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Design of snow nets

Deniz Algünerhan

Master of Science in Civil and Environmental Engineering
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Supervisor: Arne Aalberg, KT

Norwegian University of Science and Technology
Department of Structural Engineering

Department of Structural Engineering
Faculty of Engineering Science and Technology
NTNU- Norwegian University of Science and Technology

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Design of snow nets

Beregning av snønett

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Deniz Algünerhan

SUMMARY:
The need for protection against snow avalanches has led to the development of different protection methods. One type of protection aims to stabilize the snowpack with supporting structures, to prevent failure and thus the resulting avalanche. These structures consist of steel rigid barriers or wire-rope nets. Calculating the distribution of forces in the net type, after the structure is being subjected to snow pressure, is complicated. The structure is flexible, and force distribution depends heavily on the strained geometrical shape of the net.

With development of the digital computer, finding the structural response can be done with various methods. Numerical software, based on cable mechanics, has been developed to obtain this. Another strategy consists of using the discrete element method. This method is well adapted to describe the behaviour of granular materials like snow, and to simulate large displacements. A coupled mechanical analysis is obtained using the method, which makes modelling of the snow and net behaviour in the same program possible. Use of the finite element method is another possible strategy to model the snow nets. The method is leading in computer-oriented mechanics. With the use of commercial software, the structure can be modelled and internal forces can be found. The method is a powerful tool, but as most tools it must be properly used.

In this thesis, an example structure of a snow net is created. The structure is modelled in Dynamo using visual programming, and FE-analysis is run in Robot. Obtained results are compared with an easy method based on a simplified two-dimensional static. It is also compared with field experiments from France, Austria and Iceland.

RESPONSIBLE TEACHER: Arne Aalberg

SUPERVISOR: Arne Aalberg

CARRIED OUT AT: Department of Structural Engineering, NTNU

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Norges teknisk-naturvitenskapelige
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Fakultet for ingeniørvitenskap
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Institutt for konstruksjonsteknikk

MASTEROPPGAVE VÅREN 2018

Deniz Algünerhan

Beregning av snønett

Design of snow nets

1. Bakgrunn

Stålnett laget av tråd eller vaiere brukes til beskyttelse mot fallende steiner fra skråninger, og til å holde tilbake snømasser i skråninger. Vegvesenet i Norge er en stor bruker av nett, bolter og kabler til sikring av fjell- og jordskråninger. Det eksisterer ingen felles europeiske prosjekteringsstandarder verken for belastning eller styrke til slike nett. Det var nylig tenkt å benytte snønett til snøskredstabilisering i en fjellskråning ved Longyearbyen på Svalbard, Men en ble i vurderingsprosessen klar over at beregningsgrunnlaget for slike konstruksjoner var mangelfullt og at kunnskapen i det norske ingeniørmiljøet var meget begrenset. Innsats på dette området er derfor viktig.

Oppgaven skal ta for seg stålnett og vaierkonstruksjoner brukt til barrierer og forankringskonstruksjoner for snø i bratte skråninger, for å se hvordan de beregnes for snøkrefter og evt hvordan de kan brukes for å holde tilbake snø fra å utløses til snøskred.

2. Gjennomføring

Oppgaven kan gjennomføres med følgende elementer:

- Gjøre rede for typiske snønett, materialer og oppbygging, konstruksjon og forankring.
- Se på beregningsanvisninger for last og bæreevne for slike nett i den grad dette eksisterer.
- Tilpasning til norske forhold.
- Se på hvordan dette kan beregnes, ved håndberegning og elementmetodeberegninger.
- Gjøre rede for bærevirkningen for typisk vaier/kabel.
- Etablere en elementmodell for en valgt snønettkonstruksjon.
- Søke å finne veldokumenterte forsøk i litteraturen. Gjøre vurderinger.

Kandidaten kan i samråd med faglærer og veileder velge å konsentrere seg om enkelte av punktene i oppgaven, eller justere disse.

3. Rapporten

Oppgaven skal skrives som en teknisk rapport i et tekstbehandlingsprogram slik at figurer, tabeller og foto får god rapportkvalitet. Rapporten skal inneholde et sammendrag, evt. en liste over figurer og tabeller, en litteraturliste og opplysninger om andre relevante referanser og kilder.

Oppgaver som skrives på norsk skal også ha et sammendrag på engelsk. Oppgaven skal leveres igjennom «DAIM».
Sammendraget skal ikke ha mer enn 450 ord og være egnet for elektronisk rapportering.

Masteroppgaven skal leveres innen 11. juni 2018.

Medveileder er professor emeritus Per Kristian Larsen, NTNU.

Trondheim, 12. januar 2018
Arne Aalberg, Professor NTNU/ UNIS

Abstract

Snow is in many forms responsible for human enjoyment, but can also cause human losses in addition to severe property and environmental damage through snow avalanches. Especially mountain side roads and towns are at risk to experience the fatal consequences. The need for protection against this phenomenon has led to the development and use of different protection methods. One of many available protection methods are supporting structures. This type of protection aims to stabilize the snowpack to prevent failure and thus the resulting avalanche.

The supporting structures of today typically consist of steel rigid barriers or wire-rope nets. Calculation of the structural response for steel rigid barriers can be done with simple methods in classical mechanics. Wire rope nets, on the other hand, require a more detailed computation due to the structure flexibility: the distribution of forces depends heavily on the strained geometrical shape of the net. This is a significant difference to rigid structures. The complication is to find the shape of the net after the structure is being subjected to snow pressure.

A easy method that can be used with hand calculations is based on Haefeli's theory. This is based on a simplified two-dimensional static where a section across the snow net is examined. But with the development of the digital computer, the problem can be solved with various other methods. Firstly, it has been developed numerical tools based on cable mechanics to obtain the structural response.

Another strategy consists of using the discrete element method (DEM). This method is well adapted to describe the behaviour of granular materials like snow, and to simulate large displacements. With the use of this method, a coupled mechanical analysis is obtained and both the snow and net behaviour can be modelled in the same program.

Use of the finite element method (FEM) is another possible strategy to model the flexible net fences. FEM is the leading method in computer-oriented mechanics. With the use of commercial software, the structure can be modelled and the internal forces can be found. The method is a powerful tool, but as most tools it must be properly used. To model a correct representation, considerations regarding structural elements and loading is important.

The main goal of this document is to study the mechanical behaviour of the snow nets, and to set out a general methodology for undertaking design. The document summarizes theoretical developments, combining and comparing them with design guidelines and field experiments to formulate design recommendations. To do this, various methods of calculating the internal forces is mentioned and used. All of the methods have not been tested by the author of this document, but mentioned from past research. It is also compared with measurements and field experiments from France, Austria and Iceland.

Sammendrag

Snø kan skape glede i mange former, men også skape fortvilelse ved snøskred. Spesielt veier og byer langs fjellsider er i fare for å oppleve de dødelige konsekvensene. Behovet for beskyttelse mot dette fenomenet har ført til utvikling og bruk av ulike beskyttelsesmetoder. En av mange tilgjengelige beskyttelsesmetoder er støtteforbygninger. Denne typen beskyttelse tar sikte på å stabilisere snødekket for å forhindre at skredet utløses.

Støtteforbygningene i dag består vanligvis av stive konstruksjoner eller wirenett. Beregning av indre krefter, etter belastning fra snøtrykk, gjøres for den stive typen med enkel mekanikk. Nettene derimot krever en mer detaljert beregning på grunn av konstruksjonens betydelige tøyning: kraftfordeling i nettet er sterkt avhengig av nettets form etter påkjenning. Komplikasjonen blir dermed å finne denne.

Med utviklingen av den digitale datamaskinen kan problemet løses med ulike metoder. En enkel metode som kan brukes med håndberegninger er basert på Haefeli's teori. Dette er basert på forenklet todimensjonal statikk, hvor et snitt på tvers av snønettet undersøkes. Det har også blitt utviklet numeriske verktøy basert på kabelmekanikk for å oppnå den strukturelle responsen.

En annen strategi er å bruke diskret elementmetode (DEM). Dette numeriske verktøyet er godt tilpasset til å beskrive oppførselen til granulære materialer som snø, og til å simulere store forskyvninger. Ved bruk av denne metoden fås en kombinert mekanisk analyse, og både snøen og snønettets oppførsel kan modelleres i samme program.

Bruk av elementmetoden (FEM) er en annen mulig strategi for å modellere det fleksible snønettet. Metoden er ledende i datorientert mekanikk, og ved bruk av kommersiell programvare kan strukturen modelleres og de interne kreftene kan finnes. Metoden er et kraftig verktøy, men som de fleste verktøy må det brukes riktig. For å modellere en korrekt representasjon av virkeligheten, er hensynet til konstruksjonselementer og laster avgjørende.

Hovedmålet med denne oppgaven er å studere snønettets mekaniske oppførsel, og å utarbeide en generell fremgangsmåte for å gjennomføre prosjektering av slike konstruksjoner. Dokumentet oppsummerer teoretiske utviklinger, kombinerer og sammenligner dem med retningslinjer og felteksperimenter, for å formulere prosjekteringsråd. For å gjøre dette er ulike metoder for beregning av interne krefter nevnt og brukt. Alle metodene har ikke blitt testet av forfatteren av dette dokumentet, men nevnt fra tidligere forskning. Resultatene er sammenlignet med målinger og feltforsøk fra Frankrike, Østerrike og Island.

Foreword

This master's thesis was prepared during the spring of 2018 at the Norwegian University of Science and Technology (NTNU), Department of Structural Engineering.

The thesis investigates the possibility of improving avalanche safety with the use of snow nets. It provides technical guidance for the design of these type of protection structures. It also serves as a guide to inform others about the design process and the nature of work involved in designing protection structures.

Because this master's thesis is written for Norwegian University of Science and Technology, NTNU, and in collaboration with The University Centre in Svalbard, UNIS, Norwegian building regulations are mostly taking into account. Huge parts of the thesis is in addition based on experience from Switzerland and the Alpine region.

I would like to thank my supervisor, professor Arne Aalberg, for good support during the work on this thesis, and for great hospitality during my visit at Svalbard.

Trondheim,
June 11, 2018

Deniz Algunerhan

Contents

1 Introduction

1.1 Purpose

As a natural hazard, snow avalanches can be placed into the group of mountain-slope hazards. Due to the fact that snow is the weakest surficial material on Earth, snow avalanches are one of the most frequent mountain-slope hazards [1]. Despite not having the same importance as other natural hazards on a world scale, snow avalanches still require a high level of safety awareness. The consequences are human losses in addition to severe property and environmental damage. Thus, it can represent a serious problem for society, especially with the development of mountain regions as more habitable areas and increasing tourism in avalanche-prone areas.

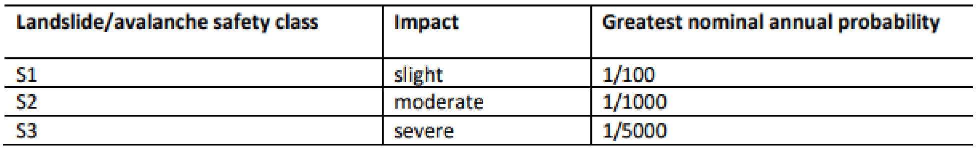
The need for increased avalanche safety has led to the development of different protection methods. One of many available protection methods is the use of supporting structures. This type of protection aims to stabilize the snow mantel to prevent failure and thus the resulting avalanche [1]. The supporting structures of today have required a long time of development. Starting from simple earth and rock walls, to timber terrace walls, they got followed by concrete and aluminum structures due to advances in material technology. Today, the structures typically consist of steel rigid barriers or wire-rope nets. Snow nets are often preferred due to being more economical and far less visible than rigid barriers.

To sufficiently satisfy safety requirements, the supporting structures need to be properly designed. As for any other structure, they must satisfy structural rules. These rules vary with country. In Norway, a country where avalanches are very common, accidents caused by avalanches have always been a problem. The principal legal act in Norway concerning building regulations is the Planning and Building Act, which was last revised in 2008. Only two paragraphs in the Planning and Bulding Act of 1985 [2] are of special importance concerning snow avalanches:

- §25 defines the different regulation areas. Danger areas is defined as "... areas where, due to risk of landslide, flood or other special hazard, building is not permitted or shall be permitted only on special conditions out of consideration for safety."
- §68 sets demands on the building land. "Land may only be divided or developed when there is adequate safeguard against risk or significant inconvenience as a result of natural or environmental conditions."

Supplementary to the act is the Regulations on technical requirements for construction works. In chapter 7, protection against acts of nature is covered. Quoting from an unofficial English translation of the regulation: "The landslide or avalanche safety class of construction works in areas prone to landslides or avalanches shall be stipulated pursuant to the table below. Construction works and their related outside areas shall be sited, designed or protected against landslides or avalanches such that the largest nominal annual probability in the table (figure 1) is not exceeded." [3]

The laws and regulations do not specify any technical information. But the Norwegian Public Roads Administration has constructed technical guidelines on different



Landslide/avalanche safety class	Impact	Greatest nominal annual probability
S1	slight	1/100
S2	moderate	1/1000
S3	severe	1/5000

Figure 1: Safety classes for siting construction works in areas prone to landslides or avalanches [3]

protections against avalanches. The Norwegian roads have been very exposed to avalanches. In the period 1998-2008, about 6500 snow avalanches were registered on Norwegian roads [4]. In addition to the Norwegian guidelines, should Swiss guidelines be used in design. Switzerland has been one of the leading countries in Europe in avalanche research. Alongside protection forests, supporting structures represent the primary form of protection from avalanches in Switzerland [5]. Since the mid-1900s, the Swiss have been constructing technical guidelines on supporting structures. With over 50 years of development, the technical guidelines represent a valid design source. Compared to the Norwegian guidelines, the Swiss guideline is more comprehensive.

With the use of laws, regulations and guidelines as basis of design, the next step in the design process is the analysis and computation of the structural response. The complexity of the computations depends mainly on the complexity of the structure. While the structural response of protection structures of steel rigid barriers can be calculated with simple methods in classical mechanics, the wire rope nets require a more detailed computation. The net introduce complexity due to its flexibility. The distribution of forces depends heavily on the strained geometrical shape of the net, which is a significant difference to the rigid structures.

1.2 Audience

The audience for this thesis is all interested in the topic of avalanche safety. All from engineering students to experienced professionals seeking guidance on, or information about design of protection structures. The audience should have in mind that the document is written with a focus on a Norwegian approach.

