THE DESIGN AND CONSTRUCTION OF SLUSH-FLOW NETS IN VANNLEDNINGSDALEN LONGYEARBYEN SVALBARD

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ABSTRACT: Slush-flows from Vannledningsdalen valley in Longyearbyen Svalbard have posed a threat to the residential area on Haugen and below Sukkertoppen mountain in springtime. For decades, the municipality has been trenching the snowpack in Vannledningsdalen in late May to drain the snowpack and reduce slush-flow risk. To reduce the threat from slush-flows, various mitigation measures were considered, including the use of deflecting dams and modified debris-flow nets. The municipality decided to implement the net solution. The height of the construction ranges from 4 m to 8 m and includes fourteen nets strategically placed along roughly 1200 m of the valley floor.

Debris-flow nets have not been previously used on such a large scale for the purpose of mitigating slush-flows. The criterion for their dimensions is not firmly established but it is believed that the rheology and dynamics of slush-flows are akin to those of debris-flows. As a result, the load assessment for the planned nets relies on the understanding and techniques used for debris-flows nets. One of the issues was to define the size of the slush-flow release between the nets and how the slush-flow would react to the nets. RAMMS::DEBRIS FLOW was used to estimate the loading. Based on the defined loads, static and dynamic verifications for the load-bearing capacity of the different slush flow barriers were carried out, leading to the final design of each net and barrier components.

The thickness of the active layer is estimated to be between 1.0 and 1.5 m in the valley, based on thermistor measurements. Due to predicted climate changes, a vertical thickness of the active layer of 2.0 m and 2.5 m is used as a project basis. The rockmass in Vannledningsdalen is mainly a layered sandstone/siltstone/shale/slate of various competence and with layers of coal in some locations. The anchors of the nets are designed to withstand creeping forces, frost heave induced forces, increased active layer thickness and increased weathering of rock mass during the lifetime of the nets.

Construction work began in 2023 with foundations and side anchors and the work will be finalized later in 2024. Three barriers are already installed.

KEYWORDS: Mitigation measures, slush-flow, debris-flow nets, Vannledningsdalen, Svalbard.

1. INTRODUCTION

The Svalbard archipelago, with Longyearbyen as its administrative hub, is experiencing rapid climate changes that have unexpected impacts on human activities, as well as on local flora and fauna. The settlement is situated on a narrow strip of land between the mountains and the Longyear River. Haugen, one of the residential areas, is positioned on the alluvial fan beneath Vannledningsdalen, a narrow side valley known for its slush-flow activity.

In recent years, warmer temperatures, and mid-winter rain, driven by the warm climate, have triggered slush-flow activity. The dark winter period, coupled with safety concerns, makes it nearly impossible to observe and monitor the snow cover in Vannledningsdalen.

For decades, the valley has been trenched with bulldozers late in May to drain the snowpack. This work is not possible during the dark period mid-winter.

A long-term solution was required to safeguard the residential area at Haugen. In 2012, NGI suggested constructing a deflecting dam along the stream on the alluvial fan (Jónsson and Gauer, 2014). Following the devastating avalanche in Lia in December 2015 and the avalanche from Sukkertoppen mountain in February 2017, authorities began efforts to protect the residential area in Longyearbyen. Until now the Lia area and the residential area below Sukkertoppen Mnt. have been protected by supporting structures and a 5.5 m high catching dam at the root of the hill as a supplement to the supporting structures. The final phase of this project is to protect the Haugen residential area and hotel.

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This paper describes briefly the planning, designing and construction of the mitigation work in Vannledningsdalen.

2. SCHEMATIC DESIGN

2.1 Previous work

NGI's 2012 project outlines the construction of deflecting dams on both sides of the stream (Vannledningselva) on the alluvial fan; it also mentions an alternative approach involving nets in the valley. However, the net solution was rejected because restricting access along the valley bottom was considered unacceptable.

