Digitalization in rock mechanics: A parametric design for numerical models in Norway

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ABSTRACT

Determination of stress magnitude and orientation plays a vital role in rock mechanics and the underground works industry. Local stress fields are disturbed during excavation and new induced stresses influence the surrounding rock mass. Information about their magnitude and orientation is crucial because in some cases the rock strength is exceeded, resulting in instabilities which can have undesired consequences. In turn, the stress state of the rock mass may vary with diverse locations because of factors such as regional tectonics, geology, and/or topography. A rule of thumb points out that on early stages the engineer should search for stress information on a radius of 50 km. Due to scarce and restricted information this is not always possible. For example, Norwegian hydropower depends on knowledge of local rock stresses in order to find the best location and design of solutions in the underground, and to minimize the need for steel lining in pressurized tunnels.

As part of the NoRSTRESS project, the authors have created a shallow 3D model of Norway where it is possible to extract a given area by centre and square side size on a 20 m resolution. This allows for fast and accurate creation of volumes and meshes for further numerical modelling on different scales. There is no evidence of such an effort in the literature for any other country. The results are expected to help evaluating stress magnitude and orientation on early project stages as well as to contribute to develop a 3D stress map of Norway. To have a better overview and understanding of the ground conditions to come will be useful, not only for the hydropower industry, but also for the emerging mining business.

KEYWORDS

parametric design; rock mechanics; numerical modelling; rock stress

INTRODUCTION

The preparation of 3D models is an important step in the analysis and design process. It could contribute to significant time savings in the long-run (and thereby cost) if done efficiently. Parametric 3D modeling is a method of creating 3D models that uses parameters or variables to define and control the shape, size, and other properties of a model. In parametric modeling, relationships between different parts of the model are established through mathematical formulas and algorithms, allowing for quick and easy adjustments to be made to the model, thus eliminating the need for constantly redrawing a design every time changes are made to the model. This approach contrasts with traditional 3D modeling, where shapes are created and modified directly through manipulation of the model's geometry, allowing for greater control, flexibility, and efficiency in the design process. The method has been widely used in civil engineering for structural analysis and design, infrastructure design, water resources management, and geotechnical engineering. Various software tools are available for this purpose and some of the most commonly used ones include Solidworks and Rhino with Grasshopper.

Within geotechnical engineering, 3D models are created for various underground infrastructure projects such as excavations, deep foundations and tunnels. Design and construction of such geostructures could benefit greatly from parametric modelling through time savings and seamless collaboration between project stakeholders. In rock and soil mechanics, parametric modeling has been employed to study the behavior of soil and rock masses and to design foundations, slopes, and retaining structures. This can involve using software such as FLAC 3D, PLAXIS or GEO5 to create numerical models of soil and rock behavior and simulate their response to loads and boundary conditions. Detailed knowledge of stresses is an essential component in rock mechanics to improve numerical modeling and understanding of rock behavior in underground mining, civil engineering, and geological applications. Several cases of utilization of parametrical modelling for design of underground structures can be found in the literature: an underground parking project in an urban area in Lisbon [1], and the subway extension in Stockholm [2] are two good examples of such utilization. No evidence of application of parametrical modelling for the preparation of numerical models has been found in the literature.

