PRACTICAL APPLICATIONS OF 3D/4D MODELING, AND PROCESS SIMULATION IN CONSTRUCTION

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ABSTRACT: *This paper covers the application of innovative decision support technologies on two major projects in Edmonton. The first one is the West Edmonton Sanitary Sewer (WESS) stage W12. A syphon was constructed to connect the Rat Creek Trunk to the Gold Bar Wastewater Treatment Plant across the North Saskatchewan River, which was designed to control and reduce the combined sewer overflow. The other one is the 3.3-km North LRT (Light Rail Transit) extension line, which connects the current Churchill station to the future NAIT station in Edmonton. A tunnel excavated using the Sequential Excavation Tunneling Method from Churchill station to MacEwan station in the downtown area plays a critical role in the overall project, and has significant impact on project completion date and project budget. Due to the complexity of the two projects, various 3D technologies and construction simulation models were applied to facilitate decision-making processes and project controls. 3D models were developed for design review and design conflict detection, while 4D models were established to help create a robust construction schedule. Construction sequencing animation was used to convey design intents and demonstrate construction stages to contractors and workers. Construction simulation models were developed in order to analyze different scenarios and assist in selecting the best option. The combined applications of 3D technologies and construction simulation helped the project team to identify critical issues, and assured effective communication among engineers, management, contractors, and other parties. Therefore, it provided better opportunities for the success of the projects.*

KEYWORDS: *Construction management, drainage construction, design review, 3D modeling, construction simulation, animation*

1. INTRODUCTION

In general, large-scale, complex, unique construction projects bring significant difficulties and challenges to management, engineers, designers, contractors, workers and other project stakeholders.
These projects involve day-to-day problem solving dealing with design, construction and project management issues. High quality and efficient decision making increases the chance of project success. This paper introduces the practical application of 3D/4D modeling and construction simulation technologies which provided decision-making supports on two multi-million-dollar projects in Edmonton, Alberta, Canada.

The first project is the West Edmonton Sanitary Sewer (WESS) stage W12. The Rat Creek outfall was targeted as part of the West Edmonton Sanitary Sewer project. WESS W12, a syphon connecting the Rat Creek combined trunk to the South Highlands Interceptor, was designed to take overflow and convey it safely to the Gold Bar Wastewater Treatment Plant on the south side of the river. This was expected to reduce the CSO discharges into the North Saskatchewan River by over 70%, significantly improving water quality. Ultimately, the syphon would convey all flow from the 7 km of West Edmonton Sanitary Sewer project to the Gold Bar Wastewater Treatment Plant for treatment. Flow would be controlled by the Real Time Control (RTC) No. 3 structure located deep beneath the city streets. Associated Engineering was the designer for the project.

The other project is the 3.3-km North LRT (Light Rail Transit) extension line, which connects the current Churchill station to the future NAIT station in Edmonton. A tunnel excavated using the Sequential Excavation Tunneling Method from Churchill station to MacEwan station in the downtown area plays a critical role in the overall project, and has significant impact on project completion date and project budget.

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Due to the complexity of these two projects, various 3D technologies were applied to facilitate decision-making processes. 3D models were developed for design review and design conflict detection, while 4D models were established to help create a robust construction schedule. Construction sequencing animation was used to convey design intents and demonstrate construction stages to contractors and workers. Construction simulation models were developed in order to analyze different scenarios and assist in selecting the best option. The combined applications of 3D technologies and construction simulation helped the project team to identify critical issues, and assured effective communication amongst engineers, management, contractors, and other parties. Therefore, it provided better opportunities for the success of the projects.

The remainder of the paper is organized into the following sections. The previous research efforts related to 3D/4D modeling are reviewed. In the section for the WESS W12 project, the project background and major challenges are introduced. That is followed by the application of construction simulation approach for selecting the best construction option and the design and constructability review using 3D models. In the section for the NLRT project, the design and construction review method is depicted, followed by the details of 4D modeling and visualized earned value analysis.