1.3 Exclusions

The thesis does not address avalanche hazard assessment and risk management, design for other load cases (eg. wind), design of foundations or connections, considerations regarding structure durability, high cost or effectiveness of the protective measures. As mentioned earlier, the protection structures can consist of steel rigid barriers, and the design of these structures are not covered. These are relatively simple structures, and the structural response can be calculated easily. It is worth mentioning that these structures are less economical, but most suitable where the forces must be brought down to the ground as pressure forces.

2 Theory

Snow avalanches are snow masses that rapidly descend steep slopes [6]. There are two general types of snow avalanches, loose-snow avalanches and slab avalanches. Loose-snow avalanches start at a single area or point and spread out as they move down the slope in a triangular pattern. They usually involve only surface or near-surface snow. This avalanche type is formed in snow with little internal cohesion among individual snow crystals [7]. The other type, the slab avalanche, is usually more dangerous. It initiates by a failure associated with a thin weak layer at depth in the snow cover, ultimately resulting in a block of snow, usually approximating a rectangular shape, that is entirely cut out by propagating fractures in the snow [1].

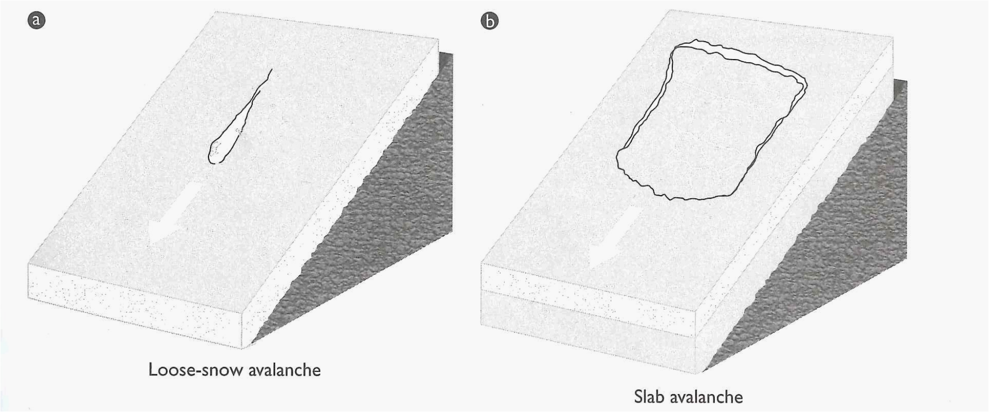


Figure 2: Illustration of loose (a) and slab (b) avalanche failure types [1]

A special type of snow avalanche is the slush avalanche. The most likely cause of slush flows is the reduction of snow cohesion due to water presence and substantial reduction of the friction component of snow strength by the hydrostatic pressure resulting from standing water in the snowpack [1]. The flow shape is similar to flooding, and experience has shown that safety measures against debris flows are also highly effective against this type of avalanches. The Norwegian Public Roads Administration do therefore treat this type of avalanches in the same category as flooding [8]. Safety measures against this special type of avalanche will not be covered in this thesis.

On a snow slope, deformation occurs in three patterns: in tension, the grains are pulled apart, in compression, the grains are forced together, and in shear, the grains are forced past each other. For either loose-snow or slab avalanches, the initial failure is in shear [1]. In order to trigger the avalanche, it is required that the acting shear-stress in the snow pack is larger than the shear strength in the critical layer. Therefore, the shear strength of snow deserves special attention.

But, as it is first and foremost the shear stresses in weak layers that are important to study the stability of the snow mantel, the compressive strength is crucial when assessing how heavy loads snow in sloping terrain can transmit to constructions. Since it is possible to stabilize the snow mantel with supporting structures, identifying the snow pressure that acts on these structures is vital. The snow pressure

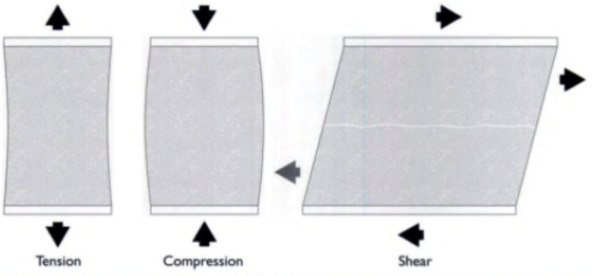


Figure 3: The three modes of snow deformation [1]

occurs due to the snow packs movement being braked or stopped by the supporting structure, resulting in snow pressure. The following two types of movement of the snow pack are distinguished: creeping and gliding.

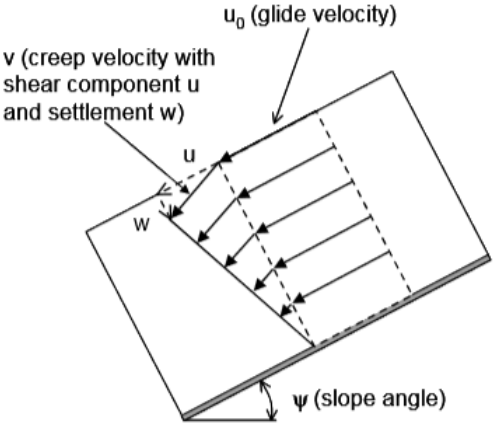


Figure 4: Schematic diagram of the creep and glide movement of the snow cover [9]

Snow creep v is the resultant of vertical settlement w of the snow and internal shear deformation u parallel to the slope. The cause of these motions is the weight of the snow cover that generates forces parallel and perpendicular to the slope. At the ground the snow creep is zero. Snow glide u_0 is the slip of the entire snow cover over the ground without essential deformation within the snow cover. Gliding affects snow pressure to a large extent, and is a very important component for the calculation of snow pressure [9]. But in Norway the gliding motion is regarded minimal, as it is only recorded for especially slippery ground conditions. It is therefore neglected in the Norwegian guideline [4]. Snow creep pressures are thus the primary design consideration in this thesis.

Based on a linear creep law, analytical expressions for snow creep pressures have been developed [10]. The design pressure for the supporting structures can be calculated with basis in this theoretical approach, and by equation:

$$\frac{\bar{\sigma}_x}{\bar{\rho} g D} = \left[\frac{2}{1-\nu}\left(\frac{L}{D}\right)\right]^{1/2} \sin\psi + \frac{1}{2}\frac{\nu}{1-\nu}\cos\psi \qquad (1)$$

where:

$\bar{\sigma}_x$ = Average snow pressure on the construction
$\bar{\rho}$ = Average snow density
D = Snow depth perpendicular to terrain
ν = Poisson ratio
g = Gravitational acceleration
ψ = Slope angle
L/D = Snow creep parameter dependent on slope inclination and viscous Poisson ratio given by:

$$\frac{L}{D} = \frac{1}{4}(\sin\psi)^{1/2} + \frac{1}{4}\left(\frac{\nu^2}{1-\nu}\right) \tag{2}$$

As the snow is acting with shear forces on the surface of the structure when the snow is settling, a force normal to the slope has to be introduced:

$$\frac{\bar{\tau}}{\bar{\rho} g D} = \frac{1}{4}(\cos\psi)^{1/2}\left[1 - \frac{3}{2}\left(\frac{\nu}{1-\nu}\right)(\sin\psi)^{1/2}\right] \tag{3}$$

where:

$\bar{\tau}$ = Average shear force on the construction

Poisson ratio for the maritime snow cover in Norway is for design purposes found to have reasonable fit with measurements for $\nu = 0.36$ [11]. With this information can (1) and (3) be written:

$$\bar{\sigma}_x = \bar{\rho} g D \cdot \left(\left[3.125\left(0.25(\sin\psi)^{1/2} + 0.05\right)\right]^{1/2}\sin\psi + 0.28\cos\psi\right) \tag{4}$$

$$\bar{\tau} = \bar{\rho} g D \cdot 0.25(\cos\psi)^{1/2}\left[1 - 0.84(\sin\psi)^{1/2}\right] \tag{5}$$

The average snow pressure is just an assumption. The actual snow pressure against a supporting surface varies with the height. Approximately can the distribution of pressure be described parabolically with zero pressure at the surface and at the ground. This gives a maximum pressure of about 1.5 times the average pressure, and the resultant is approximately in the middle portion of the snow pack.

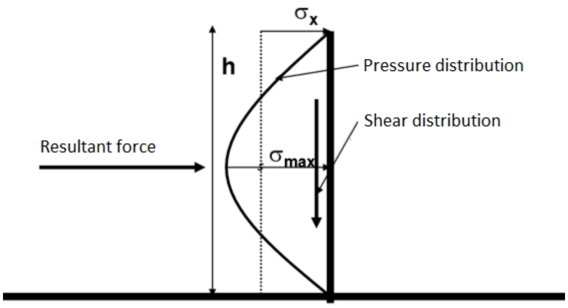


Figure 5: Parabolic distribution of snow pressure over surface height [4]

Swiss design guidelines [5] use another variant for the normal pressure. According to the guidelines, the component of snow pressure in the line of slope on a rigid supporting surface lying normal to the slope and of infinite length in the contour line amounts to:

$$S'_N = \rho g \frac{H^2}{2} K N \qquad \text{[kN/m']} \quad (6)$$

where:
ρ = Average density of snow
H = Vertical snow height at site of structure
K = Creep factor
N = Glide factor

The pressure component normal to the slope amounts to:

$$S'_Q = S'_N \frac{a}{N \cdot \tan\psi} \qquad \text{[kN/m']} \quad (7)$$

where a is a factor dependent on snow type which varies from 0.2 to 0.5. For dense, old snow or ice, this factor can be chosen as zero. Loose, new snow is greatly compressible, and for this snow type can a be taken as 0.5.

Both of the analytical expressions show that the snow pressure is mainly dependant on density, slope angle and the creeping and gliding effect. Another property that affects the snow pressure is the snowpack temperature. This factor affects the snowpack development, and when the highest snow pressure is observed. This is often in spring prior to melting of the snowpack [12].

Snow density changes during the metamorphosis. The snow metamorphism is described as the transformation of the lying snow. This is a continuous process and begins in the atmosphere. Already during the snowfall, the temperature, moisture and wind conditions change at different heights, and this affects the crystal growth and destruction [13]. The metamorphosis will last until the final melting process of the snow.

Both creeping and gliding are highly dependant on the slope angle. The creeping motion is also dependant on the snow density. The higher snow density and the steeper slope, the higher will the creeping motion be. Gliding is in addition dependent on vegetation, roughness and solar exposure of the ground, and expresses the increase in snow pressure for movement of the snow cover along the ground. The higher roughness of the ground surface, the lower is the gliding motion since small displacements of the mantel are likely to take place.

As an addition, the supporting structures are subjected to end-effect loads. These loads occur by virtue of the fact that the snow can flow laterally around the surface, so that a lateral restraining effect occurs. The end-effect loads are dependant not only on the factors determining the snow pressure on an infinitely wide surface, but also on the lateral distance between structures, the arrangement of the structures and the supporting surface dimensions, shape and roughness, and even more so on the glide factor [5]. This loading is similar to wind actions on long structures. For practical calculations, the actual distribution of the load is simplified with an assumption of a constant force over a length. In the guidelines, the size of the load is found using an end-effect factor f_R.

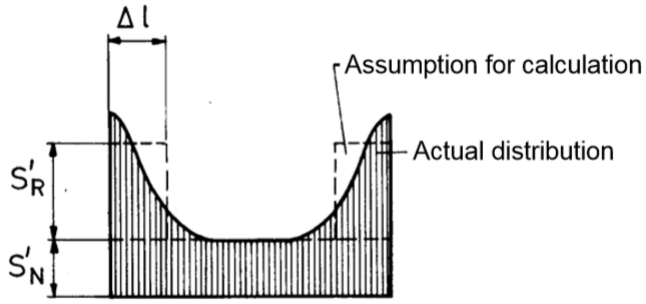


Figure 6: Snow pressure distribution on a supporting surface of finite width [5]

3 Structural system

Snow nets consist of swivel supports kept downslope with guywires and upslope with flexible steel nets. The supports are manufactured from standard steel profiles, and are flexible in all directions if they have a ball joint at the foot. They point upslope opposite vertically at 10°-20°, and the distance between supports usually varies between 3.5 and 4 meters [13]. The structure height must reach the top of the snow cover, and is thus determined from the design snow height in the area [4].

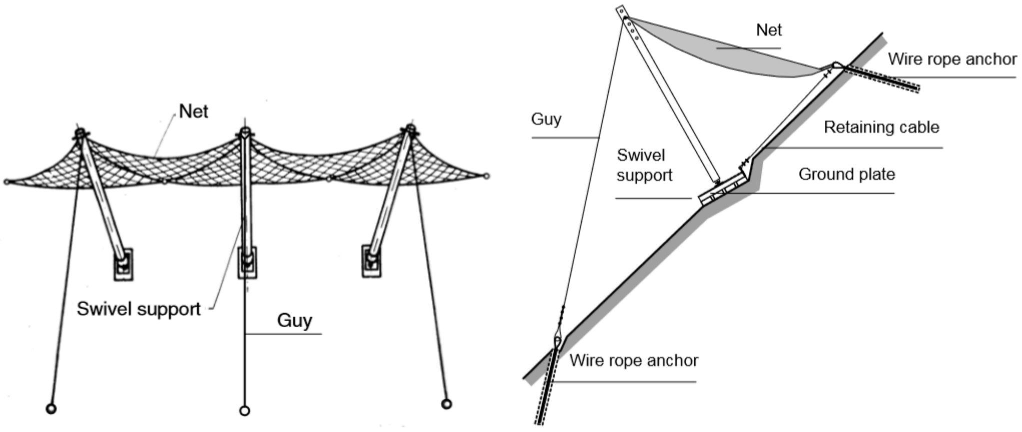


Figure 7: Snow net [5]

The classic nets is of triangular or rectangular shape. They consist of galvanized stranded cables, and 6-8 mm thick mesh cables that are fastened with clamps. The mesh size is usually 200 to 250 mm. But with this mesh size, the retention capacity of the nets was observed to be insufficient. The problem was solved by covering the nets with a wire or strip mesh of 25x25 or 50x50 mm^2 [13].

The structures are positioned in rows, where the positioning of the uppermost and lowermost structure should be chosen respectively from the highest observed or anticipated fracture line of a slab avalanche, and until the inclination of the slope has finally dropped below approximately 30° [5]. It is worth mentioning that these assessments should be critically considered, and that other technical assessments could rather be preferred. Generally, the structures should be arranged wide enough to cover an entire natural terrain unit. Where this is not possible due to circumstances of the terrain or for economic reasons, alternative arrangements need to be considered, as shown in figure 8.

