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Digital solutions for rock cuts – Experiences from the Være rock cut, E6 Ranheim – Værnes (Norway)

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Abstract

The Være rock is part of Nye Veier's project to upgrade the E6 between Ranheim and Værnes to a four-lane highway with a speed limit of 110 km/h. The rock cut, approximately 470 meters long and 31 meters high, required the excavation of 195 000 cubic meters of rock mass. It presented significant stability issues due to the unfavorable orientation of joint sets and poor rock mass quality. There were identified 19 potentially unstable wedges. The site also experienced several small rockfalls and a major planar slide of 600 m³.

To address these challenges, the software CloudCompare was extensively used for modeling, visualization, and documentation throughout the project. Drone surveys were conducted continuously during the excavation, and in total 18 3D point clouds were constructed with Structure from Motion photogrammetry. The software facilitated the visualization of semi-automatic discontinuity mapping, wedge geometry modeling, and optimization of rock support plans, ensuring precise bolt placement, length, and orientation relative to the interpreted geometries of potentially unstable wedges and other rock sections.

CloudCompare contributed to more efficient and cost-effective stabilization measures, avoiding over-dimensioning despite difficult geological conditions. The use of 3D models also improved communication and decision-making among stakeholders, maintaining project progress, and optimizing for both safety and resource use during the excavation process.

CloudCompare was particularly crucial for the precise excavation of the slide area. For this work, close control was maintained for what was assessed as a new potential unstable zone at the back, as well as monitoring the boundary between the slide masses and the intact rock during blasting. All of this was carried out with the adjacent E6 highway being closed only for brief, scheduled intervals.

Keywords

Rock slope engineering, 3D modeling and visualization, CloudCompare, Slope stability, 3D point clouds

1 Introduction

Rambøll collaborated with the contractor Acciona Construction on Nye Veier's highway project, E6 Ranheim – Værnes, as shown in Fig. 1. Rambøll was contractually part of a working coalition with Acciona Engineering, called the Design Joint Venture (DJV). Rambøll's responsibilities included engineering geological design and follow-up for the dayzones, while Acciona Engineering was responsible for the design of the three tunnels in the project, including the enlargement of existing tubes.

In late 2024, Nye Veier and Acciona Construction ended their contract for the E6 Ranheim – Værnes project. The excavation of the approximately 470 m long and up to 31 m high Være rock cut was the last major task completed under this contract. This rock cut, with a total surface area of 9600 m², was supported with over 4000 bolt meters of rock bolts for permanent support, approximately 2500 m² of nets, over 800 m² of shotcrete, and additional stabilization measures such as weep holes, filter ditches, pre-bolts, and rock bands. Originally, this rock cut was considered the "easy" or "warm-up" task, as the planned Hommelvik rock cut further east was for a long time projected to become the tallest road-related rock cut in Norway, reaching 60–70 meters in height.

The software CloudCompare (CloudCompare 2.13.2, 2024), which specializes in 3D point cloud processing and triangular meshing, was extensively used to model, analyze, and document the Være rock cut. It facilitated the integration of geometric data, geological mapping, and operational records into 3D models, significantly enhancing design accuracy, safety, and traceability. This approach was particularly critical for addressing multiple rockfalls during excavation, including a (multi-)planar slide of nearly 600 m³ in the westernmost part of the rock cut on the night of May 27, 2023. Additionally, a potentially unstable section was identified directly behind the slide area.

The use of precise, data-driven 3D modeling in CloudCompare, along with a comprehensive history of 3D models, allowed for the safe and efficient removal of the slide masses while maintaining the aesthetic integrity of the final rock cut.

