CSCE Annual Conference

Growing with youth – Croître avec les jeunes

Laval (Greater Montreal)

June 12 - 15, 2019

4D SIMULATION OF ROCK EXCAVATION PROJECTS

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Abstract: 4D simulation is commonly used in building construction projects as part of Building Information Modeling (BIM) processes. Recently, the concepts and methods used in BIM and 4D simulation have been extended to civil infrastructure projects (e.g. roads and bridges) under the umbrella of Civil Information Modeling (CIM). CIM can be further extended to represent the sequence of excavation and mining operations in 4D simulation, where excavation blocks are represented as volumetric parts. The dimensions of the blocks are selected based on the drilling equipment and dynamite capacity while taking into account the sequencing of the crew, safety issues, and the natural slope of the bedrock. This paper aims to evaluate the applicability of 4D simulation in rock excavation projects to determine the feasibility of the excavation methods and analyse the operational features of the construction site. The developed methodology integrates 3D modeling and visualization techniques with a rock excavation simulation that was validated in an actual construction project. The rock excavation operations can be evaluated with the 4D simulation. The main challenge of the 4D simulation is sequencing equipment and crews for a feasible schedule without spatio-temporal clashes, while respecting safety considerations (i.e. blast pattern, equipment protection, and distances) and other constraints. The resulting 4D simulation can be used to help the decision making of an integrated team of geologists, engineers and construction managers. A case study was used to evaluate the proposed method. The developed 4D simulation has a high level of detail (LOD) including 721 parts in the 3D model and a schedule with average task duration of 1.5 days. The 4D simulation has proven helpful by establishing a sequencing strategy where the parts are representing mining blocks.

1 INTRODUCTION

4D simulation can be used in multiple industries including natural events prediction and the built environment evolution simulation. For example, Xue et al. (2002) described 4D variation data assimilation to forecast weather temperature in predicting storms such as tornadoes. Weber et al. (2009) developed the geometric simulation of 4D cities for comparing urban plans. Recently, the concepts and methods used in BIM and 4D simulation have been extended to civil infrastructure projects (e.g. roads and bridges) under the umbrella of Civil Information Modeling (CIM). CIM can be further extended to represent important steps with the sequence of excavation and mining operations in 4D simulation, where excavation blocks are represented as volumetric parts. The rock excavation operations that can be evaluated with the 4D simulation include drilling (precut and mass), explosives loading into boreholes, blasting, scaling, anchors installation, rock injection and mocking. The objective of this article is to provide a method for using 4D simulation of hard rocks excavations while considering visualization of operations and rock geological properties. The developed method integrates 3D modeling and visualization techniques with a rock excavation simulation that was validated in an actual construction project. The rock excavation operations can be evaluated with the 4D simulation. The article first explores the related work in Section 2. Then, Section 3 describes the 4D simulation method specific to rock excavations. Section 4 provides a case study where the method has been tested. The 4D simulation general process is described in Guevremont (2017) and the levels of development of such 4D simulation are described in Guevremont and Hammad (2019).

2 RELATED WORK

2.1 4D simulation in the mining industry, underground operations and rock geomodeling

