Exploring Critical Factors Affecting upon Micro-tunnelling Equipment Productivity

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Abstract: The need to provide utility service lines with less disruption to the ground surface has increased the demand for trenchless excavation methods like micro-tunneling. The micro-tunneling has become a mainstream trenchless technique in Australasia. Ten years ago it was mainly used where no other feasible options existed, with open-cut generally being preferred as the lower cost and risk option. To those in the industry the motivation for micro-tunneling over open-cut techniques were always compelling. Some of these major drivers are increasing emphasis on minimizing traffic disruption, minimizing subsidence, avoiding relocation of existing services and personnel safety. As the number of successfully completed projects increased, so also confidence in the micro-tunneling as mainstream technique grew. Importantly, Council and Consulting Engineers in general have become increasingly knowledgeable and confident in treating micro-tunneling as a mainstream technique in their arsenal of solutions. A questionnaire was sent to micro-tunneling experts to study the factors affecting on micro-tunneling equipment productivity and their ranked importance. The participants are contractors, engineers, and manufacturers in the United Arab Emirates. This paper presents the results of analyzing the responses of the experts in the micro-tunneling industry. This research builds up the basics for modeling the micro-tunneling productivity of micro-tunneling projects. It will also help micro-tunneling contractors to identify the most affecting factors on micro-tunneling productivity and then building productivity models.

Keywords: Micro-tunneling; Productivity; Construction; Questionnaire; Trenchless technology.

I. Introduction

The need for utility service lines with less disruption to the surface increased the demand for trenchless excavation methods like micro-tunneling. Micro-tunneling is a term most often applied to remotely controlled pipe jacking techniques. The definition of micro-tunneling is slightly different in Europe, Japan, and United States. Europe and Japan define any pipe jacking machine as a micro-tunneling machine based on its size. In Japan, any size below 800 mm is a micro-tunneling while in Europe the margin is 1,000 mm [Thomson 1993; International Society of Trenchless Technology (ISTT) 1999]. American contractors consider any remotely controlled guided pipe jacking machine as a micro-tunneling machine (Salem and Hegab 2001). The micro-tunneling technique can be applied in different projects such as gravity and pressure lines, permanent ducts for cables, and crossings under railways or roads.
The first micro-tunneling machine was developed in Japan in 1972 by Komatsu and the first job was completed in 1974. Micro-tunneling spread slowly but gained popularity in Europe specifically in Germany and the United Kingdom starting in 1981 and 1984, respectively (Thomson 1993). The literature shows that micro-tunneling has become a mainstream trenchless technique in Australasia, Micro-tunneling started in the United States around 1984 and since that time, rapid growth in micro-tunneling use has been recorded (Atalah and Hadala 1996). Rapid growth of micro-tunneling is expected in urban areas because of the high benefit-cost ratio of micro-tunneling compared to open cut methods. Compared to open cut methods, micro-tunneling has better traffic control, lower reinstatement costs, less need to dig around existing utilities, and lower social cost. The low social cost results from the fact that micro-tunneling reduce traffic delay time and disruption of commercial activities (McKim 1997).

II. Review of Literature

Micro-tunneling is a trenchless technique that is used in installation of new pipelines. Micro-tunneling can be applied in gravity and pressure lines, permanent ducts for cables, and crossings under rails or roads. When bidding a micro-tunneling project, the main concern of micro-tunneling contractors is predicting the underground behavior of the machine. In other words, the micro-tunneling productivity is the key for profit in micro-tunneling projects. Contractors use their own experience in predicting approximate productivity, which risks cost estimation accuracy for micro-tunneling projects (M.Hegab 2007), The North American Society of Trenchless Technology (NASTT) defined trenchless construction as "a family of methods, materials, and equipment capable of being used for the installation of new or replacement or rehabilitation of existing underground infrastructure with minimal disruption to surface traffic, business, and other activities". Trenchless Technology (TT) has created new materials, methods and equipment for underground infrastructure rehabilitation and new installation methods. TT is a qualified alternative to replace the open trench method for underground constructions. It is applied to minimize environmental and social negative impact in addition to reducing the cost of underground works. It also provides cost effective infrastructure asset management. Contrary to open trench methodology, which causes major disturbances to surface activities, TT has minimal or no effect on earth surface. The TT family is divided into two main categories; construction and non construction methods as shown in Figure (II. 1). Wilkinson (1999) stated the following negative social impacts of the open-trench pipe construction:

• Vehicular/pedestrian traffic: Often, roadways and sidewalks will be removed from daily use in order to place pipes beneath them.

• Worker safety: Trench safety is a major concern for contractors when performing open-trench construction.

• Interruption of local businesses: Local businesses are likely to lose customers due to resulting traffic disruptions associated with open-trench pipe construction. Residential: Major inconvenience, congestion, and delays are often imposed on neighborhoods and their residents due to open-trench pipe construction nearby.

• The increased number of pavement joints at patched surfaces increases maintenance resulting in additional traffic impacts and higher life-cycle costs.

• Existing utilities: During open-trench construction, existing utilities near the trench are often damaged during the trench excavation and from subsequent soil settlement.
• Soil disposal: Contaminated soil is sometimes encountered during pipe construction.

• Air pollution: Fine soil particles may become airborne, which can blow these fine soil particles from soil stockpiles created during the open-trench excavation.

• Water pollution: Water (rain or subsurface pumping discharge) can cause soil erosion and solids may runoff into streams, rivers, and storm sewers.