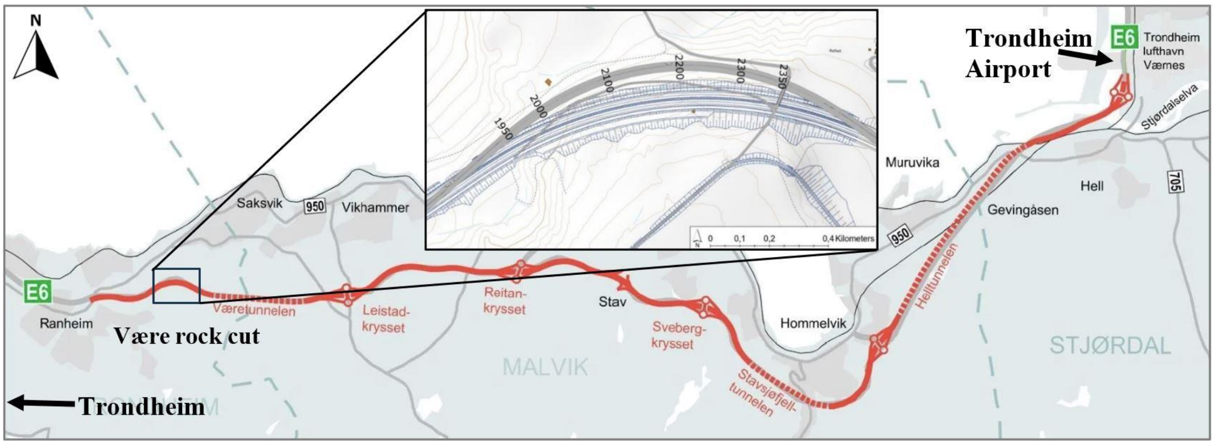

Fig. 1: Overview map of the E6 Ranheim – Værnes highway project. The project area for the Være rock cut is indicated by the black square.

2 Structural and geological setting

The Være rock cut is situated within the Trondheim Nappe Complex, part of the Upper Caledonian Allochthon formed during the Caledonian Orogeny. The bedrock in this area primarily consists of metasedimentary rocks from the Ordovician to Silurian period, specifically the Reppe Formation. This formation is dominated by greywacke, characterized by its grey to green coloration, interbedded with siltstone and phyllite. In some sections, sandstone layers are also present, reflecting local lithological variations along the rock cut (NGU, 2001).

The greywacke is typically associated with low-grade metamorphism, classified within the greenschist facies, indicating moderate pressure and temperature conditions during metamorphism. The regional structure has been heavily influenced by multiple generations of folding and faulting related to the Caledonian Orogeny. As a result, the bedrock exhibits a prominent foliation (schistosity) and a series of persistent joint sets that significantly influence the stability of the rock mass (NGU, 2001).

Field observations confirm the complexity of the structural fabric, with folding and faulting contributing to heterogeneity in rock mass quality. The joint sets are primarily aligned along two dominant orientations, consistent with regional tectonic stresses. These structural features have been critical in the formation of potential wedges and section prone to planar sliding, particularly in areas where joint persistence and spacing intersect unfavorably with the rock cut's geometry (NGU, 2001).

The interplay between lithology, structural complexity, and metamorphic history highlights the challenges faced during the Være rock cut excavation, emphasizing the need for advanced engineering geological solutions and continuous assessment to ensure the safety and stability of the excavation works. An arial overview capture during the latter part of the excavation of the rock cut is shown in Fig. 2.

Fig. 2: Overview of the rock cut prior to the planar slide at the western end and the geographical location the Være rock cut.

3 Methodology

3.1 Data acquisition, processing, and visualization

Throughout the excavation of the Være rock cut, drone surveys were conducted regularly to capture detailed imagery of the site. Using Structure-from-Motion (SfM) photogrammetry, a total of 18 3D point cloud models were created. SfM is a photogrammetric technique that reconstructs 3D models by identifying and matching surface features in overlapping 2D images through Scale Invariant Feature Transform (SIFT). This process generates high-resolution 3D datasets, including precise spatial coordinates (X, Y, Z), camera positions, and orientations (Westoby et al. 2012).

Initially, the software Pix4DMapper was used to process the drone imagery, achieving high accuracy by incorporating GPS-referenced ground control points, resulting in a precision of up to 2 cm. In the later stages, WebODM Lightning was utilized, offering similar capabilities, and used for generating 3D meshes alongside 3D point clouds.

These models provided detailed visual and spatial information of the rock masses, enabling effective monitoring of geological changes, and contributing to effective and reliable stability assessments. The ability to visualize and analyze the excavation in real-time allowed for more accurate slope design adjustments and targeted support measures, particularly in complex areas such as the slide area, ensuring both safety and resource optimization.

