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APPLICATION OF SIMULATION IN TRENCHLESS RENEWAL OF UNDERGROUND URBAN INFRASTRUCTURE

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ABSTRACT

Pipe bursting is a type a of trenchless technology that enables the construction, rehabilitation, or replacement of underground urban infrastructure with minimal disruption to surface activity. This construction process facilitates the installation of sewer pipes and gas mains of similar or larger diameters at the same location as existing lines. The upsizing capability is particularly relevant in situations where greater flow capacities are required due to increased urbanization. This paper presents an application of a simulation platform developed at the University of Alberta called Simphony, used to create a special purpose simulation application of the pipe bursting process. Results obtained from this model can assist owners, engineers, contractors, and equipment manufacturers in designing and planning pipe bursting projects.

1 INTRODUCTION

Pipe bursting was first developed in the United Kingdom during the late 1970’s for the replacement of small diameter cast iron gas mains. Initially, this process was used only in the replacement of cast iron gas distribution lines; however, it was later employed in the replacement of water and sewer lines. By 1985, the pipe bursting process had been further developed to a capacity to install up to 400 mm outside diameter (O.D.) medium-density polyethylene (MDPE) sewer pipe. Today, the majority of pipe bursting applications in North America are for the replacement of deteriorated sewer lines with typical replacement diameters ranging from 50 to 400 mm and lengths ranging from 100 to 200 m (Lueke et al. 1999).

Pipe bursting is a unique method of underground rehabilitation in that it involves the replacement of the existing, or host, pipe with a new pipe or product line with minimal surface disruption along the pipe right of way. In general, a typical pipe bursting project consists of a series of excavated pits located at intervals along the trajectory of the line to be replaced. This interval is determined by several factors, including the geometry of the project, location of manholes, ease of access for excavation purposes, and pull force limitations of the pipe bursting machine utilized.

There are three bursting systems currently used in the North American pipe bursting industry. These are the static, pneumatic, and hydraulic expansion systems. The main difference between methods is the manner in which force is generated and transferred to the host pipe during the bursting operation. This paper presents an application of a general-purpose simulation language called Simphony for simulating the static pipe bursting process. Information gained from the simulation output can assist in the designing and planning of a pipe bursting project.

2 THE STATIC PIPE BURSTING PROCESS

Static methods burst the pipe using static forces, or forces that are not generated using potential energy. The setup for a typical burst using static pipe bursting is shown in Figure 1. A large pulling force is applied to a cone shaped bursting head through rods, cable, or chain. The bursting head is then pulled through the pipe, causing the pipe to fail in tension by the radial force applied to the pipe wall from the cone within the pipe. As the host pipe is burst, the bursting head pushes the broken pipe pieces into the soil as it displaces the surrounding soil, thus creating a cavity for the new product pipe.

The majority of static pipe bursting equipment is modeled after high-powered hydraulic jacks, and is mounted horizontally rather than vertically. The smaller units usually use two hydraulic cylinders to develop the required pulling force, while the larger units usually use four or more. Mounted in the center of the pistons is a mechanism to grab the chain or rod during the pulling operation. As the rod or chain is pulled by the machine, it is disconnected and the gripping assembly moves forward to grab another section of rod or link of chain. This process is repeated until the installation is complete. If cable is used it is usually pulled by a winch.

A typical pipe bursting project is divided into sections, or lengths, that the selected pipe bursting machine is capable of bursting. The length that can be burst is dependent on existing pipe material composition, degree of upsize, soil conditions, geometry of the original installation, and type of bursting equipment and method used.

For the installation of continuous pipe, such as high-density polyethylene (HDPE), access pits must be excavated at each end of the pipeline to be replaced. On one end of the line, the machine pit is excavated into which the pipe bursting machine that pulls or directs the bursting head is located. The size of the machine pit depends on the size and type of the pipe bursting machine used. Machine pits used in static pipe bursting can range in size from 4050 mm by 2500 mm to the size of a manhole. Depending on ground conditions and depth of the host pipe, shoring may be required, though sloped walls are also an option. Shoring is generally preferred to keep the footprint of the excavation to a minimum.