2. LITERATURE REVIEW

The application of 3D and 4D technologies as a supplement to the traditional design, project control, team communication processes would help identify design conflicts, reduce rework and prevent construction incidents (Haque and Rahman, 2009). 3D/4D applications were reported by researchers which indicate that 3D/4D models can facilitate design and construction communication and problem identification, generate and optimize crane motion paths in a visualization environment, represent construction processes, enable time-space analysis, assist cut and fill calculation for earth work, etc (Hartmann and Fischer, 2007; Chi and Kang, 2010; Sampaio et al., 2010; Akinci et al., 2002; Shah et al., 2008). For underground utility construction, Kraus et al. (2007) indicate that the early identification of interference of the existing and proposed utilities is critical for timely project delivery.

3. WEST EDMONTON SANITARY SEWER W12 PROJECT

3.1 Project overview

The construction of the WESS W12 project proved to be extremely challenging; its environmentally sensitive location in the river valley as well as its extreme depth – 70 meters below downtown Edmonton – was understood. However, the geotechnical investigation revealed that almost the entire project was situated within the footprint of abandoned coal mines. Five deep shafts would have to be constructed in ground laden with coal seams, water pockets, and voids, with the detection of methane gas under pressure in several locations. The tunnel alignment would run between two coal seams. Access was also severely limited: the northern construction site was on Jasper Avenue; the main thoroughfare is through Edmonton's downtown; and most of the alignment was under the Riverdale Golf Course and the river itself.

Due to the uncertain ground conditions and other constraints, the City Drainage Design and Construction crews initially planned to work with a newly-acquired LOVAT Earth Pressure Balance tunnel boring machine, using bolted segmental liners – the best technology for the job, but not one the City of Edmonton crews are familiar with. The deep shafts meant delays in removing soil and supplying construction materials, and shaft placement was limited. Finally, construction of the RTC3 structure required tying in to a fragile, very old 3200 mm pipe, under live flow. This pipe was the current combined trunk, with flow of 3.7 m/s in dry weather, and the potential for even higher velocities if one of the sudden rainstorms common to the area happened – a major safety concern. Operation of the tunnel would also be challenging. The tunnel itself would have to meet zero-infiltration standards due to the sensitive location, and the complex RTC3 structure would need to function without flaw to avoid flooding basements upstream or pouring unnecessary CSO into the river.

3.2 Selecting the best option based on simulations

In the planning stage, three options for placement of work shafts were identified through risk and value engineering workshops in 2004. The first was to place the working shaft at 85th St and proceed with excavation to McNally (Refer to Fig. 1). The second was the reverse: the work shaft would be placed at McNally, and therefore, the excavation would proceed from McNally to 85 St (at a negative slope and in the presence of water). The third option made use of a third shaft, placed in Dawson Park. In this option, tunneling proceeded to 85 St. The tunnel boring machine was then relocated to the Dawson shaft and excavation proceeded to McNally. Excavation of the Dawson shaft and the tunnel can proceed parallel to the excavation of the two shafts at 85 St and McNally.

Three discrete event simulation models were developed in Simphony (AbouRizk and Mohammad, 2000) to support the decision of which tunneling sequence to use. The details of construction processes, material handling, and resource constraints were modeled and simulated. Tunneling from 85 St to McNally or vice versa would require a material handling process roughly 80m deep, which impacted productivity significantly in simulations.