Figure 1 shows the domain related to rock excavation and backfill projects and Table 1 summarizes its characteristics, needs and time steps of 4D simulation using hard rock for different industries. Lu et al. (2014) proposed the concept of Mining Lifecycle Management (MLM) with 4-layer structure realization (project information portal, core application, modelling and data) as modeling framework for all phases of a mining project. They considered data sub-models including mineral exploration, geo exploration, terrain, building, laneway, equipment, dispatching, mining, quality, safety, etc. Their evaluation of safety was limited to the environment monitoring system, ventilation control system, mine pressure monitoring system, underground water outburst and water level monitoring system. Royer et al. (2015) developed 4D geomodeling for mineral resources assessment, identifying potential new mineral resources and modeling ore deposits (mine planning and design). It can be useful for oil and gas industry to reproduce the dynamic evolution of structures (burial history) and reconstruct the past rock deformation history (folding). Caumon (2010) used time-varying geological modeling with different time scale, such as geological timescale or human timescale, to assess uncertainty in quantifying natural resources or mining production forecast. He mentioned that geomodels provide geological insight and could include rock features such as isotopic ages, mineral microstructures and strain analyses. Neri et al. (2006) used 4D multiphase simulation to show the dynamics of explosive volcano eruptions where the ‘dynamite’ is generated by shifts of tectonic plates boundaries. Their color coding of the Vesuvius eruption represents the total volume of particle concentration in the plume. They considered eruptive fluids and solid magma (ash, crystals, lapilli) and gas. Solid state rocks are characterized by diameter, density, specific heat and thermal conductivity. The simulation output provides their concentration, velocity and temperature with cell size of 20 m high and topography acquired at 10 m resolution. Their typical time step is 0.01 second. Their analysis is useful to help protect the 550,000 people living in the evacuation zone around the volcano. Tavchandjian and Cochrane (2001) developed resource modeling for rock resource estimation in the context of the underground mining industry. Their reporting includes collar location, topographic model, surveying of drill holes and relevant geological features to provide a global resource estimate within the mineralization domain. The mineral envelope is filled with tetrahedral cells representing mining blocks. The resulting conditional simulations help decision making for mining exploitation. Osterholt and Dimitrakopoulos (2018) developed the simulation of orebody geology with multiple-point geostatistics for petroleum reservoir modelling using color-coding. Li et al. (2013) developed integrated software for general practitioners to access uncertainty analysis on geostatistical simulations of subsurface modeling such as oil reservoirs. Their multidimensional scaling space uses visualization utilities and clustering techniques, to explore the relationships between simulation parameters. Zhu et al. (2011) explained the advantage of time-Geographical Information Systems (GIS) , or 4D-GIS, for geological and object models with geological conditions changing over time. Lilley et al. (2013) used 4D simulation to evaluate the deformation between mine wall nodes for closure history of different rock bolts to prevent failure of underground excavations such as crusher chambers, shaft pillars, block cave extraction and transfer tunnels. Their framework mentions excavation geometry, mining sequences, dynamic loading sources, in situ stress field, rock mass conditions, ground support system and failure criteria. They described rock deformation levels and prevention with fibrecrete, mesh, straps, timber poles and steel sets to avoid damages during earthquakes and dynamic load cases of mining activities. To leverage 4D simulation with automated as-built data using GIS, Vick and Brilakis (2016) compared spatial data collection method and listed them considering their cost, delivery time, accuracy, resolution, strengths and weaknesses. They evaluated methods such as manned aerial imagery and Light Detection and Ranging (LiDAR), unmanned aerial imagery, mobile LiDAR, terrestrial LiDAR, Global Navigation Satellite System (GNSS) and total station.

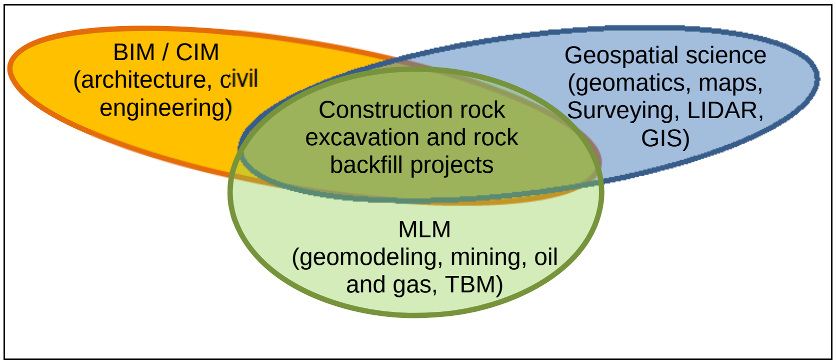


Figure 1: Domain of construction excavation projects

2.2 4D Simulation in Building Information Modeling (BIM) and Civil Information Modeling (CIM)

