Improving Planning in Congested Sites Using 3D and 4D Modelling: A Case Study of a Pile-Supported Excavation Project in Chile

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ABSTRACT

IT use in construction has grown lately and it has helped project teams to better understand and improve sizing of work packages. This supports decision making when selecting construction strategies, which is one of the main problems associated to projects late completion and cost overruns. Large excavation projects can benefit from the use of 3D and 4D models to improve efficiency of construction processes. In this study we wanted to demonstrate how the use of these technologies in the planning stage helps in the reduction of the project schedule and resource use. We developed a 3D model for a discontinuous pile-supported excavation project (56,000 m3; 18 m deep; 89 piles with up to three anchor levels). Then, we prepared two 4D models: one used to show the as-built excavation, while the other showed an improved process. The improved process included considerations such as the level of detail for the 3D model geometry, placement of key design elements (e.g., excavation access ramp); analysis of excavation strategies; etc. Both 4D models were compared to check schedule reduction (and indirectly resource use). To validate the 4D modelling of civil works, the project team was interviewed and surveyed regarding both 4D models. Results showed that 4D models used in excavation processes help the project team to better plan and select construction strategies due to a better understanding and sizing of the excavation work. The result is an improved process which is shorter, and more resource efficient than the base case (as-built model).

Keywords –
4D model, BIM, Excavation, Civil works, Construction strategy, Soil pixel.

1 Introduction

The construction industry has embraced the use tools that have transformed the traditional work processes, such as Building Information Models (BIM). First uses of BIM technologies usually include 3D modelling (geometric/spatial understanding of construction projects) for design, preconstruction or construction work [1]. Especially useful during construction, 4D models incorporate the temporal dimension to 3D models (animation of the construction process). 4D models are not new [2], [3] but technological advances in both software and hardware, besides sophisticated users in the construction industry make possible its use in everyday projects. However, the use of product based 3D models is recent and most models deal with buildings or industrial facilities [4] and there are just a few examples of 4D models for large earth movements or civil works [5], [6]. In this article, we explore the use of 3D and 4D models in an excavation project, to retrospectively address common problems they face during construction.

The case study is a 56.000 m3 excavation project which constitutes the first stage on a larger renovation project of a medical centre. Some of the complexities that the project faced included: congested construction site, location on a shopping center that remained operating during construction; conflicts with the excavation subcontractor, which was finally replaced; conflicts with the pile subcontractor; and distant offsite soil disposal location, which caused cost and budgets overruns. We addressed some of these issues using a 4D model approach. We first developed a retrospective 4D model (as-built 4D model) that represented what actually happened during the excavation. Then, we developed a second improved 4D model of what the excavation should have been and we called it the proposed 4D model. We explored the use of 4D modelling for analysing excavation strategies; for guiding construction decision making; for identification and placement of key design elements; and better understanding of the project size and complexity. The aim of this effort is to reduce the project schedule and consequently, lower the resource use. The combined use of the two 4D models was formalized on a 4D Excavation Implementation Proposal.

In the following sections we present a brief literature review that serves as a point of departure for this work, we then explain the research methodology, the validation of our work, show our results and propose suggestions for future work.

2 Literature Review

Building Information Model (BIM) has its origins in the eighties, as a way of accelerating the structural design process using this information technology (IT). Objects in a BIM model have properties, both physical and functional that helps defining them and provides a reliable source of building information [7]. BIM has been used in support of decision making, particularly due to its powerful project visualization capabilities [6].

3D models (the first uses of BIM) have evolved and since the mid nighties they have incorporated the construction schedules to become 4D models. Since then they have assisted construction teams in project planning [2].

Koo and Fischer [3] have reported the advantages and limitations of 3D and 4D models. They identified the need for parametric modelling of the geometry, which later has been incorporated into commercial CAD software (e.g., Autodesk Revit). Several authors have realized the need for standardization of 3D and 4D modelling procedures as mechanisms to facilitate the use of such tools in everyday construction projects [4]. There is a growing number of researchers that are using laser scanning techniques for quick and accurate 3D model as-built generation [8], [9], [10]. However their research focus is realistic representation rather than analysis of construction sequences. Others have suggested color schemes and color selection rationale to better communicate the construction sequences using 3D and 4D models [11], [12], [13].