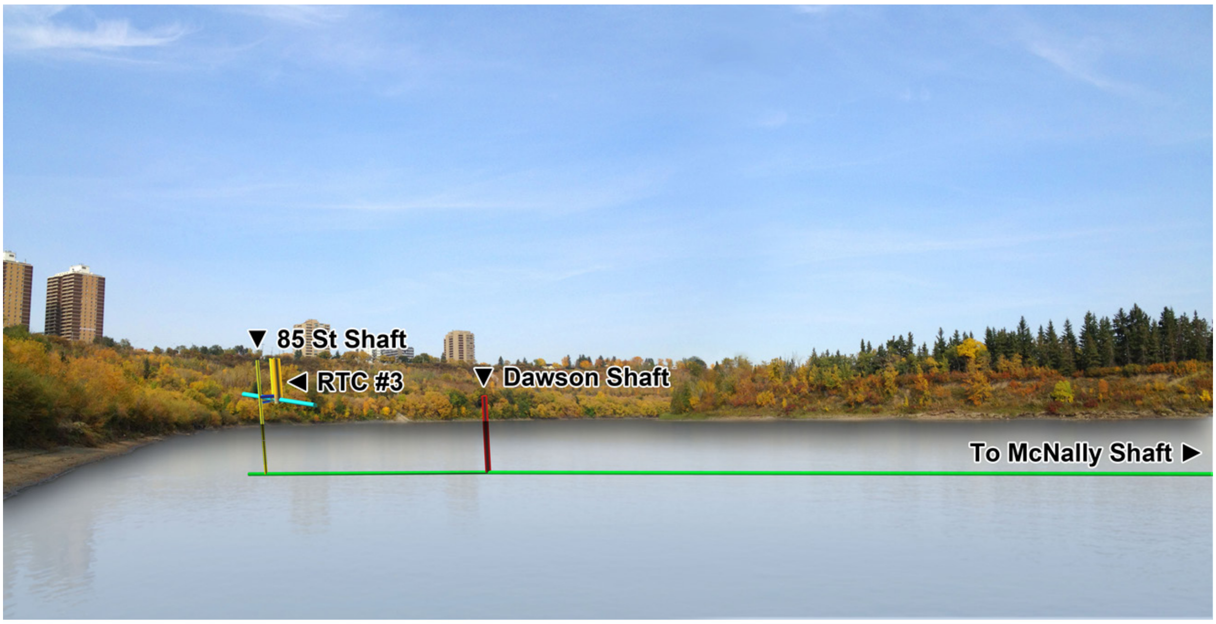

Fig. 1: Overview of the WESS W12 project

After a risk and cost-benefit analysis of all three options, the preferred option was determined to be two-way tunneling. This option had the least amount of risk associated with it, both in total value of calculated severity and in terms of risk factors that were considered “important” or higher. In addition, an 80m shaft would require a specialty hoist, with no redundancy, as no other equivalent hoist or crane is available in the city. The Dawson shaft uses hoisting technology that is readily available and can be replaced in a reasonable amount of time when required. Compounding the hoist issue, excavation from 85 St requires completion of the 85 St shaft prior to commencement of tunneling, so any delays during shaft excavation—which would be likely, given the depth—would delay the entire project. Excavating from Dawson requires only the 40m Dawson shaft, and allows the other two deeper shafts to be constructed with a greater degree of float. Finally, an analysis of expected costs and schedule (including risk) indicated that two-way tunneling was less expensive and likely to have shorter project duration.

Discrete event simulation scenarios were also developed to support the decision of what type of secondary liner to use in the tunnels. The choices were cast-in-place concrete, precast pipe sections, steel pipes with lining, or HOBAS pipe. Through consultation with the project team and a review of relevant literature, various assumptions were made: shift length, tunnel length, average production, distance between pumping wells, duration of concrete pouring activities, duration for track installation, time for grouting, and so forth.

The simulation models were developed, tested, and run. The simulation results showed that the total duration for cast-in-place liners was 220 days. If precast pipe sections were used, the duration was 204 days; steel pipes with lining were 184 days; and HOBAS pipes were 172 days.

A value analysis workshop was then conducted to discuss these choices, employing the Analytical Hierarchy Process (AHP) as the decision-making platform. The results of the AHP led to the selection of HOBAS pipes as the option with the best value, as not only was it the most schedule-friendly and one of the most maintainable and efficient options, it was also the most constructible. HOBAS pipes were installed as a secondary liner for the entire tunnel by the end of 2009, and their performance has been very satisfactory. Pressure tests have confirmed zero exfiltration for the tunnel.

3.3 Design and constructability review using 3D models

3D models of individual components of the structures to be built are constructed in CAD software to the exact specifications provided by the design/drafting team. As in the real structure, the model components can then be arranged into substructures, and those are subsequently constructed or assembled into structures of increasing complexity. We then employ additional modeling software to manage the model components, their arrangement, and their sequence in a construction context, giving the visualization a fourth dimension: time. Video replay of a construction sequence is an invaluable discussion tool.