By using parametric design in numerical modeling for rock mechanics, engineers and geologists can streamline the process of model building and meshing and dedicate more time to gain a more comprehensive understanding of rock stress behavior, and make informed decisions on design, construction, and stability of underground structures. This is in accordance with an important premise of the use of parametric modeling in underground infrastructure projects: to improve the basis for decision making at early stages to reduce project risks and thereby reduce project costs. This can be conveniently illustrated by the so-called MacLeamy's effort curve in Figure 1, which illustrates the effects of decision making at different stages of an infrastructure's lifecycle.
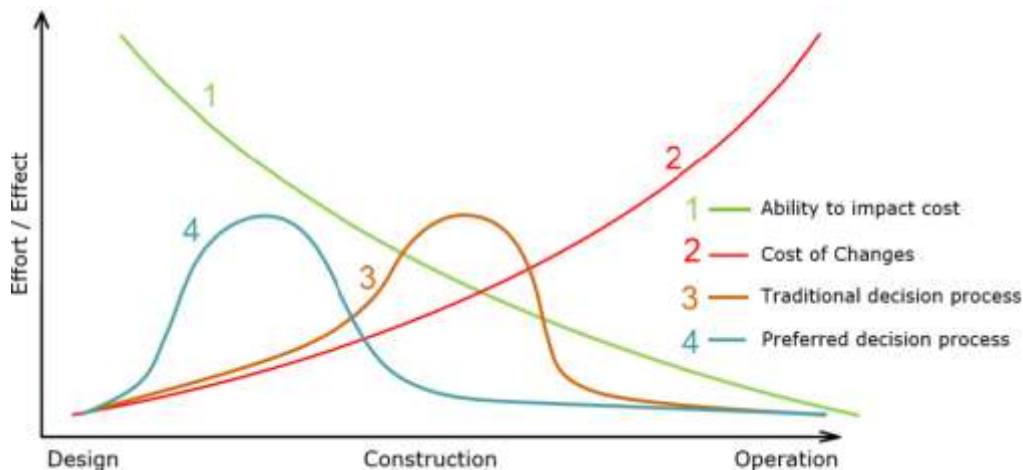

Figure 1: MacLeamy's effort curve [1].

While there has been substantial progress in the use of parametrical modeling for infrastructure above the ground, application to subsurface infrastructure in soils and rocks started receiving attention only in recent years [3]. Unforeseen ground conditions are often the most common source of uncertainty in large infrastructure projects with 37% of project overruns being due to ground problems [4]. It is estimated that 70% of public projects were delivered late and 73% were over the tender price [5]. Some estimates further show that unforeseen ground conditions could increase project costs for example by up to 8% and extend project duration by about 10% [6]. In the context of the present article, the purpose of applying parametric design solutions for the subsurface should be reducing the risk from unforeseen ground conditions due to rock stresses [3][1]. In addition to aiding the challenges related to ground conditions, the application of parametric design has a huge potential towards contributing to the green shift and sustainable infrastructure development.

1. SOFTWARE AND HARDWARE

The study has been done in a last generation computer with the following specifications:
- Intel-I9 12900KS CPU
- 64GB DDR5 RAM at 5200MHz.
- Asus ROG Maximus Z690 motherboard.
- Gigabyte GeForce GTX 1660 Ti video card.
- 2TB solid state drive (SSD) and 12TB hard disk drive (HDD).

Parametrical modelling has been done with the use of Rhino and Grasshopper, while the creation of FLAC 3D-compatible meshes has been done with a Rhino plugin called Griddle. Rhino and Grasshopper are both popular tools for parametric 3D modeling, especially in architecture and design fields. Rhino is a 3D modeling software that provides a comprehensive set of tools for creating and editing 3D models. It has a strong emphasis on precision and accuracy, and is widely used for industrial design, jewelry design, and architectural visualization. Grasshopper, on the other hand, is a visual programming language that runs as a plugin for Rhino. It allows users to create complex and dynamic 3D models using a graphical user interface, without the need to write code. In Grasshopper, users can define geometric relationships between different parts of a model using nodes, which represent mathematical operations or geometric transformations. Finally, the Griddle plugin for Rhino is a tool that is primarily used for creating parametric surfaces and meshes in Rhino. It allows users to create custom grids, or "grids of points," that can be used as a base for creating a variety of surfaces and meshes. The plugin also includes several tools for manipulating and refining the grid, such as the ability to add or remove points, adjust the spacing between points, and create irregular grids. Anyway, depending on the complexity of the mesh and the processing power of your computer, this process may take some time and require some optimization to ensure that the mesh is suitable for use in FLAC 3D.

By using Griddle and Grasshopper in combination with Rhino, users can create highly flexible and responsive 3D models that can be adjusted and updated based on changing design requirements and lately exported to a FLAC 3D-compatible format. The automatized process can significantly speed up the design and avoid engineers to focus on repetitive tasks.

