Journal of Geological Resource and Engineering 4 (2017) 188-196
doi:10.17265/2328-2193/2017.04.005

Modeling Microtunnelling Construction Operations with WebCYCLONE

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Abstract: Microtunnelling operations do not reach the highest possible productivity due to influences by different soil compositions. Hence, there is a need for a better understanding of the construction process and of those factors influencing productivity. The efficiency of MTBM (microtunnel boring machine) will be increased by that knowledge. In the paper, a flexible simulation module is developed. It helps to analyze the processes and to identify the influence of different soil compositions on the productivity of microtunnelling operations. In view of these objectives, a model describing the microtunnelling process for an actual project at the city of Recklinghausen, Germany is created by using CYCLONE methodology. Subsequently, the WebCYCLONE is applied to execute the CYCLONE model in order to get the results. It helps to analyze and identify the influence of different soil compositions on the productivity of tunnel construction with microtunnelling in the job-site.

Key words: MTBM, microtunnelling operations, WebCYCLONE; CYCLONE model.

1. Introduction

More than one thousand microtunnelling machines have been sold in the last 20 years [1]. And currently, the use of microtunnelling methods for small tunnels is growing continuously e.g. several hundred kilometers in Japan, several dozen kilometers in Germany and the UK of tunnel construction will use MTBM every year [2]. In addition, the productivity of tunnel construction with MTBM is affected by many dynamic, uncertain variables and disturbances, such as weather, space congestion, crew availability, regulatory requirements, design changes and rework. Moreover, tunnel construction with microtunnelling is a complex operation process. Therefore, if the construction process is reasonably arranged, then it can help to control and adjust the construction operation more efficiently. For this purpose, there is the need to analyze the construction process, and the factors that affect the productivity.

Simulation has been a widely used tool for the design, development, analysis and optimization of technical processes for more than 50 years [3]. In general, process simulation methodology is going to develop the simulation model representing the logic of various activities required to construct a facility, the resources involved in carrying out the work (workers, equipments, management, etc.), the technical processes and unit operations [4]. The simulation model helps to analyze causes for delay, bottlenecks and reduction of productivity during construction operations in general.

The purpose of this study is to evaluate the different soil compositions affect on the productivity of microtunnelling operations by using process simulation. The operation analysis is performed by using CYCLONE methodology [5], which is executed by helping of WebCYCLONE. The results highlight the effect of the different soil compositions on productivity.

2. Related Work

Since the development of CYCLONE, the simulation methodology has proven to be an extremely useful analysis tool and improved the performance of construction processes with many successful applications. The advantages of the

Corresponding author: Dang Trung Thanh, Dr.-Ing., research fields: geotechnical engineering, tunnel and tunnelling.

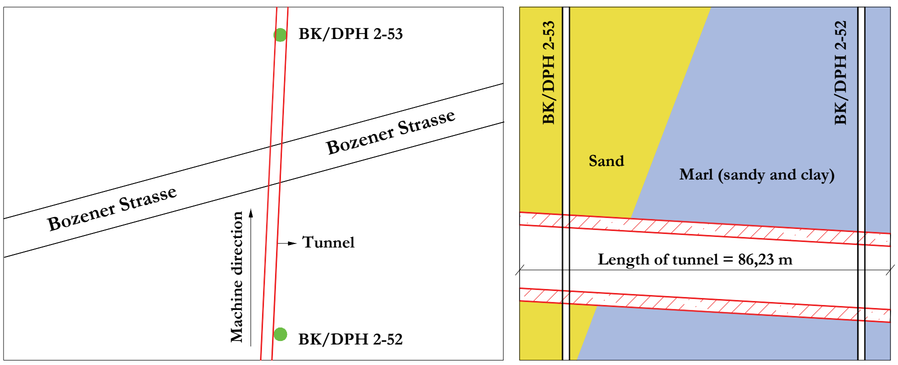
CYCLONE model are that it is well established, widely used, as well as its simplicity and the ability to effectively model many simple construction operations. Therefore, several construction processes and operations have been modeled utilizing the CYCLONE system. Cheng and Feng [6] presented an effective simulation mechanism for construction operations. They used CYCLONE with genetic algorithms with the GACOST (Genetic Algorithms with Construction Operation Simulation Tool) to find the best resource combination for the construction operation. Halpin et al. [7] represented the method of integrating CYCLONE with Web CYCLONE service. They indicated that the CYCLONE model and Web CYCLONE are concepts designed to allow users at beginners, intermediate and advanced level of simulation expertise to study and analyze construction processes using computer based simulation systems. Abduh et al. [8] attempted to improve the utilization of the simulation technique of construction operations by using the CYCLONE system. Abduh et al. also use the CYCLONE model to develop the simulation model in order to optimize the resources of earth-moving operations. Recently, Fu [9] has attempted to demonstrate the applicability of the simulation model for earth-moving operations. The author uses the CYCLONE modeling system to represent the logistics of the physical earth-moving system associated with the discrete-event simulation technique utilized to capture the interaction between the resources and the randomness of each of the activities. In addition, numerous studies have attempted to develop simulation languages based on CYCLONE e.g. MicroCYCLONE [10], COOPS [11], CIPROS [12, 13], STROBOSCOPE [14].

