USING A DISCRETE EVENT SIMULATION TOOL TO PREDICT THE SPEED OF SMALL CROSS SECTION TUNNELING BY DRILLING AND BLASTING METHOD

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Abstract

Compared to medium- and large-sized underground tunnels, construction of small cross section tunnels has different conditions: in terms of construction organization space, vehicles and workers especially transportation in narrow roads that only one vehicle is allowed to pass. This article studies the small cross section tunneling construction in rocks with different coefficients of consolidation (f_{kp}) and predicts the tunneling construction speed for the narrow segment by using EZStrobe software to simulate. The results are compared with the baseline model in case without narrow segmentation, and also indicate a reasonable number of transport vehicles should be used.

Keywords: *Simulation; modeling; EZStrobe; tunneling construction by drilling and blasting method; speed of tunneling.*

1. Introduction

Small cross section military tunnels have different construction conditions compared to medium and large-sized ones: limited construction space, using more handheld construction equipment and more labor. Such conditions have a significant impact on the construction progress. It is very difficult to predict the construction progress according to the current traditional methods, due to the randomness of the construction processes. To determine construction progress considering random time, there are tools such as PERT network [1], Monte-Carlo simulation [2] and discrete event simulation tools recently. The use of simulation tools in construction analysis has enhanced around for 50 years, pioneered by Halpin [3] with the introduction of the CYCLONE system (based on discrete event simulation). Since then, the method has evolved and made progress in a remarkable way. In the field of tunnel construction, simulation tools are used in many aspects: Project planning; Analyze bottlenecks to determine what causes system delays; Predict system performance under different

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conditions; Check productivity improvements and optimize resource usage; Offer a comparison of alternative tunnel construction scenarios; and Sensitivity Analysis to determine the factors affecting the performance of the system [4]. However, most of the above studies are conducted for underground works with large space with modern construction equipment or small underground works with special equipment [5]. In Vietnam, the popularity of discrete simulation in construction, especially in tunnel construction, is quite limited and has only been used to assess labor productivity in a number of small activities [6, 7], to analyze construction activities [8, 9] or to analyze the construction process by drilling and blasting tunnels in large space [10-12].

This article will develop from established models based on the discrete event simulation tool EZStrobe/ STROBOSCOPE to predict the construction speed of small-scale military tunnels with the above construction characteristics.

2. Simulation model to analyze tunneling productivity with narrow segment

2.1. Summary of EZStrobe simulation system in tunneling productivity analysis

The model is built on the simulation system EZstrobe which is a discrete event simulation system based on the extended and annotated Activity Cycle Diagrams. It uses the simulation engine of the general-purpose simulation programming language STROBOSCOPE and also follows the three-phase active scan simulation model. EZStrobe is evaluated as the the most potential technique to provide discovery opportunities for researchers as well as practice for management and administration work [13]. Interested readers can easily download the EZstrobe program along with detailed user manuals on Professor Photios G. Ioannou's website at: www.ioannou.org or www.ezstrobe.org.

From the theoretical issues on tunneling technology by drilling and blasting method, which are concretized by the pre-determined model presented in [14] and reference other studies on the same topic, the tunneling process by drilling method using anchor reinforcement and concrete grouting are detailed down to small steps to suit modeling. The model built based on the all-mirror construction plan is called the basic model. From the basic model, it will develop into models in other specific cases for analysis and survey of construction options.

As a result, the study has built a basic simulation model as shown in Figure 1 [10]. The model has been verified for accuracy and has been developed to analyze tunneling productivity by different methods. The mirror mining project gives positive results [11], analyzing the impact of equipment failure incidents [12].

