permafrost is often challenging, since the thermal regime in the upper layer of the earth is complex, controlled by an exchange of heat and moisture between the atmosphere and the ground surface, and the ground thermal properties. Mean annual ground temperature commonly differs from mean annual air temperature, therefore, air temperature records are of limited use in predicting the occurrence of permafrost accurately (Williams & Smith, 1989). Permafrost may not even exist in areas where the mean annual air temperature is below freezing point. Areas of land under glaciers, rivers, and streams are often free of permafrost, despite the freezing air temperature at the surface (Williams & Smith, 1989).

Many factors have the potential to change the thermal environment of the permafrost layer, such as air temperature, precipitation, radiation, thickness of the insulation layer (snow, vegetation and an organic layer), surface structure and hydraulic condition in the permafrost layer. These factors change the shape of the trumpet curve in Figure 2.1, thus and influence the distribution of permafrost. Effects of the factors mentioned above on the thermal characteristics of permafrost layer are briefly summarised in Table 2.1.

Permafrost occurs in ice-free areas of the Antarctic continent and in some of the sub-Antarctic islands in the Southern Hemisphere (Bockheim, 1995). Approximately 24% of the land surface in the Northern Hemisphere is occupied by permafrost regions (Brown et al., 1998; Zhang et al., 2003). The map of permafrost distribution indicates permafrost occurrences as far north as 84°N in northern Greenland, and as far south as 26°N in the Himalayas (Figure 2.3). Most of the permafrost in the Northern Hemisphere occurs between latitudes of 60°N and 68°N, but permafrost also exists in middle latitude mountain regions, such as the Rockies, Andes, Alps and Himalayas, Qinghai-Xizang (Tibet) Plateau, which exhibit lower mean annual temperatures at higher elevations.

Riseborough et al. (2008) summarised the numerous local models for alpine permafrost. A mean annual air temperature below -3°C can be used for first-order classification of altitudinal belts that have significant amount of permafrost in the European Alps, although this rule is often subject to many exceptions (Gruber & Haeberli, 2009).

Permafrost in Switzerland occurs in high mountain regions, which is called alpine permafrost. Keller et al. (1998) estimated the distribution of permafrost in Switzerland using the PERMAKART modelling approach, and reported that 4 – 6% of Swiss territory is covered with permafrost. The Federal Office for the Environment (FOEN) of Switzerland produced a potential permafrost distribution map in Switzerland (Figure 2.4). Nyenhuis et al. (2005) assessed the regional distribution of permafrost in the Turtmann valley in Switzerland using an empirical-statistical permafrost model PERMAMAP (Hoelzle & Haeberli, 1995), together with field data, in order to capture the occurrences of permafrost in a precise and regional point of view. Permafrost distribution in Switzerland shows that permafrost exists in the highly populated mountainous areas, or above some villages in valleys.

Table 2.1: Effects of different factors on the thermal environment of permafrost layers.

Factor	**Effects on changing the thermal environment of permafrost layers**
Air temperature	Air temperature is the upper boundary condition of the ground, which causes the trumpet temperature distribution curve throughout a year, as shown in Figure 2.1. The latitude, altitude, aspect and slope angle affect air temperature. Brown (1960) mentions that there is no close relationship between spatial permafrost distribution and air temperature, because other factors affect the occurrence of permafrost as well.
Precipitation in fluid form	Water has higher thermal conductivity than air, which results in faster heat transport to the permafrost body. Water flow between pores, on the surface of the permafrost layer or in the permafrost body, transfers surface temperature into the deep layer.
Solar radiation	The degree of exposure of ground surface to the solar radiation determines the rate of snow melt, ground heating and water runoff. The latitude, altitude aspect and slope angle affect the amount of incoming solar radiation.
Insulation layer (snow, vegetation, and organic layer)	Insulation layers play a part in damping the climate change above the ground to the ground below, which means there is a lag between temperature change at the ground surface and under the subsurface layer. *Snow cover:* A thick snow cover during winter prevents penetration of cold air temperature into the ground, whereas a long snow cover during spring or early summer months prevents penetration of heat from air (Keller & Gubler, 1993). *Vegetation:* Vegetation cover shows differences between active, in active and relict rock glaciers. A higher movement velocity of a rock glacier resulted in a decrease of vegetation cover in the Murtèl rock glacier (Burga et al., 2004). *Organic layer:* The water holding capacity is high in the organic layer, which indirectly affects the thermal environment through the change in the hydrological properties.
Surface structure	Coarse rock debris causes more cooling and warming into the subsurface ground as air temperature changes than in fine-grained soils, since air moves through the voids in the blocks (Harris & Pedersen, 1998).
Ground structure	The ground warming rate is smaller in higher volumetric ice content layers in a permafrost body (Romanovsky et al., 2010). Ice rich material enhances the temperature transport in the active layer, but the energy is used for phase change processes when the temperature of the ice is between 0 and -1°C, and no significant changes in active layer depth will occur (Schneider et al., 2012).