Due to the review of literatures discussed above, the CYCLONE methodology has many contributions. Therefore, the use of CYCLONE in order to analyze the tunnel construction with MTBM is presented in this study. In order to analyze the operation of microtunnelling, a simulation module using the CYCLONE methodology combined with the WebCYCLONE will be developed. The simulation module will be applied to analyze the processes and identify the productivity of the job-site.

3. Project Description

3.1 Project Location

For this study, data were collected on the project BV Recklinghausen V.15, located in Recklinghausen City, Germany. The tunnel went across the "Bozener Strasse" road. The total length of the tunnel in project BV Recklinghausen V.15 was ca. 86.23 meters. The first approx. 50 meters long drive went completely through marl with sand and clay. The last approx. 35 meters of the tunnel went through sand such as shown in Fig. 1. The depth to the axis was about 7.3 meters, grade 1.3‰ and the pipe size was 1.0 meters internal diameter, 1.46 meters external diameter, 4.02 meters length.



(a) Site plan (b) Simplified long section

Fig. 1 Details of BV Recklinghausen V.15.

3.2 Geotechnical Conditions

Two boreholes were put down along the centre line of the tunnels. The first borehole BK/BPH 2-52 and the second borehole BK/BPH 2-53 were put down at the beginning and the end of the tunnel to depths of 12.0 meters and 11.5 meters, respectively. According to the analysis from two boreholes at the job-site it could be concluded that: the tunnel of project BV Recklinghausen V.15 will encounter two types of soil conditions, which are sand and marl. The discussion was carried out with the manager of the project as well. Based on the information achieved, the first ca. 50 meters of the tunnel encountered the soil conditions which were clayey, marl and cohesive soil. The 30 meters before the end of the tunnel, the soil condition is sand and gravel.

3.3 Equipment

The project BV Recklinghausen V.15 was carried out by MTBM AVN 1200C using hydraulic spoil removal. The characteristic of the machine AVN 1200C is that it uses almost the same operating principle as MTBM. For details of small tunnel construction using microtunnelling theory, the book of Stein [15] and French Society for Trenchless Technology [2] is recommended for further reading.

3.4 Construction Sequences

The basic principles of microtunnelling in job-site are similar to other kinds of TBMs. The fundamental principle of the tunnel construction with MTBM is briefly as follows Stein [15] and French Society for Trenchless Technology [2]. Based on principles of microtunnelling, the sequential concept of microtunnelling is schematically illustrated in Fig. 2. As shown in Fig. 2, the microtunnelling method includes 6 activity steps, which can be summarized as follows:

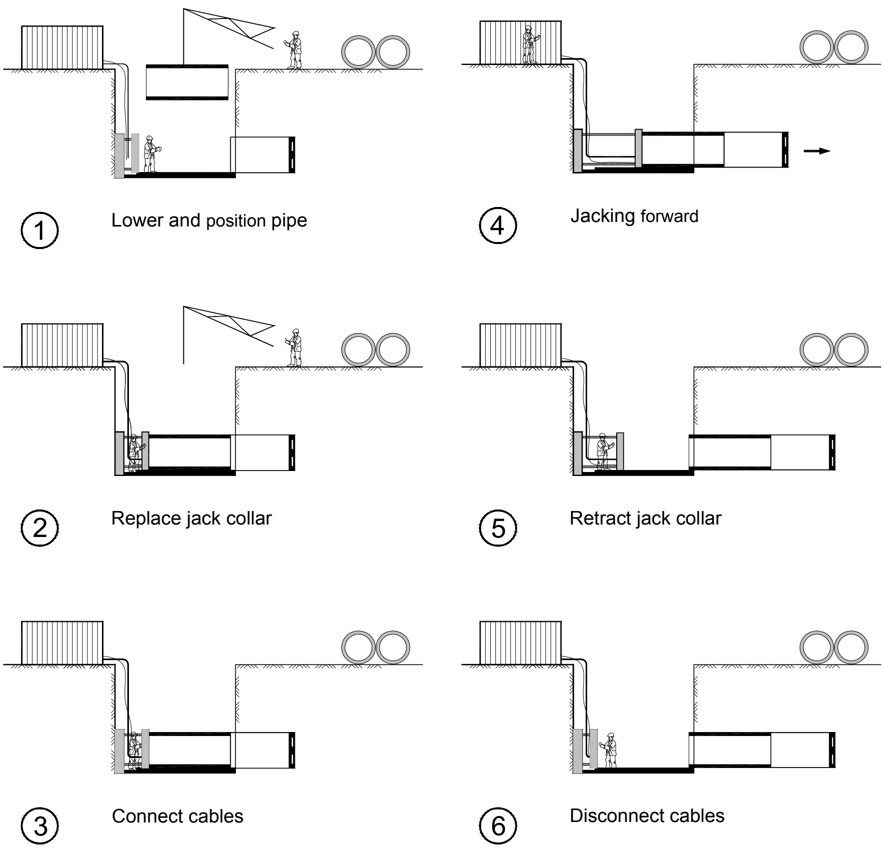


Fig. 2 Microtunnelling construction sequence (Dang 2013) [6].

Step 1—Lower pipe: represents all activities required to prepare the jacking system for pipe section placement, lower pipe section to the jacking frame, place the pipe on the launch skid;

Step 2—Replace jacking collar: accounts for the entire activities involved for the jacking collar replace and re-engage the jacking system;

Step 3—Connect cables and pipelines: represents all activities related to connect cables and pipelines;

Step 4—Jacking forward: represents the entire activities involved in the pipe driving operation which actually advances the tunnel. Also consideration for all activities related to handling and separating the materials spoil, which is transported from the working face of the tunnel to the separation plant;

Step 5—Retract jack collar: represents all activities required to retract the jack collar of the jacking system;

Step 6—Disconnect cables: represents the entire activities required to disconnect cables and reset the equipment for another cycle.

3.5 The Resources Required in Microtunnelling

An overview of the required basic equipment and resources for microtunnelling with hydraulic spoil removal is listed in Table 1.

The most main resources have been identified in this study as the following Stein [15]:

(1) The microtunnelling machine with boring and steering head as well as trailing shield segment;

(2) The separation plant when using a bentonite suspension or settling tank when using water as a pressure balancing and transport fluid;

(3) The control panel (or control container) with steering desk and hydraulic power plant when using a diesel-hydraulic drive for the jacking plant (a power generator is also required when using electric-hydraulic drive);

(4) The jacking station system (or main jacking station system) consisting of jacking frame, jacking cylinder and thrust ring;

(5) The lubrication mixture system for mixing the lubricant for lubricating the pipe string;

(6) The pump system including discharge pump, charge pump and the injection pump.

The other resources have also been identified, but they are considered as secondary resources. These involve construction equipment e.g. loader, crane, navigation system, cables, hoses, etc.