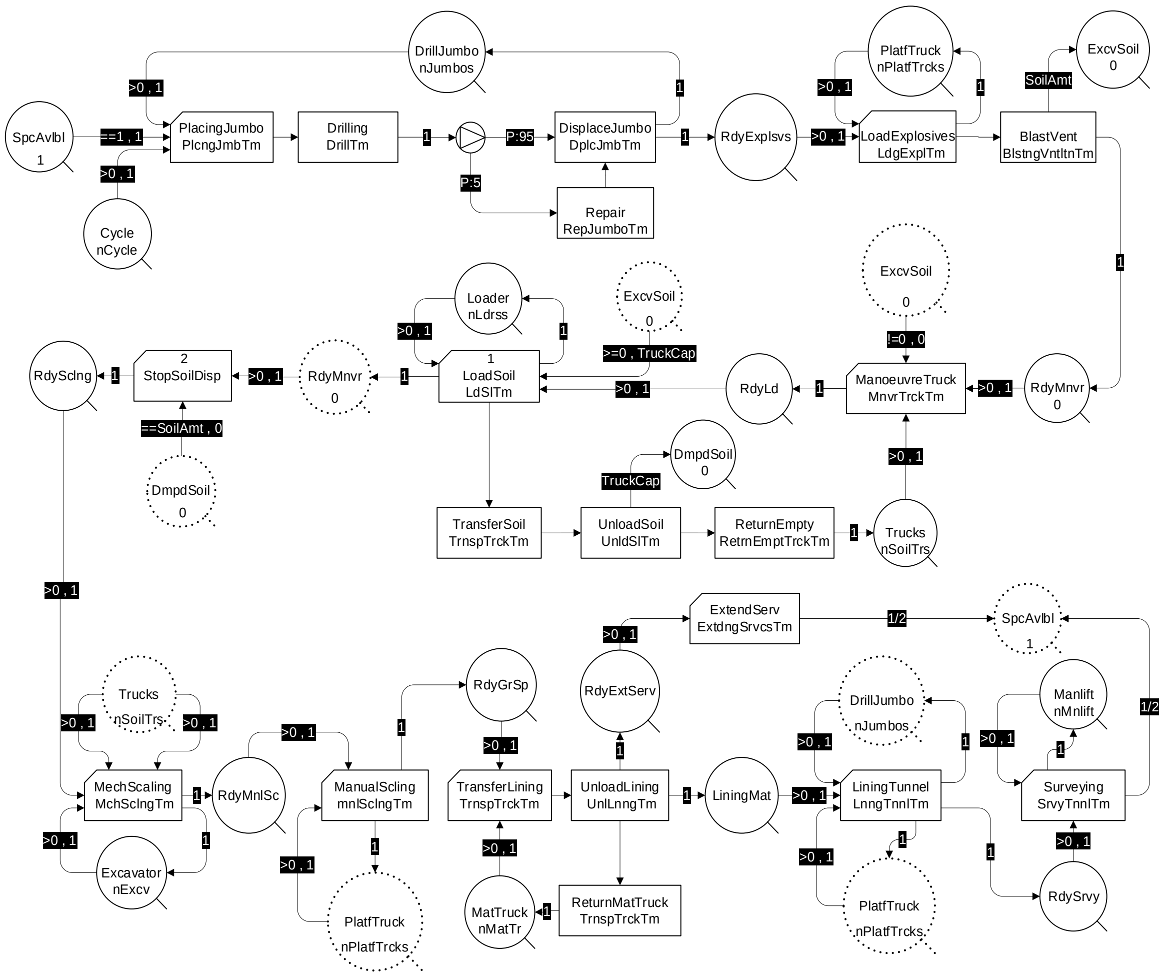

Figure 1. Simulation model of tunneling by blast drill method on EZStrobe.

2.2. Modeling a narrow segment in EZStrobe [15]

A carriageway has a narrow section that allows travel in only one direction (only one truck can enter the narrow road at a time from two sides). The direction of travel is established by the first unladen vehicle to reach the narrow segment. That direction is maintained if the vehicle continues to the segment in the same direction or until the segment is vacant. If vehicles are waiting at the other end when the segment is empty, the direction of travel will reverse to allow those vehicles to go. This section of the narrow segment model of the ACD EZStrobe in Figure 2 includes the following nodes: XeCTCh, XeCTVao, XeCTRa, KSXeKT, DuyetXe, KSXeCT, XeKTRa, XeKTVao and XeKTCh.

To understand the model, it is necessary to clearly describe how this is done in practice. In model 2, the transport path is divided into three segments, with a narrow segment in the middle. A vehicle entering a narrow segment is allowed to enter if there are no vehicles traveling in the opposite direction through the segment. In addition, for physical space reasons, a vehicle must wait until the vehicle in front has fully entered the narrow segment before it is allowed to enter (i.e., the narrow segment entrance must be cleared). In the model discussed here, it is assumed that this takes 0.3 min and is represented by the Conditional Jobs XeCTVao (vehicle loaded towards the narrow segment dump site) and XeKTVao (vehicle). no load back loading area excavator into narrow segment). Resources are initially placed in the DuyetXe queue ensuring that only one vehicle enters the narrow segment at either end at a time. This unique resource is required for XeCTVao or XeKTVao to start and is removed from DuyetXe when either job begins. When DuyetXe is empty (out of resources), neither XeCTVao nor XeKTVao can execute.