Meshes and 3D point clouds each offer distinct benefits for visualization and analysis. Meshes are particularly advantageous for certain perspectives, especially when photorealism or transparency is needed, while point clouds are easier to manipulate and carry out analyzes for. The software CloudCompare facilitates easy conversion between these formats and enables simultaneous visualization of both, along with other data types such as labels and polylines. This versatility enhances the efficiency of engineering geological and other geotechnical assessments.

3.2 General modeling and analyses

3.2.1 Extraction of discontinuity sets from 3D point clouds

Semi-automatic discontinuity mapping was regularly conducted for the Være rock cut, using advanced 3D remote sensing techniques to address the biases of traditional field methods. This two-phase approach combined a Python script by Østerås (2022) and Discontinuity Set Extractor (DSE) software by Riquelme et al. (2014, 2015).

The Python script identified true discontinuity surfaces in 3D point clouds derived from photogrammetry, classifying them based on orientation and surface area while effectively filtering out artifacts such as sub-planar surfaces and blasting features (sub-vertical). The results can be visualized in stereoplots using software like Dips (Rocscience). However, the script's limitations included its inability to account for discontinuity size or to differentiate minor sets within large datasets.

To refine the results, DSE was employed in the second phase, using kernel density and pole density analyses to group surfaces into representative discontinuity sets. This method effectively highlighted minor sets, such as transverse discontinuities, and captured variations within discontinuity sets due to folding, offering a detailed network characterization.

While neither approach directly identifies lineaments, their integration enhances the identification and spatial interpretation of critical discontinuities, supporting stability assessments in complex, anisotropic rock masses, such as the folded rock masses in the Være rock cut. Some of the results from discontinuity mapping with DSE can be seen in Fig. 3.

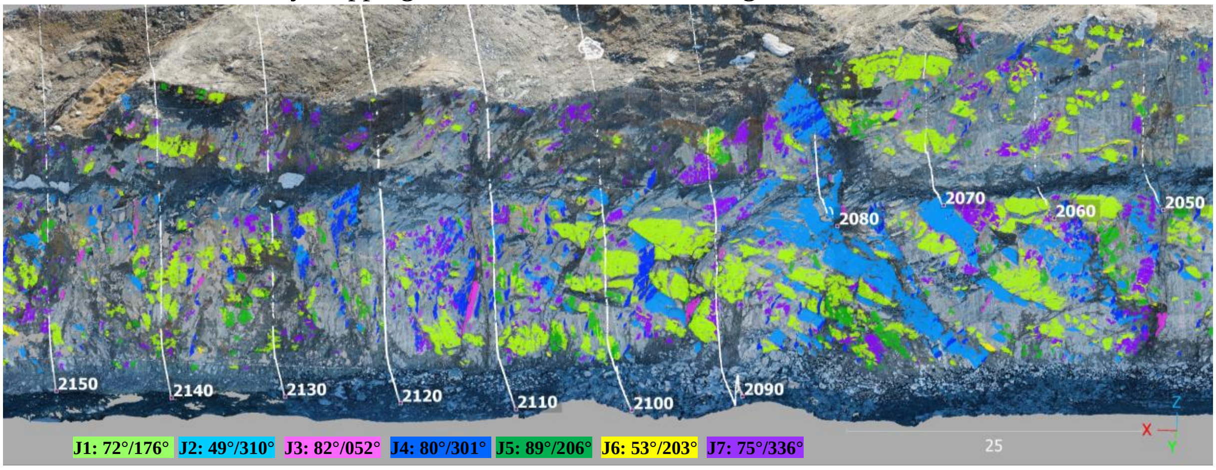

Fig. 3: Semi-automatic discontinuity mapping carried out for the rock cut. The chainage is marked at 10 m intervals. Some of the discontinuity sets are more dominant at the edges of the rock cut such as J6. Orientation is in dip/dip direction.

3.2.2 Rock support approach and documentation

The planning and execution of rock support for the Være rock cut followed Eurocode 7 (EC7) guidelines, emphasizing a combination of empirical methods and detailed analyses. Initial recommendations were based on perspective measures, where rock bolts were placed and oriented according to field observations and practical experience (Standard Norge 2020). For sections deemed structurally controlled, additional calculations were performed to ensure stability, and supplementary support was installed as required.