Kim and Fischer (2013) applied a 4D model-based decision-support system (the Development Strategy Simulation (DSS)) to a US tunnel project including tunnel, portals, access road and ventilation building. Their motivation case was about four new hydro-tunnels in Nepal Himalaya where they compared class 1 to class 7 rock mass conditions based on Q-system (rock mass classification) and Rock Mass Rating (RMR) systems. With poor quality rock (class 7), there is a high requirement for shotcrete and rock bolts. The performance metrics they analysed included the number of trucks, amount of concrete, hours of labor, and quantity of excavation. Zhang et al. (2010) proposed a simulation evaluation of tunnel constructions for the decision making process with a high level architecture-based distributed simulation. Their methodology integrates 3D modeling and visualization techniques with the tunneling construction simulation that was validated in a real-life tunnel project. It included shaft preparation, excavation and lining, then tunnel excavation, lining, resetting of Tunnel Boring Machine (TBM), TBM breakdown, dirt removal from the tunnel face to the undercut, dumping dirt from undercut to ground, and loading carts with materials. Koch et al. (2017) developed a framework with tunnel information modelling with four interlinked subdomain models to cover an entire project performance data: a ground model, a boring machine model, a tunnel lining model, and a build environment model. The models are created individually and then linked within an open IFC environment using the concepts of Proxies, Property Sets and Model View Definitions. Kim et al. (1999) evaluated discontinuous deformation analysis of rock (stability and stress) considering excavation sequences for tunnels as finite and deformable blocks. Their study was limited to 2D evaluation but included rock reinforcement (rockbolts, shotcrete and concrete lining) as hydro-mechanical coupling between rocks and steady water flow in fractures. As described by Wang (2011), 4D simulation can be used for civil work integration with the building models. He reviewed three GIS to determine the level of feasibility and operational features of technical support necessary to implement the site-linked BIM model. The evaluated site conditions included underground situation, logistic site condition and site-linked BIM model. He evaluated software including Autodesk Revit, AutoCAD Civil 3D, Bentley products and ArchiCAD. Chang et al. (2016) proposed a review of CIM and proposed a categorization of civil infrastructure facilities with 13 categories: bridges, roads, railways, tunnels, airports, ports and harbors, power generation, oil and gas, mines, utilities, recreational facilities, water and wastewater facilities, and dams, canals and levees. Costin et al. (2018) provided a similar review of CIM categories, with only few categories (tunnel, geotech, road and railways) considering hard rock excavation while mining and geological engineering categories are not in their BIM/CIM classification. A limitation of past research on CIM is that it only partially covered hard rock manipulation, movement, and operations. Guevremont and Germain (2012) used 4D simulation for a dam project. The color coding used with parts distinguished backfill types, levels (heights) and structures. The 4D models also used GPS positioning with coordinates. Shah et al. (2008) developed a 4D simulation prototype to visualize the progress of earthwork operations. They investigated road design data, quantities of cut-and-fill and productivity model for automatic generation of terrain surfaces with earthworks progress profiles.

Their typical cross-sections for cutting and filling road projects are used on flat and transverse slope of terrain surfaces.

Table 1: Related work characteristics of 4D simulations related to rock operations

Industry	Characteristics	Needs	Typical time step
Mineral resource exploration	Geological insights, faults, rock structures, drill holes, mineralization events	Evolution of geological deposits	Geological timescale
Oil and gas	Folding, burial history, fluid migration, erosion, faults, fracturing	Shaping the resource reservoir	Geological timescale
Mining (open pit and underground)	Ramps, shafts, pit, ore deposit, blasting	Mine life evolution	Day, week, month, year
Tunnel boring machines	Lining, carts, undercut, dumping	Feasibility and schedule optimization	Day, week, month, year
Rock excavation and backfill operations	Ramps, blasting, rock mass, layers, bench, faults, rock type, drilling, scaling, consolidation	Feasibility and schedule optimization	Day, week, month, year
Volcanology	Volcano eruption behavior, plume particles, magma	Citizen safety	0.01 sec