However, there are few examples that document the use of 4D models for representing excavation sequences. Akbas [5] proposed a methodology to decompose the 3D geometry on a large civil works project. Kim et al. [14] though discussed the use of 4D models on heavy civil projects, mainly focused on the product model describing the geometry of the superstructure (a suspended bridge in that case) and the associated construction sequence. Hartman and Fischer [15] documented the extensive use of 3D and 4D models on a congested site in New York City. The project included risky large scale excavation, however most modelling effort on this front was devoted to the pile wall support system and not much attention was given to the excavation sequence itself.

3 Research Methodology

We organized the research work as follows: first we participated in the project and performed field observations to understand, identify and conceptualize the major challenges during the excavation. The field observation was complemented with a photographic record kept during the project, that later enabled us to recreate the actual construction sequence. Quantitative information regarding the actual daily productivity was gathered and triangulated among subs and the general contractor. We used all project information to first develop a 3D model that captured the excavation geometry and spatial considerations. We then developed two 4D models: the first aimed at capturing the as-built construction sequence, while the second aimed at exploring and improved process. Then, we generated a proposal for 3D and 4D modelling of large excavation projects that was validated by the project construction professionals.

4 Development of the models

Our research team developed several 3D and 4D models to represent the excavation project geometry and to explore strategies for the construction sequence.

4.1 Project features

The excavation project is the first stage of a large medical centre renovation/expansion effort. It consists of a massive 56,000 [m3] excavation, surrounded by 89 piles with two or three anchor levels (13.4 [m] and 21.0 [m] in depth, respectively). The project site is very congested and logistically challenging, because it is located next to a crowded shopping center, which remained operating during the construction, and adjacent to the entrance of the medical facility undergoing renovation. Therefore, pedestrian and vehicular flows coordination where a constant and permanent concern throughout the project construction.

4.2 3D model

We developed the 3D model using Autodesk Revit. We modelled the main structural components: piles, anchors, slabs, circulation ramps, columns, beams, etc. based on the project’s drawings and specifications. Additionally, we modelled all relevant elements necessary for the understanding of the project geometry and its challenges (for instance, surrounding buildings, existing structural members to be demolished, etc.). We paid special attention to the representation of the soil to be removed during the excavation. The product breakdown structure (PBS) in this case was based on a fundamental geometric unit we called a “soil pixel” (SPX). Therefore, we partition the massive 56,000 [m3] excavation into many SPXs. The sizing of the SPX conforms to the following considerations:

(i) Width and length: surface area of the SPX must consider the geometry of the excavation at large. The width and length of the site should be a multiple of the SPX width and length. Any construction sequence singularity or consideration, such as size of circulation corridors, equipment work areas, etc., should be easily represented by a SPX or a multiple of it.

(ii) Height: the total excavation depth should be a multiple of the SPX height and it should also consider the distance between the anchor levels.

(iii) Volume: the total volume of a SPX should be a function of the level of detail provided for the excavation work breakdown structure (WBS), i.e., a SPX or a group of SPXs should describe an excavation work package.

In the context of the case study, the site has a rectangular shape, so does the SPX. Besides, the anchor boring machine needs a minimum working distance in front of each pile of 7 [m]. Therefore, the length of the SPX is 7 [m] and the width 4.5 [m]. We'll keep two SPXs in front of the piles on the longitudinal sides of the site, before installing the anchor levels (9 [m] width, which satisfies the minimum). The height of the SPX is 2.5 [m], given the distance between anchor levels. Therefore, the volume of a single SPX is 79 [m3]. Figure 1 depicts the size of the SPX in the context of the excavation site.

4.3 4D model

Both 4D models followed the same color coding (see Table 1). In general terms, all activities except excavation are represented with two colors/tones: red when the activities take place (then they disappear for demolition activities); and green for elements being built (i.e., anchors, concrete slabs, etc.), that later turn grey (going to the background this way).

The main color coding difference between both 4D models is that the as-built 4D model does not have a critical path, while the improved process 4D model does not have unnecessary soil movement (as in the as-built case). Following we describe both 4D models and their features.

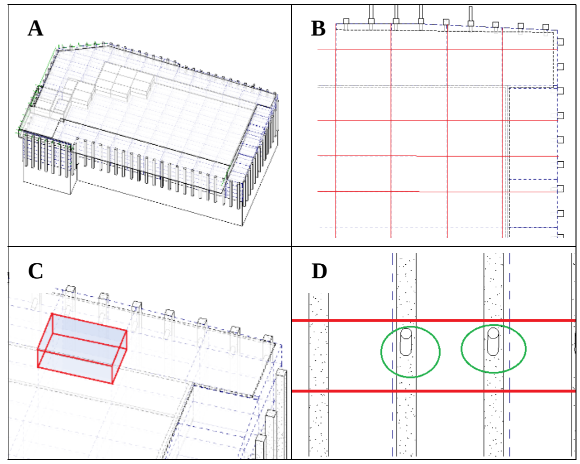

Figure 1. Detail of a SPX. 1A shows the entire excavation site. 1B shows the subdivision of the site on the fundamental SPXs (red lines). 1C depicts the size of a SPX compared to the site. 1D indicates the vertical spacing of anchor levels (green circles) and the height of the SPX (red lines).