Opposite the machine pit is the insertion pit through which the new pipe or product pipe and bursting head are inserted into the existing or host pipe. Insertion pits are generally smaller than the machine pits. As a rule of thumb, the length of the insertion pit should be twelve times the diameter of the new product pipe plus a length to account for the slope depending on the depth of the excavation at a ratio of 1.5 to 2.5 run to 1 depth. The slope ratio largely depends on the bend radius of the product pipe. The width of the insertion pit need only be 1200 mm.

Any services along the pipe route connected to the host pipe must be disconnected prior to the start of the burst with access to the lateral connections achieved through service pits. Service pits may be excavated with a minimal surface footprint. The size of pit depends on the depth of excavation and the maneuverability of the excavation equipment in the confined space of the pit. Generally, a service pit need only be 1200 mm in diameter to provide enough space for a worker to disconnect and reconnect the lateral. These pits may be shored using large diameter steel pipe sections, depending on the pit depth.

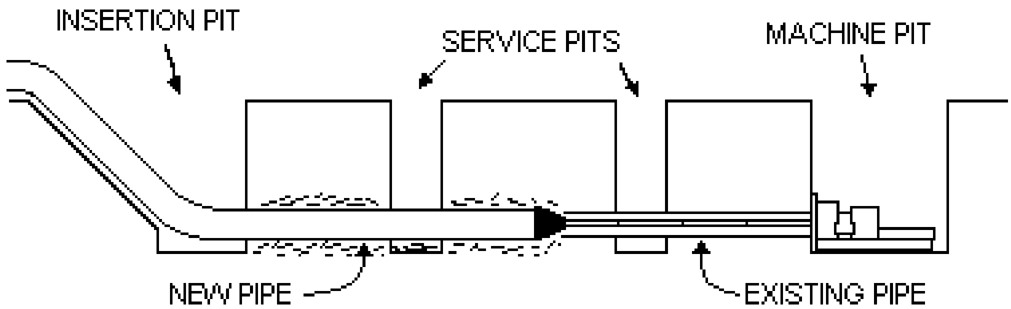

Figure 1: Typical Configuration for Static Pipe Bursting (Ariaratnam et al. 1999)

3 INTRODUCTION TO SPECIAL PURPOSE SIMULATION (SPS) FOR CONSTRUCTION APPLICATIONS

Special purpose simulation (SPS) is defined as "*a computer-based environment built to enable a practitioner who is knowledgeable in a given domain, but not necessarily in simulation, to model a project within that domain in a manner where symbolic representations, navigation schemes within the environment, creation of model specifications and reporting are completed in a format native to the domain itself*" (AbouRizk and Hajjar 1998). Building a SPS tool requires knowledge in three main areas, namely: the tool's intended application domain, simulation theory, and object oriented programming. The process is iterative, requiring good design and implementation strategy based on a balance between flexibility of the modeling environment and ease of use. SPS has been shown to be a promising approach for integrating simulation into the construction management process (AbouRizk and Hajjar 1998). Its application; however, has been hindered by the effort and resources required to build a individual SPS tools.

4 BACKGROUND OF SIMPHONY

Simphony is a simulation platform for building SPS and other simulation tools referred to as Simphony templates. Simphony is based on an "object oriented application framework" approach, which provides a structured approach for building a new template. The services provided under the framework include simulation (a discrete event simulation engine), trace manager (to trace required simulation events, errors encountered, etc), statistics collection, graphical (enabling a structured and cost effective approach for creating visual/iconic interfaces for a given template), random number generation, report generation, and planning. At the heart of Simphony is the concept of a modeling element, which is a class that encapsulates functionality common across most SPS tools. This modeling element provides a structured way for extending the functionality of the system for the intended domain.

5 SPECIAL PURPOSE SIMULATION FOR PIPE BURSTING PROJECTS

To model the pipe bursting process, essentially only two classes of elements are constructed. These element classes consist of pipes and pits. Pits represent the physical manifestation of the excavations used to access the pipe. The pipe element is used to connect the pit elements and transport the entity through the model. Pits are grouped by function into categories: machine pits that house the pipe bursting machine and insertion pits where the product pipe is inserted into the original pipe to be pulled to the machine pit. Depending on the layout and orientation of the host pipe and the manholes, the sequence and number of machine and insertion pits may vary.