The use of 3D models created from drone photogrammetry significantly enhanced the design process. These models provided detailed visualization of the rock cut, allowing for precise bolt placement and orientation. For example, a fan-shaped distribution of rock bolts was implemented in the lower part of the wedges, ensuring sufficient anchorage length behind the interpreted critical joints. This approach enabled optimizing the rock bolt lengths, minimizing the use of rock bolts with insufficient or excessively long anchorage length, even under challenging conditions.

The rock bolts used included fully grouted rebar bolts and combination bolts, ranging in length from 3 m to 8 m. Recommendations were documented in geologist follow-up memos, often accompanied by 3D model illustrations to improve communication with contractors and subcontractors, such as the illustration in Fig. 4 (b). Adjustments to the rock support design were made iteratively based on observed conditions, ensuring the overall stability of the rock cut and in the sections deemed structurally controlled. A total of 933 rock bolts (Fig. 4 (a)), amounting to 4000 bolt meters, were installed in the rock cut as permanent support (ignoring removed and excavated rock bolts). This is lower than the detailed design estimate of 4500 bolt meters and the estimate from the zoning plan of 5100 bolt meters. This outcome highlights the efficient and optimized use of rock bolts, even under more challenging geological conditions than originally expected.

Rockfall nets and shotcrete were also essential to the rock support strategy, addressing sections with weathered rock and areas prone to icing. Rockfall nets covered approximately 24% of the rock cut, securing jointed and weathered zones effectively.

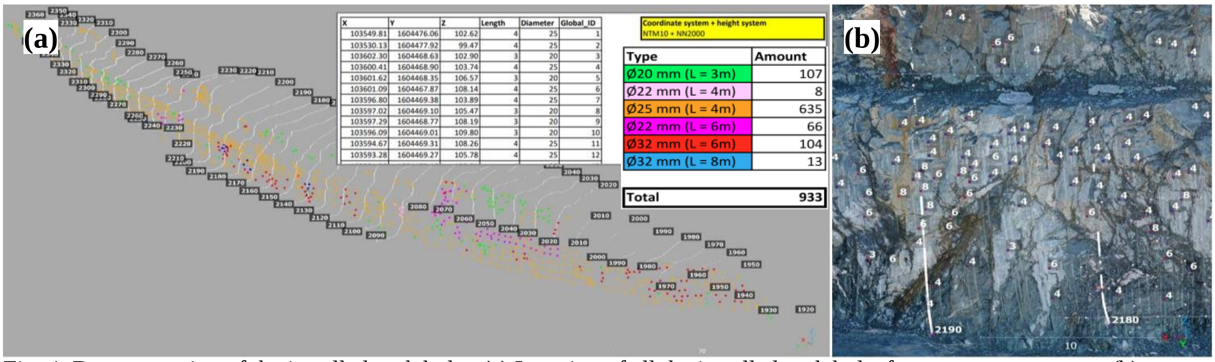

Fig. 4: Documentation of the installed rock bolts. (a) Location of all the installed rock bolts for permanent support. (b) Installed rock bolts with labels indicating the length of them.

3.2.3 Documentation and analyses of large-scale structures

Large-scale structures in the Være rock cut were analyzed using 3D models and stability assessments, focusing on 19 identified wedges as shown in Fig. 5 (a) as well as several overhangs. Critical sections, such as overhangs between Ch. 2330–2240 and an overhang above the basal cavity in the shotcrete area between Ch. 2032-2026, were evaluated using RS2 shear strength reduction analysis, to ensure sufficient factor of safety for long-term stability.

Support recommendations were based on detailed discontinuity mapping and monitoring data from optical prisms, which showed no significant block movements. The potential domains and critical joints of the interpreted large-scale structures were optimized in CloudCompare and adjusted after site observations. This process enabled an efficient workflow for developing accurate stability models in CloudCompare while ensuring alignment with corresponding models in Swedge and RS2.

An approach for determining joint waviness from 3D point clouds in CloudCompare was applied to the larger or more problematic wedges. This method was based on the principle that the waviness angle can be calculated as the difference between the average dip (derived from the best-fit plane of a critical joint) and the minimum dip. The minimum dip was estimated as the Gaussian mean of all values (points belonging to the representative joint surface) below the angle of the best-fit plane. The initial step of this approach is illustrated in Fig. 5 (a). Fig. 5 (b) shows the minimum bolt length required to intersect the critical joints for a wedge (called Wedge 2052), and Fig. 5 (c) shows the assumed orientation of the installed rock bolts in the same wedge with the interpreted critical joints.