4.3.1 As-Built 4D Model (AB4D)

We built this model using the project 3D model and we added the as-built scheduling information, including verbal recollection of the construction sequence (based on the field experience), daily excavation reports (based on the trucks' site access control), picture records, and high level project Gantt Charts for the piles and anchors. We triangulated all this information to create a daily as-built schedule of the project that we used for assembling the AB4D.

Table 1. 4D Color Coding Scheme.

Activities	Sub tasks	Color definition					Construction Method
		Color	RGB			% Trans.	
Piles	Excavation		255	0	0	70	• Manual work. Section: 0,80x0,80 [m2] approx.
	Support		175	0	175	70	• Installation of wooden soil support. Only on the side facing the excvation.
	Rebar install.		255	255	0	70	• Rebar installation. Reinforcement steel built in situ, one rebar at a time.
	Concrete pouring		0	255	0	70	• Offsite premixed concrete poured by truck pump or by telescopic pump.
Demolition	-		255	0	0	70	• Demolition of existent structural elements such as: slabs, ramps, columns, etc.
Construction	-		0	255	0	70	• Construction of post-tension slab and parking ramp (parallel work to excavation).
Excavation	Excavation		255	255	0	70	• SPX removal (geometric representation of excavation process).
	Soil displacement		191	139	108	0	• Soil displacement within project site (without offsite disposal). Evidence of inefficiency.
Anchors	Drilling		255	0	0	0	• Drilling throughtout pile for anchor installation and grout inyection.
	Stressing		0	255	0	0	• Stressing of tendoms/cables after fifth day of grout inyection and anchor installation.
Critical Activities	-		255	128	0	70	• Critical path activity for the project.

From the AB4D we can highlight two types of soil movement: (i) the excavation and removal of the soil (for offsite disposal), and (ii) the excavation that only produces soil displacement within the project site (without offsite disposal). The first is the desired outcome and the most common soil movement, however, sometimes we were able to observe examples of the later, particularly when the access ramp was relocated (several times during the project).

Figure 2 depicts several distinctive moments during the excavation. The resemblance of the picture and its respective 4D model for the same date is shown. The SPXs depict the intermediate state of the excavation and the location of key elements such as the access ramp, and site boundaries. Reddish SPXs depict soil movement as explained in the previous section.

4.3.2 Improved Process 4D Model (IP4D)

We built this model using the project 3D model and this time we defined an excavation strategy and construction sequence that is an improvement over the process that actually took place.

Excavation activities are usually planned an controlled as linear activities, i.e., defining a productivity rate and a general strategy for construction, but little detail is formalized on construction documents and most excavation decisions are made on the spot and without much information about the impacts they could have on future work. In the first place, we identified zones within the project site that could not be freely intervened due to construction activities that can only occur before the excavation. Secondly, we created a CPM schedule and identified the critical path, which is governed by the activities related to the installation of the anchor system. These activities have a large duration and only after they have been executed and the soil have been stabilized vertically (usually in groups of 8 or 10 anchors), we can continue with the excavation around the site edges and then near the center. Third, we identified key construction elements for the excavation work. In our case study, the access ramp constitutes one such key element, because its location and eventual relocation during the excavation might negatively impact the duration of the project, generating unnecessary earth displacement activities (as it actually occurred in the project, situation depicted in the AB4D in Figure 2).

When modelling we kept the SPX dimensions (3D unaltered on both 4D models). For the IP4D the excavation rate we used was constant at a rate of 12 SPX per day (equal to approx. 956 [m3], which was the maximum 5-day moving average of the actual project). For the anchors, we considered a rate of 4 drillings and 8 anchors stressing per day, based on the actual subcontractors' records for the case study.

Both 4D models are compared in Figure 3 for the same dates and the improvements are evident on each case. Figure 3 shows in orange the critical path of the IP4D (bottom row).