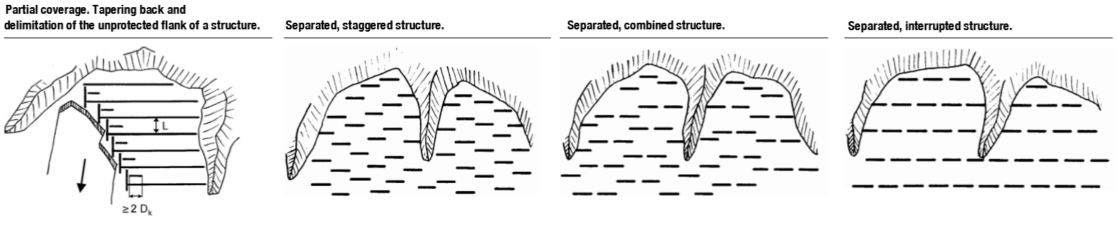


Figure 8: Alternative arrangement of structures [5]

Supporting structures must withstand the static snow pressure and also the dynamic forces, since a sliding layer of snow can occur. Withstanding the dynamic forces is highly influenced by suitable arrangement of the structures and the distance between the rows. This will ensure that the structures suffer no or very little damage from the dynamic forces. The distance between structures can be calculated using the Swiss guideline.

There are various companies offering systems of snow nets. In Europe, the sector is dominated by countries in the central region, especially the Alpine countries. The companies has through the years developed well-known products, and they have emphasized systems that are easy to install and easy to adapt to the topography. Since installation of the structures involves difficulties like high altitudes, steep slopes and different ground characteristics, simple and well-proven structural methods are essential for successful installation of the structures.

Starting from empirical production without theoretical foundation or structural design, great damage occurred to the first structures. Based on these experiences, the systems has been improved significantly in the course of time. Today, the structures are approximately four times as strong [13]. Among the leading suppliers are Trumer Schutzbauten GmbH, Geobrugg AG and Maccaferri. These companies have shared product data on their websites together with structural drawings. An example of the different structural elements proposed by Trumer is shown in figure 10.

In 1996, Trumer Schutzbauten GmbH started the development and production of the Omega-Net. This type of net consists of single, wave-like forebent wire ropes. The ropes are made of thickwired, galvanised spiral ropes. The net has proven to be capable of taking on high energy impacts, and thus it is used frequently in rock fall protection systems. Around 2000, high tensile steel wire mesh called TECCO was introduced in North America as another high-strength mesh alternative. These two net types are popular in the market today.

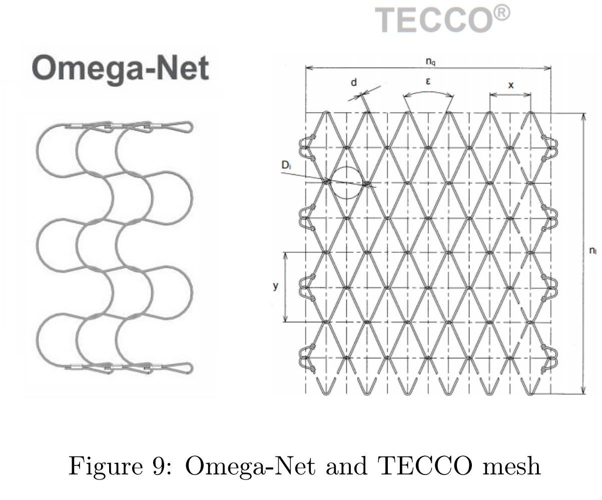


Figure 9: Omega-Net and TECCO mesh

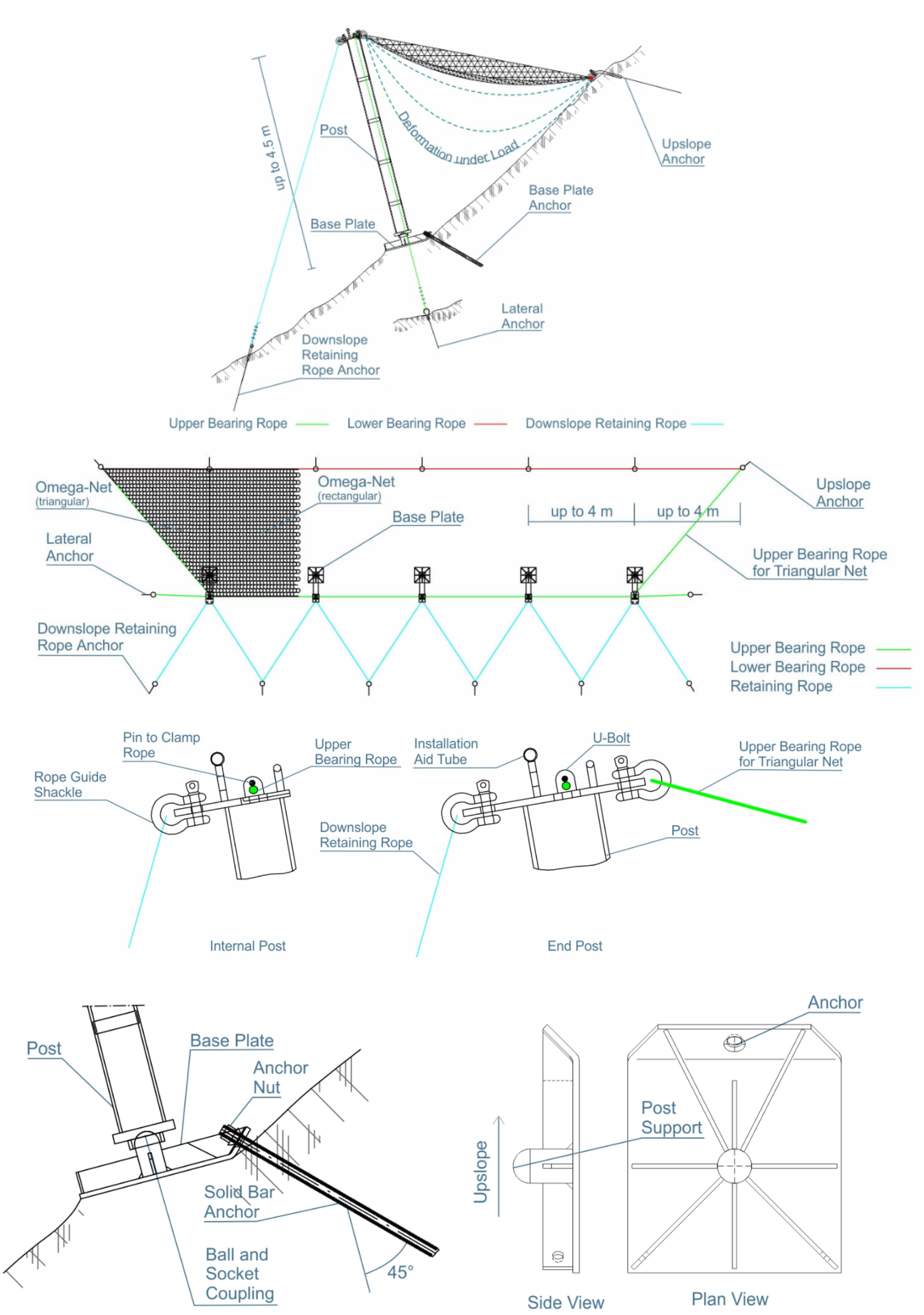


Figure 10: TS-LV Snow Net from Trumer Schutzbauten GmbH [14]

4 Basis of design

Structural design is the methodical investigation of the stability, strength and rigidity of structures [15]. The basic objective is to produce a structure capable of resisting all applied loads without failure during its intended life. The structural design of any structure first involves establishing the loading and other design conditions that must be considered in its design. This is followed by the analysis and computation of the structural response. Finally comes the selection of dimensions, materials and connections.

Many countries follow structural design codes, codes of practice or technical documents to obtain the necessary design conditions. In Europe, the Eurocodes are design codes which specifies how structural design should be conducted within the European Union. The Eurocodes are also implemented in Norway, where there are no other national standards used in parallel. But use of the Eurocodes in Norway is not obligatory. Other methods can be chosen, proving that they are technically equivalent [16].

As mentioned earlier, Norway and Switzerlad have been constructing technical guidelines since the mid 1900s. These guidelines represent a valid design source. Quoting from EN 1990 [17]: "The Eurocode standards provide common structural design rules for everyday use for the design of whole structures and component products of both a traditional and an innovative nature. Unusual forms of construction or design conditions are not specifically covered and additional expert consideration will be required by the designer in such cases." With this in mind, the technical guidelines are emphasized, especially reference [5]. This is the oldest and best established standard in the field of snow supporting structures in the starting zone.

4.1 Loading

Effects from snow pressure is complex and very varied, especially on flexible surfaces. In this thesis, it is mainly assumed that the loading applied by the snow mantel onto the structure can be assessed using technical guidelines. This is a standard design procedure and will permit a simpler design procedure. It is important to be aware of this assumption.

The loading that should be included in the design of the snow nets are:

- Snow pressure in the line of slope
- Weight of the snow
- End-effect loads

Based on the guideline, the snow pressure component normal to the slope S'_Q can be neglected for snow nets.

The guideline has based their calculation of snow pressure on a rigid supporting surface. However, snow pressure on a flexible surface can be reduced. The reduction is achieved by applying a reduction factor $f_s = 0.8$. This factor is dependant on the gliding motion, and also the construction of the net (e.g. wire sag, shape, inclination and mesh size). Snow pressure in the line of slope is then given by:

$$S'_N = f_s \cdot \rho g \frac{H^2}{2} K N \qquad \text{[kN/m']} \tag{8}$$

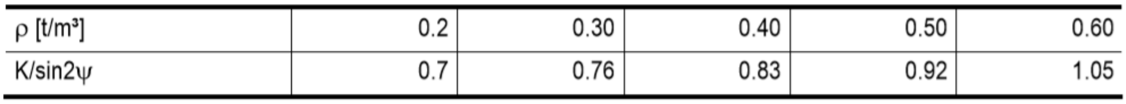
Here the altitude factor, which represents the generally observed increase in density with altitude, is neglected.

Average snow density is set to a uniform value of 270 kg/m^3 in the Swiss guideline. But as the guideline is based on the continental climate in the Alps, the Norwegians have made their own approach, which reflect maritime snow conditions. This mainly implies use of a higher snow density, which leads to greater pressure on the structures [18]. Snow density have been monitored by Norwegian Geotechnical Institute, NGI, from 1976 to 1990. Based on the study, a average density of 500 kg/m^3 is found to be appropriate for design [11].

Gliding in Norway is as mentioned earlier regarded minimal. The minimum value of the gliding factor N in the Swiss guideline is 1.2. This can be chosen for Norwegian adaptation. An alternative, is to use a relatively high gliding factor, which has essentially the same effect as a higher density. Observations and other relevant data from Iceland and Norway indicate that the most important difference between conditions in Iceland and those of Alpine countries is the higher snow density [19]. The ratio between the average density of snow in Norway and the one in the Swiss guideline is 500/270=1.85. Multiplying this value with the glide factor 1.2 gives a modified gliding factor of 2.2. This alternative can be used to adapt the Swiss guideline to maritime conditions, but this approach is not used in this thesis.

Vertical snow height at site of the structure should be determined from the design snow height at the construction area. It is recommended to use a return time of 100 years to determine this [18]. In most cases, long-period observations of snow heights at construction sites are not available, so that required measurement series must be taken from neighbouring observation stations.

The creep factor K can be found using the guideline, as shown in figure 11.



ρ [t/m³]	0.2	0.30	0.40	0.50	0.60
K/sin2ψ	0.7	0.76	0.83	0.92	1.05

Figure 11: Creep factor K as function of average snow density and slope inclination [5]

Alternatively can K be calculated from: [13]

$$K = (2.50\rho^3 - 1.86\rho^2 + 1.06\rho + 0.54) \cdot \sin 2\psi \tag{9}$$

The snow prism, whose weight G' must be added to the snow pressure, is formed by the net area, and the area normal to the slope passing through the upslope edge of the net, as shown in figure 12. To find the size of this load, the area of the deformed net is needed (shaded area in the figure). As this is unknown, further assumptions need to be made. Assuming a parabolic net shape with a sag of 15% of the cord, and with the use of basic calculus, can the area of the snow prism be found as $A_1 + A_2 = 0.5D^2 \tan\delta + 0.1D^2/\cos^2\delta$. Force decomposition in slope-parallel and slope-vertical components gives respectively $G'_N = G' \cdot \sin\psi$ and $G'_Q = G' \cdot \cos\psi$.

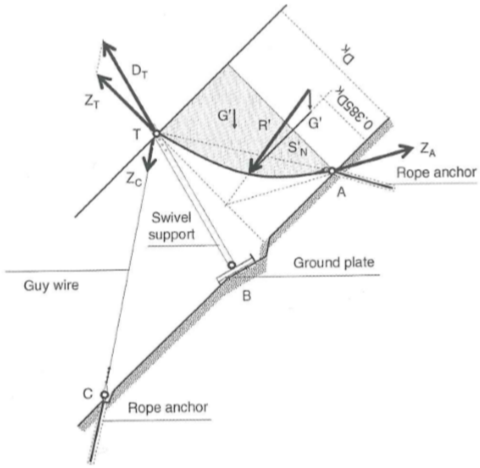


Figure 12: Snow pressure forces [13]

Size of the resulting snow pressure R' is calculated from the vector addition of the slope-parallel and slope-vertical components:

$$R' = \sqrt{{R'_N}^2 + {R'_Q}^2} = \sqrt{(S'_N + G'_N)^2 + (S'_Q + G'_Q)^2} \quad \text{[kN/m']} \qquad (10)$$

Direction of the resultant is calculated from:

$$\tan\varepsilon = \frac{R'_Q}{R'_N} \qquad (11)$$

End-effect load S'_R must be added to the slope-parallel components within its length of application. Note that in the area of the end-effect load, ε is smaller.

$$S'_R = f_R \cdot S'_N \qquad \text{[kN/m']} \qquad (12)$$

where f_R is the end-effect factor:

$$f_R = (0.92 + 0.65 \cdot N) \cdot \frac{A}{2} \leq 1 + 1.25 \cdot N \qquad (13)$$

where:

N = Glide factor
A = Distance between structures [m]

Length of the applied end-effect load can be found from:

$$\Delta l = 0.60 \cdot \frac{A}{2} \leq \frac{D}{3} \qquad [\text{m}] \quad (14)$$

where D is the effective net height.

Definitions of the different heights can be seen in figure 13. When the vertical snow height is determined, the effective net height can be found from $D = H \cdot \cos\psi$. B is the average height of the supporting surface normal to the contour line. When assuming the same parabolic net shape with a net sag of 15%, and with the use of theory computing the arc length of a function, can $B = 1.06 \cdot D/\cos\delta$ be found. δ is the angle between the supporting surface and the plane normal to the slope.