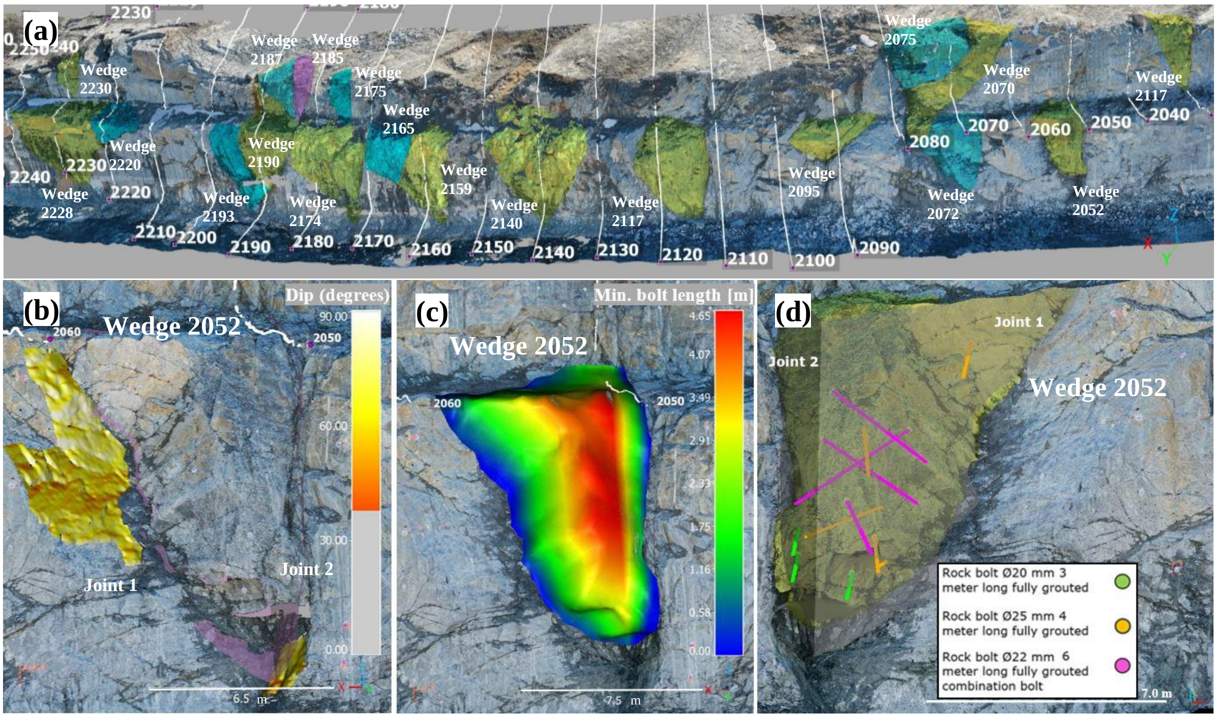

Fig. 5: (a) Identified wedges for the Være rock and are tinted yellow, cyan, and pink. Some of them share critical joints. (b) Dip for the surface of the interpreted critical joints. (c) Indication of minimum bolt to reach critical joints given the rock bolts are installed N-S which is approximately normal to the face of the rock cut. (d) Assumed orientation of installed rock bolts and critical joint planes plotted.

4 Integrated approach to slope stability: lessons from the slide area

4.1 Evaluation of the planar slide

On May 27, 2023, a rockslide occurred at the Være rock cut, classified as a multiplanar failure with a curved sliding surface formed by the intersection of multiple discontinuities, see Fig. 6. An inspection was conducted by the DJV on May 30, 2023, supported by a 3D model generated from drone imagery captured on May 29. The failure involved the collapse of rock bridges and the rupture of surfaces, resulting in a complex geometry reconstructed using eight best-fit planes. The estimated slide volume was approximately 600 m³, as calculated in CloudCompare by comparing pre- and post-slide models.

Before the slide, site inspections and 3D models identified potential sliding joints but did not reveal the full extent of the failure surface due to its concealed curvature. Installed rock support was designed to improve local stability, based on visible structures and estimated block size. However, the slide occurred along previously unobserved discontinuity planes, compromising the total stability.