The design team identified five options as being feasible construction options for the configuration of the three RTC No. 3 shafts (Fig. 2) that satisfied the required diversion and the intended hydraulic design. In order to select the best option, a structured selection process was facilitated based on value analysis, constructability reviews, and risk analysis. Value analysis was used to identify the options with a high value and present them for further analysis. Constructability reviews were conducted to understand the construction process and the construction challenges. After that, risk analysis was undertaken to identify and evaluate the option's risk and integrate that risk value in the selection process. This value analysis led to the initial decision to proceed with a two-shaft option, on the alignment but with a bypass and a "bulkhead shaft."

However, there were safety and technical feasibility concerns with the process of lowering the bypass bulkhead through the RTC No. 3 shaft, horizontally through the back tunnel, and then vertically into place in the existing 3200mm tunnel under live flow conditions. There were also grave concerns with entering the existing tunnel to anchor the bottom part of the bulkhead to initiate bypass of the flows. These same concerns would come into play when it was time to remove the bypass bulkhead.

In order to provide a clearer understanding, a 3D visualization of the RTC structure was generated and was used to create a 4D visualization depicting the construction sequence of the RTC structure as it was proposed. The animations generated were an invaluable visual aid, allowing decision-makers to see the process taking place without ambiguity.

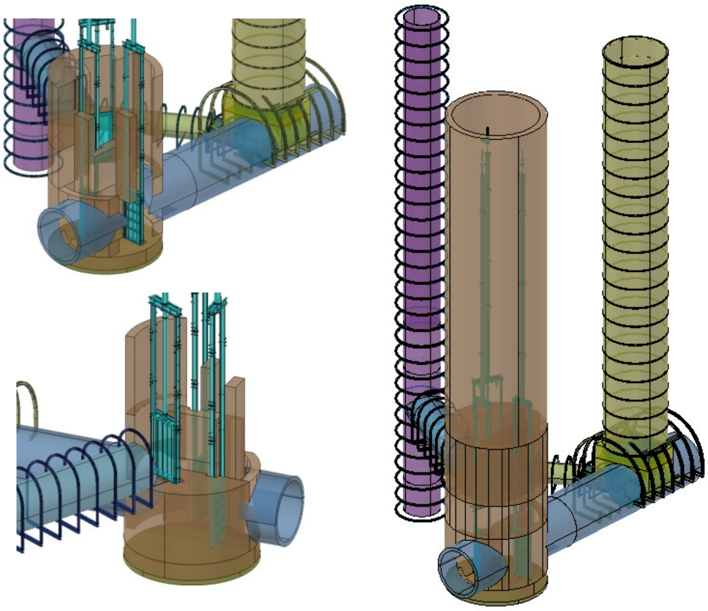

Fig. 2: Real Time Control (RTC) No. 3 structures – Top left: RTC No. 3 Shaft; Bottom left: RTC No. 3 Gates; Right: Overall of the RTC No. 3 Shaft

After reviewing the visualization, it was decided that the bypass bulkhead should be installed vertically through another shaft. The bypass bulkhead would extend vertically above the existing 3200mm tunnel and be held in alignment during installation and removal by channels forming slots in the bulkhead shaft. The bypass bulkhead would be installed near the center of the bulkhead shaft to allow entry to fix the bulkhead to the liner of the existing

3200mm tunnel. This would also allow for monitoring for leakage between the bypass bulkhead and the safety bulkhead and for pumping out any leakage.

The construction of the project was completed in 2011 and the tunnel is now in operation, successfully conveying flow to Gold Bar Wastewater Treatment Plant. The initial budget and schedule underwent two revisions due to external events, construction challenges, and additional scope, and totaled \$44 million. Zero exfiltration was confirmed by pressure tests. Two CEA (Consulting Engineers of Alberta) showcase awards under two different categories were announced to recognize the successful application of 3D/4D and construction simulation technologies on the W12 project.