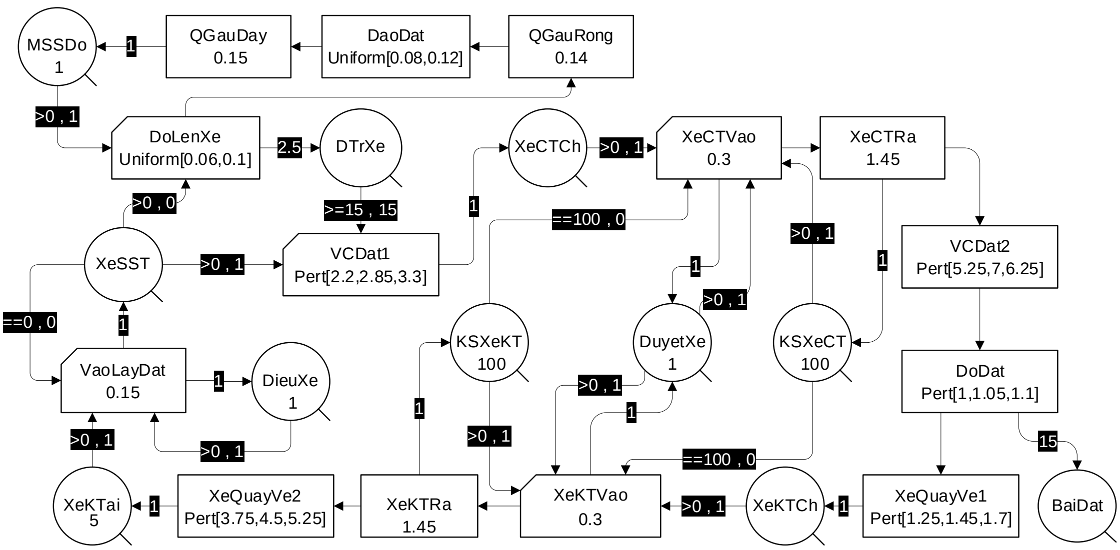

Figure 2. ACD for land transport with unidirectional narrow segment.

The rest of the narrow segment requires 1.45 min travel time. This is represented by XeCTRa and XeKTRa jobs bound to XeCTVao and XeKTVao respectively (e.g. an instance of XeCTRa or XRKTRa starts each time an instance of XeCTVao or XeKTVao ends). Because the time to pass through the rest of the narrow segment (1.45 min) is greater than the time to pass through the entrance (0.30 min), it is possible that some instances of XeCTra or XRKTra will take place simultaneously (for example, some trucks with 0.3 min spacing can pass through a narrow segment).

Every time XeCTVao starts, it removes a resource from KSXeCT. Every time XeCTra finishes, it sends a resource into KSXeCT. Since KSXeCT is initialized in bulk (100), its resource count will never go down to zero. In fact, the number of resources under 100 in KSXeCT is the number of trucks with loads that are passing through the narrow segment (i.e. XeCTVao and XeCTra are ongoing). When KSXeCT's resource is 100, then no loaded vehicles are passing through the narrow segment. This information is very valuable and is used as one of the necessary conditions to allow idling vehicles to enter the narrow segment (‘==100’ in the link connecting KSXeCT with XeKTVao).

Similarly, KSXeKT and its links with XeKTVao and XeKTRa jobs maintain and provide information on the number of idling vehicles passing through the narrow segment. The condition that no unladen vehicles pass through the narrow segment (i.e., KSXeKT's resource count is 100) is used similarly as one of the necessary conditions for a loaded vehicle to enter the narrow segment.

Therefore, according to the ACD of Figure 2, in order for a loaded vehicle to enter the narrow segment, the following 4 conditions are required: (1)- The resource amount of XeCTCh must be greater than 0 (that is, a loaded vehicle must be wait to enter); (2)- KSXeKT's resource amount must be 100 (meaning no idling vehicles can pass through the narrow segment); (3)- DuyetXe's resource amount must be greater than 0 (meaning narrow segment entrance must be freed) and (4)- KSXeCT's resource amount must be greater than 0 (this will always happen).

When XeCTVao starts (i.e. a loaded vehicle into a narrow segment), it (1)- gets a resource from XeCTCh; (2)- maintains the same amount of resources of KSXeKT; (3)- acquires a resource in DuyetXe and (4)- acquires a resource from KSXeCT (this resource will not be returned to KSXeCT until the XeCTRa instance bound to the starting instance of EXeCTVao ends).

By modeling the empty direction of the narrow segment in the same way, it is possible to control the vehicle passing operation as desired.

The conditions and resource maneuvers shown in the connection of the queue to the Conditional Activity are very tight. This example illustrates how it is possible to model moderately complex logic using resource allocation conditions and selections with just a few procedures.