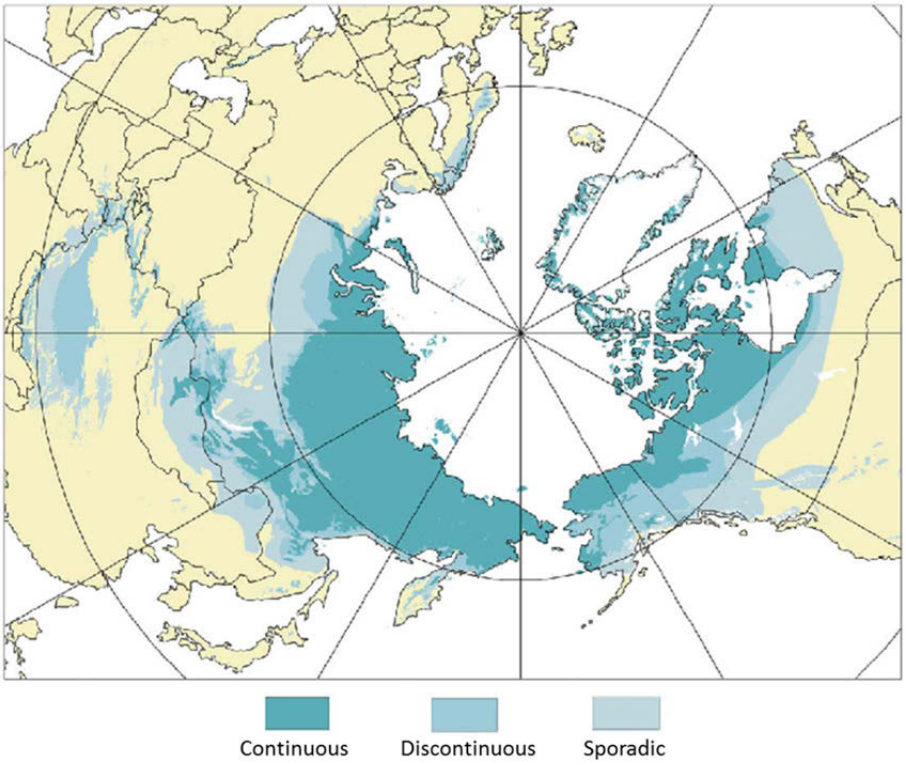

Figure 2.3: Permafrost zonation in the Northern Hemisphere. Zones are defined on the basis of percentage of land surface underlain by permafrost: continuous zone, 90 - 100%; discontinuous zone, 50 - 90%; sporadic zone, 10 - 50%. (USARC (2003) and Nelson et al. (2002) adapted from Brown et al. (1997; 1998)).