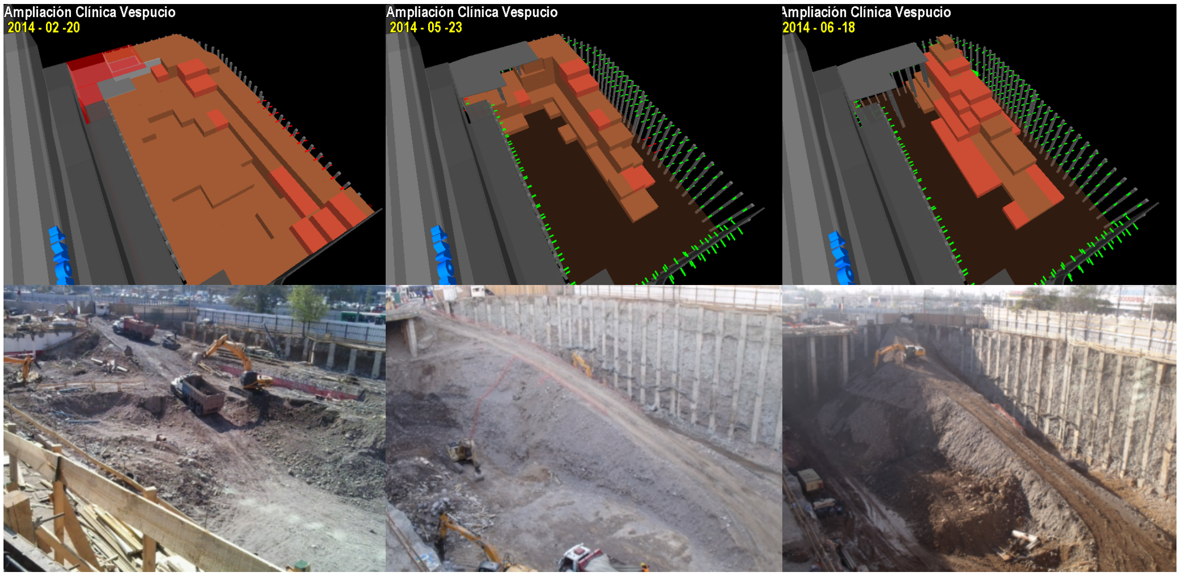

Figure 2. As-Built 4D Model (AB4D). The set of pictures on the top shows screen captures of the AB4D, while the bottom shows actual pictures of the project site for the same dates (shown in yellow at the upper left of each picture).

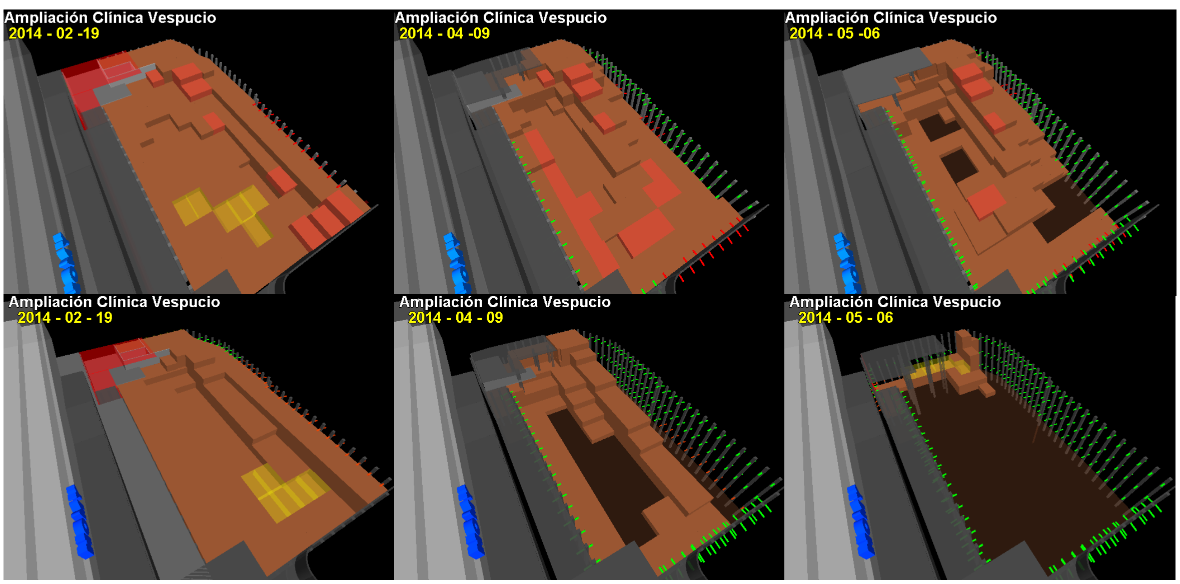

Figure 3. Improved Process 4D Model (IP4D). The set of pictures show the three main improvements of the IP4D (bottom row) and the comparison with the as-built project for the same dates (AB4D in the top row): *bottom left*, construction zone (in red) that can only happen before excavation; *bottom row*, critical path, governed by anchor level (in orange in upper edge of excavation); *bottom middle*, access ramp, clearly visible on the right of the picture and identified as key element.