4. NORTH LIGHT RAIL TRANSIT EXTENSION PROJECT

4.1 Project overview

The North Light Rail Transit (NLRT) extension project is to construct an extension line for the existing LRT transportation system in downtown Edmonton, Alberta, Canada. The total length of the extension line is 3.3 km. The features of the project include three new stations – MacEwan, Kingsway, NAIT, underground connections between MacEwan Station and Churchill Station, Street-level LRT between 105th Ave and NAIT, and Relocation of Kingsway bus terminal at Royal Alexandra Hospital. The project was started in 2011and planned to be completed in 2014. The total project budget is estimated at \$755 million.

The major challenges of the project can be summarized in the following. First, brown field construction involves relocation of existing utilities and drainage and coordination of existing and proposed utilities and drainage. The currently used 2D approach cannot effectively handle the massive information, and it caused inefficient communication, inconsistent representation, and hard-to-discover design conflicts. Second, the construction of the big curved LRT tunnels connecting the existing Churchill station to the new MacEwan station in downtown Edmonton; as it is on the critical path of the project, monitoring the tunneling progress became important. Finally, the overall monitoring and controlling of the project, which involves more than twenty disciplines in an intuitive way, became difficult. Traditional scheduling and reporting approaches cannot reveal the geographical based inter-relationships of work packages. 3D approaches were applied to improve the current practice either in design review or project control.

4.2 Design and construction review

Linear transportation construction involves not only the above ground construction but also the underground utilities and drainage along the right of way. In order to satisfy the clearance requirements in which distances are measured based on the track alignments, existing utilities and drainage in the clearance zone need to be removed. New utilities and drainage are proposed to replace the removed ones and also to meet the requirements of the new LRT line. Due to the limitation of area in downtown Edmonton, underground utilities and drainage constitute several complicated networks which make utility design a time-consuming and tedious task.

2D drawings and utility matrix are the major utility design tools in current practice, although 3D/BIM (Building Information Modeling) tools are becoming more and more prevalent in building design, structure design, road design, track design, etc. Fig. 3 shows the typical utility drawings for Kingsway station. The 2D approach has the following disadvantages. 1) Missing utilities on cross sections. Cross sections are generated at certain intervals. While utilities run between two cutting planes and do not intersect with the cutting planes, they are not easily captured by the cross sections. 2) Inefficient elevation representation. Elevations or depth of utilities from ground surface are not represented on plan views. It requires the users' translation to generate virtual 3D models in mind by referring to the cross section views at specific locations, which is hard for most project participants due to the complexity of utilities resulting in poor communication. 3) Unified-width lines do not reflect actual sizes of utilities on plan drawings. Unified-width lines are used to represent utility layout on plan drawings. For utilities that are large width-wise, potential design conflict might not be able to be identified until late stage construction. 4) Lack of communication with other disciplines. 2D drawings are not efficient to communicate the design of utility relocation. Thus, it becomes an obstacle in the multiple discipline design review process.

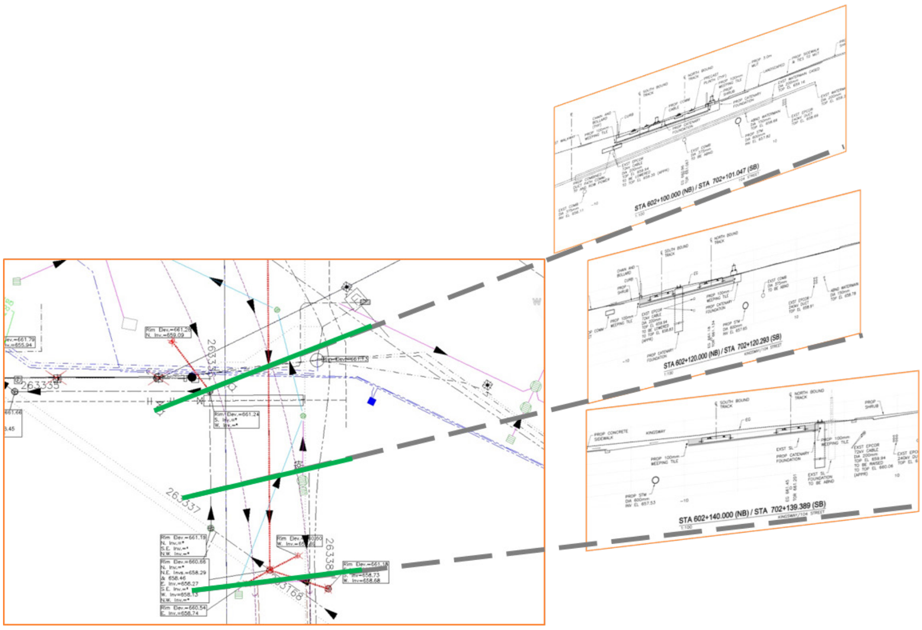

Fig. 3: Typical Utility Drawings in Plan and Cross Section View at Kingsway Station