3. Simulating the construction process of military tunneling by drilling and blasting method

3.1. Description of case study

The work used for simulation is a special tunnel, the total length of the tunnel along the axis excluding the shrimp antennae is 829.85 m, the public service and mobile routes are 134.5 m and 87.5 m, the dimensions are cross section of the passage is 1.5 × 2.7 m (width × height), the dimensions of the expansion chambers are 3.5 × 2.7 m and 4.5 × 3.4 m, the geology of the main tunneling area is mainly is in rocks with f_{kp} = 4 ÷ 6 (about 420 m long) and f_{kp} = 6 ÷ 8 (377 m). The tunneling method is divided into 2 phases: Phase 1 - tunneling with a cross-sectional area of 1.5 × 2.7 m throughout the entire tunnel and phase 2 is digging expansion chambers according to the design. In this article, the excavation speed is studied and simulated for a tunnel section in phase 1 digging in a narrow section with an excavation area of about 8.05 m^2 (corresponding to a passageway of 1.5 × 2.7 m). The construction method is the full-mirror drilling and blasting method, transporting by specialized vehicles, manually anti-temporary using shaped steel, the mirror step is 1m, when transporting at a time, only 1 vehicle can move in the same time. tunnel. In this study, the excavation speed is simulated for the section with the excavation mirror area of the tunnel section of 8.05 m^2 in the soil and rock with f_{kp} = 4 ÷ 6 at 80 m from the tunnel entrance C (including the conduction furnace) and in the soil and rock with f_{kp} = 6 ÷ 8 is 100 m away from tunnel C door, distance from tunnel C's location to waste dump site is 134.5 m. The tunnel plan is shown in Figure 4. Construction process of tunneling by drilling and blasting method is shown in Figure 3.

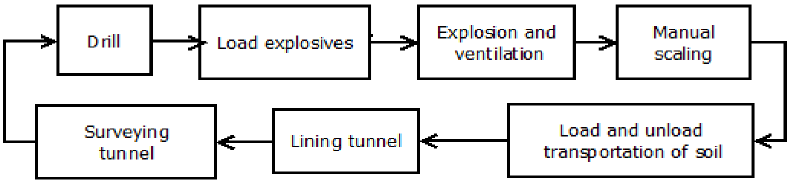

Figure 3. Construction process of tunneling by drilling and blasting method.

Resources used include: 02 drills Y26, drill diameter d42; 01 specialized excavator, bucket capacity 0.2 m^3; 02 vehicles with a capacity of 0.8 m^3; The average vehicle speed in the tunnel is 5 km/h; Outside the tunnel is 10 km/h, about 11 people.

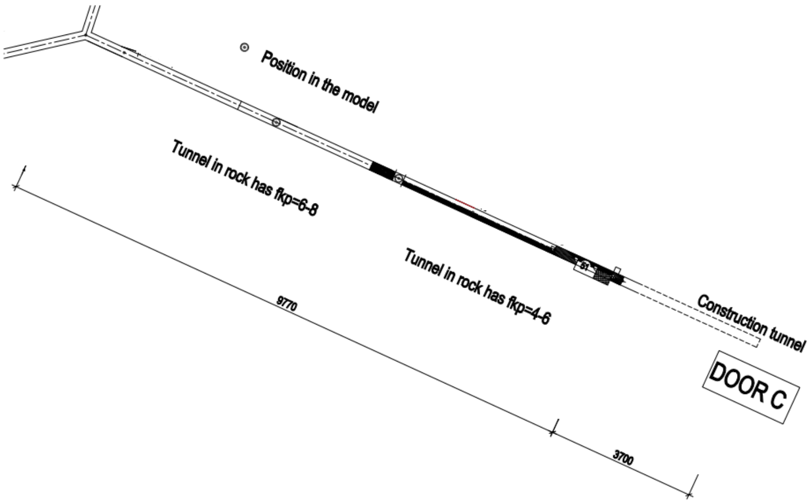

Figure 4. Plan of a tunnel section near gate C (size in the picture is cm).

3.2. Prepare data for the model

The tunnel was built by the Engineering Corps, the time to collect data on the construction process from June 2022 to August 2022. The resource variables used in the model of the Special tunnel project are described in Table 1, which shows the variable symbols on the model and their actual values. ExcvSoil and DmpdSoil variables are automatically defined during simulation.

Table 1. Variables on resources used in the model

Order	Variable model	Variable symbol	Value
1	Number of Truck	nSoilTr	2
2	Truck capacity (m^3)	TruckCap	0.8
3	Number of material trucks	nMatTr	1
4	Number of excavators	nLdrs	1
5	Number of drill jumbo	nJumbo	2
6	Number of man-lifts	nCrew	11
7	Amount of soil (m^3)	SoilAmt	7.2
8	Amount of soil and rock excavated (m^3)	ExcvSoil	n.a.
9	Amount of soil poured at the soil treatment area (m^3)	DmpdSoil	n.a.

The probability distribution of the duration of each activity used in the simulation model is listed in Table 2. Based on the collected data and consultations with the staff directly on the construction site, after carry out statistical analysis, using a description of the majority of activity durations according to the triangular distribution decided to apply (Triangular).