In tunnel construction operations with MTBM, three different classifications of the labor crew are normally required as follows:

(1) The second crew is named Crew 1 and defined as two laborers working on the surface. A worker is responsible for the mixing of the lubricant fluid, rigging the pipe section and preparing the pipe section before jacking pipe section forward. Another worker can be defined as one operator who is involved in the task of job management and also operates the entire equipment in the job-site e.g. control container, loader, crane;

The last crew is named Crew 2 defined as three labors working in the shaft. Crew 2 is involved in helping to replace the jack collar and to connect or disconnect cables or hoses.

Table 1 Resources considered in simulation of MTBM.

Equipment	Crew	Materials
MTBM Separation plant	Crew 1—working on the surface	Pipe sections Slurry
Control container Jacking station	Crew 2—working in shaft	MTBM energy use
Lubrication mixture Pump system	Operator	Water

3.6 Project Site Layout

Due to the location of the project in an urban area, the working place was constrained. The position of the construction site was easily accessible. The device site layout is considered a critical factor defining simulation module, due to the fact that it reflects the resource cycle patterns of the project. Project site layout provides adequate space for the microtunnelling operation, ease of material delivery, and the equipment arranged reasonably to minimize any waste of time of the resources cycle. In order to generalize the site layout for the simulation module, the site layout of microtunnelling project is redrawn based on job-site (shown in Fig. 3).

4. Simulation Approach

4.1 Cyclone Methodology

For the analysis of the microtunnelling operation on the project BV Recklinghausen V.15, a PC based simulation program that is based on the CYCLONE methodology is used for modeling and simulation of the process. The CYCLONE (CYCLic Operations NEtwork) method is the oldest one and helps to make process simulation methodology popular. It is a modeling technique that allows the graphical elements (e.g. queue, normal, and combined nodes in CYCLONE) representation and simulation of discrete systems that deals with deterministic or stochastic variables. The basic modeling elements used in CYCLONE are presented in Table 2 which consists of two active elements (COMBI and NORMAL) and four idle elements (QUEUE, FUNTION, ARROW and COUNTER).

The actuality of the CYCLONE model will depend on the identification and definition of two common resource flow patterns (NORMAL and COMBI) together with the associated QUEUE nodes, arrow, and logical relationships. In the CYCLONE system only elements that are logically dependent are the QUEUE node and COMBI processor. A COMBI professor can be preceded only by a QUEUE node and, conversely, the only element that can follow a QUEUE node is a COMBI processor. The reader is referred to Daniel W. Halpin [16] book for a more detailed description of the CYCLONE methodology.

4.2 Resource Cycles

In this article, the author uses the CYCLONE methodology to formally describe the resource cycle

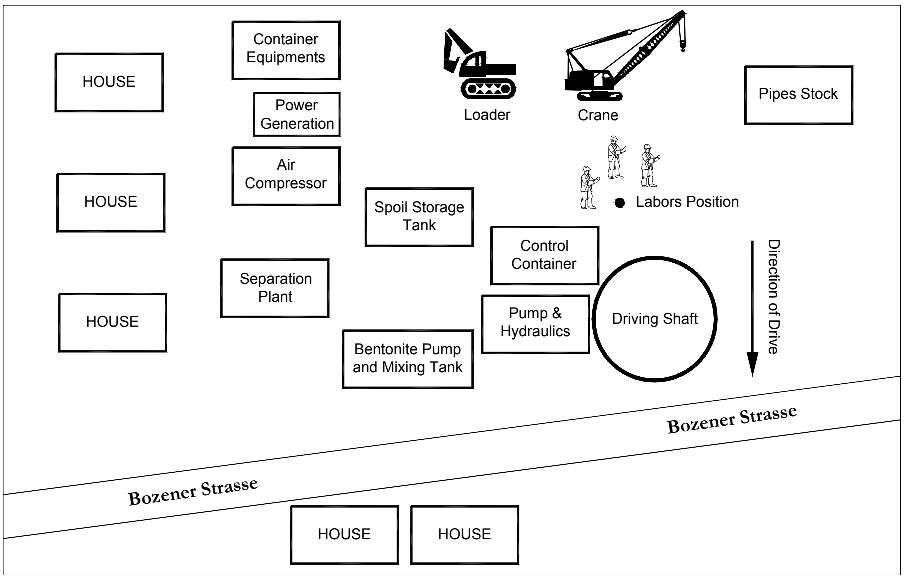
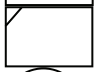
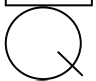
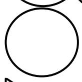
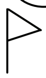


Fig. 3 Site layout of the observed operation.