2. METHODOLOGY

The following is the methodology for creating the parametric 3D model of an area of a given size from an orthophoto of Norway using QGIS and Rhino. Note that this is a general approach, and the specific steps may vary depending on the details of the project and the versions in use of QGIS and Rhino, Grasshopper and Griddle. The general steps are:

1) Import the orthophoto into QGIS. The orthophoto used is based on European Terrestrial Reference System 1989 ensemble (EPSG:6258). It has a limited accuracy of at best 0.1 meters.
2) Extract contour lines at different intervals from the orthophoto in QGIS. Intervals were chosen thinking on the future use and extension of the model, at 200m, 100m, 50m, 20m and 10m.
3) Import the desired contours into Rhino. Assign them to a surface feature on Grasshopper. This gives the flexibility to alternate between different contour resolutions without repeating the design process.
4) Define the area of interest by selecting a point on screen and assigning it to the initial point feature on Grasshopper. These areas were selected based on an internal rock stress measurement database from SINTEF, shown in Figure 2 as a heatmap. Exact locations cannot be disclosed due to confidentiality reasons. The ultimate idea is to be able to calibrate the numerical models based on actual measurements in areas with good availability of information and afterwards run it in areas with few or no datapoints and check the degree of accuracy of the predictions. Therefore, it is extremely useful to be able to quickly shift areas and sized during the design phase.

The following steps were automatized and parametrized on Grasshopper based on the initial selection on 4).

5) Contour clipping. This involved selecting and cutting contour lines that can be fully or partially inside the area of interest.
6) Create the surface terrain model. Meshes were created using Delaunay triangulation and regular squares.
7) Extrude the surface to create a box for a 3D representation of the area of interest.
8) Identify possible fault zones and at its correspondent surface lines. Manually define dip and direction. The algorithm generates the rest of the geometry based on faults crossing the whole block or just partially contained on it.
9) Export the terrain model from Grasshopper to Rhino.

To export the 3D model created in Rhino for use in FLAC 3D, one needs to export the model in a format that is compatible with the latter. The most common format for this purpose is the f3grid format. This was done using the Griddle plugin and the following steps:

10) Select the 3D box from 6) and the faults from 8) and create the initial mesh. The initial mesh is not very good, but it will be remeshed in future steps.
11) Intersect all meshes. The process allows to define a tolerance for the intersection. All other parameters were kept at defaults.
12) Select all objects again with and use Griddle Surface command to remesh the meshes from 11). It is very important to select eventual fault borders as well, because they will serve as hard edges to preserve conformity with the 3D box mesh. Parameters such as the overall block shape, and minimum and maximum edge length were found to be very relevant for further steps.
13) Do the volume meshing with the Griddle Volume. This tool typically marks parts of surface meshes causing meshing errors with red outlines.
14) Open FLAC 3D and import the f3grid file exported from Rhino. The 3D model should now be ready to use in the FLAC 3D simulation.

Using the Griddle tools to create a mesh from the contour lines or point data is a finicky process and the selection of parameters highly influences the corrections to be done and errors to be solved for achieving a successful geometry export.

Note that this is a general methodology, and the specific steps may vary depending on the details of the project and the versions in use of QGIS and Rhino, Grasshopper and Griddle.
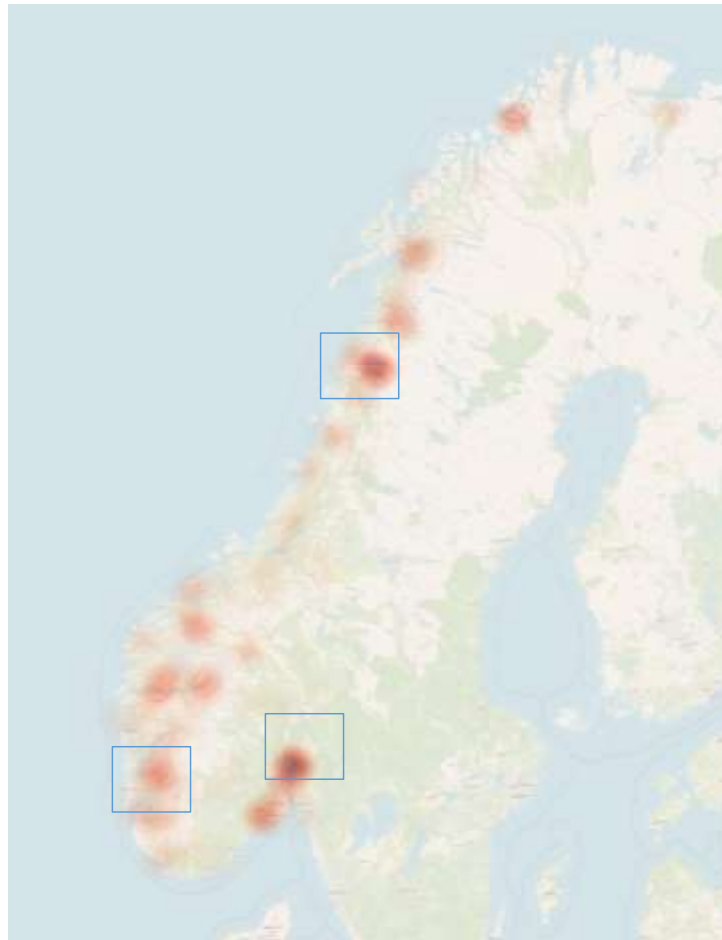