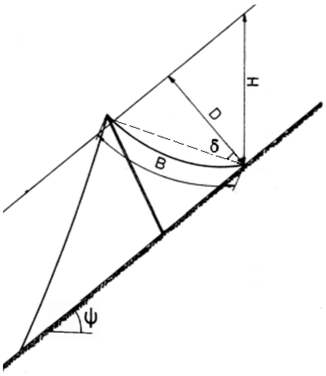


Figure 13: Definitions of heights and angles [5]

As mentioned earlier, the pressure distribution on the supporting surface is often irregular. This makes more stringent assumptions necessary for the specific loading on the grate. To find the specific snow pressure p_h normal to the grate, a pressure distribution over the grate by a settled snowpack with a snow height of 77% of the structure height is assumed. The specific snow pressure p_h is then:

$$p_h = \frac{R' \cdot \cos(\delta - \varepsilon)}{0.77 \cdot B} \qquad [\text{kN/m}^2] \quad (15)$$

The supports are also subjected to external forces due to snow masses attached to the underside of the structure. The Swiss guidelines introduces an influence factor η to describe the magnitude of this load. With heavy snow glide, this factor increases. Further is it assumed that the snow pressure on the supports q_s' can be assumed as a uniformly distributed line load with a direction normal to the axis of the support, as shown in figure 14:

$$q_s' = \eta \cdot S_N' \cdot \frac{\text{support diameter}}{\text{support length}} \cdot \sin\alpha \qquad [\text{kN/m}] \quad (16)$$

where:

S_N' = From equation 8
α = Angle between the support axis and the surface of the ground
η = Influence factor

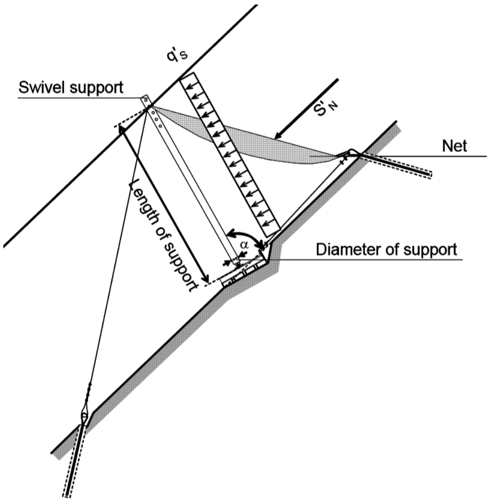


Figure 14: Snow pressure on supports [5]

Greatly increased end-effect forces act on slim objects such as supports. The width of action on these objects can be much larger than their actual width, because the snowpack can flow around the component from both sides. To include this effect, the influence factor η was introduced by Professor Robert Haefeli [13]. It can be calculated as follows:

$$\eta = 1 + c \cdot \frac{H}{W} \tag{17}$$

where:

c = Factor that varies between 0.6 for low gliding conditions to 6 for sites with extensive snow gliding
H = Snow height [m]
W = Component width [m]

4.2 Materials

Steel is the choice of material in this thesis. The guideline specifies the use of quality class JR or higher. The wires in the net and the wire rope anchors must be zinc plated as specified in EN 10264, respectively Class B and Class A, or alternatively galvanized as specified in DIN 2078. For wire rope anchors located in a chemically aggressive environment, additional corrosion protection must be provided.

4.3 Analysis

Requirements to the structural analysis is that the internal forces must be determined elastically, and that the structure must be supported on statically determined bearings. In practice, this means hinged connections.

5 Design

For the structural analysis and dimensioning, only the ultimate limit state of the structures must be verified. Proof of the serviceability is not required. But the service life of the materials used, must accord with the intended duration of use. The loads presented are regarded as characteristic values. With the use of partial factor method, the ultimate limit state is verified with the following design criterion:

$$E_d \leq R_d \tag{18}$$

where: $E_d = \gamma_Q Q_k =$ Design effect of actions (loading)
$R_d = R_k/\gamma_M =$ Design resistance
$Q_k =$ Characteristic value of the variable action
$R_k =$ Characteristic value of the resistance
$\gamma_Q = 1.5 =$ Load coefficient
$\gamma_M =$ Coefficient of resistance
$\gamma_{M1} = 1.05$ For steel strength and stability approval purposes
$\gamma_{M2} = 1.25$ For steel connections and verification in net section
$\gamma_{M3} = 1.35$ For wire ropes

5.1 Action

The supporting structures should according to the guideline be verified for two different load cases:

- Case 1: Full snow loading with snow height H
- Case 2: Partial snow loading with snow height $0.77 \cdot H$. R' have the same magnitude and direction as with load case 1, but different point of action.

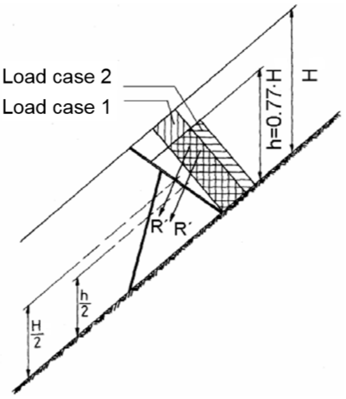


Figure 15: Points of action for resultants and snow pressure distribution for the two load cases [5]

The background for these two load cases is experience, as the resultant snow pressure is found approximately in the middle portion of the snowpack. But as the snowpack becomes wet and dense during spring, the resultant force appears to act lower on the structure [12]. For this reason, it is differentiated in two load cases.

5.2 Resistance

To verify the resistance, a capacity check of the different structural elements needs to be verified. The capacity check of the poles can easily be done with the use of *Eurocode 3: Design of steel structures*, when internal forces like moments, axial and shear forces are known. Verifying the wire ropes is a bit more complicated.

A wire rope is a structure made up of layers of strands wrapped helically around a central straight strand core, while a strand is a structure made up of layers of helical wires wound around a central core of a straight wire. Therefore, in a wire rope, only the central wire core of the core strand is straight. The outer wires of the core strand and the central core wires of all other strands are single helices, while remaining wires in outer strands take on the forms of a double helix [20].

This makes it more complicated, and the section properties of the wires can not be found in the same ways as for straight, simple rods. To find the necessary design information *Eurocode 3 - Design of steel structures - Part 1-11: Design of structures with tension components* can be used. The code divides the different tension elements in groups, e.g. rods, spiral strand ropes or parallel wire strands. Each group has their own design directives. Common for all is that in ULS, applied axial loads shall not exceed the design tension resistance. The tension resistance is found using the section and material properties for the corresponding tension element. Despite being a bit more complicated, this verification is still a straightforward operation once the design force in the wires are known.

Elastic modulus is a measure of the stiffness of a solid material. It is a mechanical property of linear elastic solid materials [21]. For steel wire ropes the E-modulus is more of a construction constant, than a material constant. The modulus of elasticity varies with different rope constructions. Due to specific manufacturing factors, wire dimensions and other factors, the E-modulus varies between different wire ropes of the same construction and dimension [22]. In this thesis, it is selected a E-modulus of 150 000 N/mm^2. This is close to typical values.

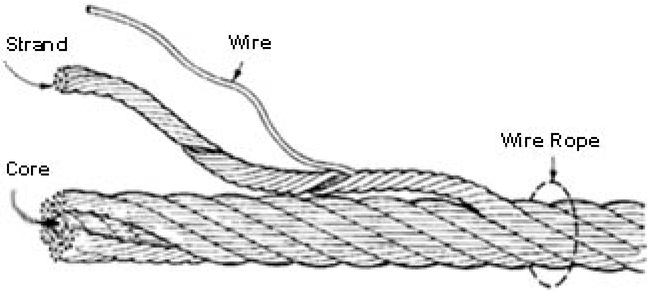


Figure 16: Wire rope

6 Design using simplified model

Theoretical basis for a simplified two-dimensional static of snow nets was made by Professor Robert Haefeli. In accordance therewith, a section across the snow net is examined and the net is replaced by a parabola. Furthermore, it is assumed that the sag of the net is carried out in such a way that at the support head the tangents to the net parabola is perpendicular on the ground. Thereby, using the resulting snow pressure, it is possible to calculate the sizes of the wire end forces and the direction of the wire end force on the upslope anchor [13]. It is then possible to use the wire end force to find the remaining unknown forces in the structure.

Traction S in the net can be calculated using the specific snow pressure p'_H:

$$S = \sqrt{S_H^2 + S_V^2} = \sqrt{\left(\frac{p'_H \cdot s^2}{8 \cdot f}\right)^2 + \left(\frac{p'_H \cdot s}{2}\right)^2} \qquad \text{[kN]} \quad (19)$$

where:

p'_H = Linear normal load of the snow pressure. Calculated using the specific snow pressure from equation (15) with corresponding net width [kN/m']
s = Length of the wire chord [m]
f = Wire sag [m]

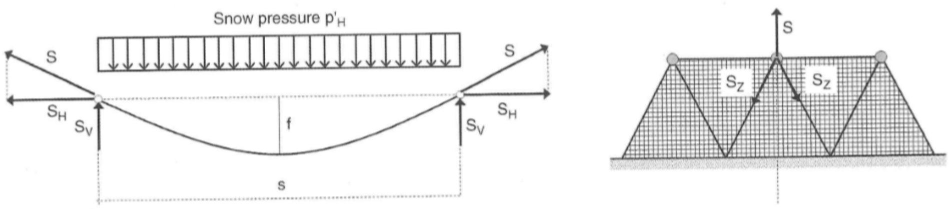


Figure 17: Calculation of the wire tension and internal forces [13]

A net sag of 15% of the net cord has proven to be effective. Note that for smaller sagging, the force increases greatly, and with excessive sagging the net can touch the supports. With this sag can (19) be written:

$$S = 0.97 \cdot p'_H \cdot s \qquad \text{[kN]} \quad (20)$$

7 Design using numerical software

This method [23] is based on the mechanical balance of cable structures, inspired by concepts from solid mechanics [24]. It has led to the development of computational software where the objective is to find the strained geometrical shape of the net, because it strongly influences the distribution of forces in the structure.

Interaction between the snow mantel and the structure is assumed to be uncoupled, and the loading applied by the snow mantel onto the structure is found using the Swiss guidelines [5], as described in earlier chapters. A difference to the loads described earlier is the weight of the snow prism. In this method, the surface of the snow prism between the bow of the net and the normal direction to the ground surface, is calculated, and not assumed.

The main structural elements is composed as explained in section 3, and as shown in figure 18. It is assumed that every panel has an isosceles geometrical shape, defined by three perimeter wires where the base side is distinguished from the two lateral sides. The two lateral perimeter wires of every panel located at the end are called external lateral wires. The other ones are called internal wires.

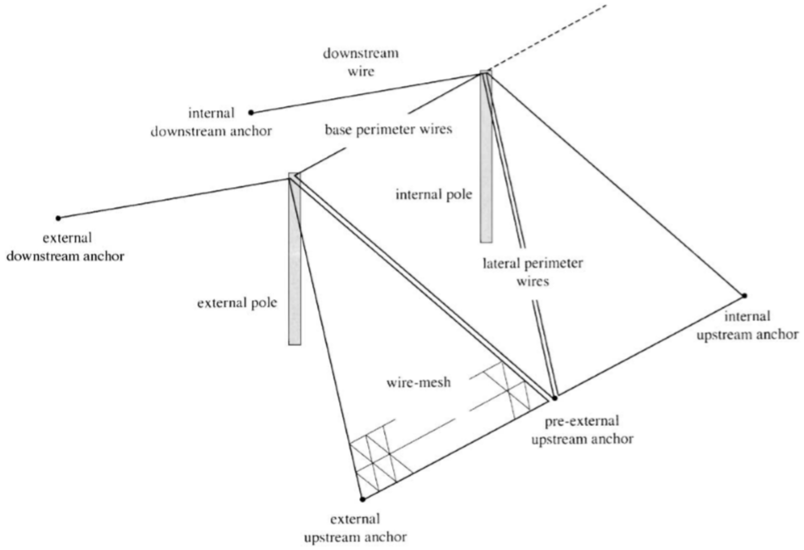


Figure 18: Technological elements of the structure [23]

A plane (Π) can describe the ground surface, and the set of developed equations can be written in the orthonormal base ($\vec{i}, \vec{j}, \vec{k}$):

$\vec{i}$ = Direction of the main slope of Π
$\vec{j}$ = Horizontal direction of Π
$\vec{k}$ = Normal direction of the plane Π

Every perimeter wire is submitted to a distribution of forces from the net. This vectorial distribution is assumed to be uniform. Further, it may be assumed that the

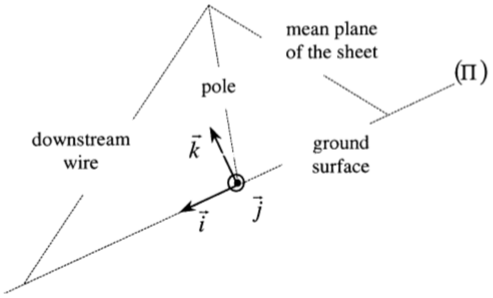


Figure 19: Definition of the orthonormal base [23]

vectorial loading applied to base perimeter wires belongs to the direction $\vec{u}$, where $\vec{u}$ is the initial direction of the slope of every panel. Vectorial loading applied to lateral perimeter wires belongs to the direction $\vec{w}$. Direction of the loading applied by the snow mantel is described by $\vec{v}$. This vector belongs to the vertical plane defined by vectors $\vec{i}$ and $\vec{k}$.

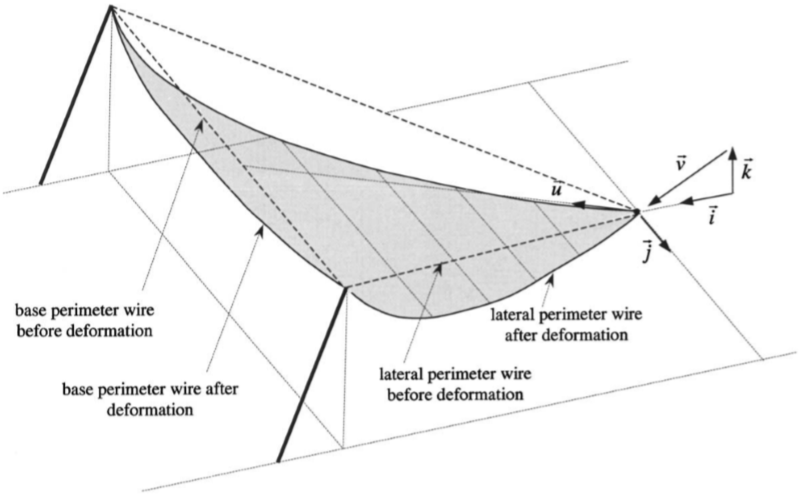


Figure 20: Geometric shape of a strained net [23]

With the assumptions made, and taking the mechanical balance of the net sheets, can equations for determination of a uniform pressure applied to the internal and external perimeter wires be found. The reader is advised to check reference [23] for a more detailed explanation, and to find the obtained equations. This is neglected, because the method has not been tested by the author of this document.