Table 2. Probability distribution of duration of activities used in the model

Order	Operation model	Variable symbol	Value (min)
1	Placing the drill jumbos at the face of the tunnel from its starting position	PlcngJmbTm	Triangular[2,2.5,3]
2	Drill holes in the rock $f_{KP} = 4 \div 6$	DrillTm	Triangular[90,105,120]
	Drill holes in the rock $f_{KP} = 6 \div 8$	DrillTm	Triangular[210,240,270]
3	Drill jumbo gets displaced from the face of the tunnel	DsplngJmbTm	Triangular[2,2.5,3]
4	Repairing the drill jumbo	RepJumboTm	Uniform[5,10]
5	Load explosives in the rock $f_{KP} = 4 \div 6$	LdgExplTm	Triangular[15,20,25]
	Load explosives in the rock $f_{KP} = 6 \div 8$	LdgExplTm	Triangular[18,22,26]
6	Blasting and ventilating the tunnel	BlstnVntltnTm	Triangular[20,25,30]

Order	Operation model	Variable symbol	Value (min)
7	The truck is in position to excavate soil	MnvrTrck1Tm	Triangular[1,1.5,2]
8	Loading soil in the trucks by a loader	LdSlTm	Triangular[4,5,6]
9	Transporting waste rock in the tunnel	TrnspTrckTm	Triangular[1,1.5,2]
10	Transporting waste soil outside the tunnel	TrnspTrck1Tm	Triangular[1,1.5,2]
11	Unloading the soil	UnldSlTm	Triangular[1,1.5,2]
12	Empty truck returns to its starting position	RetrnEmptTrckTm	Triangular[1,1.5,2]
13	Empty truck moving in the tunnel	MnvrTrckTm	Triangular[1,1.5,2]
14	Manual scaling	MnlSclngTm	Triangular[9,10,11]
15	Unload lining material	UnlLnngTm	Triangular[35,40,45]
16	Lining tunnel	LnngTnnlTm	Triangular[25,30,35]
17	Surveying tunnel	SrvyTnnlTm	Triangular[5,7,9]
18	Extending services	ExtndngSrvcsTm	Triangular[3,4,5]

3.3. Simulation model by EZStrobe

Analyze the tunneling process by explosive drilling with the main stages shown in Figure 4, detailed into the following stages: Mine hole drilling - Explosive loading - Explosion and ventilation - Blasting - Transporting waste soil and rock - Supporting and reinforcing - Surveying and preparing for the next cycle. On that basis, make a simulation model as shown in Figure 5.

The process of transporting soil and rock was developed by the author from the theoretical basis presented in Section 2.2. In this model, the transportation distance consists of 2 segments, the segment in the tunnel is a narrow segment (in the theoretical model it is 3 segments and a narrow segment in the middle). This part of the narrow segment model of ACD EZStrobe in Figure 5 (the dashed area represents LAND TRANSPORT) includes the following nodes: LdTruck, TrnspTrckTm, CoTruck, EmptyCar, MnvrTrckTm, MnvrTrck1Tm.

In this narrow segment, a vehicle entering the narrow segment is allowed to enter if there is no vehicle traveling in the opposite direction through the segment. In addition, for physical space reasons, a vehicle must wait until the vehicle in front has fully entered the narrow segment before it is allowed to enter (i.e., the narrow segment entrance must be cleared). In the model it is represented by the Conditional Jobs TrnspTrckTm, (loaded vehicle towards the dumping site into the narrow segment) and MnvrTrckTm (the unloaded vehicle returns to the loading area into the narrow segment). The initial resource placed in the CoTruck queue ensures that only one vehicle enters the narrow segment at either end at a time. This unique resource is required for

TrnspTrckTm or MnvrTrckTm to start and is removed from CoTruck when either job begins. When CoTruck is empty (out of resources), neither TrnspTrckTm nor MnvrTrckTm can execute.