2.2 Climate

Svalbard is located within the permafrost zone north of 64°N. Currently, during the summer, the active layer reaches depths of between 1 and 2 meters in most areas of Longyearbyen, a figure that is expected to increase by several tens of centimeters over the coming decades due to rising temperatures. In February 2019 a new report titled "Climate in Svalbard 2100" was published by I. Hanssen-Bauer (I. Hanssen-Bauer et al., 2019). This report is based on the RCP8.5 scenario from the IPCC, which represents a "business as usual", worst-case scenario. If extreme projections hold true, Longyearbyen could be free of permafrost by the end of the 21st century. Such significant climatic changes pose considerable challenges for built infrastructure, particularly affecting foundations and general groundwork.

2.3 Safety class

The safety class has been designated as S2 by NVE in accordance with TEK17 (Regulations on technical requirements for construction works) (Direktoratet for byggkvalitet (DiBk), 2017). This S2 classification equates to an annual probability for significant damages on new buildings from natural hazards occurring at 1 in 1000.

2.4 Conceptual study of mitigation type

The design of the previously proposed deflecting dam (2.1) was updated based on the most recent understanding of slush-flow behavior. The dam's height was raised, geometry modified, and new plans were made to redesign the bridge on road 500, allowing slush-flow to move through and reach the Longyear River.

Following extensive discussions in late 2018 and early 2019, the municipality decided against the deflecting dam solution and opted to further investigate the use of nets in the valley, Figure 1.

The project team had limited data regarding the wintertime snow height on this approximately 1200 m long valley floor. Some information had been collected during NGI's previous work, and UNIS, the Arctic university, had conducted terrestrial lidar scanning of a portion of the valley. Available data did not represent the extreme snow conditions, but reference snow height was estimated from available data, photos and by interpretation of the terrain formation.

Another key factor for the design of the nets was the slush-flow velocity and the distance between the barriers. In the initial phase the distance between the barriers was set to approximately 70 – 100 m. It was thought reasonable to estimate the velocity in the range of 10 – 15 m/s on these sections, but for design purposes 15 m/s was chosen. The volume of released snow/slush-flow in RAMMS simulation was in the range of 1000 m³ to 4000 m³ for each of the sections.

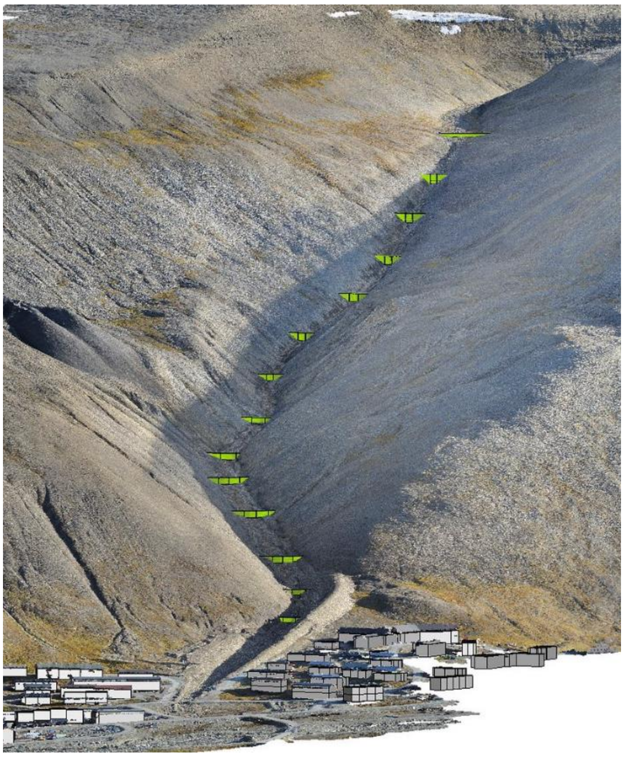

Figure 1 shows Vannledningsdalen and the planned sites for 14 slush-flow nets (highlighted in yellow-green) overlaid on a 3D point cloud model. Fig.: HNIT Verkfræðistofa.

Currently there is a limited knowledge of this kind of construction and therefore the client asked three known suppliers of debris-flow net-constructions to deliver a design concept for the superstructure. The suppliers were Geobrugg AG, Maccaferri Deutschland GmbH and Trumer-Schutzbauten GmbH. After an evaluation process Geobrugg AG was chosen to deliver detailed design of the superstructure.