To understand the mechanical analysis of the whole structure, the mechanics of a single wire fixed at both ends, loaded by a uniform pressure, is essential. Initially, the wire is straight. Submitted to the loading, the wire is strained and its arc shape is described by an equation $y = f(x)$. The angle θ is defined by the equation:

$$\tan\theta = \frac{dy}{dx} \tag{21}$$

Mechanical analysis of a small wire provides the following relations:

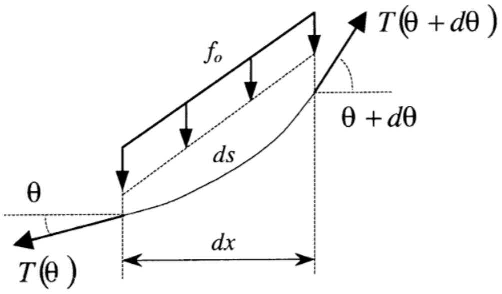


Figure 21: Mechanical balance of a small wire [23]

$$\frac{d}{dx}(T(\theta)\cos\theta) = 0 \tag{22}$$

$$\frac{d}{dx}(T(\theta)\sin\theta) = f_o \cdot \frac{ds}{dx} \tag{23}$$

Integration of equation 22 gives:

$$T(\theta) = \frac{\mu}{\cos\theta} \tag{24}$$

where μ is a constant.

For an infinitesimally small line, we have $ds^2 = dx^2 + dy^2$, which gives:

$$\frac{ds}{dx} = \sqrt{1 + y'^2} \tag{25}$$

Combining the equations gives the differential equation of the catenary:

$$\frac{y''}{\sqrt{1 + y'^2}} = \frac{f_o}{\mu} \tag{26}$$

A catenary is the curve that an idealized hanging chain or cable assumes under its own weight when supported only at its ends. The catenary curve has a U-like shape, very similar to a parabolic arch, but it is not a parabola. The catenary curve is the graph of the hyperbolic cosine function [25], and this function is the solution of the differential equation.

Further, is it through Hooke's law possible to write a relation between the lengthening of the wire and the force in the wire. Based on this, the previous equations and some more assumptions, the set of equations provides a complete mechanical analysis of perimeter wires. Again, the reader is advised to check reference [23] for a more detailed explanation. This mechanical analysis is possible to solve through a numerical process. When the forces in the perimeter wires is known, the forces transferred to the poles and anchors can be found.

8 Design using DEM

The discrete element method is a numerical tool originally designed to describe the behaviour of granular media, and most of its application remain still in that field [26]. Snow can be described as a granular medium. A granular material is a conglomeration of discrete solid, macroscopic particles characterized by a loss of energy whenever the particles interact [27]. After snowfall have occurred, gravity effects occur and the physical structure of the snowpack changes in interaction with the ground and the meteorological conditions. Rather rapidly, initial snow crystals are transformed into ice grains and the resulting snow cover can be considered as a porous material made of ice grains and air. Each ice grain can be modelled as a rigid particle, and between neighbouring grains, contacts may occur and solid bonds may be created [28].

DEM is also well adapted to large displacements. This is beneficial for modelling flexible protection structures, where huge strains may occur during loading. DEM models is therefore much recommended since the loading can be more easily modelled in the same media as the protection structure. This allows for a coupled analysis of both the net structure and the snow mantle. It has been developed a method to design snow nets by using a DEM approach [29]. This approach introduces concepts from both solid mechanics and numerical modelling.

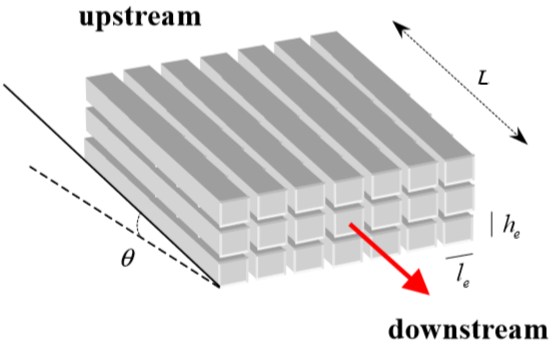


Figure 22: Spatial description of the snow mantle [29]

Consider the case of a stratified snowpack, located above a net structure, and laying on a uniform slope θ. The snowpack is assumed to have uniform properties with length L, width l, height H and is composed of layers. By denoting h_e, l_e and L, respectively the height, the width and the length of each snow element, the volume V_e is given by the relation:

$$V_e = h_e \cdot l_e \cdot L \tag{27}$$

Each snow element I is in contact with four other neighbouring elements. It is submitted to the action of both its weight and a set of four contact forces $T_I(i)$. If the element is in contact with a node belonging to the net sheet, it is submitted in addition to a reaction force R_I. If not, then $R_I = 0$.

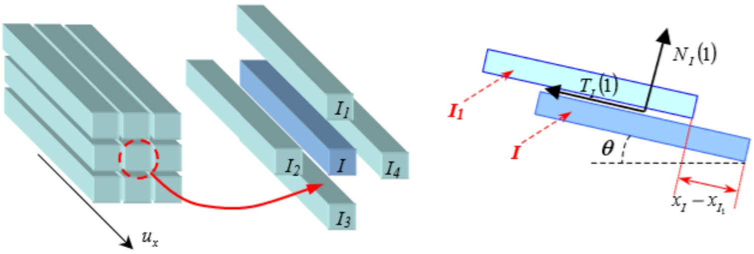


Figure 23: Description of snow elements [29]

The kinematics of each snow element is completely described by a single parameter x_I, which represents the total displacement of element I in direction u_x. Force equilibrium gives:

$$\rho V_e \cdot \ddot{x}_I = \rho g V_e \sin\theta + \sum_{i=1}^{4} T_I(i) + R_I \tag{28}$$

The contact force $T_I(i)$ is computed by integrating the shear stress $\tau_I(i)$ along the surface at the interface of the two elements I and I_i. The shear contact law that should be modelled is explained in detail in reference [30].

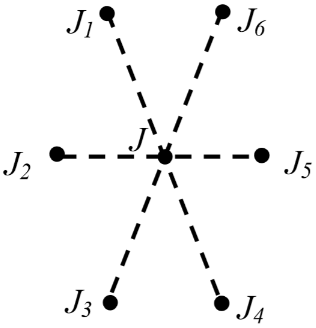


Figure 24: Set of neighbouring nodes in the net sheet [29]

It is assumed that the net has an isosceles geometrical shape. Each node J belonging to the net sheet is therefore connected to six neighbouring nodes J_j. In each wire joining neighbouring nodes J and J_j acts an elastic force $F_J(j)$. The mass of the net sheet is assumed equally concentrated into each node, and denoted m. The vectorial location x_J of node J, in contact with snow element I, is given by:

$$m\ddot{x}_J = mg + \sum_{j=1}^{6} F_J(j) - R_I u_x \tag{29}$$

with:

$$F_J(j) = EA \frac{\| x_{Jj} - x_J \| - l_{oj}}{l_{oj}} \frac{x_{Jj} - x_J}{\| x_{Jj} - x_J \|} \tag{30}$$

where:

E = Elastic modulus of the steel
A = Cross section of the wire
l_{oj} = Initial length of the wires

It is here assumed that each single wire belonging to the strained sheet keeps a linear geometrical shape between two intersection points.

Further, is it assumed that during contact between a snow element I and a node J, the node does not penetrate into the element I. Thus, at each time, the incremental displacements of the two bodies I and J in direction u_x are equal:

$$dx_j \cdot u_x = dx_I \tag{31}$$

This kinematic condition allows reaction force R_I to be computed. Numerically, the equations can be solved using a finite-difference method. This method has not been tested by the author of this document.

9 Design using FEM

Finite element method is the leading method in computer-oriented mechanics. The basic idea in the method is to divide a system with a complex behaviour into subsystems with "known" behaviour. The subsystems consist of elements connected at nodes. Elements are further assembled into a system by requiring kinematic compatibility and static equilibrium at all nodes. This discretization process has transformed the mathematical problem from differential equations, into a finite set of linear, algebraic equations [31].

Many different, commercial finite element softwares can be used for analysis. Each program has its advantages and limitations. Due to the authors experience with Robot Structural Analysis 2018 [32], it is decided to use this software in this thesis.

Modelling of the snow nets can be done in various ways. At first, it is natural to model the poles with beam elements. The poles are subjected to axial, bending and shear forces, and this is exactly what the beam elements are capable of taking. Thus, this will be a correct representation of their structural behaviour. Secondly, with the wire-ropes and the net, it seems logical to model them using cable elements. Wires can only take tension, and they have no bending or torsional rigidity. Selection of cable elements in the software is therefore a possibility. But despite the good characterization of the structural behaviour using cable elements, it introduces difficulties.

Cable element theory in Robot is based on the general theory of cables with a small value of sag. According to this theory, cable rigidity is an implicit function of cable tension rigidity, pretension, support displacements and transverse loading in both directions. Because of the non-linearity of the cable element, its definition in the structure requires applying iterative methods of structure analysis [33]. The cable elements can be used together with the beam element, and thus the poles and characterize the behaviour of the perimeter wires very well. But the problem occurs when introducing the wire mesh. To correctly model the wire mesh, it needs to be attached to the perimeter wires. The problem with the cable elements in Robot, is that attaching other elements in between the cable is not possible. It only registers connection to other elements in the start or end node. For this reason, other elements need to be used to model the structure.

An alternative approach is to model the whole structure using beam elements. Doing this without restriction, the structural analysis is based on linear statics, and the structural response will be dominated by a bending behaviour. This will not be a correct representation of the structure, as in real life this can not transfer any moments. Since the structure is flexible, and have the ability to deform considerably, introduction of non-linear analysis with large displacements needs to be done. This will also introduce the important effects of axial forces in the structure, which is absolutely significant, as this is the structures way to take up the forces. The approach can be shown using an example.

Consider a straight wire element with cross-sectional area of 113 mm^2, length of 5 m and obviously a pinned connection at both ends. The wire is subjected to its self-weight. A model of the structure using a cable element and a 2-noded beam element calculated using linear statics is shown in figure 25. The results is quite different. The correct one is the one modelled as a cable.

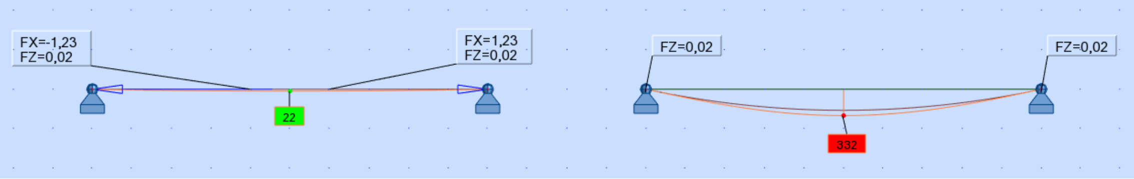


Figure 25: Cable and 2-noded beam element analyzed using linear statics

From the figure, it can be seen that the influence of axial forces in the beam model is not taken into account. To achieve this, changing the analysis to non-linear analysis taken into account large displacements needs to be done. But as the element is 2-noded, and since these nodes are fixed, the axial forces in the structure will still not be introduced. This is solved by applying a node within the element. Doing this, gives very good results. But the largest displacement should be in the midspan, and this is not the case as seen in figure 26.

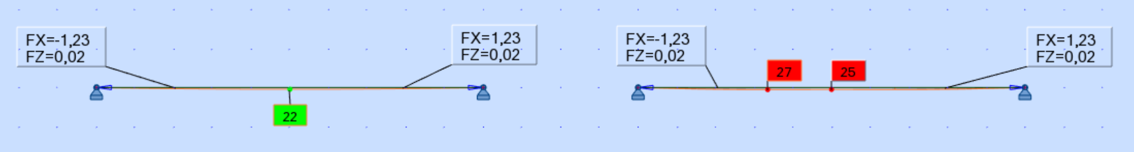


Figure 26: Cable and 3-noded beam element analyzed using non-linear statics

Dividing the element in more parts, and generating more nodes within the element is the solution to avoid this. But this will introduce a convergence problem when running the analysis. The default parameters for the non-linear analysis, the incremental method, is matrix update after each subdivision. Changing this to matrix update after each iteration solves the convergence problem. The solution method by direct substitution is often inefficient, and is more likely to encounter convergence difficulties than tangent stiffness methods [34]. Increasing the load increment number is also relevant to avoid the convergence problem.

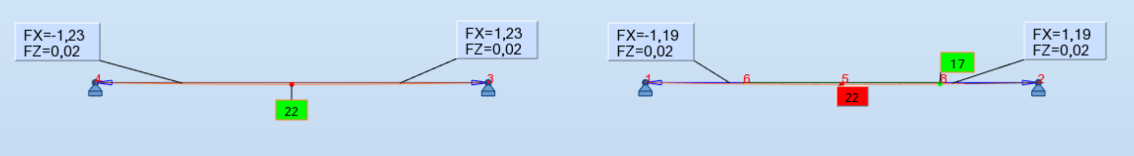


Figure 27: Cable and 5-noded beam element analyzed using non-linear statics

Deformation and reaction forces for the beam element is now matching fairly well with the cable element. But as this is only checked for a straight cable element, it needs to be checked for arch shaped elements. The engineering approach to curved structures has been to approximate the curved line with a series of straight lines. Results using respectively the cable and the arch gives again the approximate same answers. Thus, for these reasons, the whole structure is modelled using beam elements.

For the modelling of the whole structure, it is convenient to use parametric modelling. The many elements in the wire mesh, in combination with their arch shape, makes it difficult to model the structure by a standard approach. Dynamo is a plug-in for Robot, and allows for creation of parametric and complex structural frame models. The modelling is done in Dynamo using visual programming, and then submitted to Robot for further analysis. In this thesis, creation of both a parametric model of a standard rectangular and triangular net type has been made.

The problem could also be investigated using specially designed software for calculation of flexible structures exposed to static and dynamic loads. This has been developed in several different fields. In the aquaculture industry, there is large, flexible structure subjected to forces from wind and waves. AquaSim is at the forefront of advanced analysis tools for flexible constructions, and is based on many years of research from NTNU in marine structures and building technology. AquaSim arose when there was a need for an analysis tool that provided the ability to simulate structures that deform strongly under load from wind and waves. In such cases, traditional analysis tools, where the structures are considered rigid, could produce very incorrect results. AquaSim has been validated and used commercially for more than a decade, and is the leading tool for the aquaculture industry in Norway [35]. The same software can be used for the modelling of the snow nets, but is not tried out in this thesis due to lack of time.