Table 2 CYCLONE system modeling elements.

Name	Symbol	Function
Normal activity		Units arriving at Normal will be processed right away without delaying.
Combination activity (COMBI)		Unit arriving at COMBI will be processed if units are available in all preceding Queue node
Queue node		Queue provides positions that allow units are delayed pending COMBI activities
FUNCTION Element		Consolidate function node performs the consolidate marking
Counter		Counter measures the modeled system's production rate
Arrow		Arcs show the logic that units flow from element to element.

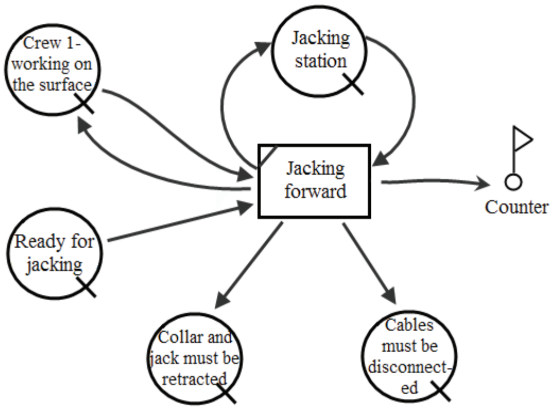


Fig. 4 Resource cycle for jacking forward.

for the following main construction activities such as mentioned in the Section 3.4: Lower and position pipe; Replace jack collar; Connect cables; Jacking forward; Retract jack collar and Disconnect cables. Each activity should be developed separately. The following is a description of the jacking forward, which is the main activity component of the microtunnelling operation.

The jacking station is leading resource, its cycle is shown in Fig. 4. After a pipe is lowered and in position, jack collar is replaced; cables are connected then operator is steering the jacking process, the jacking station "jacks" or pushes the pipe. After the jacking takes place then the slurry and hydraulic lines are disconnected. The collar and jacks must be retracted once again ready to begin another cycle. The jacking system consists of: the jacking frame, one worker is always inside the shaft cleaning and observing the jacks, the MTBM and its operator who also controls the jacks and separation plant.

4.3 Cyclone Model

The Cyclone Model is the integration of the independent resource cycles. When all of the flow unit cycles have been identified, they can be integrated for development of the comprehensive process model. See Fig. 5 for the complete CYCLONE model. In order to perform the simulation, the duration information of six activities at the job-site must be collected. The duration information for various activities is shown in Table 3.

5. Simulation Results

5.1 Validation of Simulation Results

Before using the CYCLONE simulation module, the module must be demonstrated to achieve simulation module credibility. The use of the validation process is to gain the credibility. Therefore, in order to demonstrate the CYCLONE module credibility, the validation processes are applied in this study.

In order to validate, a total of 1,500 simulations were executed with the CYCLONE simulation module for the soils encountered in project. Table 4 shows the productivities obtained from these simulations. A comparison could be easily received from these simulations. Such as the results mentioned above, Table 4 shows that the productivities between data from job-site and the output data are quite similar. When the soil condition was clayey, marl and cohesive,