The understanding of the slush-flow process is not well understood nor is the interaction with constructions. It is believed that the rheology and dynamics of slush-flows are similar to those of debris-flows and the load assessment for the planned nets relies on the understanding and techniques used for debris-flows nets. Debris-flow nets are used worldwide and are capable to withstand highly dynamic flowing mass impacts (Berger et al., 2020; Wendeler, 2008). The slush flow barrier consists of a high tensile ring net that is connected to support ropes that are spanned horizontally across the channel. The ropes are then connected to the supports (posts), which are distributed as evenly as possible across the barrier span. Thus, the impact load is transferred from the net to the ropes and supports, and subsequently to the anchors/foundations. Despite some differences in rheology between debris-flow and slush-flow part of the impact behavior of slush-flows on flexible barriers can be considered equal to the one from debris flows. Thus, energy absorption and deformation of the barrier can be accounted with the same design concept as for debris-flow.

By analyzing the local conditions and considering the recorded events and snow history at Vannledningsdalen, fourteen barriers had to be designed along the valley and four different load case scenarios, which act on the slush flow barrier, were identified. Load cases 1 - 3 are related to different processes (static and dynamic) that have a direct impact on the superstructure. Load case 1 describes the static winter snow pressure over the corresponding snow height. Load case 2 contains static slush snow pressure over the system height. In load case 3 the dynamic slush flow pressure over the flow height is described and can occur anywhere over the system height. Load case 4 is defined as the total acting load on the superstructure and is a combination of the static impact and dynamic impact.

Other natural hazards such as snow avalanches from the valley sides, rockfall and debris-flow are discussed in (Skred AS, 2022a).

Further information on the design can be found in: (Geobrugg AG, 2024; HNIT Verkfræðistofa, 2022, 2024; Rambøll Norge AS, 2021; Skred AS, 2022a, b).

2.5 Geotechnical considerations

The rock mass in Vannledningsdalen is mainly a layered sandstone/siltstone/shale/slate of various competence and with layers of coal in some locations. Also, layers of ice of 1 m thickness have been detected in the ground. In the valley sides there are significant amount of loose material above rock that affect several of the foundation parts.

Thermistors were installed at four representative locations in Vannledningsdalen to gather data prior to detailed design. In addition, data from two existing thermistors in Sukkertoppen Mnt. is used. The thickness of the active layer is estimated to be between 1.0 m and 1.5 m in the valley, based on thermistor measurements nearby. Due to predicted climate changes after scenario RCP8.5, (IPCC, 2013) a vertical thickness of the active layer of 2.0 m and 2.5 m is used as a basis for the project.

To estimate the adhesive strength (f_{bfn}) in the rock, a total of sixty test anchors were installed in Vannledningsdalen and pullout tests were performed. Based on the tests a characteristic f_{bfn} =1 MPa is used in the calculation of necessary anchor length.

2.6 Other mitigation measures

In addition to installing barriers in the valley, the project involved increasing the height of a section of the existing deflecting dam on the alluvial fan, building an access road to the work zone in Vannledningsdalen along the deflecting dam, and constructing an approximately 1-meter-high deflecting dam along road 217 to prevent slush-flow from reaching nearby residential buildings. The elevation difference between the top of the dam and the riverbed is in the range 2 to 3 m. These measures will not be further described in this paper.

2.7 Service life

Due to uncertainties in climate, ground conditions and processes that can affect proposed structures involved actors suggested 40 - 50 years' service life.

3. DETAILED DESIGN

3.1 Design criteria

The slush-flow scenarios are based on NGIs research (Norges Geotekniske Institutt NGI, 2021) and Art Mears research (Art Mears, 1982), and they are further described in project reports (Skred AS, 2020, 2022a). It is assumed that slush-flows accelerate fast, and it is essential to limit the speed before the slush hits the nets. The distance between barriers projected to horizontal planes was adjusted to new calculations and is between 68 and 122 m.