10 Field experiments

In order to measure internal forces and check calculated values, snow nets have been instrumented in France [23], Iceland [36] and Austria [37]. At the sites, snow tests were carried out in order to characterize the snowpack. But due to the authors lack of all necessary technical information about the test structures, direct comparison with calculations and measured values has not been possible in this thesis. It is therefore focused on a interpretation of the measured values, and the lessons learned from the performance of the structures.

10.1 Flaine, France

During the 1998-1999 winter, several snow avalanche net structures were monitored in the French Alps. The analysis of the experimental results showed that results from the test site of Flaine provided the most reliable and usable results, and therefore data from this site were chosen for analysis [23]. The site is located at an altitude of 2050 m and faces west. The slope above the structure is approximately 35°. The structure consists of 7 poles with distance between poles equal to 3.5 m. The height of the net sheet is equal to 4 m. Every pole has a diameter equal to 168.3 mm and a thickness 4.5 mm.

Force sensors were mounted in order to record the forces acting in the upstream anchors. The maximum force was recorded during winter 2000-2001 and was equal to 126 kN.

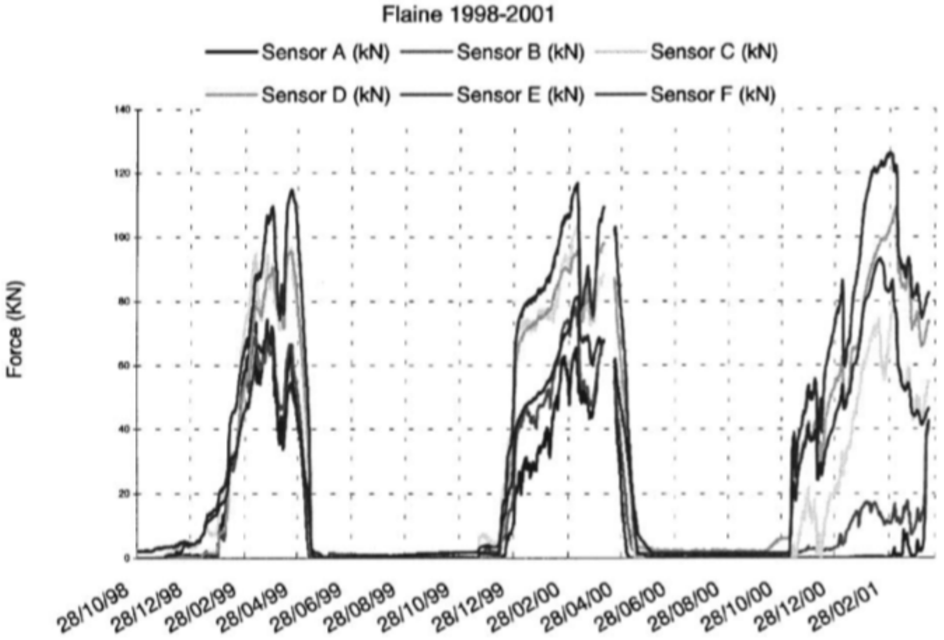


Figure 28: Recorded forces from 1998-2001 [23]

10.2 Hafelekar, Austria

In the autumn of 2006 in Austria, a test site at the Hafelekar above Innsbruck was installed to analyze the snow net systems of different companies. The site was located at 2250 m altitude. The records of the ski station in the area indicated an average snow height of about 3 m, and a maximum up to 6 m. The slope faced south with an inclination of 38°. Three different types of snow nets were built to comparison: two triangular net types and one rectangular [37].

Based on the study, the calculations using the simplified method of Haefeli with a snow pressure on the nets according to the Swiss guideline, was found to be higher than the corresponding measured values.

10.3 Siglufjörður, Iceland

In the autumn 1996 above the village of Siglufjörður in northern Iceland, experiments on steel bridges and snow nets started. The structures were located at 490-530 m altitude arranged in four rows. Two of the rows consisted of snow nets. The snow depth perpendicular to terrain *D* was in the range 3 to 5 m.

Tension in upper anchors and compressive forces and moments in a post of the snow nets were measured with continuously recording instruments. The maximum tension measured in upper anchors of the snow nets was approximately 350 kN while the maximum compressive force and moment in the snow net post was approximately 150 kN and 15 kNm, respectively. The maximum snow pressure on the steel bridges averaged over the whole construction was inferred to be approximately 30 kPa. The equivalent average snow density for loading computations was found to be 400-500 kg/m^3 during most of the winter [36].

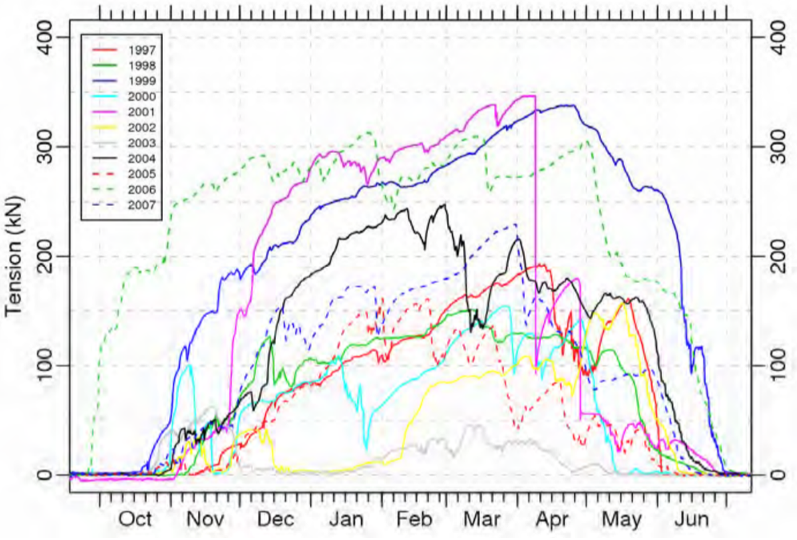


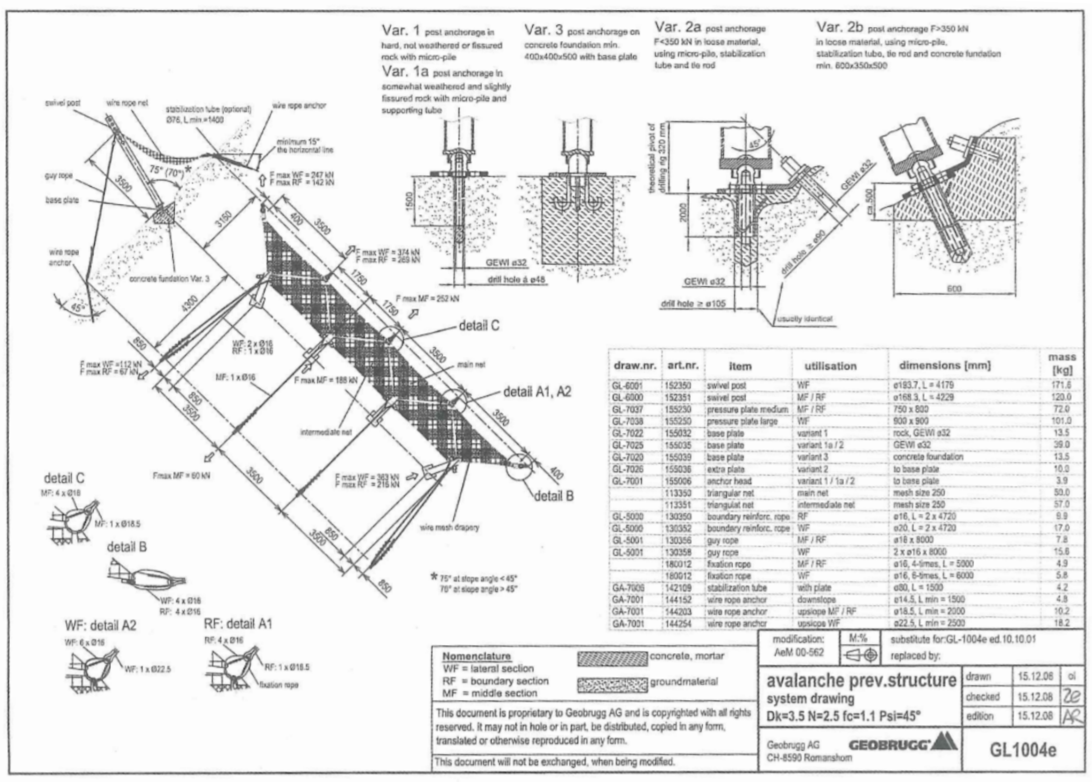
Figure 29: Measured tension in an uphill anchor [36]

11 Calculations

In this chapter, calculations with the use of the simplified Haefeli's method and FEM is explained. A example structure is created, aiming to emulate the field experiments in chapter 10. This is done for comparison purposes. Due to lack of all the necessary parameters to correctly model the different test structures, only the example structure is calculated. Modelling of the structure is done in Dynamo using visual programming, and then submitted to Robot for the analysis.

11.1 Example structure

It is selected to model an example structure from a structural drawing made by Geobrugg found in reference [13].



draw.nr.	art.nr.	item	utilisation	dimensions [mm]	mass [kg]
GL-6001	152350	swivel post	WF	ø193.7, L = 4179	171.6
GL-6000	152351	swivel post	MF / RF	ø168.3, L = 4229	120.0
GL-7037	155230	pressure plate medium	MF / RF	750 x 800	72.0
GL-7038	155250	pressure plate large	WF	900 x 900	101.0
GL-7022	155032	base plate	variant 1	rock, GEWI ø32	13.5
GL-7025	155035	base plate	variant 1a / 2	GEWI ø32	39.0
GL-7020	155039	base plate	variant 3	concrete foundation	13.5
GL-7026	155036	extra plate	variant 2	to base plate	10.0
GL-7001	155006	anchor head	variant 1 / 1a / 2	to base plate	3.9
	113350	triangular net	main net	mesh size 250	50.0
	113351	triangulat net	intermediate net	mesh size 250	57.0
GL-5000	130350	boundary reinforc. rope	RF	ø16, L = 2 x 4720	9.9
GL-5000	130352	boundery reinforc. rope	WF	ø20, L = 2 x 4720	17.0
GL-5001	130356	guy rope	MF / RF	ø18 x 8000	7.8
GL-5001	130358	guy rope	WF	2 x ø16 x 8000	15.6
	180012	fixation rope	MF / RF	ø16, 4-times, L = 5000	4.9
	180012	fixation rope	WF	ø16, 6-times, L = 6000	5.8
GA-7006	142109	stabilization tube	with plate	ø80, L = 1500	4.2
GA-7001	144152	wire rope anchor	downslope	ø14.5, L min = 1500	4.8
GA-7001	144203	wire rope anchor	upslope MF / RF	ø18.5, L min = 2000	10.2
GA-7001	144254	wire rope anchor	upslope WF	ø22.5, L min = 2500	18.2

Nomenclature
WF = lateral section
RF = boundary section
MF = middle section

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Figure 30: Structural drawing by Geobrugg found in reference [13]

Table 1: Parameters for modelling of structure

Parameter description	**Value**	**Symbol**
Slope angle	45°	ψ
Snow height perpendicular to terrain	3.50 m	D
Distance to upslope anchor	3.15 m	
Distance to downslope anchor	4.30 m	
Number of poles	4	
Distance between poles	3.50 m	L
Angle between support axis and ground surface	75°	α
Pole profile	HEA-220	
Guyropes	Ø20 mm	
Perimeter wires	Ø24 mm	
Mesh wires and size	Ø6 mm / 250 mm	

Table 2: Parameters for load calculations

Parameter description	**Value**	**Symbol**
Snow density	500 $\mathrm{kg/m^3}$	ρ
Vertical snow height	5 m	$H = D/\cos\psi$
Glide factor	1.2	N

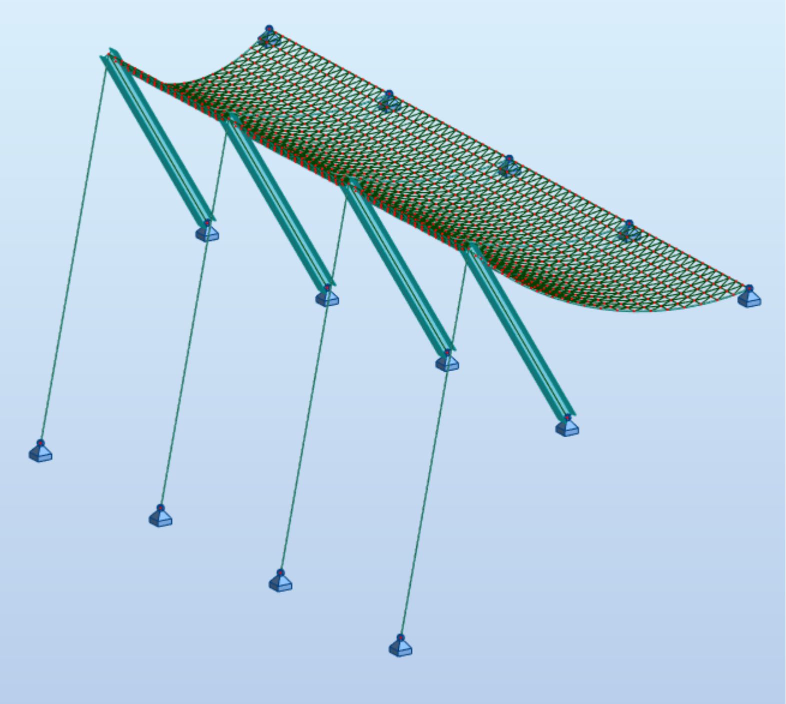


Figure 31: Structural model in Robot

After running calculations, it is seen that pre-external anchors are the most loaded ones, whereas external anchors are the least loaded ones. This point is in agreement with experimental measures from Flaine. It is obvious that this is the case, as the pre-external anchors are subjected to the high end-effect loads. The external anchors is also subjected to these, but as this point only takes "half" the load due to being at the end of the structure, this takes up the least load.

Further, it is seen that load case 1 introduced the highest forces in the pole, while load case 2 gives higher reaction forces in the down- and upslope anchors. For load case 1, the external load is closer to the pole end, compared to load case 2. Since the external load will travel the "shortest" way to the ground, this load case gives the highest forces in the poles. Similarly for load case 2, the external load is closer to the upslope anchor. This results in higher tensile forces in the structure, thus higher forces will be experienced in the anchors.