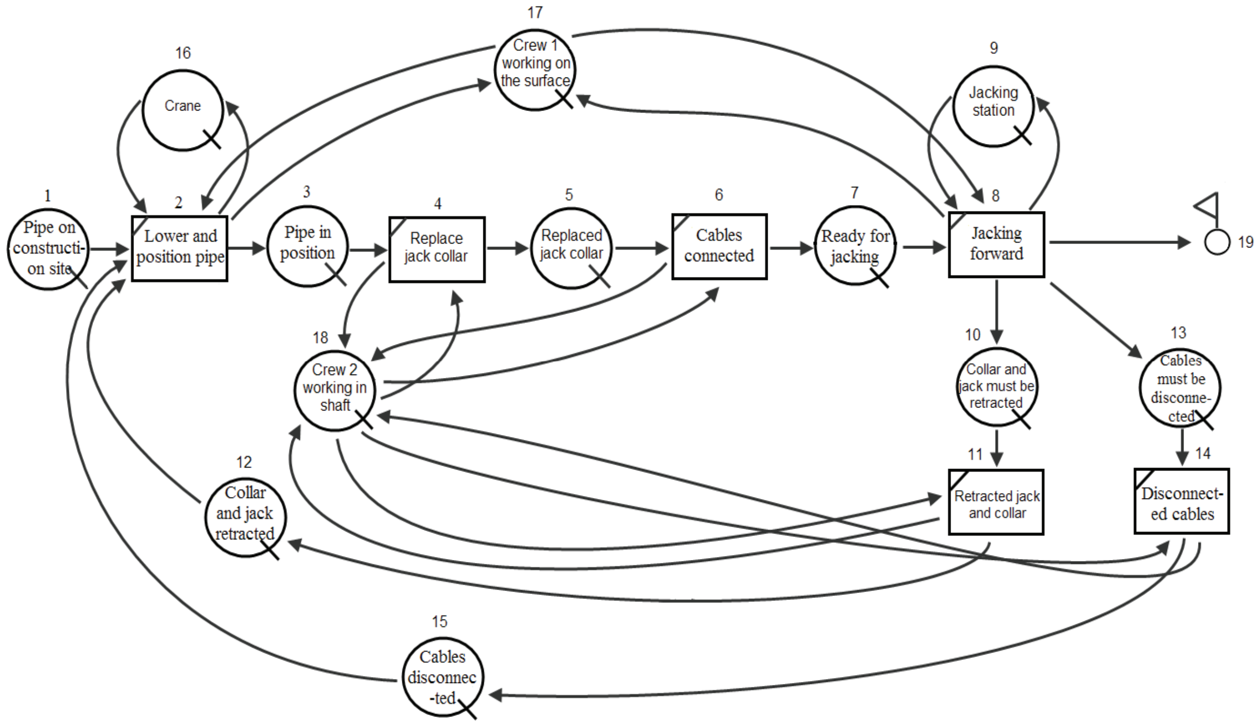


Fig. 5 CYCLONE model for the observed operation.

Table 3 Duration information.

Activity number	Activity	Minimum value (min)	Mode value (min)	Maximum value (min)
1	Lower and position pipe	4.15	5.4	7.05
2	Replace jack collar	0.57	1.10	1.20
3	Cables connected	15.51	17.40	19.20
4	Jacking forward	234.23[a] 83.45[b]	280.0[a] 124.0[b]	336.32[a] 138.34[b]
5	Retracted jack collar	1.20	1.35	1.50
6	Cables disconnected	11.23	11.59	13.12

[a]: Jacking forward for Clay, marl & cohesive soil;
[b]: Jacking forward for Sand and Gravel.

Table 4 Comparison of productivity between data from job-site and simulated in project BV Recklinghausen V.15.

Type of soil	Cycle No.	Prod. for one pipe (simulated)	Prod. for one pipe (job-site)
Clayey, marl and cohesive	750	320.82 min	316.84 min
Sand and gravel	750	152.54 min	160.84 min

the average productivity from job-site for installing one 4.020 m pipe section was 316.84 min, the average simulated duration from 750 cycles is 320.82 min, which means that 1.26% are higher than the average productivity obtained in the job-site. When the soil condition was sand and gravel, the average productivity from job-site for one pipe section was 160.84 min, the average simulated duration from 750 cycles is 152.54 min that means that 5.44% are lower than the average productivity obtained in the job-site. Based on the analysis of results it could be concluded that: the CYCLONE model is clearly in a reasonable range of a typical microtunnelling project.

5.2 Analysis of Simulation Results

The use of CYCLONE model to analyze the effect of different soil compositions on the productivity of MTBMs is studied next.

Fig. 6 shows the productivity and the operation time of the MTBM in the case that the soil encountered at the construction site is clayey, marl and cohesive. The fastest, average and longest durations are 270.60, 320.82 and 372.90 min per 4.020 m of tunnel, respectively. The percentage of working time and waiting time of the MTBM is 11.74% and 88.26%.