Flow density was estimated to be 700 kg/m³ during the slush-flow process and winter snow density for snow on the ground is set to 400 kg/m³. Pressure coefficient Cd was set to 1.0 and gliding factor N was set to 1.8. Flow height for all barriers was estimated to be 2,0 m and estimated impact range on the barriers is between 0-5 and 0-7 m. Different values for RAMMS::DEBRIS FLOW (RAMMS AG, 2024) were tested, but Skred AS ended up with constant ξ (Xi) of 2500 and μ (My) value in the range 0,08 and 0,1 depending on the release scenarios (Skred AS, 2022a). Table 1 shows some of the parameters and design results.

Table 1 shows some of the parameters and results. Reproduced from (Geobrugg AG, 2024; HNIT Verkfræðistofa, 2022; Skred AS, 2022a).

	Velocity [m/s]	Distance to next [m]	Load case 3 [kN/m²]	Load case 4 [kN]	Net height* [m]	Post size HEM
Net 1	10	77	70	2749	4	220
Net 2	10	90	70	3614	4	220
Net 3	11	120	118	12217	5	400
Net 4	12	90	101	10763	5	340
Net 5	10	68	70	7080	5	280
Net 6	10	94	70	5820	5	300
Net 7	12	116	101	7739	5	340
Net 8	12	94	101	6832	5	300
Net 9	12	98	101	7784	6	340
Net 10	12	80	101	7884	6	340
Net 11	13	80	118	8512	6	340
Net 12	12	80	101	8694	7	500
Net 13	12	122	101	8089	7	500
Net 14	-	-	-	1350	2,5	220

*Approximately 1 m foundation height can be added to these numbers to determine the total height of the barriers.

3.2 Geotechnical design-substructure

Geotechnical design covers the substructure such as the concrete foundations and anchor systems. The anchor system of the nets is designed to withstand creeping forces, frost heave induced forces, increased active layer thickness and increased weathering of rock mass during the lifetime of the nets.

Forces from creeping and frost heave will not disappear when the ground freezes but will persist until there is a deformation in the construction. Frozen ground is stiff, and creeping and frost heave will not contribute to deformation in the slush flow season. Consequently, it is assumed that creeping force and frost heave will not act together with forces from slush flow.

A 3 m long casing is used in the anchor system in the layer of loose material and weathered rock mass. The anchoring system requires rock of good quality or rock mass that will be frozen during the lifetime of the net. Creeping and frost heave forces will act on the casing, and these forces are included when calculating the anchor length. In the valley sides the anchors are grouped together (Figure 2). It is assumed that the anchors affect each other and form a group of which pullout capacity is calculated from assumed conical perimetry form of the group.

Various foundation types for the anchors on the side slope were considered. In areas without permafrost, concrete blocks around the anchor groups are the standard and most used foundation type. However, due to issues such as creeping material, permafrost, poor surface material quality, and logistical difficulties, the use of concrete blocks was abandoned. Also, the concept of using sections of steel beams draped on the side slope to stabilize the anchors was explored, but this idea was also rejected as it was not deemed safe or stable enough.

Figure 2 shows 2 and 3-anchor houses used for horizontal anchoring/ropes on side slopes. Photo: Arni Jonsson.

The concept for a steel casing instead of concrete blocks is inspired by rigid supporting steel bridges. Similar to a typical upper foundation, it features both vertical and horizontal anchors. Geobrugg AG adapted this idea, resulting in the "house" shown in Figure 2. The number of support ropes varies at different levels of the nets, requiring between two and four ropes/anchors. The connection from the anchor bar to the support ropes is facilitated by a flexible element known as FLEXHEAD[i].

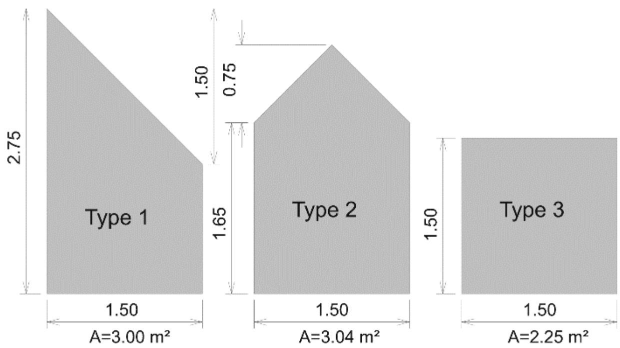

Figure 3 show three types of concrete foundations for barrier posts. Fig.: HNIT Verkfræðistofa.