3 DEVELOPED METHODOLOGY

The natural terrain is mapped using surveying and LIDAR scanning with drones. The details of the rig triangles (facets) affect the 4D-LOD. The 3D model of the excavation area includes the natural terrain obtained from a map using GIS. The shapes of the natural terrain with slopes are representing the natural elevations and iso-contours as shown on a map. The 3D model requires numerous rig triangles (facets) to represent the natural terrain. The 4D-LOD is described in Guevremont and Hammad (2018). In rock excavation, continuity of cells must be addressed with the natural terrain. The size of the resulting file must be considered and is impacted by the size of rock blocks and the number of triangles in the 3D model. There are seven operations included in 4D simulation of rock excavations: (1) drilling, (2) loading of dynamite, (3) blasting, (4) mocking and hauling, (5) scaling, (6) consolidation, and (7) surveying operations. These operations are represented on Figure 2 and performed after adequate planning. Some operations, such as surveying, drilling, loading dynamite and blasting, are performed for bench height of 10 m while other operations, such as mocking, hauling, scaling and consolidation, are performed twice for every bench: a first pass for the upper portion (first 5 to 7 m) and a second pass for the remaining portion of the bench (3 to 5 m). The reasoning behind this breakdown is to ensure workers safety. The equipment of all operations and details of rock explosion operations are not included in the current simulation and will be added in the future. The relevant geological features which influence the spatial distribution of excavation operations (e.g. faults, the quality and type of the rock for the sizing of blocks) are considered in the 3D model. In addition, the site layout is modeled including the original ground level and the ramps made from backfill or untouched rock.

Drilling: First, drill holes pattern are generated on a rock mass. Then, the drill rig is used with a drill operator to perform the drilling of the rock mass. Pre-cut drilling is used to manage the exact line of the final excavation. Mass hole drilling is performed with the intent to maximize the productivity of the hauling operation. The duration of the drilling activity is defined by multiplying the number of holes by the length of each one of them and considering a productivity factor for the rock type and the equipment used. The initial maximum height of 10 m of benches is constrained with the precision of the pre-cut drilling that has an approximate diameter of 75 mm and is more unstable than mass drilling holes. The work face evolves as the blasts are completed and exposes the next rock cells to be drilled. Access such as ramps can also dictate the flow of operations. Ramps are an operational constraint and considerations included slope angle for safe access of workers and normal functioning of equipment for transportation and maintenance. The drilling of the next rock cell can start when the preceding one is scaled and consolidated pending on the site conditions.

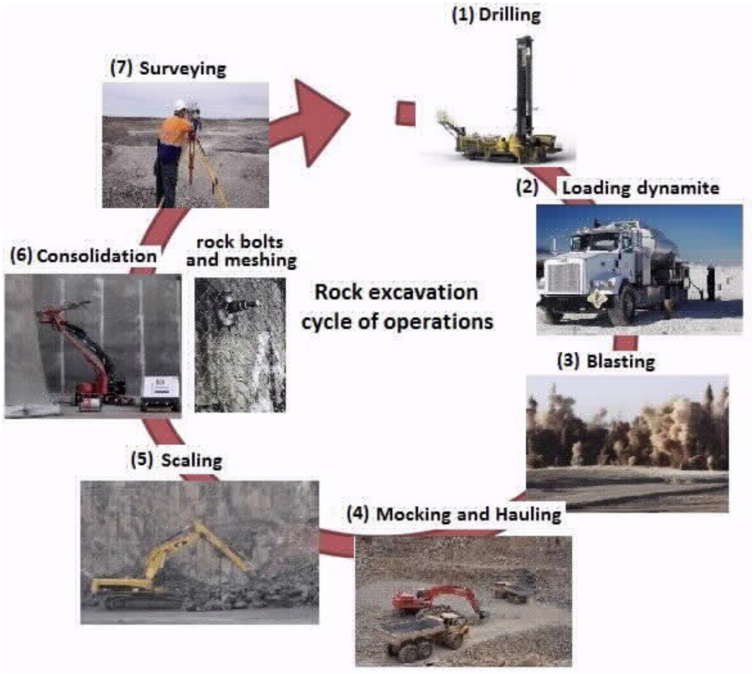


Figure 2: Conceptual process of operations for rock excavation

Loading of dynamite and blasting: Once the drilling is completed for a specific rock mass, the next operation is to load the dynamite in the drilled holes with a dynamite truck that contains the liquid dynamite (slush). Once the loading is completed, the blaster adds detonators (wires and sensors) to complete the task. There are several considerations when using the dynamite such as the proximity of equipment and workers and the proximity of installed rock bolts and meshing on final excavation walls.