Figure 2: Locations of existing rock stress measurements (red) and parametric model areas (boxes in blue) in Norway.

3. RESULTS

3.1. Processing Times

3.1.1. Contour lines

The processing time for generating contour lines from an orthophoto of the whole of Norway (4Gb in size) in QGIS depends on several factors such as the processing power, complexity of the terrain, and the selected contour interval. A rough estimate of the processing time for generating contour lines at different intervals might vary from a few seconds (in 200m scale) to minutes in extent (in 10m). In general, it is obvious than the shorter the interval the longer to process. These estimates are rough and may vary depending on several factors, as mentioned earlier. Actual processing time for the different cases are shown in Table 1:

Table 1. Processing time for contour line extraction

Contour [m]	Time [s]
200	53
100	104
50	231
20	694
10	1345

From the table, we can conclude that the processing time increases significantly as the interval between contours decreases. This is expected as the calculations become more complex and computationally intensive when the intervals are smaller. We can also see that the difference in processing time between intervals of 200 meters and 100 meters is relatively small compared to the difference between intervals of 50 meters and 20 meters or 20 meters and 10 meters. This indicates that the processing time do not increase linearly with decreasing interval size. Extrapolating processing times for intervals of 5 meters and 10 centimeters based on the given data is straightforward with a power regression (R^2 = 0,997). We can estimate that the processing time for a 5-meter interval may be around 2 983 seconds (or 50 minutes) and the processing time for a 10 centimeter interval may be around 222 303 seconds (or 2,6 days). The latter may not be possible to reach due to floating storage/memory constraints.

Even though the orthophoto can be clipped to a minor extent in QGIS, and therefore allow for extraction of contour lines on intervals of 10m and even smaller, this creates a repetitive task for each time a new location and area is to be chosen.

3.1.2. Computing time versus square side/area

Equally as the case of contour lines, the processing time for a parametric model clipping contour lines at 20m interval for a given area depends on several factors such as the processing power, complexity of the terrain, and the selected contour interval. Figure 3 presents an overall overview of the four squares side sizes tested during the project: 25, 10, 5 and 1km. Table 2 presents the processing times in minutes for contour curves of whole Norway being clipped at specific locations with different sizes using a parametric model in Grasshopper. The first and second columns indicates the side of the square and its area, with the previously mentioned values of 25, 10, 5 and 1 kilometers. The next three columns show the processing times for each area, namely North, West, and East. Table 2 can be used to compare the processing times for different area sizes and regions, which may be useful for optimizing workflows and improving efficiency in contour curve processing.

Table 2. Processing time for contour clipping and 3D model building.