Two secondary factors possibly contributed to the failure too. A trimming blast conducted on May 23 may have weakened the rock mass, further opening a transverse joint and damaging critical rock bridges. Additionally, heavy rainfall on May 26–27 could have increased water pressure and reduced joint friction, further destabilizing the rock body. These factors compounded the inherent challenges of the complex geological structure.

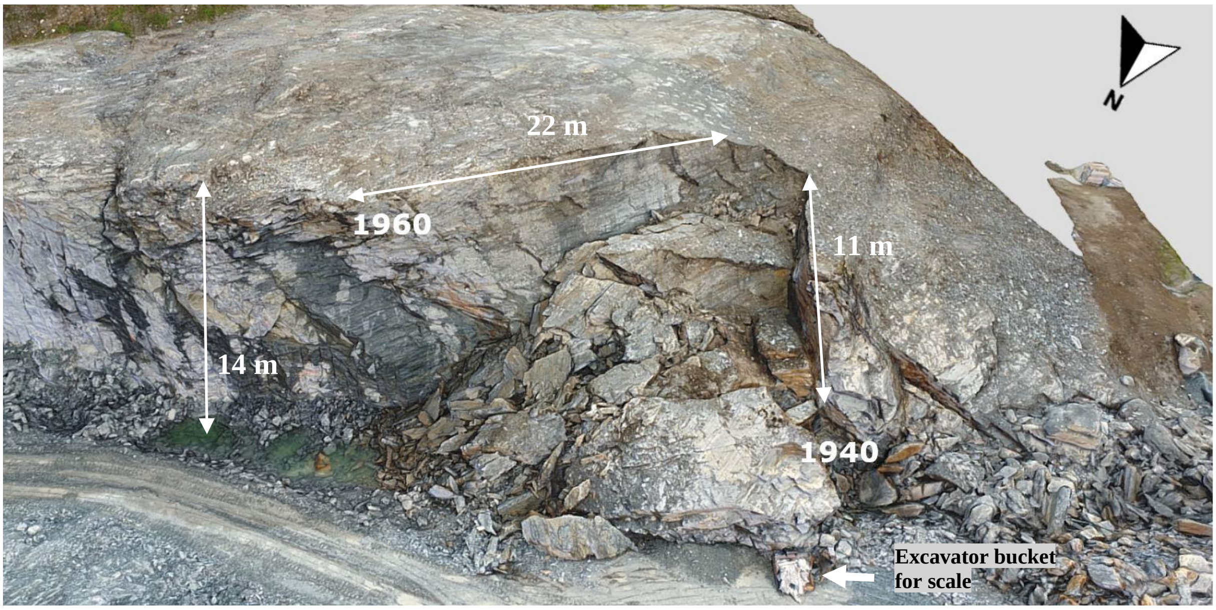

Fig. 6: Overview of the (multi-)planar sliding that occurred in the western part of the Være rock cut.

4.2 Proposed slope redesigns and stability improvements

Following the planar slide, a comprehensive redesign and stabilization strategy was developed to address the complex geological conditions and ensure long-term slope stability. Three alternatives were evaluated: (1) systematic bolting of the existing rock cut, (2) partial blasting of the area directly behind the slide, and (3) complete excavation along the joint forming the potential new sliding plane (parallel to the plane of the planar slide that had occurred). After thorough analysis and consultations among the involved stakeholders, Alternative 2—blasting and excavating the area directly behind the slide—was recommended as it provided a balance between improved stability and aesthetic considerations.

The excavation process was carefully sequenced, incorporating the installation of geophones, optical prisms, and preliminary rock support. The use of 3-meter benches and smaller, controlled blasts allowed adjustments to match the revealed geological structures. This proposed excavation sequence is illustrated in Fig. 7. To minimize damage to the remaining rock mass, drilling and blasting were aligned with natural joint planes, with potential adjustments to the blue plane (Fig. 7 and Fig. 8) as excavation progressed. This approach resulted in a combination of Alternative 2 and Alternative 3.

The redesign also included a temporary rockfill platform, which provided slope stabilization during excavation, improved accessibility for support installation, and reduced the risk of flyrock. Monitoring was conducted at critical intervals, focusing on deformation trends to ensure safety. Stability analyses, including sensitivity analyses using RocPlane (Rocscience), guided the implementation of additional support measures as new geological structures were exposed.