Mocking and hauling: Once the mass is blasted, the following operations including mocking, hauling, scaling and consolidation are done from top to bottom of the rock cell. The hauling activity typically takes 1 to 2 working shifts per rock cell.

The scaling and consolidation are divided into two parts within each mass representing the lower or upper section of a specific bench. This sectioning is done to respect a maximum height constraint for safety of the workers according to the regulations. Scaling is first performed mechanically with heavy excavators and completed in a secondary stage by manual intervention of workers with scaling bars. From the consolidation point of view, a wall that is not considered final does not get any rock bolts or meshing. The 2nd pass for the bottom 3 to 5 m of a rock cell can sometimes skip the consolidation step as rock bolts and meshing are installed only after the underlying bench is blasted to prevent additional damages and waste.

Finally, the surveying can be performed using multiple techniques such as LIDAR and drones imagery. Following a blast, coordinates of an upcoming mass can be surveyed.

The aforementioned operations for specific rock masses can be achieved with prior consideration as illustrated in Figure 3: (1) The context of the natural terrain is mapped using GIS. (2) The design of the powerhouse is modeled. (3) The 3D model of the powerhouse is used to determine the rock volume to be excavated. The inputs for the 4D simulation are the 3D mock-up with confirmed scope of work, confirmed quantities and validated access for the performance of the work. The complete rock mass volume to be excavated is modeled in 3D. (4) The rock volume is then divided into 10 m rock benches. Benches consider the context of the natural terrain and the design model of the powerhouse. (5) Benches are then divided into discretized rock masses, where 3D masses represent rock cells and ramps. Partitioning of benches into masses depends on availability of access (ramps and rock faces). For the decision of block sizes depends on the maximum width measured on the final excavation wall for each mass (15 m in the case study presented in the next section). This defines the number of rock cells per bench. One rock cell can typically contain two to three drill rigs. In Step (6), the preliminary excavation project schedule is generated based on the benches and all rock masses and related operations. Steps (7-12) and (14-18) are described in details in Guevremont and Hammad (2018). Rock cells represented in the 3D model receive a color code for each operation performed on them. Step (13) is with the 3D model containing the complete list of rock cells, teams are assigned with labor and equipment for the optimization of the schedule considering rock work faces, work shifts, productivity and sequencing. Different scenarios are possible combining unique or concurrent rock work faces and/or benches. Distinct rock work faces are independent from each other with respective equipment, workers and full processes cycle as shown in Figure 4. Figure 4(a) shows a sequence with one rock work face and Figure 4(b) shows the same bench with a sequence considering two rock work faces. The 4D simulation can be updated with revised as-planned or as-built information including delays. Also, the temporal dimension is not equivalent for each operation represented in Figure 2. For example, visualization of blasting can require adjustment to the 4D-LOD and the speed of the 4D simulation. Numerous safety parameters are included in the 4D simulation such as the correct distances from rock cells when blasting for employees and equipment safety. Further, scaling is first performed mechanically with an excavator to ensure workers safety. Special safety mats are also used when blasting to prevent rocks from flying in the air.