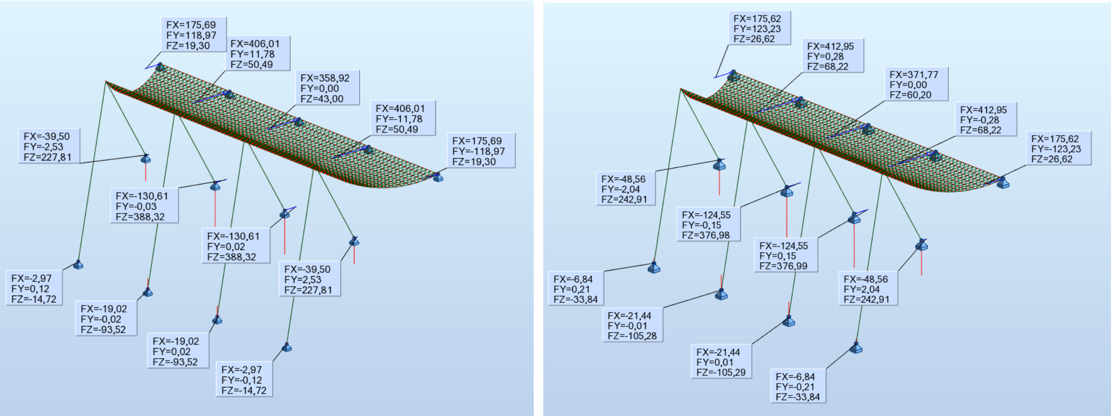


Figure 32: Reaction forces: Load case 1 and 2

Using FEM, the highest reaction force in the upslope anchors is found to be about 420 kN. Calculation using Haefeli's method gives:

$$S = 0.97 \cdot p'_H \cdot s = 0.97 \cdot \frac{p_h + p_{hR}}{2} \cdot L \cdot \frac{D}{\cos \delta} = 435kN$$

As seen, this is very close to the FEM-calculated value. The simplified method is very effective compared to the complicated non-linear analysis in the software. As experienced in the study in Hafelekar, the calculations using the simplified method of Haefeli gives a higher force than the corresponding measured values. In other words, the method is conservative, but as seen it gives quite nice results as the FE-analysis does. Because of their easy usage, calculation of snow nets using Haefeli's theory has been very common [13].

Maximum tension force in the perimeter wires is found to be 225 kN using FEM. Haefeli's method gives, using force decomposition:

$$F = \frac{S}{2} \cdot \frac{\sqrt{(\frac{L}{2})^2 + (\frac{D}{\cos \delta})^2}}{\frac{D}{\cos \delta}} = 236kN$$

Using graphic statics, forces transferred to the guywires R_1, and poles R_2, can be found. The results are $R_1 = 200kN$ and $R_2 = 560kN$. Compared with the FEM-values, respectively 105 kN and 400 kN, the results are quite conservative.

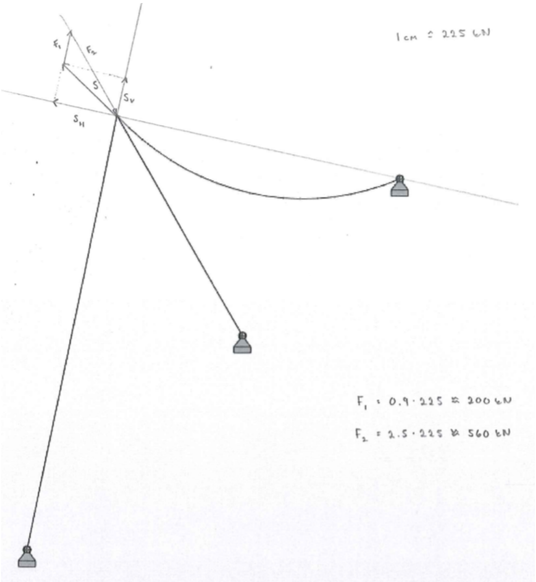


Figure 33: Forces transferred to guywires and poles using graphic statics

Table 3: Maximum forces in kN from FEM and Haefeli calculations

	FEM	**Haefeli**	**Haefeli-FEM-ratio**
Upslope anchor	420	435	1.04
Perimeter wire	225	236	1.05
Pole	400	560	1.40
Guywire	105	200	1.90

As seen in table 3, Haefeli's method gives higher forces compared to FEM. For the upslope anchor and the perimeter wire, the forces are very similar. In the pole and guywire however, the forces are quite different, and this is a interesting result. It looks like the difference in values increase in distance from the upslope anchor.

Without the uniformly distributed line load on the support, the poles will only be subjected to compression, assuming no eccentricity from the guywire or net into the pole. However, the line load will introduce moments in the pole. In the FEM approach, load on the support is applied in the same load case as the load on the net. Differentiating in two load cases, and later combining them, introduces difficulties. In non-linear problems, the principle of superposition does not apply. Each different load case requires a separate analysis. Also, for a given set of loads there may be more than one solution. If load cases are sequentially applied, reversing the sequence of application may produce different results [34]. For simplicity, considerations regarding this is not taken into account. Loads on the support and net are thus applied in the same load case.

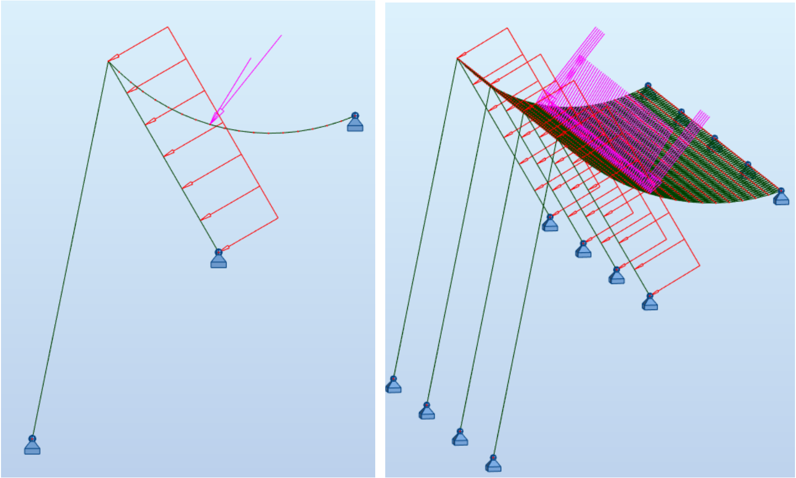


Figure 34: Snow loading on structure

Assuming that superposition can be applied when using Haefeli's method, the moments in the pole can be found by known statics of a beam subjected to a uniformly distributed line load. The FE-analysis gives a maximum moment in the pole of 70 kNm. From linear statics, the moment can be found from:

$$M = \frac{q_s' \cdot L_s^2}{8} = \frac{45 \cdot 3.6^2}{8} = 73\mathrm{kNm}$$

This is a relatively large moment, especially when compared with the experiment in Siglufjörður in Iceland, which had a moment of 15 kNm. This is only 20 % of the calculated one. Obviously, these two moments can not be directly compared because of different design conditions and structural properties. But the significant difference can be explained, with that the calculations is based on the design situation. This is related to extreme values, and this can not be expected during the field experiment. For design of the poles, the moments is essential. The huge moment, in combination with the compression, is the design situation for the poles. It can therefore be argued that the moment load is large because of increased structural safety.

Maximum stress in the wire mesh is found to be about 1950 N/mm^2. This is over the acceptable value. Wires with a tensile strength of 1770 N/mm^2, has an ultimate strength of 1770/1.35=1310 N/mm^2. As this limit is obviously passed, the solution is either to increase the wire size or tightening the mesh. Generation of a mesh of 135x135 mm, in other words dividing the mesh in two (calculations are based on a 250 mm mesh), will be a solution to reduce the stresses in the structure. But the deformation shape and stress distribution in the structure from the FE-analysis, shows huge signs of incorrectly modelling. This is very important, and will be explained more in the next chapter.

Example structure

Parameters of structure:

$\psi := 45\ deg$	Slope angle
$D := 3.5\ m$	Snow depth perpendicular to terrain
$L_1 := 3.15\ m$	Distance to upslope anchor
$L_2 := 4.3\ m$	Distance to downslope anchor
$L := 3.5\ m$	Distance between poles
$N_{pol} := 4$	Number of poles
$L_L := N_{pol} \cdot L = 14\ m$	Length of structure
$\alpha := 75\ deg$	Angle between the support axis and the surface of the ground
$L_s := \dfrac{D}{\sin(\alpha)} = 3.623\ m$	Length of support
$d := 220\ mm$	Pole width
$\delta := \operatorname{atan}\left(\dfrac{L_1 - \dfrac{D}{\tan(\alpha)}}{D}\right) = 32.295\ deg$	Angle between the supporting surface and the plane normal to the slope

Parameters for calculation:

$\rho := 500\ \dfrac{kg}{m^3}$	Average snow density
$g = 9.807\ \dfrac{N}{kg}$	Gravitational acceleration
$H := \dfrac{D}{\cos(\psi)} = 4.95\ m$	Vertical snow height at site of structure
$N := 1.2$	Glide factor
$A := 3\ m$	Distance between structures (rows)

Load calculations:

$$\sigma_x := \rho \cdot g \cdot D \cdot \left(\sqrt{\left(3.125\ \left(0.25 \cdot \sqrt{\sin(\psi)} + 0.05\right)\right)} \cdot \sin(\psi) + 0.28 \cdot \cos(\psi)\right) = 14.341\ \frac{kN}{m^2}$$

$$\tau := \rho \cdot g \cdot D \cdot 0.25 \cdot \sqrt{\cos(\psi)} \cdot \left(1 - 0.84 \cdot \sqrt{\sin(\psi)}\right) = 1.059\ \frac{kN}{m^2}$$

$$K := \sin(2\ \psi) \cdot \left(2.5 \cdot \frac{\rho^3}{\left(\frac{tonne}{m^3}\right)^3} - 1.86 \cdot \frac{\rho^2}{\left(\frac{tonne}{m^3}\right)^2} + 1.06 \cdot \frac{\rho}{\left(\frac{tonne}{m^3}\right)} + 0.54\right) = 0.918$$

$$S'_N := 0.8 \cdot \rho \cdot g \cdot \frac{H^2}{2} \cdot K \cdot N = 52.906\ \frac{kN}{m}$$

$$G' := \rho \cdot g \cdot \left(0.5 \cdot D^2 \cdot \tan(\delta) + 0.1 \cdot D^2 \cdot (\cos(\delta))^2\right) = 23.274\ \frac{kN}{m}$$

$$G'_N := G' \cdot \sin(\psi) = 16.457\ \frac{kN}{m} \qquad G'_Q := G' \cdot \cos(\psi) = 16.457\ \frac{kN}{m}$$

$$R'_N := S'_N + G'_N = 69.363\ \frac{kN}{m} \qquad R'_Q := G'_Q = 16.457\ \frac{kN}{m}$$

$$R' := \sqrt{{R'_N}^2 + {R'_Q}^2} = 71.289\ \frac{kN}{m} \qquad \varepsilon := \operatorname{atan}\left(\frac{R'_Q}{R'_N}\right) = 13.347\ deg$$

$$f_R := min\left(\left(0.92 + 0.65 \cdot N\right) \cdot \frac{A}{2\ m}, 1 + 1.25 \cdot N\right) = 2.5$$

$$\Delta l := min\left(0.6 \cdot \frac{A}{2}, \frac{D}{3}\right) = 0.9\ m$$

$$S'_R := f_R \cdot S'_N = 132.265\ \frac{kN}{m}$$

$$R'_R := \sqrt{\left(S'_R + G'_N\right)^2 + {R'_Q}^2} = 149.63\ \frac{kN}{m} \qquad \varepsilon_R := \operatorname{atan}\left(\frac{R'_Q}{S'_R + G'_N}\right) = 6.315\ deg$$

$$B := 1.06 \cdot \frac{D}{\cos(\delta)} = 4.389\ m$$

$$p_h := \frac{R' \cdot \cos(\delta - \varepsilon)}{0.77 \cdot B} = 19.952\ \frac{kN}{m^2}$$

$$p_{hR} := \frac{R'_R \cdot \cos(\delta - \varepsilon)}{0.77 \cdot B} = 41.877\ \frac{kN}{m^2}$$

$$\eta := 1 + 0.6 \cdot \frac{H}{d} = 14.499$$

$$q'_s := \eta \cdot S'_N \cdot \frac{d}{L_s} \cdot \sin(\alpha) = 44.988\ \frac{kN}{m}$$

Nodal loads for load case 1:

$n := 63$ Total nodes

$n_1 := 6$

$$F_1 := -R' \cdot \frac{\left(L_L - 2 \cdot \Delta l\right)}{n - n_1} = -15.258\ kN$$

$$F_2 := -R'_R \cdot \frac{\Delta l}{n_1} = -22.444\ kN$$

$\alpha_1 := -(\varepsilon + \psi) = -58.347\ deg$

$\alpha_2 := -\left(\varepsilon_R + \psi\right) = -51.315\ deg$

Nodal loads for load case 2:

$n := 64$ Total nodes

$n_1 := 6$

$$F_1 := -R' \cdot \frac{\left(L_L - 2 \cdot \Delta l\right)}{n - n_1} = -14.995\ kN$$

$$F_2 := -R'_R \cdot \frac{\Delta l}{n_1} = -22.444\ kN$$

$\alpha_1 := -(\varepsilon + \psi) = -58.347\ deg$

$\alpha_2 := -\left(\varepsilon_R + \psi\right) = -51.315\ deg$

12 Discussion

Several points need to be mentioned in the discussion of different aspects in the thesis:

Loading
Snow load on flexible supporting surfaces is complicated by many factors. As mentioned in earlier chapters, there are different ways to describe this load. Briefly explained, it can be modelled as a line load or a surface load. In Robot, there is an option to distribute loads using claddings. Cladding is a surface that lets you distribute planar, linear and concentrated loads. Due to the arch shape and the many elements in the wire mesh, creating this surface is very difficult and highly inconvenient. For this reason, applying the load as a surface load has not been favoured.

The most convenient way to apply the loads was by nodal loads. The snow pressure of infinite length in the contour line, has thus been converted to equivalent nodal values. Is this a sufficiently correct representation of the load, is a question that one must ask oneself.

In the design, no load factor has been used. All calculations are based on characteristic values, but it has been assumed that using design values for snow height and density is equivalent to the use of load factor with partial factor method. In addition, the formulas in the Swiss guideline calculating the load is also assumed to be conservative. For these reasons, high safety measures are considered to be already implemented in verifying the ultimate limit state of the structure.