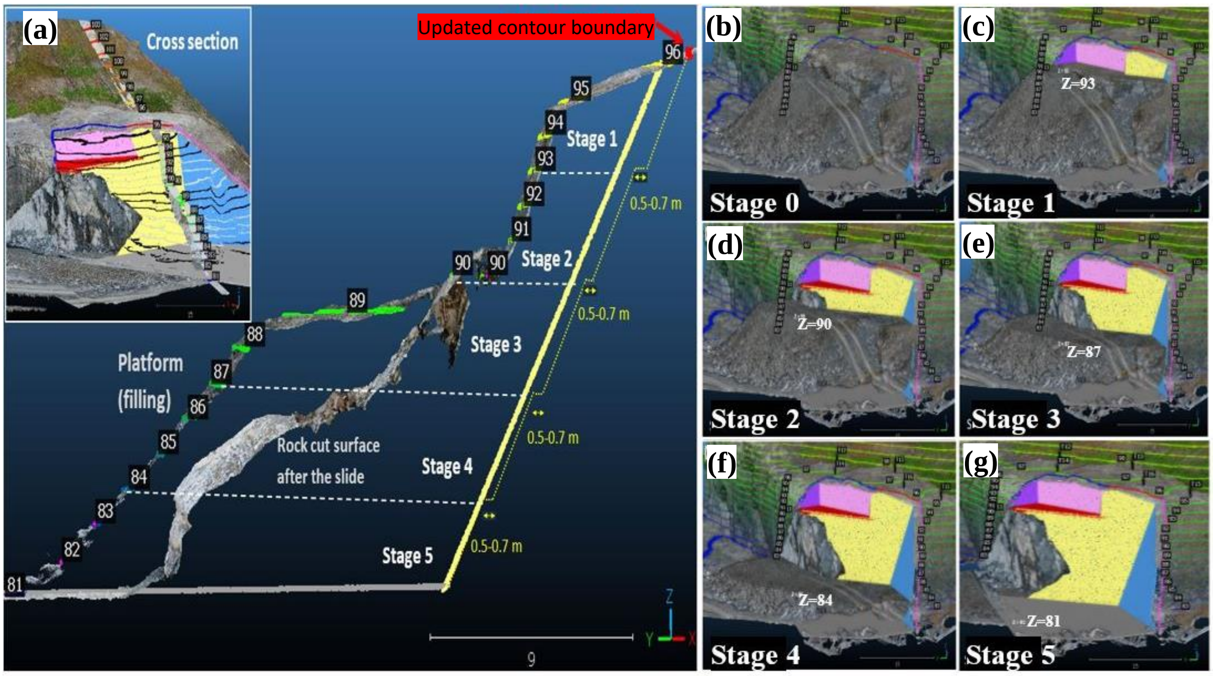

Fig. 7: Proposed excavation sequence for the rock cut at the slide area. (a) Cross-section of the slide area. (b - g) Illustrations of the proposed excavation stages with changes to the temporary rockfill platform.

4.3 Excavation procedures and sequence for the slide area

The excavation of the slide area was thoroughly planned to address the geological complexities following the planar slide. Stabilization measures were implemented because the current design required blasting along the sliding surface's parallel structure (yellow plane in the figures). Additionally, a potential depression or weakness zone parallel to the sliding surface was identified, raising concerns about further instabilities. This depression was considered capable of daylighting or intersecting the geometry of the final rock cut, warranting additional precautions.

A temporary rockfill platform was constructed to stabilize the slope, prevent uncontrolled sliding, and reduce flyrock risks. Monitoring instruments, including optical prisms and geophones, were installed to track slope movement, with a 6 mm deformation threshold set to ensure safety.

The excavation was carried out in three stages, using controlled blasting to follow natural joint planes and minimize damage to the rock mass. Stage 1 reached Z-level +93, focusing on scaling weathered rock and persistent joints, see Fig. 8 (a). Stage 2 extended the cut to Z-level +90, targeting unstable rock masses and addressing intersecting joints to improve stability, see Fig. 8 (b). Stage 3 was initially planned to stop at Z-level +87 but was extended to Z-level +81, as the exposed rock mass showed no signs of the potential weakness zone or large-scale structures intersecting the final rock cut. The improved rock mass quality allowed this stage to be completed in a single blast.