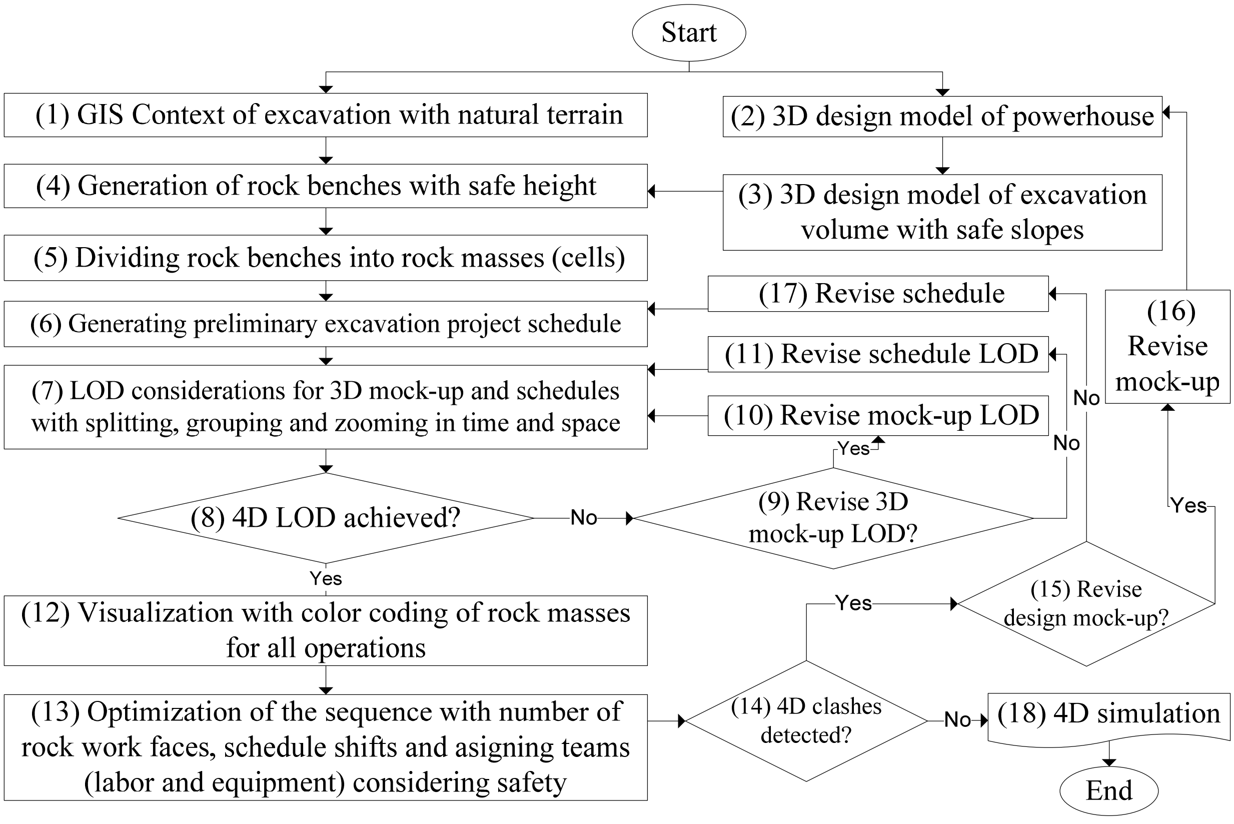
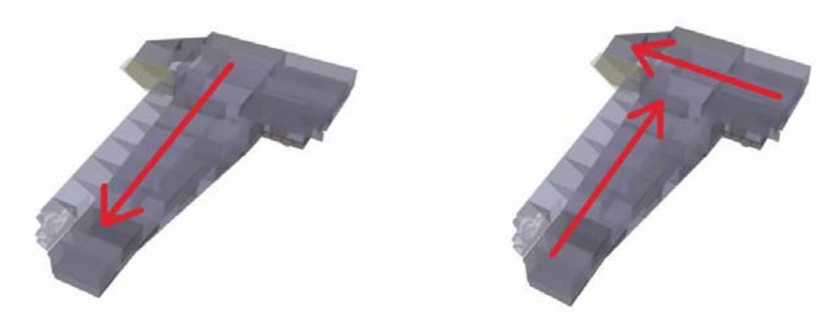