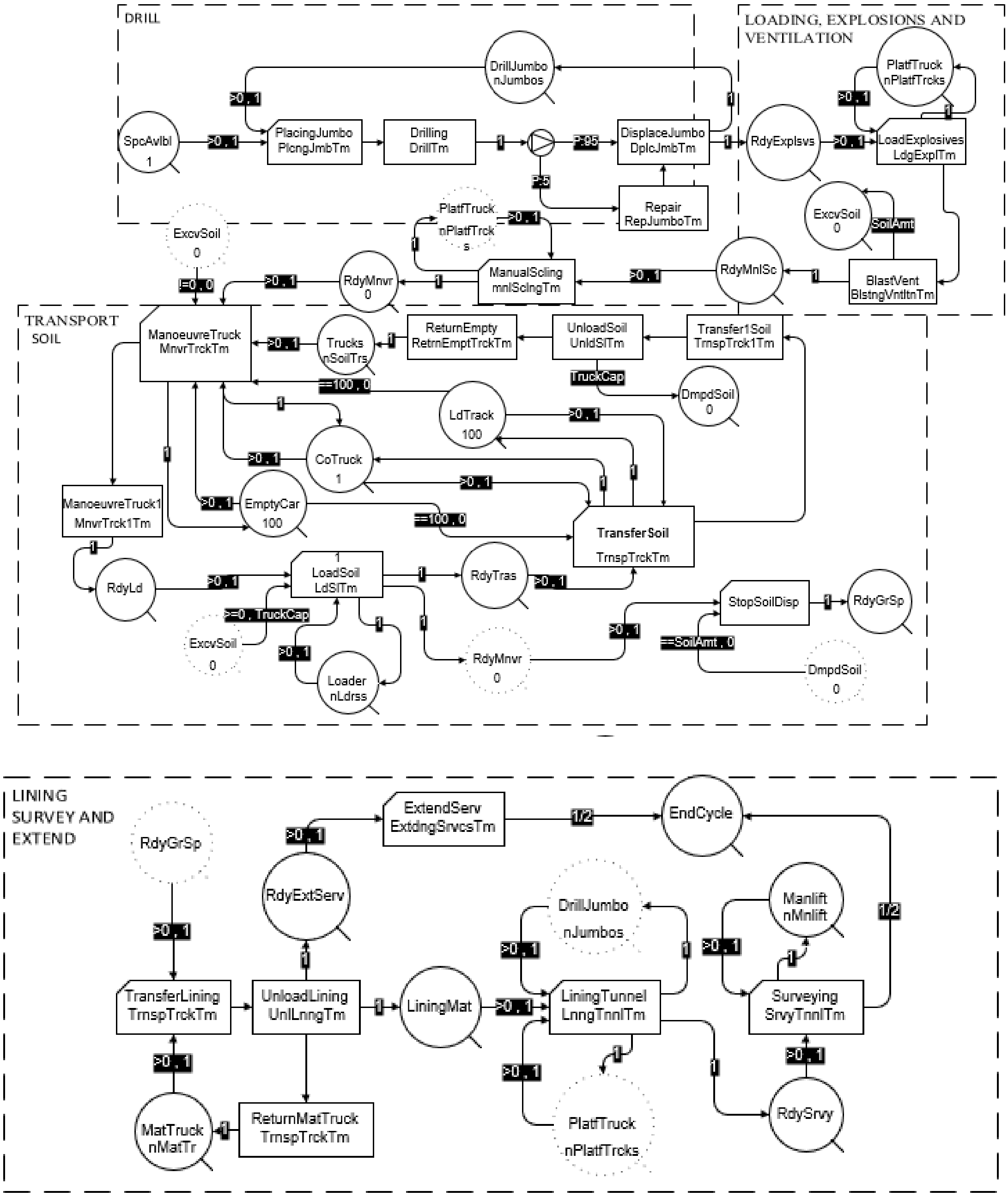

Figure 5. Simulation model of the construction process of small cross section tunnelings by drill and blast by EZStrobe.

Every time TrnspTrckTm starts, it takes a resource from LdTruck. When it finishes, it sends a resource into LdTruck. Since LdTruck is initialized at a large number (100), its resource will never decrease to zero. In fact, the number of resources under 100 in LdTruck is the number of trucks with loads that are passing through the narrow segment (i.e., TrnspTrckTm in progress). When LdTruck's resource is 100, then there are no loaded trucks going through the narrow segment. This information is very valuable and is used as one of the necessary conditions to allow idling vehicles to enter the narrow segment (‘==100’ in the link connecting LdTruck to MnvrTrckTm).

Similarly, EmptyCar and the links that connect it to the MnvrTrckTm jobs maintain and provide information on the number of idling vehicles passing through the narrow segment. The condition that no unladen vehicles pass through the narrow segment (i.e., EmptyCar resource count is 100) is used similarly as one of the necessary conditions for a loaded vehicle to enter the narrow segment.

Therefore, in order for a loaded vehicle to enter the narrow segment, the following 4 conditions are required: (1)- RdyTras' resource amount must be greater than 0 (meaning a loaded vehicle must wait to enter); (2)- EmptyCar's resource amount must be 100 (meaning no idling vehicles can pass through the narrow segment); (3)- CoTruck's resource amount must be greater than 0 (meaning narrow segment entrance must be released) and (4)- LdTruck's resource amount must be greater than 0 (this will always happen).

When TrnspTrckTm starts, i.e., a vehicle with a load into a narrow segment, it (1)- gets a resource from RdyTras; (2)- keeps the same amount of resources of EmptyCar; (3)- acquires a resource in CoTruck and (4)- acquires a resource from LdTruck (this resource will not be returned to LdTruck until the TrnspTrckTm instance ends).

The established model is checked for errors by running the animated model, reporting detailed process results. The results show that the model has worked correctly and can be used for simulation.

3.4. Simulation results and evaluation

a) About cycle time and tunneling speed

Run the small cross section tunnelinging model (narrow segment - Figure 5) with the number of simulations of 10,000, the results are obtained about the construction speed of small cross section tunnelinging by blast drilling with the parameters as shown in the Table. 3.