In general, for each section of pipe that is to be replaced in the ground, one machine pit and one insertion pit are required. Alternatively, if two sequential sections of pipe are to be replaced, there need only be one machine pit at the junction of the pipe segments and two insertion pits at each end a pipe segment. Subsequently, the setup may be performed using two machine pits and one insertion pit at the junction of the pipe segments. Sequencing of pits is constrained by the amount of space available on site. Insertion pits typically require more space than machine pits since the entire length of the new line must be strung out of the pit prior to pipe bursting commencing.

In the simulation model, six types of pits are identified and constructed to model actual project conditions. These are distinguished by the direction in which the product line is inserted into the pit, as well as the direction that the pipe bursting machine pulls the product line into the ground. Therefore there is a machine and insertion pit for pulls and installations that occur from the left side of the screen to the right, right to left, and from both directions. In actuality, there is no difference between how machine pits operate amongst the different directions of operation, but is available to more closely represent the orientation and setup of the project. Additionally, pits can be linked together to represent conditions where essentially a new pit is required to complete the installation.

To complete the model two other elements were added, the Job Start and Job Finish elements. The Job Start element created one entity that is sent in a linear fashion through the model. This entity transports information to the Job Finish node, where productivity values are calculated and stored. In the Job Finish element the user may also view the productivity data for the project. Project elements used in the simulation model are illustrated in Figure 2.

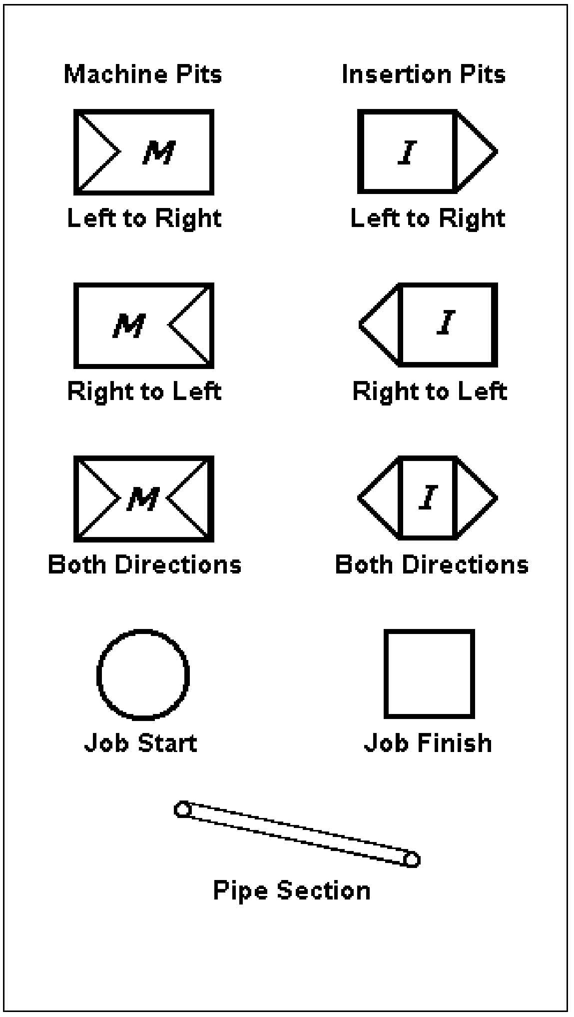

Figure 2: Simphony Pipe Bursting Modeling Elements

To construct a model based on a given project, the user need only click and drop the project elements into the project model. An illustration of the user interface is shown in Figure 3. In this figure, a typical bursting project is composed, consisting of two insertion pits with two machine pits. Between the pits are three pipe sections to transport the project entity through the network. On the left hand side of the network is the Job Start node, as well as the Job End node at the other end of the network.