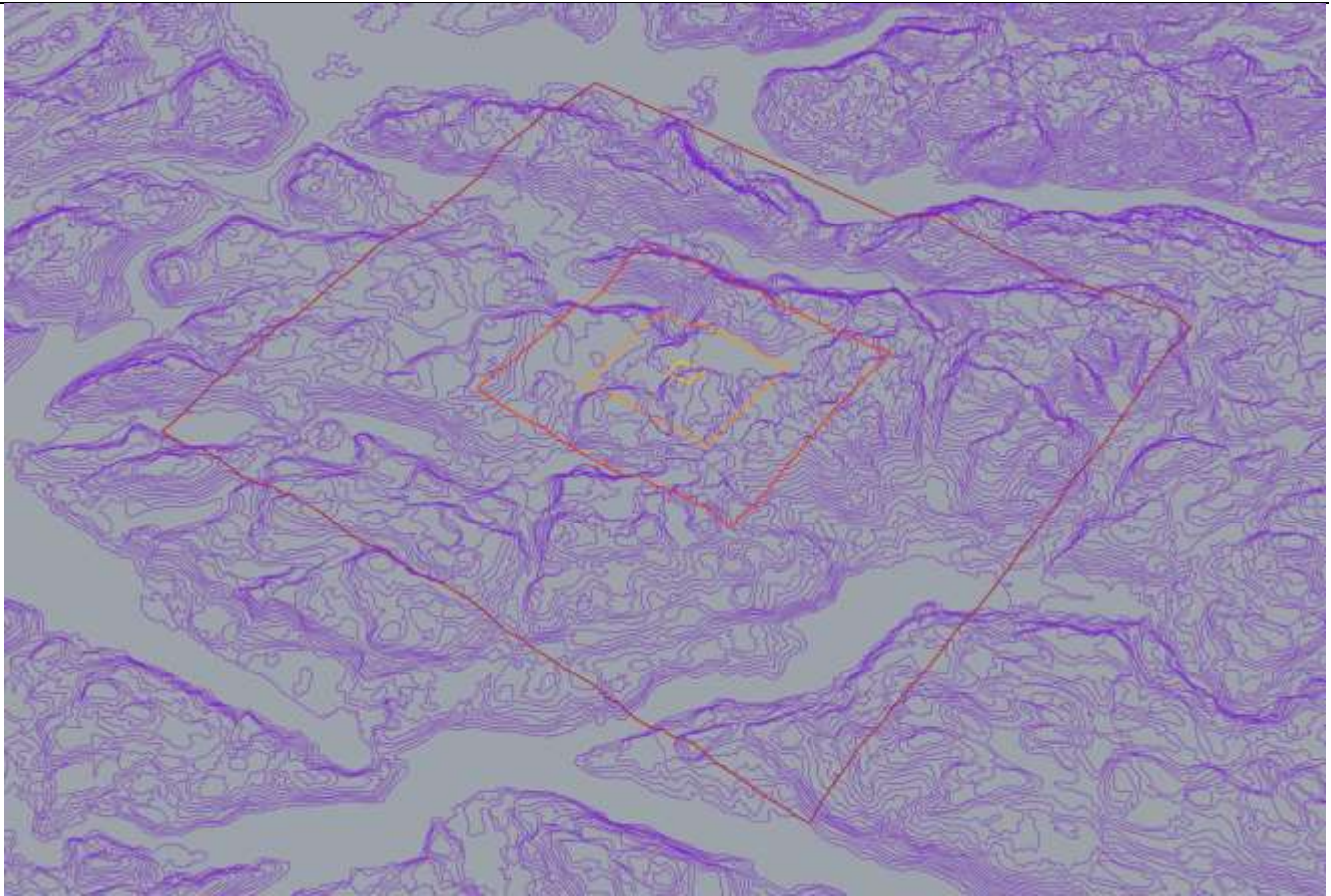| Side size [km]	Surface [km^2]	Processing time [min]		
		North Area	West Area	East Area
25	625	8,0	11,1	2,4
10	100	17,3	39,8	3,0
5	25	9,1	1,2	12,7
1	1	6,8	5,8	25,3

Figure 3: Areas for testing parametrical model building (square side 1km (yellow), 5km (orange), 10km (red), and 25km (dark red)).

Based on the data in the table, it appears that the minimum processing time varies depending on the size of the square area and the specific region of Norway being processed. Upon closer inspection of the table, it appears that the processing times for the East Area of Norway are actually longer for the 5 km and 1 km square side sizes compared to the 25 km and 10 km sizes. This suggests that the processing time is not solely determined by the area size, but also influenced by other factors such as data density, complexity of terrain, and algorithm efficiency.