Fig. 7 shows the probability of production cycle duration in minutes for the case of clayey, marl and cohesive, the fastest time of 270 to 309 min, average duration of 310 to 349 min, and longest productivity of 350 to 390 min correspond to a probability of around 31.1%, 58.1% and 10.8%, respectively.

Fig. 8 shows the productivity and the operation time of the MTBM in the case that the soil encountered at the construction site is sand and gravel. The fastest, average and longest durations are 118.80, 177.40 and 152.54 min per 4.020 m of tunnel, respectively. The percentage of working time and waiting time of the MTBM is 24.55% and 75.45%.

Fig. 9 shows the probability of production cycle duration in minutes for the case of sand and gravel, the fastest time of 110 to 150 min, average duration of 151 to 170 min, and longest productivity of 171 to 190 min correspond to a probability of around 38.1%, 54.5% and 7.3%, respectively. For all cases mentioned above, the disturbances are not considered, the resources are always available, and the equipment is not maintained during construction.

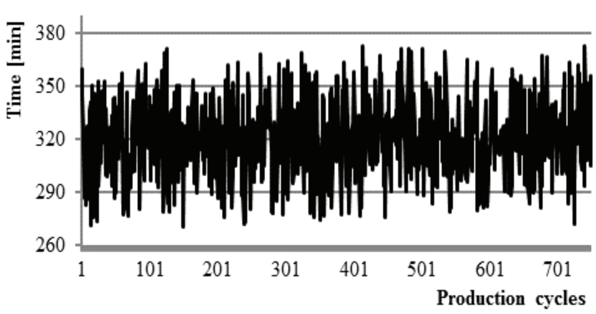


Fig. 6 Simulation cycle durations with clay, marl and cohesive soil.

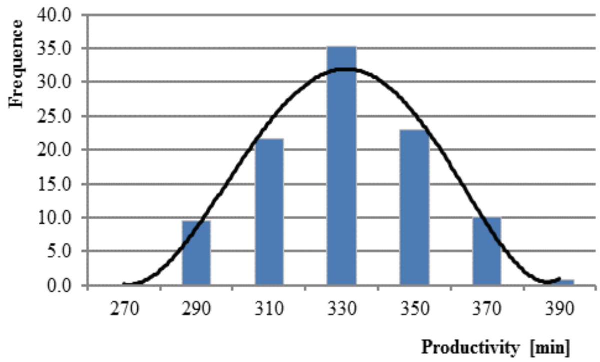


Fig. 7 Cumulative distribution of productivity with clay, marl and cohesive soil.

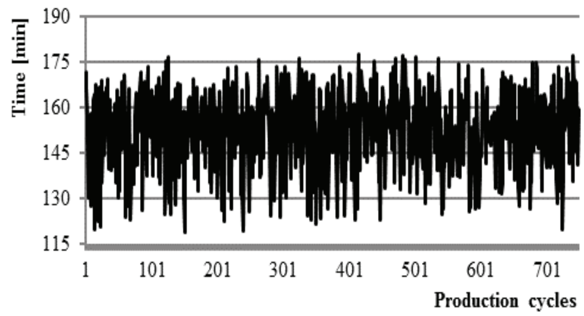


Fig. 8 Simulation cycle durations with sand and gravel.

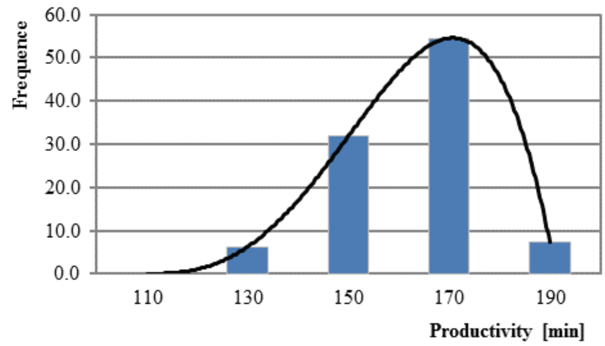


Fig. 9 Cumulative distribution of productivity with sand and gravel.