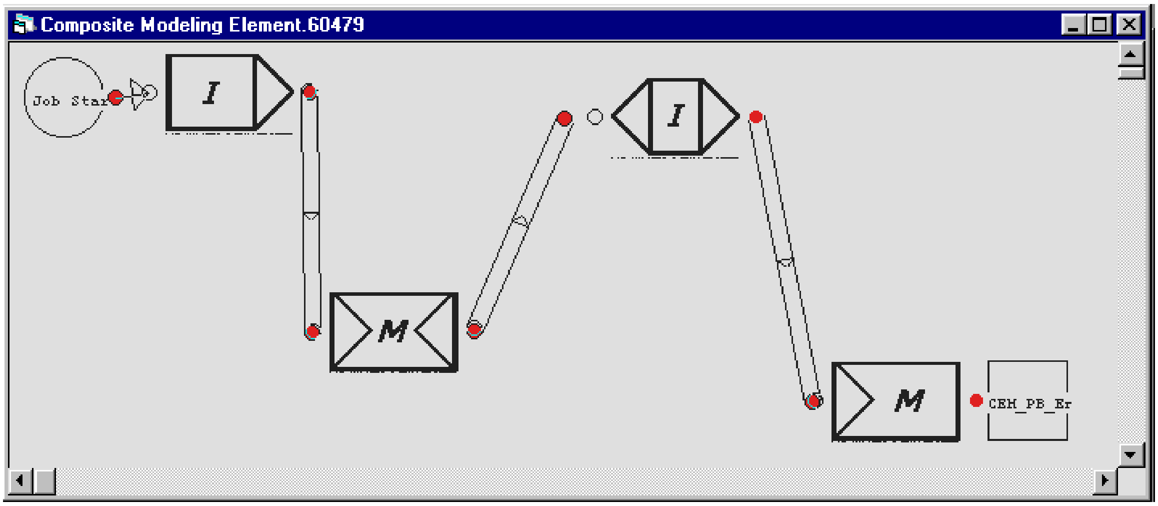

Figure 3: Pipe Bursting Project Model in Simphony

Each element in the simulation model has both a series of properties and attributes that are assigned by the user at the start of the simulation and those that change as the simulation progresses. These properties can be classified as micro properties, which are assigned for each model element, or as macro properties that are assigned at the project level. Simphony utilizes a micro and macro hierarchy structure which allows the user to assign properties to the level from which they were used and directly affected the process. Project and element user defined attributes are shown in Table 1. The attributes related to the pipe segment are used to determine the time as well as the amount of force required to burst the line. This in turn will calculate whether the selected equipment specifications, as outlined in the project, are sufficient to complete the pull. Currently, modeling the relationship between soil and pipe type, as well as the degree of upsizing as related to the force required to burst the pipe is still under development.

Table 1: Project and Element User Defined Attributes

Element Attributes		**Project Attributes**
Pipe Segment	**Pits**	
Length	Length	Rod Length
Original Diameter	Width	Cylinder Stroke Length
New Diameter	Depth	Cylinder Diameter
Soil Type	Excavation Productivity	Number of Cylinders
Pipe Type	Machine Placement Time	Pump Flow Rate
	Product Placement Time	Coupling Time
	Time to Disconnect Lines	Rod Load and Unload Time
	Time to Reconnect Lines	Bursting Head Attach Time

Attributes related to the machine and insertion pits determine the time required to excavate the pits, place the machine (for machine pits) or product line (for insertion pits), as well as the time to disconnect and reconnect the line after the burst is complete. In the bursting operation, the existing line must be taken out of service until the new line is installed. Pit attributes are unique for each pit and depend on the accessibility and available space to set up either the machine or insertion pit. Additional element and entity attributes are used though out the model but are kept hidden from the user. These attributes are used to store data for the simulation as well as to pass information from one element to the next via the entity.

In general, the contractor would use the same pipe bursting machine though out the entire project, therefore attributes relating to the machine and activities not dependant on the layout of the site may be stored in the macro or project level. There are a number of attributes relating to the pipe bursting machine that can be changed to determine the effect on bursting productivity. This was one of the main objectives of the simulation model, not only to assist in project planning but also to assist in equipment design as selection for a given set of project characteristics. In the model, pre-determined equipment specifications with assigned attributes will be available, from which the user can modify to suit various project requirements.

6 MODEL LAYOUT

In the creation of the special purpose pipe bursting simulation, key activities or events were identified that would be scheduled in the model. The essential steps in the bursting process as were modeled are shown in Figure 4. Each event as listed in the flow chart represents an event that Simphony scheduled during simulation. There are two loops that occur in the process, one where rods are pushed through the existing line to the insertion pit, and the other where these rods are then pulled back through the line with the bursting head and product line attached to actually burst the pipe. The continuation of these loops is dependent on the length of the line being replaced as well as the length of the bursting rods, as specified by the user. Schedule times relating the push loop and the bursting loop are calculated according to machine specifications. In this manner the user could determine the effects that modifications to the basic bursting machine would have on the overall productivity of the operation.