Furthermore, the minimum processing time for each area is not consistent across different area sizes. In the North area, the minimum processing time is for the 1km area size. In the West area, the minimum processing time is for the 5km area size. Finally, in the East area, the minimum processing time is for the 25km area size. Therefore, the minimum processing time varies for different area sizes and regions, and it may be necessary to optimize the area size based on the specific region and processing requirements. The times obtained can be useful information to select an appropriate square size for generating 3D models in numerical simulations, where computational efficiency is crucial for obtaining results in a reasonable amount of time.

Additionally, two supplementary models were generated for the East Area, for 50km and 100km sizes, with processing times of 2.9 and 4.4 minutes, respectively. These results suggest that larger area sizes may lead to more efficient processing times, with a significant reduction in processing time observed at the 25km size. The findings may be useful for optimizing workflows and improving efficiency in contour curve processing for the East Area of Norway. These phenomena was not observed on the other areas and calls for future analysis.

3.1.3. Minimum element size to model side ratio versus meshing errors

Each of the 12 squares (4 on each region) were used to automatically generate 3D models of a region. In turn, these 3D models were used to generate 3D volumes to be exported to FLAC 3D. The overall block shape, was kept the same, while the minimum and maximum edge length were iterated at different ratios with respect to the edge size and compared to the number of errors. The minimum edge length determines the smallest allowable edge length in the mesh, while the maximum edge length determines the largest allowable edge length. By

adjusting these parameters, it is possible to create a mesh with the appropriate level of detail for the intended use case while minimizing errors. There is no universal optimal edge size that works for all meshing applications, even though There are several publications that discuss mesh generation and optimization for different applications [7][8][9], none of them are in rock mechanics. The appropriate edge size depends on various factors such as the geometry of the object being meshed, the desired level of detail, and the computational resources available.

The errors considered were Meshing Error, Naked Edges and Clashing Faces. Meshing errors, naked edges, and clashing faces are common issues that can arise when using Griddle. Meshing errors occur when the mesh is not properly formed or has inconsistencies, such as overlapping vertices or incorrect face connections. These errors can result in an irregular or distorted mesh, making it difficult to create accurate and precise models. Naked edges are edges of a mesh that are not connected to any faces, which can occur when creating or modifying a mesh. Naked edges can create problems during the volumetric meshing process, as they can cause gaps or holes in the final exporting of the model. Clashing faces occur when two or more faces of the mesh intersect or overlap each other, which can also cause issues during the meshing and exporting process. It is important to identify and fix clashing faces to ensure the mesh is accurate and can be printed properly. Errors are shown in the red screen as illustrated in Figure 4. No faults or weakness zones were considered during the process.
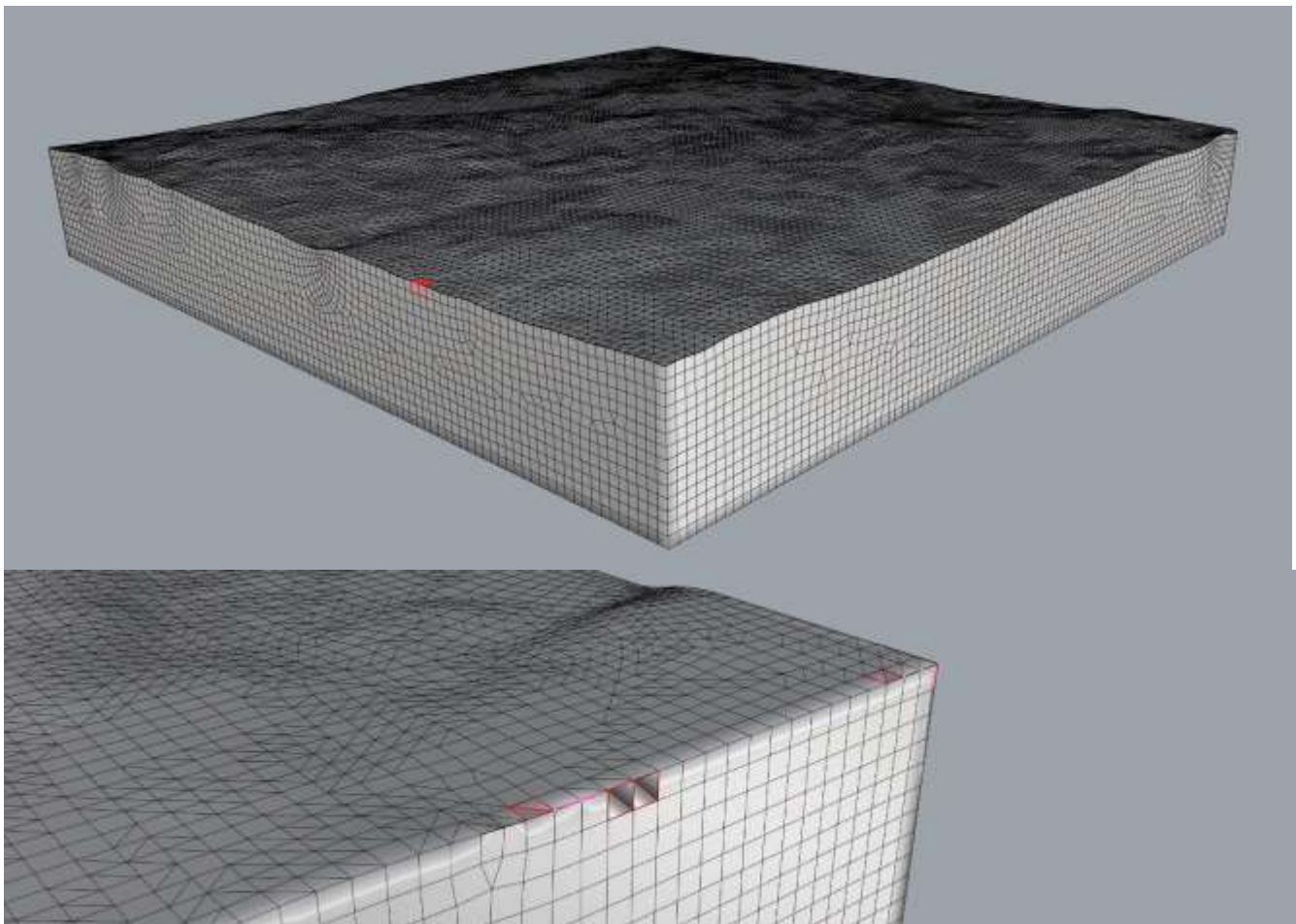