Throughout the process, designs based on Alternative 2 were continuously refined. Adjustments were made on-site as new geological conditions were revealed, ensuring alignment with exposed structures. Real-time evaluations using drone-based 3D models guided support recommendations and validated stability measures, resulting in a final slope that was stable, safe, and consistent with project goals.

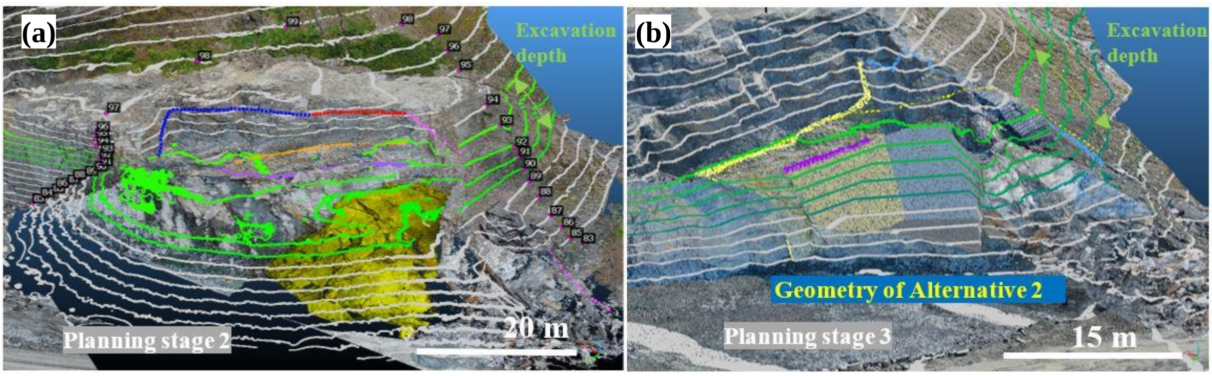

Fig. 8: Planning of the (a) second and (b) third excavation stage in CloudCompare. Contour lines for the elevation is indicated for every meter. The excavation depth for the respective stage is indicated with green contour lines.

5 Conclusions

Optimized rock support through 3D models: the use of 3D models significantly reduced over-support in uncertain and unstable sections, enabling more effective use of shorter rock bolts and eliminated the need for self-drilling anchors. The reliance on 8-meter-long rock bolts was limited, striking a balance between safety and resource efficiency. Stability analysis was enhanced by accurately mapping wedge structures and other potentially unstable sections, allowing for more precise and calibrated support solutions. Additionally, the documentation achieved a higher level of detail compared to what is seen regularly in Norwegian reports, providing a good foundation for future inspection and maintenance.

Improved project oversight: the used of 3D models provided better control over changes during the excavation and blasting phases, enhancing the accuracy of rock support recommendations by allowing precise identification of larger, hard-to-detect structures. This approach enabled the targeted placement of rock bolts and weep holes, which were verified through the models, ensuring effective stabilization. Additionally, it facilitated better blasting planning by ensuring contour holes were positioned in stable rock rather than in slide masses, improving both safety and efficiency during the excavation process.

Management of large potentially unstable rock structures: potential instability from large geological structures was identified as a significant risk factor. When the inherent rock mass strength and rock bridges in the rock cut were considered insufficient to ensure stability, detailed analysis and extensive stabilization measures were recommended. Proposed solutions included the use of rock bolts in different lengths and dimensions, the installation of weep holes, the creation of intersecting ditches, and the modification of the rock cut geometry to better align with the natural geological structures. These measures aimed to enhance overall stability and mitigate the risk of failure.

Future inspection and maintenance: comprehensive records of the coordinates and dimensions of the installed rock bolts will significantly enhance future inspection processes. This detailed documentation allows for easier identification of specific stabilization elements, ensuring long-term safety and improving the efficiency of maintenance operations. Additionally, future inspections can be carried out even without access to the current 3D models. Since all coordinates and dimensions are included in the engineering geological completion report, new 3D models can be recreated if necessary, providing a reliable basis for ongoing stability assessments and maintenance planning.

6 Acknowledgements

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