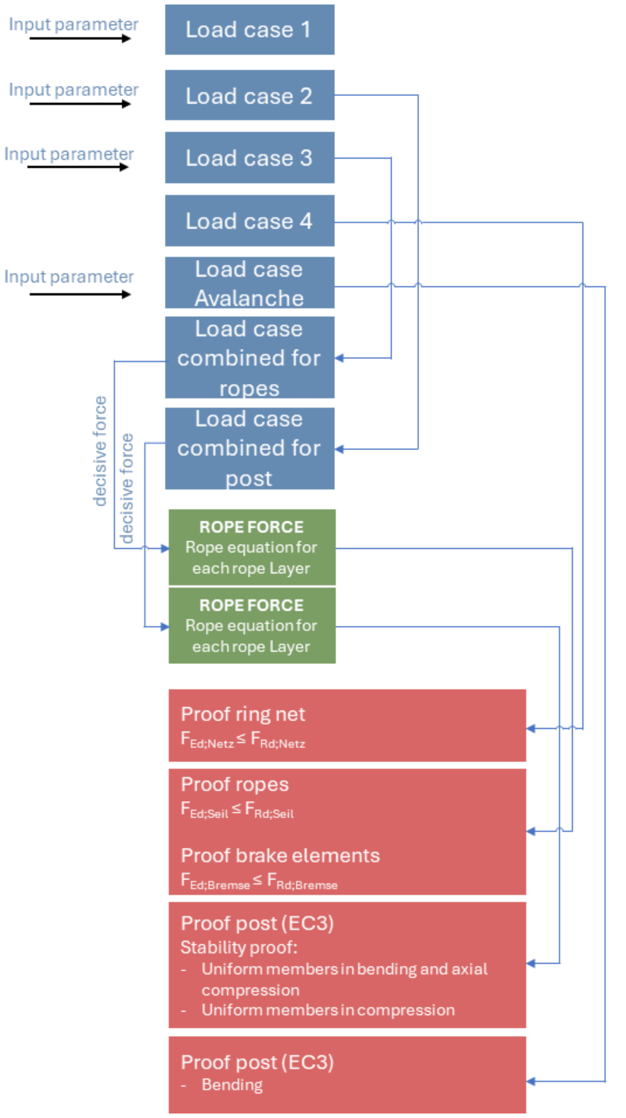

Figure 4. Flow chart for flexible slush flow barrier design calculation (Geobrugg AG, 2024). Fig.: Geobrugg AG.

The house transfers vertical forces from the creeping horizontal anchor group to the vertical anchor or miropile.

The load from the slush-flow impacting the superstructure is transferred to the ground via concrete foundations and anchoring systems. Three foundation types were designed (Figure 3): Type 1, the most common, positioned on each side of the stream; Type 2, situated at net locations 3-5 in the middle; and Type 3, designated for net 14 at the top of the valley. The heights of Type 2 and Type 3 foundations range from 1.0 m to 1.5 m, while Type 3 is 1.0 m high.

3.3 <u>The superstructure</u>

RAMMS::DEBRIS FLOW software (RAMMS AG, 2024) was used to determine the initial parameters of the dynamic impact such as slush-flow velocity and flow height (Table 1). Four load cases (1-4) were set up (Geobrugg AG, 2024). For each of them and for each barrier location, the impact load was calculated. The critical load case at each barrier location was then used to verify the acting loads on the main system components, including ropes, ring net, and posts (Figure 4).

No partial safety factor (γ_F) was added to the design load, i.e. γ_F=1.0, but partial safety factors were applied on material resistance. Applying a partial safety factor to the acting load would result in over-dimensioning the system, as the initial parameters already account for some uncertainties. Additionally, a scenario with a 5000-year return period was considered.

In case of a slush flow event, the impact acts only on determined locations of the barrier. By assuming an evenly distributed acting load over the whole barrier span, an extra safety results automatically in the dimensioning. Moreover, the model used for system dimensioning tends to overestimate the forces on the barrier, especially when dynamic processes are considered, and static models are applied to highly deformable systems like slush flow barriers.