4.3.3 Proposal for 3D and 4D modelling of large excavations

Based on the observations and models created for the case study, we developed a proposal for 3D and 4D modelling of excavation projects. The points to consider include:

- 3D Model. Define the soil pixel or SPX (the basic unit for describing the excavation). The SPX must be able to describe the excavation geometry and follow the guidelines described in 4.3.1. Other construction elements (besides excavated soil), should be modelled according to technical specs and the level of detail of scheduled activities.

- Schedule (Gantt chart). We propose a higher level of detail to describe excavation activities, beyond the typical extraction rate. Formalization of excavation sequence using Gantt charts let us identify a critical path.
- 4D Models. Based on the case study we propose creating two types of 4D model. First, develop a 4D Master Plan to explain the excavation strategy using the techniques applied for the IP4D. This 4D model should be developed early in the project life cycle as a communication tool. Second, during the project execution, we propose the use of a 4D model using the techniques developed for the AB4D for short term planning and project control.

In order to better take advantage of the modelling effort, the earlier the 4D Master Plan is developed, the better. At this stage the 3D model is developed, and therefore, most of the modelling effort is concentrated here. During project execution, we propose using and creating a weekly 4D model for short term planning and control as suggested in Figure 4. The 4D model can then be shared in projects meeting as a communication tool for the project team. Figure 4 shows an example of a weekly plan (based on the case study).

5 Results

The AB4D had a duration of 146 days with a 6-day working week (Monday through Saturday). Two weeks were not considered due to problems with the excavation subcontractor that finally abandoned the project (two weeks for the replacement). Therefore, the corrected actual project duration was 132 calendar days or 114 work days.

The IP4D meant a reduction of the project duration to just 68 work days on a 5-day working week (Monday through Friday), i.e., over 40 work days saved (or 8 weeks). Therefore, the 4D modelling in this case allowed us to better plan the excavation reducing unnecessary work (soil displacement within project site) and avoiding costly mistakes such as the relocation of the access ramp.