In order to deal with the above-mentioned drawbacks, the project team decided to adopt the 3D approach to review design drawings before the utility relocation work began. 3D models of electricity, gas, water, cable, traffic signals, communication, drainage, duct bank, and foundation were generated. The models were imported to Navisworks and reviewed. Dozens of design conflicts were identified, and one of the major ones is at the Kingsway station. A proposed communication duct bank clashed with a proposed sewer line and an existing drainage pipe. The timely design conflict identification avoided construction delay and saved project cost. Fig. 4 shows the 3D models and identified design conflicts.

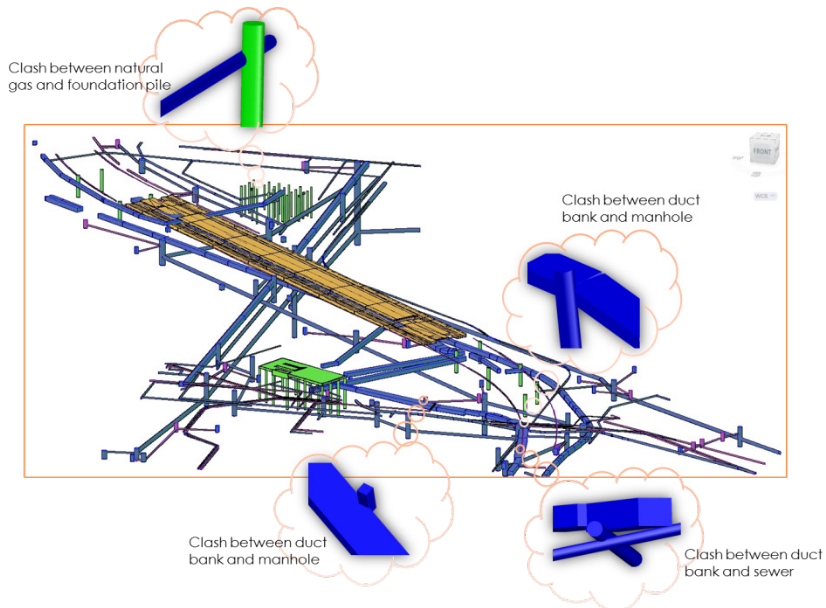

Fig. 4: 3D Models and Identified Design Conflicts at Kingsway Station

4.3 Project control using 3D technologies

4D construction visualization was introduced as a supplement to the traditional project control tools, such as bar chart and Gantt charts. A 4D model integrates the 3D models of physical work packages with the construction schedule. The work under construction is represented in Green. As a linear project, construction work is distributed in different geographical locations. The visualization of the work can help the project team coordinate work by location. It can also help verify the accuracy of activity relationships and logic. Fig. 5 demonstrates the construction of Kingsway station.