Figure 3: Flow chart for decision making process

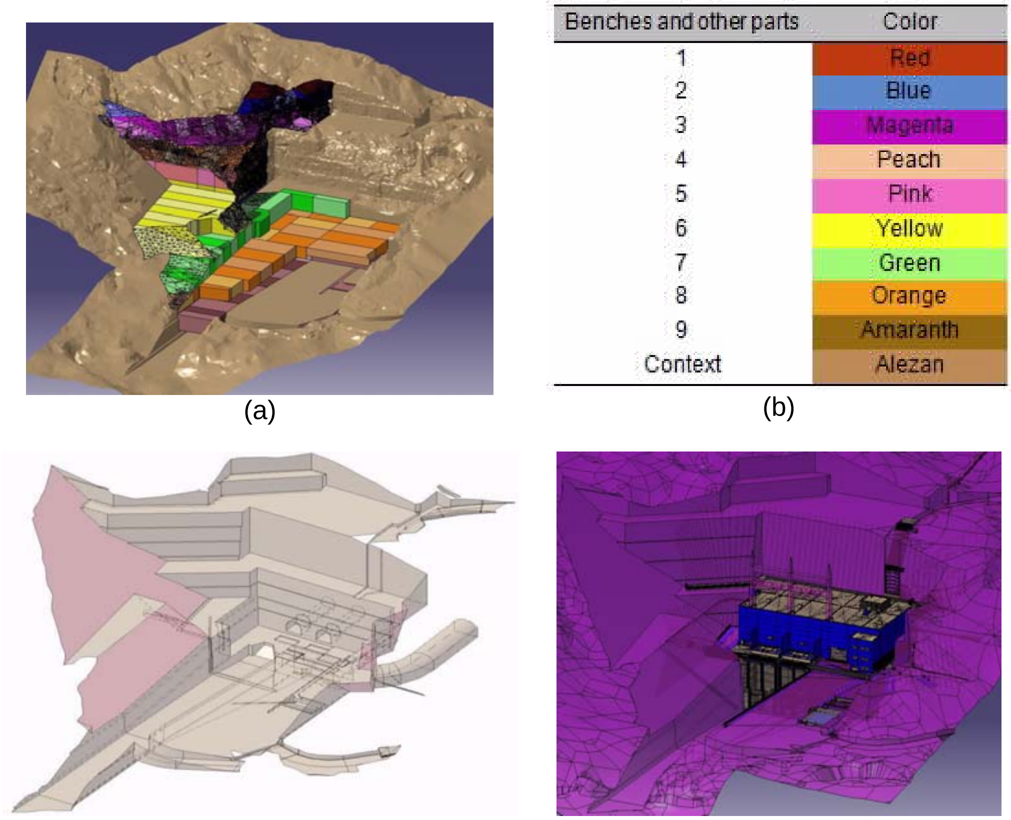


(a) (b)

Figure 4: Number of rock work faces on one bench (a) One and (b) Two

4 CASE STUDY

This case study is about the mass excavation of a powerhouse project in the Province of Quebec, Canada, and was generated with the decision process represented in Figure 3 and considered the rock excavation operations of Figure 2. The scale of this excavation is approximately 100 m (depth and width) by 200 m long (water flow axis) as shown in Figure 5(a). The figure shows the 3D model of the case study with the evolution of the excavation into nine subsequent benches. In this case study, a bench contains between four and 42 masses with an average of approximately 15 masses per bench. Figure 5(b) describes the color coding used in considering the excavation progress. The initial 3D model had 599 objects and the schedule had 995 construction activities. The mock-up shows the ramps to excavate the rock masses. The detailed work schedule with basic constraints (hard logic) considered the excavation method and the physical constraints identified in the 3D model. The 3D model and the schedule used for this case study generated 721 associations including 183 drill holes (71 pre-cut and 112 mass), 112 dynamite loading and blasts, 420 mocking, hauling, scaling and consolidation (with implied anchors and injections) and 6 ramp setups. The rig triangles (facets) representing the natural terrain in the 3D model are included using Catia software for modeling and Cyclone to collect the survey results. Additional objects were included to consider excavation details, such as the draft tube elbow (see last image of Figure 5(c) and also a mechanical well. Another object was used for the context with the natural terrain. Figure 5(d) shows the powerhouse to be built after the excavation is completed. Figure 6 shows the 4D simulation of the excavation project. Table 2 explains the color coding used in the 4D simulation (Figure 6) grouped by trade. Each mass is represented at every phase. In this 4D simulation, the bottleneck operations were mocking, hauling, scaling and consolidation with more than 50% of the total schedule duration. Figure 5(a) shows rig triangles in high numbers for the excavation benches and also for the backfill objects. In Figure 5(a), some benches are hidden until the time is at their respective drilling operation. The objective of this case study was the validation of schedule scenarios (numerous sequences had to be analysed), the detection of spatio-temporal clashes, the demonstration of the schedule feasibility of the selected scenarios of the owner and contractor, and the evaluation of potential schedule acceleration. The objects in the 4D simulation represent rock masses and were all included for the project scope of one contractor. The average duration of an activity is 1.53 days and there were an average of 42 activities per month (or an average of 60 activities per month for the active months). Objects of the 4D simulation are color coded as described in Table 2. The simulation speed is slowed down for the appropriate understanding of the sequence of the work to a speed of about 1 second per calendar day. This simulation speed has to be slower to get an appropriate visualization of dynamite loading and blasting operations.