Figure 4: Meshing errors for one of the 3D models (Top: general overview; bottom, detail of clashing faces (red), meshing errors (dots) and naked edges (pink)).

Table 3 presents information on the squares side size, ratio, minimum and maximum edge length, meshing errors, naked edges, clashing faces, and status of the exporting process of the 3D models for the Eastern Area. The ratio column represents the aspect ratio of the minimum edge size of the mesh elements, while the maximum has been fixed at 10 times the minimum. The status column provides information on the final outcome of the export process without further healing of the meshes. Meshing errors, naked edges, and clashing faces are also reported in the

table, which may help identify potential issues with the mesh. This information can be useful for assessing the quality of the mesh and making any necessary adjustments to optimize its performance.

Table 3. Summary of errors and status outcome.

Side size [km]	Ratio	Minimum edge [m]	Maximum edge [m]	Meshing Errors	Naked Edges	Clashing Faces	Status
25	1 to 20	1250	12500	25	1	0	Not Meshed
	1 to 100	250	2500	2	0	2	Meshed
	1 to 200	125	1250	12	0	1	Not Meshed
10	1 to 20	500	5000	17	1	0	Not Meshed
	1 to 100	100	1000	5	0	1	Meshed
	1 to 200	50	500	12	2	0	Not Meshed
5	1 to 20	250	2500	2	5	0	Meshed
	1 to 100	50	500	1	2	2	Not Meshed
	1 to 200	25	250	12	5	6	Not Meshed
1	1 to 20	50	500	29	4	2	Not Meshed
	1 to 100	10	100	1	0	1	Meshed
	1 to 200	5	50	4	5	4	Not Meshed

The table shows that meshing with a minimum edge to side size ratio of 1 to 100 results in the lowest number of meshing errors, naked edges, and clashing faces, while maintaining an acceptable range for the minimum and maximum edge lengths. Comparing it to a ratio of 1 to 20, we see an increase in all error types and a decrease in the maximum edge length, indicating that the mesh is too coarse. On the other hand, comparing it to a ratio of 1 to 200, we see a decrease in errors, but also a significant decrease in the minimum edge length, indicating that the mesh is too fine. Therefore, it can be concluded that a ratio of 1 to 100 provides the optimal balance between mesh quality and computational efficiency. Furthermore, it should be noted that using a minimum edge to side size ratio of 1 to 100 not only reduces meshing errors, naked edges, and clashing faces, but also leads to more successful exports to FLAC 3D.