If the snow pressure load defined in the Norwegian guideline [4] was selected for design, further considerations need to be made. The load in the Norwegian guideline does not include the end-effect-load or the weight of the snow prism. For these reasons, load factor should be included in the load calculations using this approach. Comparing the two loads in the Norwegian and Swiss guideline, then shows that the results are very similar:

$$R_{No} = 1.5 \cdot \gamma_Q \cdot \sigma_x \cdot L = 1.5 \cdot 1.5 \cdot 14.34 \cdot 3.5 = 113kN/m$$
$$R_{Sw} = \frac{R' + R'_R}{2} = \frac{71.3+149.6}{2} = 110kN/m$$

The extra factor in the expression for R_{No} comes from the fact that the maximum pressure is about 1.5 times the average pressure.

Net shape
It has been assumed that the net consists of an isosceles shape. This is not the standard mesh shape for snow nets. The most popular net shapes are quadrilateral. As this is not modelled, increased inaccuracy is expected. Change of the net shape, will change the distribution of forces in the net. But it is assumed that the distribution of forces in the entire structure will not be heavily affected. It is recommended to change this in further work, and check how the changes affect the structural response.

Deformation shape

This point is very important, maybe the most important in this thesis. From the deformation shape of the structure, it can be seen that there are compression forces in the wire net: the only way the base perimeter wire can deform this way is if it is under compression. This is absoulutely not possible, and shows that the model using only beam elements does not sufficiently model the structure. Despite getting reasonable values for reaction forces, the deformation of the net is essential, as it highly affects the distribution of forces in the structure. Looking at figure 35, the deformation shape after being subjected to snow pressure is clearly not correct. The base perimeter wires are lifted upwards. This type of deformation can not occur for a tension element. A correct deformation shape is shown in figure 20.

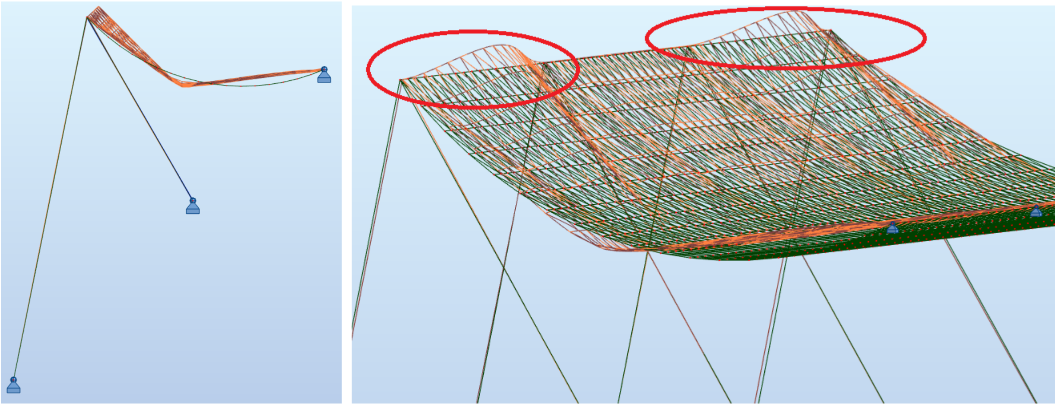


Figure 35: Deformation shape of structure

Element selection

Modelling the whole structure using beam elements is clearly the reason for the wrong deformation shape. The beam element is capable of taking compression. This is not true for the wire ropes. For this reason other elements should be selected for modelling of the wire net. As mentioned, solving the problem using specially designed software for flexible structures is an alternative. These softwares have elements with an element stiffness matrix that can correctly represent the behavior of elastic nets. This approach is highly recommended, as the full beam model approach is not giving a correct deformation shape.

Further research

For further research, the calculations, analytical models and finite element simulations presented earlier should be compared with other FE-models, before they could be used to develop design recommendations. Field tests should also be carried out as part of a new research study. Testing of the net, the poles and the snow pressure are all relevant areas of test work. All of the factors above, and also the assumptions throughout the thesis, should be more properly analyzed.

13 Conclusion

Aim of this study was to study the mechanical behaviour of the snow nets, and to set out a general methodology for undertaking design. To conclude, this is done, but several key points need to be validated before design recommendations can be formulated. First of all, as it was a goal to obtain design of the structure using a simple method usable by engineers, Haefeli's method has proven to be an alternative. This method can be a very good design tool. With its easy use, calculations can be done very quickly.

There are obviously significant differences between the complicated FEM-analyis and Haefeli's method, but the results are interestingly very similar. Results of the FEM-analysis give reasonable values for reaction forces in the structures. Thus, the parametric structural model created can be used to calculate the reaction forces in the snow net. The parametric model reduces modelling time, and makes it possible to test the affect of different parameters. This significant reduce in time makes the model effective for testing and experimenting, as well as a viable model for optimization purposes.

But due to no testing of the structure, all conclusions need to be critically evaluated. Despite, the reasonable reaction forces and effective modelling, the deformation shape and compression forces in the wire net, show that the choice of element selection of beams is not correct to represent the entire structure. In further research, a more correct element should be used for modelling of the wire net. The results should be compared with the model presented here.

For the loading, which is possibly the most significant design condition, both the Norwegian and Swiss guideline shows very similar results. In further research, testing this is also a relevant area.

To conclude, this thesis mentions different approaches to solve the problem. All models should ideally be compared with each other, and design recommendation should be made hereafter. This thesis has only presented the first step of this approach.

References

[1] D. M. McClung and P. Schaerer, *The Avalanche handbook.* Mountaineers Books, 2006.

[2] “Planning and Building Act (1985).” http://app.uio.no/ub/ujur/oversatte-lover/data/lov-19850614-077-eng.pdf. Accessed: 2018-02-07.

[3] “Regulations on technical requirements for construction works (Byggteknisk forskrift - TEK17).” https://dibk.no/globalassets/byggeregler/regulation-on-technical-requirements-for-construction-works--technical-regulations.pdf. Accessed: 2018-02-07.

[4] Statens vegvesen (2014), “Veger og snøskred. Håndbok V138.” Vegdirektoratet, Oslo.

[5] S. Margreth, “Defense structures in avalanche starting zones. Technical guideline as an aid to enforcement,” *Environment in Practice no. 0704. Federal Office for the Environment, Bern; WSL Swiss Federal Institute for Snow and Avalanche Research SLF, Davos.*, 2007. 134 pp.

[6] J. Schweizer, J. Bruce Jamieson, and M. Schneebeli, “Snow avalanche formation,” *Reviews of Geophysics*, vol. 41, no. 4, 2003. 1016.

[7] Wikipedia, “Loose snow avalanche.” "https://en.wikipedia.org/w/index.php?title=Loose_snow_avalanche&oldid=818870497, 2018. [Online; Accessed 7-March-2018].

[8] Statens vegvesen (2014), “Flom- og sørpeskred. Håndbok V139.” Vegdirektoratet, Oslo.

[9] S. Margreth, “Snow pressure on cableway masts: Analysis of damages and design approach,” *Cold Regions Science and Technology*, vol. 47, no. 1, pp. 4 – 15, 2007. A Selection of papers presented at the International Snow Science Workshop, Jackson Hole, Wyoming, September 19-24, 2004.

[10] J.O. Larsen and D.M. McClung, “Snow creep pressures: Effects of structure boundary conditions and snowpack properties compared with field data,” *Cold Regions Science and Technology*, vol. 17, no. 1, pp. 33 – 47, 1989.

[11] J. O. Larsen, “Design criteria for avalanche supporting structures exposed to snow creep forces in maritime climate,” *Snow Engineering: Recent Advances and Developments, Proceedings of the Fourth International Conference on Snow Engineering*, pp. 109–111, 2000.

[12] J. O. Larsen, D. M. McClung, and S. B. Hansen, “The temporal and spatial variation of snow pressure on structures,” *Canadian Geotechnical Journal*, vol. 22, no. 2, pp. 166–171, 1985.

[13] F. Rudolf-Miklau, S. Sauermoser, A. Mears, and M. Boensch, *The Technical Avalanche Protection Handbook.* Wiley, 2014.

[14] Trumer, “TS-LV Snow Net.” https://trumer.ca/products/avalanche-fences/ts-lv-snow-net/. [Online; Accessed 9-May-2018].

[15] FAO, *Rural structures in the tropics. Design and development.* Rome, 2011.

[16] “State of implementation of the Eurocodes in the European Union.” http://eurocodes.jrc.ec.europa.eu/show_Entity.php?file_id=EC_00000114. Accessed: 2018-02-26.

[17] European Standard, “EN 1990. Eurocode: Basis of structural design.”

[18] J. O. Larsen, “Skredsikring og fundamentering i permafrost.” https://www.nve.no/Media/5369/201607038-2-mulighetsstudie-skredsikring-svalbard-pdf-1956251_1_1.pdf. Accessed: 2018-02-14.

[19] T. Jóhannesson and S. Margreth, “Adaptation of the Swiss Guidelines for supporting structures for Icelandic conditions,” *Veðurstofa Íslands Report*, 1999.

[20] W. Jiang, “A General Formulation of the Theory of Wire Ropes,” *Journal of Applied Mechanics*, pp. 747–755, 1995.

[21] Wikipedia, "Young's modulus," 2018. [Online; Accessed 5-June-2018].

[22] Erling Haug, "Properties of Extension of Steel Wire Ropes." http://www.haug.no/en/product-supply/technical-information/steel-wire-rope/technical-information/properties-of-extension-of-steel-wire-ro__22299. [Online; Accessed 5-June-2018].

[23] F. Nicot, M. Gay, and J. Tacnet, "Interaction between a snow mantel and a flexible structure: a new method to design avalanche nets," *Cold Regions Science and Technology*, vol. 34, no. 2, pp. 67–84, 2002.

[24] S. Velinsky, "General nonlinear theory for complex wire rope," *International Journal of Mechanical Sciences*, vol. 27, no. 7, pp. 497 – 507, 1985.

[25] Wikipedia, "Catenary," 2018. [Online; Accessed 14-May-2018].

[26] G. de la Cruz Alcala, "Design and Modelling by Discrete Elements of Tree-Anchored Rockfall Protection Fences," *Universidad de Castilla-La Mancha*, 2016.

[27] Wikipedia, "Granular material." https://en.wikipedia.org/wiki/Granular_material, 2017. [Online; Accessed 4-April-2018].

[28] F. Nicot, "From constitutive modelling of a snow cover to the design of flexible protective structures Part I—Mechanical modelling," *International Journal of Solids and Structures*, vol. 41, no. 11, pp. 3317 – 3337, 2004.

[29] F. Nicot and M. Gay, "Modelling of interaction between a snow mantle and a flexible structure using a discrete element method," *Natural Hazards and Earth System Sciences*, vol. 2, no. 3/4, pp. 163–167, 2002.

[30] F. Nicot, O. Gagliardini, and B. Boutillier, "Modelling of a snowpack in interaction with a flexible structure using a coupled Lagrangian-discrete approach," *International Journal for Numerical and Analytical Methods in Geomechanics*, vol. 27, no. 4, pp. 259–274, 2002.

[31] K. Bell, *An Engineering Approach to Finite Element Analysis of Linear Structural Mechanics Problems.* Akademica Publishing, 2013.

[32] Autodesk, "Robot Structural Analysis Professional." https://www.autodesk.com/products/robot-structural-analysis/overview, 2018. [Online; Accessed 8-May-2018].

[33] Autodesk, "Cables in Robot." https://knowledge.autodesk.com/support/robot-structural-analysis-products/learn-explore/caas/CloudHelp/cloudhelp/2015/ENU/Robot/files/GUID-C718E208-2359-49A0-9C8E-FAB4EA496948-htm.html. [Online; Accessed 27-May-2018].

[34] R. D. Cook, D. S. Malkus, M. E. Plesha, and R. J. Witt, *Concepts and Applications of Finite Element Analysis, 4th Edition.* Wiley, 2001.

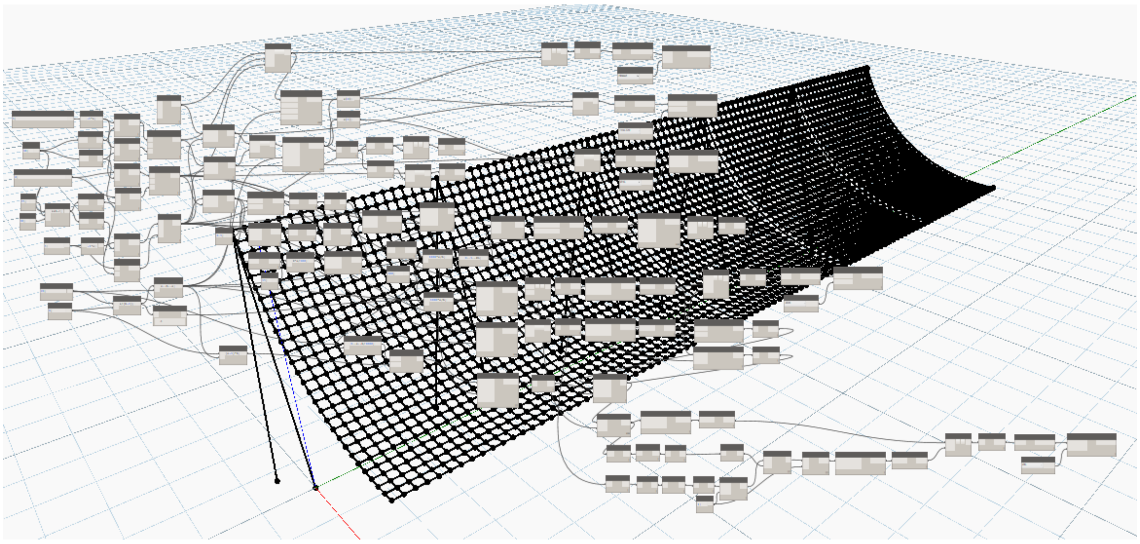
[35] Aquastructures, "AquaSim." http://aquastructures.no/aquasim/. [Online; Accessed 6-June-2018].

[36] T. Jóhannesson and J. Hopf, "Loading of supporting structures under Icelandic conditions. The type of structures and structural requirements in future projects. Results of a field experiment in Siglufjörður," *International Symposium on Mitigative Measures against Snow Avalanches*, pp. 143–150, 2008.

[37] L. Rammer and M. Granig, "Three years Snownet Project Hafelekar/Innsbruck," *International Snow Science Workshop, Davos*, pp. 582–586, 2009.

Appendix

A Dynamo: Rectangular net type



B Dynamo: Triangular net type