The model utilizes three resources though out the simulation; these include the pipe bursting machine, a surface crew, and an underground crew. For each activity, various combinations of these crews are required to complete the task. Due to the linear nature of the process, events in the model will rarely wait for these resources to be released from prior activities, these resources are used to determine resource utilization from a project management perspective.

7 SIMULATION RESULTS

The initial validation of the pipe bursting simulation template was performed on field data collected from an actual pipe bursting project conducted in Naniamo, British Columbia in May of 1999. Three installations of varying lengths and soil conditions were measured. The project itself was the replacement of a 16-inch O.D. concrete sewer pipe with a new 26 inch O.D. high-density polyethylene line. Information pertaining to the project statistics is listed in Table 2. Soil and bearing capacity qualifications are based on subjective field observations. Additionally, the number of hydraulic cylinders used to pull the rods and pipe are indicated in the table. The number of cylinders directly affects the travel speed of the carriage for both the push and pull back operations.

To validate the model project data was entered into a project network consisting of one insertion pit, one machine, and a pipe section. A Job Start and Job Finish node were added to complete the node. Each installation length was simulated as an independent event to correlate actual productivity. The simulated and actual burst completion times and productivity are compared in Table 2. The table reveals that the productivity simulated for installation 2 and 3, are very similar to the actual burst productivity, while the productivity for installation 1 was calculated to be much lower than the actual productivity. This difference could be attributed to the lower bearing capacity of the soil that was the predominate condition throughout the first installation. To improve the simulation accuracy, validation will continue with additional simulation factors added to account for varying project characteristics, and in particular, soil conditions.