4. CONCLUSIONS

Object - based parametric modelling is a major change for the building industry that is greatly facilitating the move from a drawing - based and handcraft technology to one based on digitally readable models that can be exchanged with other applications. Parametric modelling facilitates the design of large and complex models in 3D but imposes a style of modelling and planning that is foreign to many users. Like CAD, it is most directly used as a documentation tool separate from designing. A growing number of companies, however, use it directly for design and for generating exciting results.

As expected, the present work shows that processing times for generating contour lines from an orthophoto of the whole of Norway in QGIS increases significantly as the interval between contours decreases. Anyway, the difference in processing time between intervals of 200 meters and 100 meters is relatively small compared to the difference between intervals of 50 meters and 20 meters or 20 meters and 10 meters, indicating that the processing time does not increase linearly with decreasing interval size. This supposes a trade-off between resolution and computing times. On this side, clipping the orthophoto to a minor extent in QGIS allows for extraction of contour lines on intervals of 10m and even smaller, but this creates a repetitive task for each time a new location and area is chosen.

Once the contour lines have been generated, the processing time for a parametric model clipping such contour lines at a given area depends on several factors such as the processing power, complexity of the terrain, and the selected contour interval. The processing times for different area sizes and regions may vary depending on data density, complexity of terrain, and algorithm efficiency. The minimum processing time for each area is not consistent across different area sizes, as it varies for different area sizes and regions, and it may be necessary to optimize the area size based on the specific region and processing requirements. The times obtained can be useful information to select an appropriate square size for generating 3D models in numerical simulations, where computational efficiency is crucial for obtaining results in a reasonable amount of time. The results show that there

seem to be an inflection point on all three areas, but at different sizes. Further research on these findings may be useful for optimizing workflows and improving efficiency in contour curve processing for the East Area of Norway.

On the exporting side, it is found that using a minimum edge to side size ratio of 1 to 100 not only reduces meshing errors, naked edges, and clashing faces, but also leads to more successful exports to FLAC 3D. It seems that the 1 to 100 ratio strikes a good balance between mesh density and computational efficiency, resulting in smoother and more accurate numerical models. Therefore, based on the findings and the surface topography and conditions it is recommended to use a minimum edge to side size ratio of 1 to 100 when building surface meshes for numerical modeling in FLAC 3D or similar software. Adjusting the minimum and maximum edge length in the mesh can create a mesh with the appropriate level of detail for the 3D models of the region. The optimum ratio of minimum element size to model side length may vary depending on the specific region, and a high ratio may lead to an increase in meshing errors.

Overall, the article discusses the advantages and challenges of object-based parametric modeling in the building industry, which enables the design of complex 3D models that can be exchanged with other applications. Even though the processing time for generating contour lines from an orthophoto in QGIS increases significantly as the interval between contours decreases, the clipping time of such contour lines at a given area depends on several factors such as processing power and complexity of terrain. These results are expected to help building a baseline for estimating the maximum radius of influence of stress measurements to accurately forecast stress conditions in other location.

The authors are of the opinion that the full potential of this enabling capability within Geotechnics and Engineering Geology is to be developed during the next decade because its implications and new uses are discovered gradually. What is currently known is that object - based parametric modelling resolves many of the fundamental representational issues in architecture and construction and allows quick payoffs for those transitioning to it, even with only partial implementation. These payoffs include a reduction in drawing errors due to the built-in consistency of a central building model and the elimination of design errors based on spatial interferences. The same is expected to be developed for Geotechnics and Engineering Geology over the coming years.

5. ACKNOWLEDGEMENTS

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