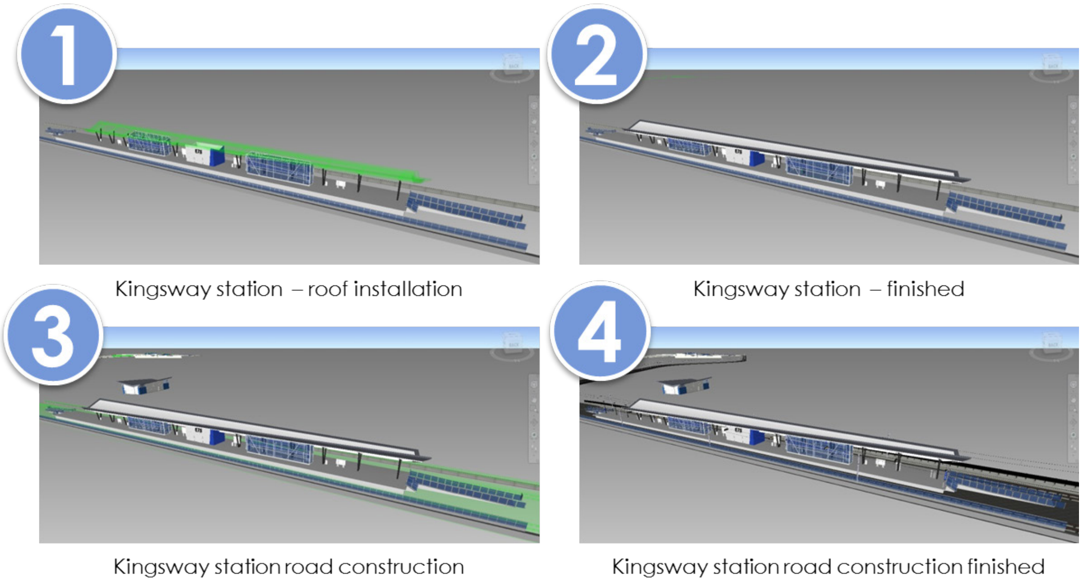

Fig. 5: Construction Visualization of Kingsway Station

Earned value analysis is widely adopted in the industry to monitor the performance of project schedule and cost. SPI (Schedule Performance Index) and CPI (Cost Performance Index) are two indices reflecting the project performance. The indices are equal to or greater than zero. The higher the value, the better the performance is. In order to position the most important issues based on earned value analysis (EVA), color codes were defined as follows, Pink: 0-0.5; Red: 0.5-0.85; Yellow: 0.85-1.0; and Green: equal or greater than 1.0. A customized data column was created to store the EVA color codes. It enables Navisworks to read and present the EVA status in 3D. Areas with poor performance bring immediate attention (Fig. 6).

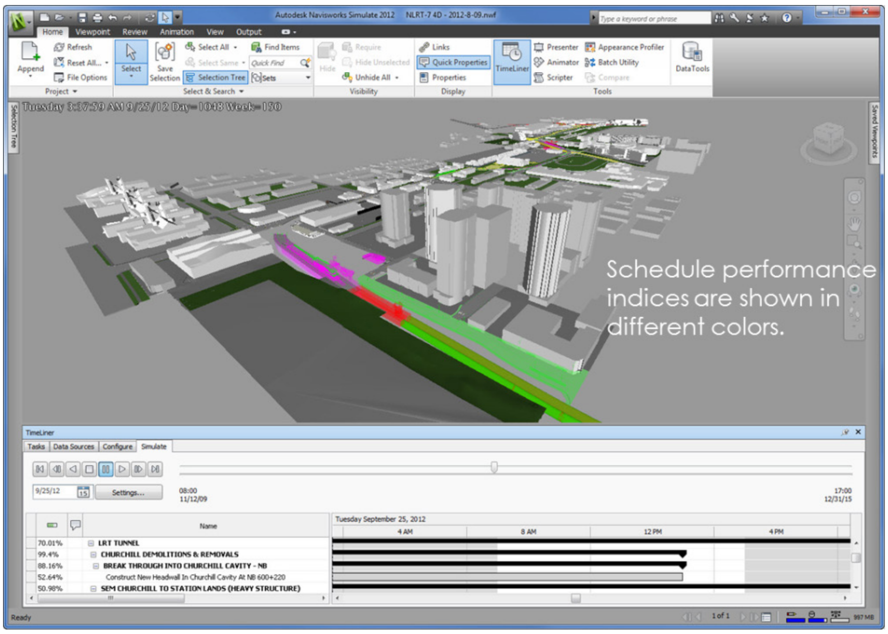

Fig. 6: Earned Value Analysis Status Shown in 3D

5. CONCLUSION

The combined applications of 3D technologies and construction simulation helped the project team to identify critical issues, and assured effective communication among engineers, management, contractors, and other parties. Therefore, it provided better opportunities for success of the projects.

6. ACKNOWLEDGEMENTS

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