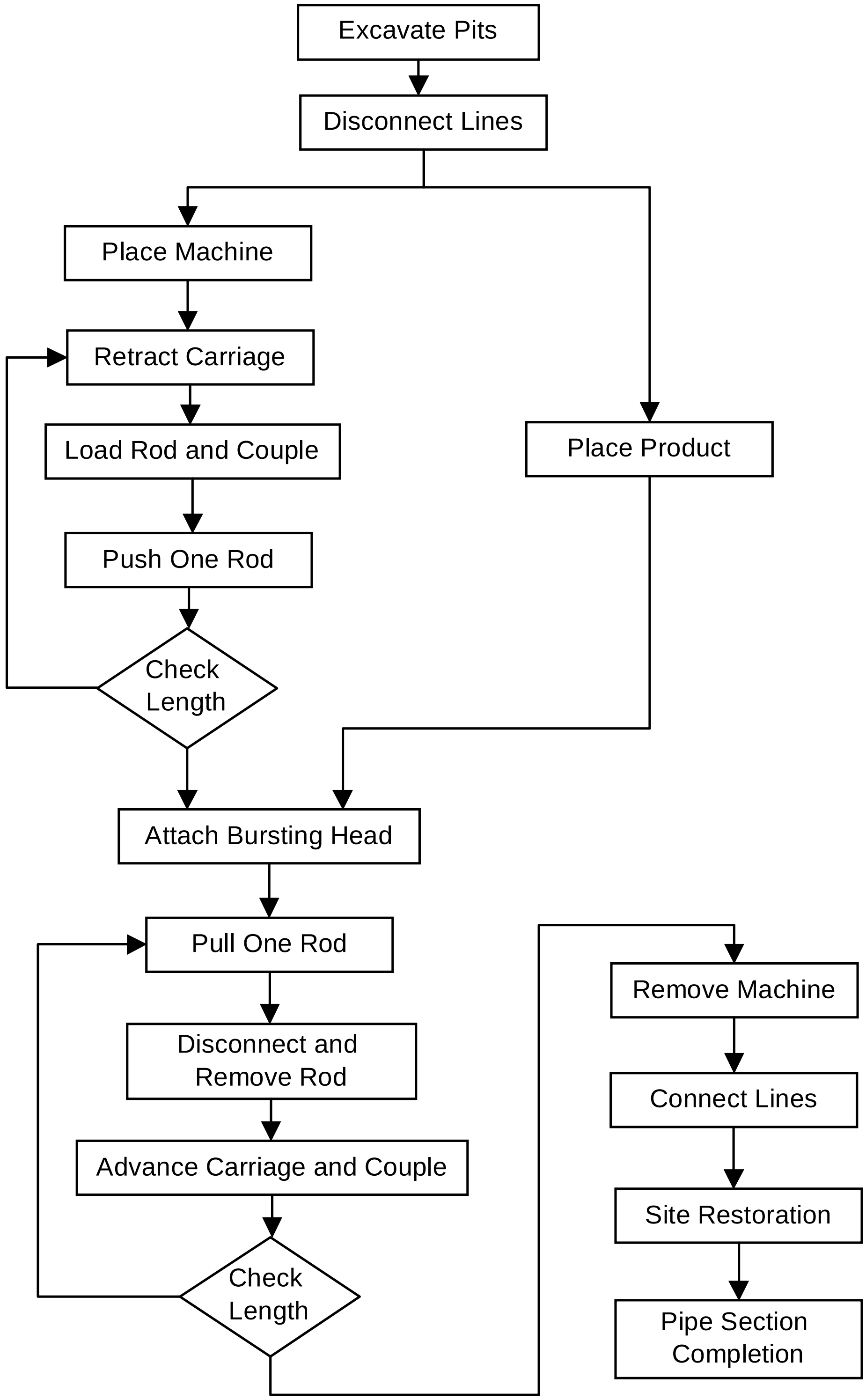

Figure 4: Pipe Bursting Process Flowchart

Table 2: Simulated and Actual Project Productivity Results

	Installation #1	Installation #2	Installation #3
Length (ft)	561	541	229
Soil Description	Clay	Clay/Gravel	Clay
Bearing Capacity	Low	Medium	Medium
Water Table	N/A	N/A	High
Number of Cylinders	4	4	2
Actual			
Total Time (hrs)	2.60	3.85	2.13
Productivity (ft/hr)	215.8	140.6	107.7
Simulated			
Total Time (hrs)	3.86	3.75	1.87
Productivity (ft/hr)	145.4	143.9	122.1

8 FUTURE ENHANCEMENTS

It is important to realize that there are many factors that contribute to the pipe bursting process as well as to the success of a project. Presently, the simulation model accurately depicts the progression of events based on the mechanics of the pipe bursting operation. To make this model more valuable as a planning tool various situations pertaining to events that affect the operation must be incorporated. These events would add elements of uncertainty that can be simulated to gain a more accurate perspective on the proper utilization of equipment, as well as the success of the project.

Currently, there are four variables in the process of being incorporated into the simulation template to improve the modeling of bursting projects. These variables include factors for soil conditions, crew experience, environmental conditions, as well as the geometry of the original pipe installation. It is proposed that these variables be based on a numeric scale to incorporate the judgement of the user into the mechanics of the bursting simulation.

Soil factors would account for soil bearing capacity, water table location, and the available information from geotechnical investigations. This factor affects the amount of force required to displace soil in upsizing operations, as well as combine with equipment specifications to determine the chance of overpowering the equipment during the burst. Crew experience directly affects the productivity of the operation, and is accounted for in the time to complete activities. Issues relating to the amount of space available to move equipment and excavate are considered in the environmental factor. The original pipe installation geometry determines the force required and success of the burst based on the equipment and soil factor. To depict actual project conditions, soil, environmental and geometry factors would be applied for each pipe section. With the addition of these factors and issuing multiple runs, productivity rates and project success rates with various project and equipment specifications will be achieved.

To enhance the project management and planning aspect of the model, it is essential that a cost estimation module be added. Costs could be calculated from the variables entered in the modeling elements with the addition of a database to provide crew compositions and rates. This would assist planners to simulate costs and productivity over multiple runs to determine the best cost and productivity for the level of risk that the planner wishes to undertake.

9 CONCLUSIONS

The simulation modeling of trenchless renewal of underground urban infrastructure using Simphony, a simulation platform developed at the University of Alberta, has been presented. Simphony was designed to act as a platform to enable the creation of special purpose simulation models for real-world applications.

The developed model was compared to actual field results obtained from a trenchless pipe replacement project in Nanaimo, British Columbia in May of 1999. Productivity simulated for two of the three installation sections modeled similarly to actual productivity. As additional factors are added to the model to account for project uncertainty and differing soil conditions, the accuracy of the simulation should increase thus providing benefits to owners, engineers, contractors, and equipment manufacturers in the designing and planning of trenchless pipe replacement projects.

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