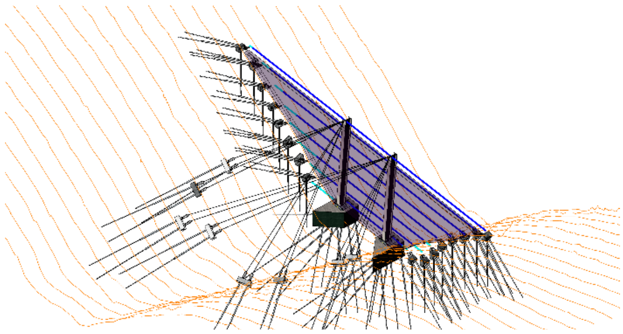

Figure 5 shows a 3D view of typical sub- and superstructure, i.e. retaining ropes, net, ropes, posts, concrete foundations and the anchoring system. Orange lines illustrate the terrain surface. Flow direction is from left to right. Fig.: HNIT Verkfræðistofa.

The design loading for each barrier location varied, leading to differences in barrier dimensions and resistance, such as the number of ropes and the size of the post profiles.

A safety factor was used to design the foundation and anchors for the support ropes. The anchors must withstand a load of at least 350 kN, which corresponds to the braking load of the ropes, including their brake elements, to absorb dynamic impact forces.

Figure 5 shows net 13 and the complexity of the anchoring system.

4. TENDERING PROCESS

Arctic climate and permafrost conditions require experienced and well-equipped contractor for the work in Vannledningsdalen. Since a project of this magnitude has never been undertaken in Norway before, estimating the construction cost was challenging. The initial tender had to be canceled because it exceeded the financial budget. In the second round, one of the contractors made a complaint about the tendering process, and the tender had to be cancelled. It took until the third and final round, along with almost a year of delays, before the procurement was completed and construction work could begin.

The total construction cost is estimated to be approximately 95 million NOK (€8.1 million).

5. CONSTRUCTION WORK

The construction work was assigned to LNS Spitzbergen AS, a local contractor experienced in arctic conditions. They engaged two subcontractors: one specializing in concrete work and another handling the drilling, grouting, and installation of the superstructure.

The construction work usually cannot begin until late May or early June due to avalanche- or slush-flow risk and snow on the ground. During summertime the meltwater and the stream causes problem in the valley but in the autumn the “active layer” shrinks due to frost and work becomes easier and water seepage is considerably reduced or absent.

5.1 The substructure

Constructing the concrete foundations proved to be demanding due to the heavily fractured and loose Svalbard bedrock, as well as the constant seepage of groundwater. Each foundation includes ten ground anchors, many of which are inclined to counteract horizontal forces from slush-flows. The extensive reinforcement of the concrete foundation complicated the positioning of the ground anchors and baseplate bolts for the superstructure post. Maintaining precise drilling angles for the foundation anchors was crucial. Even minor deviations in these angles complicated the installation of the reinforcement and baseplate bolts (Figure 6). The concrete for the foundations was delivered by helicopter because it was the most efficient and rapid method to do the job.

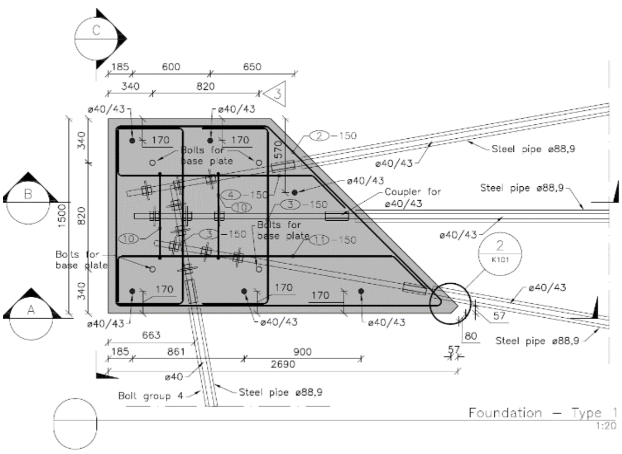

Figure 6 shows the top view of reinforcement and anchors of foundation type 2. Fig.: HNIT Verkfræðistofa.