Table 3. Simulation results of cycle time and construction speed of tunnels by drilling and blasting method in a narrow segment model

Content	The average value	Differrence	The greatest value	Smallest value
1. In the rock there is f_{kp} = 4 ÷ 6				
Cycle time (h)	5.369	0.128	5.864	4.952
Construction speed (m/8h)	1.491	0.036	1.616	1.364
2. In the rock there is f_{kp} = 6 ÷ 8				
Cycle time (h)	7.654	0.219	8.391	7.010
Construction speed (m/8h)	1.046	0.030	1.141	0.953

With the data in Tables 1 and 2, run the basic model [9] with the number of simulations 10,000 times, the results are shown in Table 4.

Table 4. Simulation results of cycle time and construction speed of tunneling by drilling and blasting in basic model

Content	The average value	Differrence	The greatest value	Smallest value
1. In the rock there is f_{kp}= 4 ÷ 6				
Cycle time (h)	5.218	0.129	5.704	4.783
Construction speed (m/8h)	1.534	0.037	1.673	1.402
2. In the rock there is f_{kp}= 6 ÷ 8				
Cycle time (h)	7.500	0.217	8.223	6.855
Construction speed (m/8h)	1.068	0.031	1.167	0.972

The above results show that the time of 1 construction cycle of small cross section tunnelinging (with narrow segment) is a random quantity, ranging from 5.6 hours to 6.595 hours for soil and rock with f_{kp} = 4 ÷ 6 and from 7.702 h to 8.966 h for rocks with f_{kp} = 6 ÷ 8. Compared with the actual construction time, the average construction time of construction units in rocks with f_{kp} = 4 ÷ 6 is about 5 hours and in rocks with f_{kp} = 6 ÷ 8 is about 7 hours.

In the case of running with the basic model (no narrow segmentation), the results show that the average speed in the case of soil and rock with f_{kp} = 4 ÷ 6 on average is 1.534 and in the case of rocks with f_{kp} = 6 ÷ 8 on average is 1.068 bigger than in the narrow segment model of 1.491 and 1.046, which can be explained because in the narrow segment model there is a blockage in soil transport but not in the basic model.

b) About the reasonable number of transport vehicles

Using a simulation model to analyze the construction time of tunneling by drilling and blasting when using different numbers of transport vehicles, the results are as shown in Table 5.

Table 5. Cycle time and tunneling speed with different numbers of transport vehicles

Number of trucks	**Average cycle time (h)**		**Average tunneling speed (m/8 h)**	
	In the rock f_{kp}= 4 ÷ 6	**In the rock f_{kp}= 6 ÷ 8**	**In the rock f_{kp}= 4 ÷ 6**	**In the rock f_{kp}= 6 ÷8**
1	6.137	8.422	1.304	0.950
2	5.369	7.654	1.491	1.046
3	5.340	7.623	1.499	1.050
4	5.342	7.623	1.498	1.050
5	5.340	7.623	1.499	1.050

The above results show that using 3 trucks transporting soil and rock is the most reasonable, giving the highest construction speed, when increasing the number of transport vehicles to more than 3, the speed does not increase but sometimes even decrease. This is explained by the characteristics of the small-sized tunnel that the process of transporting soil and rock must pass through narrow segments, so it is not possible to arrange too many transport vehicles.

4. Conclusion

From the research results with random factors during the completion of the construction stages, it can help the commanders of the direct construction units to analyze and consider the possibility of completion compared with the plan assigned to be able to arrange and adjust the shift and construction points accordingly.

From the results compared with the basic model, it shows that the absence of narrow segments during the transportation of soil and rock will help the construction speed be faster, so during the construction process, the construction units try to make the best use of their resources. use extension sections to limit transportation distances with narrow sections to speed up construction.

The simulation results also show that the reasonable number of vehicles transporting soil and rock in this case is 3 and the use of only 2 vehicles in the actual transportation of the construction unit in terms of construction speed is not high best. Therefore, the construction unit can rely on the simulation results to consider arranging the appropriate number of transport vehicles to both meet the construction speed and ensure the cost and also not waste vehicles due to the fact that leaving the transport vehicle inefficient operation.

References

[1] Bùi Đức Năng (chủ biên), *Giáo trình tổ chức thi công xây dựng*, Học viện KTQS, 2016.

[2] Lại Hải Đăng và Lưu Trường Văn, "Mô phỏng tiến độ thi công công trình bằng phương pháp Monte Carlo," *Tạp chí Khoa học công nghệ xây dựng (IBST),* số 2/2007, tr. 46-52.

[3] Halpin, D. W., "CYCLONE: Method for modeling of job site processes," *Journal of the Construction Division 103(CO3)*, pp. 489-499, 1977. DOI: 10.1061/JCCEAZ.0000712.