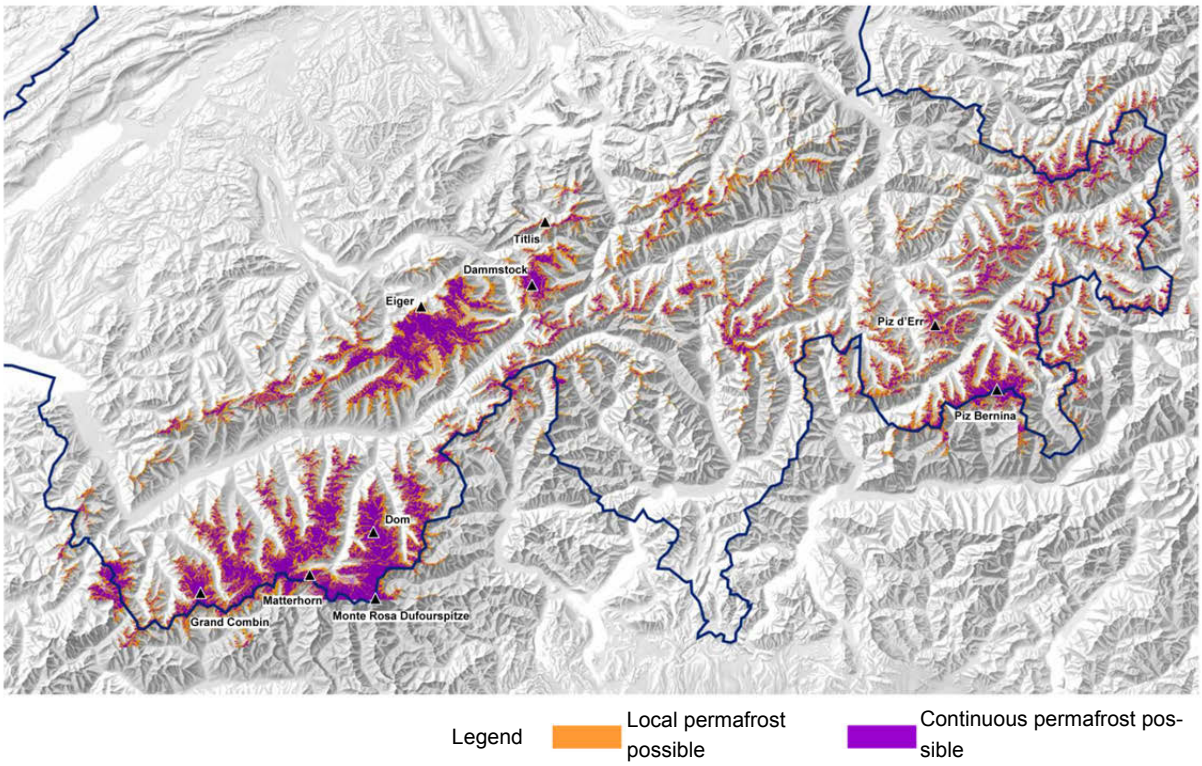

Figure 2.4: Potential permafrost map of Switzerland (after BAFU, 2005).

2.1.3 Climate change and permafrost

The permafrost response to climate change has been investigated by many researchers in order to seek ways of identifying the hazards to infrastructure in cold regions, and to establish distinct uncertainties through a risk based consideration and estimating the consequences of some key damage scenarios (e.g. Williams & Smith, 1989; Guodong & Dramis, 1992; Koster & Nieuwenhuijzen, 1992; USARC, 2003; Cheng & Wu, 2007). A gradually rising Mean Annual Air Temperature (MAAT) together with fewer 'freezing degree days' causes the permafrost layer to become thinner or disappear altogether (e.g. Burn, 1998; Shaoling et al., 2000; Harris et al., 2009; Arenson et al., 2010). Further retreat of permafrost and changes in groundwater hydrology and vegetation are accompanied by more extreme rainfall conditions and melting of the ice phase, which release groundwater into the voids (Springman et al., 2012), which affect the thermal conduction of the permafrost.

The latest IPCC report (Lemke et al., 2007) summarises past permafrost conditions and gives an overview of the changes in permafrost temperature in the northern hemisphere. It also reports the temperature increase at the top of the permafrost layer in the Arctic by up to 3°C since the 1980s, and the thawing rate of the permafrost base of up to 0.04 m/yr. Permafrost degradation causes changes in land surface characteristics and drainage systems. This has been greatest at lower elevations, e.g. typical of Switzerland. Moreover, Ladanyi (1995) pointed out that the effect of a few degrees warming in the mean annual temperature of permafrost is extremely serious in the discontinuous zone, because the temperature range of discontinuous permafrost lies within a few degrees below thawing point. Romanovsky et al. (2010) synthesize the thermal state of permafrost in the polar northern hemisphere, in North America, Russia and Nordic region, and a comparison between current thermal state and previous ground thermal conditions, which show that warming rates are much smaller for warm permafrost at temperatures close to 0°C than for colder permafrost.

2.1.3.1 Climate change and permafrost engineering

The issues of the effect of climate warming on infrastructure have been addressed by many researchers (e.g. Esch & Osterkamp, 1990; Nixon, 1990; Ladanyi, 1995; Instanes, 2003; Qingbai et al., 2008; Rongved & Instanes, 2012). Permafrost degradation and warming affect the stability of infrastructure in cold regions, such as buildings, roads, pipelines, airports, tailings dams, etc., because the temperature change in frozen ground causes a major change in strength and deformation properties, even without considering any thawing phenomena (Williams & Smith, 1989). For instance, the warming of permafrost body causes an increased creep rate around the existing piles and footings. In case of thawing of permafrost, settlement occurs because ice changes form into water and drains away creating volume loss, and the soil skeleton must adapt itself to a new structure. This may cause uneven settlement and damage to the structures. Furthermore, the bearing capacity of piles, which are widely used in construction in permafrost areas, may decrease as permafrost warms due to an increase of the amount of unfrozen water in frozen soil (cf. Section 2.2.1) and loss of adhesion forces (Williams & Smith, 1989). Moreover, development of talik zones, which are a layer or body of