The cold temperatures, particularly the permafrost, significantly affect the drilling progress. Due to the presence of permafrost, all anchors need to be injected on the same day as the drilling, which is a much lengthier process compared to typical conditions on the mainland. Consequently, water can seep into the borehole and freeze shortly thereafter. Additionally, the permafrost causes the injection pipe to become filled with ice and part of the anchor to be encased in ice, preventing the borehole from being fully filled with expanding grout. There were also recurring issues with drilling due to the fractured rock. Additionally, the large amount of water in the stream bed significantly complicates the drilling process. In some cases, it was necessary to drill with a casing system, which took about twice as long. The best progress for the drilling proved to be from May to middle of June i.e. before considerable snow melting. Grouting was also easier in that period. In September, the ground begins to freeze again, and the boreholes keep their shape after drilling and anchors can be installed very easily. However, as the temperature decreases, other issues occur during the grouting process. Anchors need to be inserted rapidly; otherwise, the expanding grout within the pipes and pump will freeze. Additionally, cleaning the grout pump in the cold conditions on the mountain is nearly impossible.

The highly accurate placement of different horizontal anchor groups (in a house) at the superstructures presented several challenges at the beginning of the construction process. It needed to be executed with great precision to prevent the vertical anchors from intersecting with the horizontal ones. Excessive deviations would cause the horizontal ropes of the nets to not align precisely with the posts of the superstructure.

The excavation for foundations, as well as the drilling of side anchors and retaining rope anchors, encountered significant difficulties due to the loose soil and fractured rock in Svalbard. The goal was to remove only the loose material, but as drilling progressed, additional material became dislodged and had to be cleared away. In numerous areas, we ultimately excavated roughly 1 meter for the anchors.

As part of the construction process, test holes were drilled for anchor pullout tests. Additionally, six extra holes were drilled along the valley, where anchors were mounted and grouted. The objective is to assess the pullout capacity of these anchors in 40 years to estimate the remaining capacity of the barrier anchors.

The contractor DS Entreprenør AS had gained valuable experience from previous projects in Svalbard, including the supporting structures on Sukkertoppen mountain. Utilizing helicopters for transporting and

Figure 7 shows installation of 7 m high posts at net 13 on 19th of August 2024. The horizontal ropes and retaining ropes are connected to the Flexheads/anchors but the work on the ring net is still under way. The photo also shows how fractured and loose the Svalbard rock and soil is. Photo: Arni Jonsson.

relocating equipment and construction components was crucial for the project's advancement. Helicopter use is prohibited from beginning November due to darkness.

5.2 *The superstructure*

The superstructure is an adapted debris-flow net, engineered to support the snow cover and to halt or diminish the energy of slush-flows in Vannledningsdalen. The height of the barriers and the size of the posts vary significantly across the valley, Table 1. The tallest and heaviest posts (HEM500) are in the upper part of the valley, with posts at barriers 12 and 13 standing at 7 meters above the concrete foundation. Due to logistical challenges, each post had to be split into three sections for transportation to the site for assembly. At other locations, the posts are smaller, only some of them are spilt into two sections.

The heavy lift of split posts at barriers 12 and 13, approximately 1100 kg, requires the right flying conditions and skilled workers for the installation, Figure 7.

5.3 *Additional anchoring points*

Throughout the barriers' service life, maintenance and occasional material clearance will probably be required. The barriers obstruct access at the valley bottom starting from net 3 and extending up the valley. Accessing various locations can be achieved by removing the nets from the posts, but this process is quite time-consuming. As an alternation to this, additional anchors with hooks were installed at side slopes above the nets, allowing "spider" machines to climb over/past the nets.

5.4 *Logistics*

Svalbard is relatively easily accessible by air and sea for travelers even though it is located at 78 degrees north. However, freight only arrives to Longyearbyen from Tromsø every second week and that is why construction work requires good planning. Any logistical miscalculation or machinery breakdown can cause delays in construction work.

6. EPILOG

The construction work is still ongoing when this extended abstract is written. A torrent in July 2024 caused significant problems but the plan is still to finish the work late this fall.

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