6. Conclusions

In this paper, the analysis of production performances influenced by different soil compositions in the project BV Recklinghausen V.15 of microtunnelling using CYCLONE method and executing based on WebCYCLONE is described. In the research, an appropriate and adaptable simulation model for an actual project in the city of Recklinghausen based on CYCLONE methodology was developed. The CYCLONE model was used to conduct on the cycle of the microtunnelling process, including pipe segments preparation to pipe section jacked in place. The CYCLONE model provides managers and engineers with information on the effect of different soil compositions on the advance rate.

In near future studies, the CYCLONE simulation model can be expanded to include sub-models to estimate the effect of the disturbances to productivity, the time, cost of tunnel construction with MTBM. In addition, the simulation module can also be upgraded with different types of MTBMs, projects, such as tunnel construction with auger spoil removal or pneumatic spoil removal.

Acknowledgments

The author gratefully acknowledges the financial support received for this research from the Ministry of Education and Training of Vietnam under Grant No. B2016-MDA-09ĐT.

References

[1] Herrenknecht, A. G. 2017. "The Information from the Company Herrenknecht AG." Accessed on June 19, 2017. http://www.herrenknecht.de/aktuelles/presse/pressearchiv/2005/.

[2] French Society for Trenchless Technology. 2004. *Microtunneling and Horizontal Drilling: Recommendations*. John Wiley & Sons.

[3] Jeffrey, S. S. 2003. "Survey on the Use of Simulation for Manufactoring System Design and Operation." *Journal of Manufacturing Systems* 22 (2): 157-71.

[4] AbouRizk, S. 2010. "Role of Simulation in Construction Engineering and Management." *Journal of Construction Engineering and Management* 136 (10): 1140-53.

[5] Purdue CEM Web-Cyclone Simulation Lab. Accessed November 12th, 2017. https://tomcat.itap.purdue.edu/WebCYCLONE/Cyclone.jsp.

[6] Cheng, T., and Feng, C. 2003. "An Effective Simulation Mechanism for Construction Operations." *Automation in Construction* 12 (3): 227-44.

[7] Halpin, D. W., Jen, H., and Kim, J. 2003. "A Construction Process Simulation Web Service." In *Proceedings of the Winter Simulation Conference*, Volume 2, New Orleans, LA, pp. 1503-9.

[8] Abduh, M., Shanti, F., and Pratama, A. 2010. "Simulation of Construction Operation: Search for a Practical and Effective Simulation System for Construction Practitioners." In P*roceedings of the first Makassar International Conference on Civil Engineering*, Makassar, South Sulawesi, Indonesia, 1311-9.

[9] Fu, J. 2012. "A Microscopic Simulation Model for Earthmoving Operations." *World Academic of Science, Engineering and Technology* (67): 218-23.

[10] Halpin, D. W. 1990. *MicroCYCLONE User's Manual*. Div. of Civil Construction Engineering and Management, Purdue University, West Lafayette, Ind.

[11] Liu, L. Y., and Ioannou, P. G. 1992. "Graphical Object-Oriented Discrete Event Simulation System." In *Proceedings of the 24th Conference on Winter Simulation, Association for Computing Machinery*, New York, USA, pp. 1285-91. ISBN: 0-7803-0798-4.

[12] Odeh, A. M., Tommelein. I. D., and Carr R. I. 1992. "Knowledge Based Simulation Construction Plans." In *Proceedings of the 8th Conference on Computing in Civil Engineering*, Volume 7, ASCE, New York, USA, pp. 1042-9.

[13] Tommelein, I. D., Carr, R. I., and Odeh, A. M. 1994. "Assemply of Simulation Networks Using Design, Plans, and Methods." *Journal of Construction Engineering and Management* 120 (4): 796-815.

[14] Martinez, J. C. 1996. "STROBOSCOPE-State and Resource Based Simulation of Construction Process." Ph. D. thesis, The University of Michigan.

[15] Stein, D. 2005. *Trenchless Technology for Installation of Cables and Pipelines*. Bochum, Germany. ISBN 3-00-014955-4.

[16] Halpin, D. W. 1992. *Planning and Analysis of Construction Operations*. Wiley-Interscience.