Benches and other parts	Color
1	Red
2	Blue
3	Magenta
4	Peach
5	Pink
6	Yellow
7	Green
8	Orange
9	Amaranth
Context	Alezan

(a) (b)

(c) (d)

Figure 5: (a) Benches sequence extracted from the 3D model, (b) Color code of the 3D model (planned design), (c) Penstock design, and (d) Powerhouse

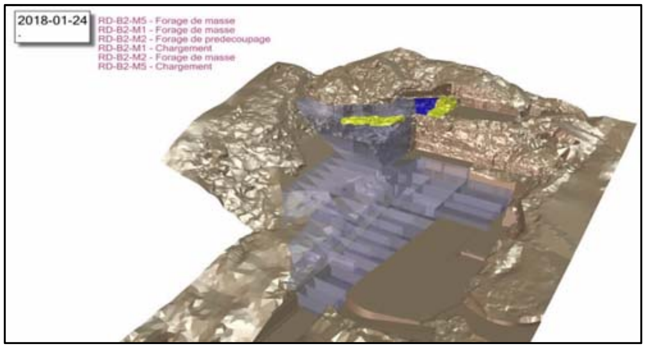

2018-01-24
RD-B2-M5 - Forage de masse
RD-B2-M1 - Forage de masse
RD-B2-M2 - Forage de predecoupage
RD-B2-M1 - Chargement
RD-B2-M2 - Forage de masse
RD-B2-M5 - Chargement

Figure 6: View of the 4D simulation for the excavations masses (high-LOD)

The operations equipment (drill rigs, haul trucks, dynamite truck, scaling equipment, consolidation equipment, surveying equipment) were not shown in this simulation. The operational constraints considered in this case study include the maximum bench height and the maximum slope (12%-15%) for safe equipment traveling on the ramps for hauling with trucks. The 4D simulation also shows a conservative sequence of work from the schedule point of view with one rock work face most of the time. A second rock work face was represented when access, equipment and labor were available. Re-planning must also be considered when there are special changes such as a blast that did not occur because of dynamite issue.

Table 2: Case study - Color code of the 4D simulation

Phases with rock masses (3D object)	Color
Drilling (pre-cut and mass holes)	Blue
Dynamite loading and blasting	Green
Mocking, hauling, scaling and consolidation	Yellow

5 SUMMARY, CONCLUSIONS AND FUTURE WORK

The 4D simulation helped with schedule validation for project stakeholders, and provided an enhanced decision tool when compared to the Gantt Charts used in the past. The 4D simulation helped discussions with contractors since it provided a basis to enhance the opinions for specific topics, such as the use and planning of ramps for performance of the work with one or two rock work faces. This 4D simulation can help the project owner and contractor to revise project teams and locations to generate a successful schedule for all stakeholders. The proposed method can support negotiations with a quick visualisation of the rock masses and their required operations (drilling, loading dynamite, blasting, mocking, hauling, scaling, consolidation and surveying). For hydro-electric projects, future research work with 4D simulation could include: (1) interface management for concrete contracts; (2) detailed safety aspects of excavation operations (water levels, ice hazards for equipment, unstable rocks, blasting mats) to match-up reality; (3) operation equipment (drilling rigs, haul trucks, excavators), material (dynamite, metal meshing, rock bolts) and operation activities (dynamite loading and blasting, rock blasting and hauling); (4) visualisation of operational constraints (e.g. water levels, bench heights and rock slopes); and (5) automation of the process.

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