[4] Ruwanpura, J. Y., S. M. AbouRizk, K. C. Er, and S. Fernando, "Experiences in implementing simulation for utility tunnel construction," in *Annual Conference of the Canadian Society for Civil Engineering*, Canada, Montreal, Quebec, pp. 135-145, 2000.

[5] Thanh Dang, T., "*Analysis of microtunnelling construction operations using process simulation*," Dissertation, Ruhr-Universität Bochum, Bochum, Germany, 2013.

[6] Lương Đức Long, Lê Phong Vương Bảo, "Mô phỏng sự kiện rời rạc cho quá trình thi công để giảm thiểu sự lãng phí, chờ đợi và gián đoạn trong xây dựng," *Tạp chí Xây dựng*, số 10/2015, tr. 32-35.

[7] Phan Trọng Lễ, Lương Đức Long, "Nâng cao năng suất lao động bằng mô phỏng sự kiện rời rạc. Trường hợp nghiên cứu: Công tác cốp pha nhôm," *Tạp chí Xây dựng*, số 01/2019, tr. 126-134.

[8] Nguyễn Quang Nam, Bùi Đức Năng, "Dự báo tiến độ thi công kết cấu nhà bê tông cốt thép toàn khối bằng công cụ mô phỏng rời rạc," *Tạp chí Người xây dựng*, số 12/2020, tr. 37-41.

[9] Quang Nam Nguyen, Duc Nang Bui, "Forecasting construction schedule of bored pile with discrete event simulation tool," *Journal of Science and Technique - Section on Special Construction Engineering*, Le Quy Don Technical University, Vol. 04, No. 02, 2021, pp. 44-56.

[10] Nguyễn Tiến Tĩnh, Đỗ Như Tráng, Bùi Đức Năng, "Sử dụng phần mềm Ezstrobe mô phỏng quá trình đào hầm bằng phương pháp khoan nổ," *Tạp chí Địa kỹ thuật*, số 1-2021, tr. 10-17.

[11] Nguyễn Tiến Tĩnh, Đỗ Như Tráng, Bùi Đức Năng, Trần Anh Bảo, "Phân tích năng suất đào hầm theo phương án chia gương đào bằng công cụ mô phỏng rời rạc," *Tạp chí Công nghiệp mỏ*, số 3-2021, tr. 30-36.

[12] Nguyễn Tiến Tĩnh, "Sử dụng công cụ mô phỏng đánh giá ảnh hưởng của sự cố thiết bị thi công tới tốc độ đào hầm bằng khoan nổ," *Tạp chí Người Xây dựng*, ISSN 0866-8531, số 363 & 364/2022, tr. 63-66.

[13] Fahimeh Zaeri, "*Exploring the Potential for the Application of Simulation Methods in Construction Project Delivery in New Zealand*," Doctoral Thesis, School of Engineering Auckland University of Technology, New Zealand, 2017.

[14] Nguyễn Tiến Tĩnh, Bùi Đức Năng, Trần Anh Bảo, "Xây dựng mô hình xác định của quá trình thi công hầm bằng phương pháp khoan nổ," *Tạp chí Người xây dựng*, ISSN 0866-8531, số 333 & 334/2019, tr. 47-51.

[15] Nguyễn Tiến Tĩnh, "*Nghiên cứu lựa chọn phương án thi công khoan nổ đường hầm bằng mô phỏng*," Luận án tiến sĩ, Học viện KTQS, 2022.

SỬ DỤNG CÔNG CỤ MÔ PHỎNG SỰ KIỆN RỜI RẠC DỰ BÁO TỐC ĐỘ ĐÀO HẦM KHẨU ĐỘ NHỎ THI CÔNG BẰNG PHƯƠNG PHÁP KHOAN NỔ

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Tóm tắt: *Thi công đường hầm khẩu độ nhỏ có những điều kiện thi công khác biệt so với công trình ngầm khẩu độ vừa và lớn, về không gian tổ chức thi công, phương tiện và nhân công được sử dụng, đường vận chuyển trong hầm hẹp thường chỉ cho phép một xe qua. Bài báo nghiên cứu sử dụng phần mềm EZStrobe để mô phỏng quá trình thi công đào hầm khẩu độ nhỏ trong các loại đá có hệ số kiên cố (f_{kp}) khác nhau và dự báo tốc độ thi công đào hầm dựa trên việc phát triển mô hình cho phân khúc hẹp. Kết quả được so sánh với trường hợp sử dụng mô hình cơ bản không có phân khúc hẹp. Kết quả cũng chỉ ra được số lượng xe vận chuyển hợp lý nên được sử dụng.*

Từ khóa: Mô phỏng; mô hình; EZStrobe; thi công đào hầm bằng phương pháp khoan nổ; tốc độ thi công.

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