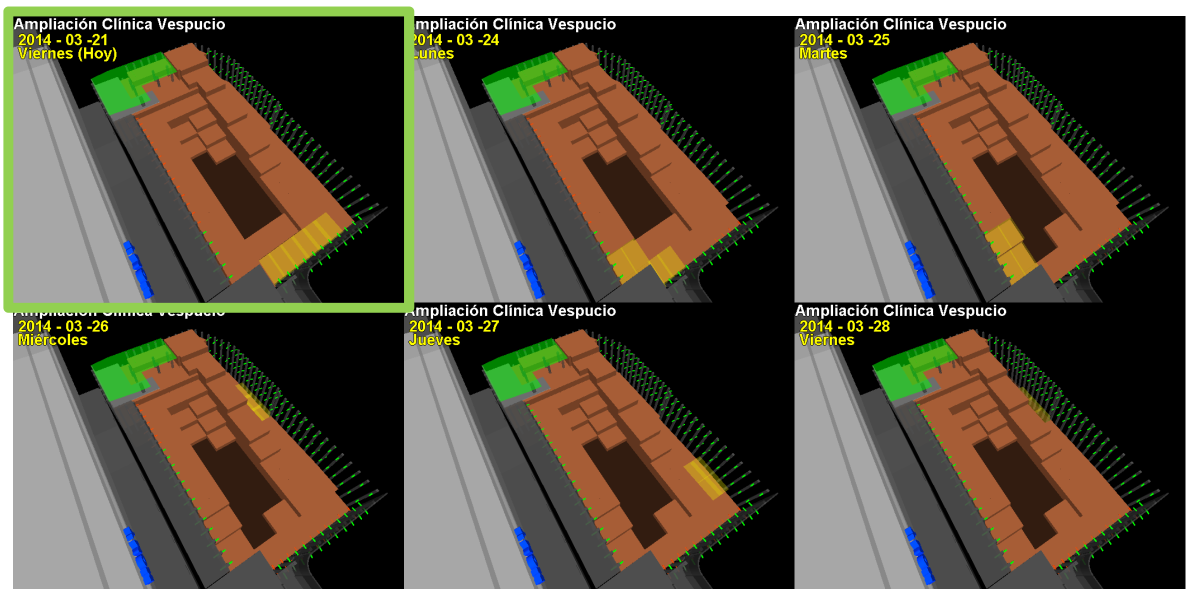

Figure 4. 3D and 4D Modelling Proposal. The sequence of pictures shows how to use a 4D model for short term planning and control of the excavation progress. On the upper left corner we see the current state of progress for the excavation. Following there are five screen captures that detail the expected progress for each day from Monday (upper middle) to Friday (bottom right). This information can be shared on construction meetings to plan the excavation work.

6 Validation

We validated our 4D models, their usefulness, and the proposal through interviews and questionnaires applied to members of the project case study. The focus of the validation was to summarize the opinions of the team members using the net promotor score technique [16]. The results are summarized in Figure 5. We tested if our models were able to help team members to explain excavation strategies, identify key elements, and guide decision making reducing unnecessary work.

The questionnaire had three sections: the first about the AB4D; the second about the IP4D; and the last one about our proposal for 3D and 4D modelling.

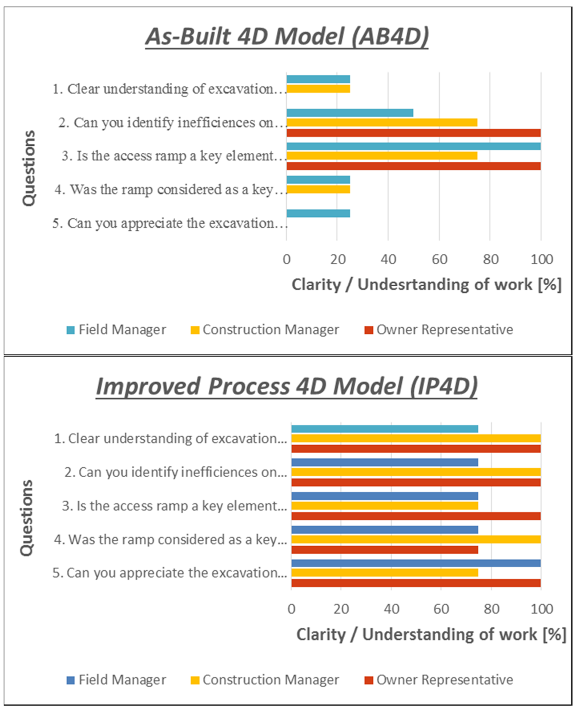

Figure 5. Validation Results. Top: AB4D results. 4D model show inefficiencies of actual sequence and SPX are able to identify the access ramp as key element. Bottom: IP4D results. All 5 questions are positively evaluated for the improved process.

The third part of the validation was unanimous for the team members and they all recommended the use of the 3D and 4D proposal for future projects. Therefore, they all were net promotors of the proposal [16].

Though we obtained positive feedback from team members regarding our models and proposal for prospective 3D and 4D modelling, we acknowledge that a larger number of interviews/opinions might be needed to better validate our work. For instance, a Charrette Test [17] with advanced Civil Engineering students is scheduled for validation purposes in late 2015.

7 Conclusions

Though the tool development and most applications of 4D models have focused on building construction, through the case study we showed a methodology to implement 3D and 4D modelling on excavation projects. For that purpose, we propose the creation of a fundamental excavation unit we called a soil pixel or SPX, that allowed us to describe the excavation 3D geometry accurately; to develop an excavation strategy; and to plan and control short term work progress.

We were able to use the SPXs to replicate the as-built excavation sequence with an AB4D. The same techniques can be applied for short term planning and project control during the project execution as shown.

Using the SPXs and learning from the AB4D bad decision making, we were able to propose an improved process that reduced unnecessary work and identified key elements for the excavation sequencing on an IP4D. Using the same techniques developed for the IP4D we propose to develop a Master Plan to communicate the excavation strategy to team members early on the project lifecycle to better plan, discuss and formalize the excavation work process.

8 Future Steps

We see potential in testing the concept of the soil pixel (SPX) in different type of excavations, such as trenches, tunnels and mining operations. The case study considers a pile supported excavation, but we could also explore other unsupported types of excavations and test there the SPX. Finally, the key element we represented in the case study was the access ramp; however, we could explore others for different excavations.

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