• Roadways: Open-trench construction often requires sawing, demolition, or removal of pavements followed by subsequent restoration. This significantly reduces pavement life by up to 40% (Stahli and Hermanson, 1996).

• Noise: Open-trench excavation requires the use of heavy equipment that produces levels of noise that cause disturbances to hospital, schools, business, and residences.
• Land defacement: Open-trench pipe construction frequently causes damage and can have adverse short-term effects on grass, trees, and other landscaping features.

• The no dig emerging TT eliminates the need of digging up roads or pathways for sewer, water, telecommunication and gas pipe installation, replacement or rehabilitation. Accordingly, trenchless technology allows for the reparation of pipes without having to excavate along the road section, thereby minimizing or eliminating traffic problems and save on road repair costs.
Eighty-seven municipalities in Canada have participated in a survey to provide an indication of current and future trends in the application of trenchless construction technologies in the municipal field (Ariaratnam et al, 1999). The survey concerned the percentage of projects that employed trenchless technology, frequency and type of technologies employed and contractor selection methods. The municipalities were asked to rank the technologies that had the highest possibility for future development. The results showed that for new construction techniques, the greatest potential growth was in horizontal directional drilling (HDD) followed by pipe bursting, auger boring, **micro-tunneling (MT)**, and pipe jacking.

Table II. 1 shows the summary of main advantages and disadvantages of the most commonly used TT techniques.

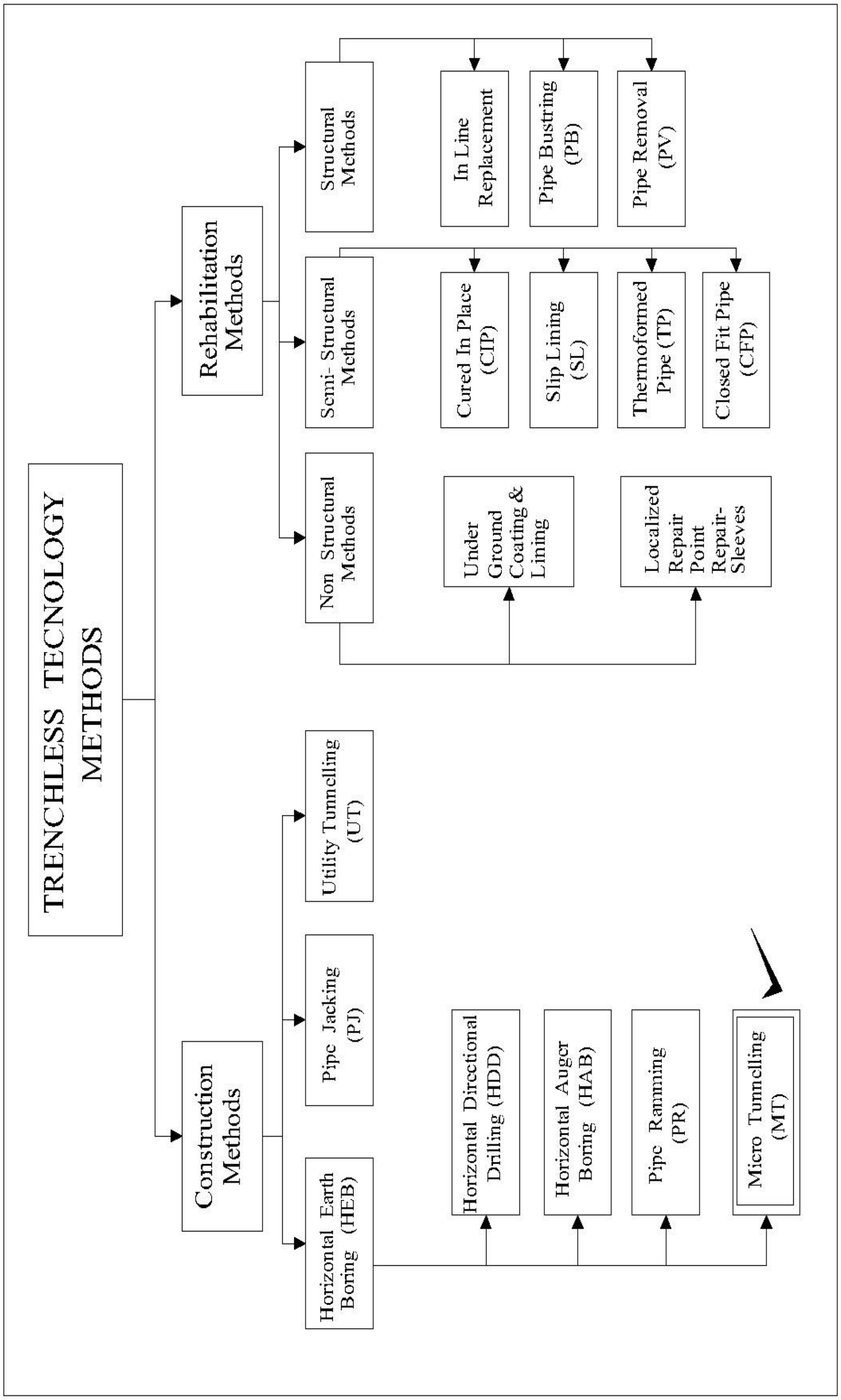


Figure II.1 Trenchless Technology (TT) Methods (Najafi,2005)

Table II.1 Advantages and Limitations of Trenchless Technology (TT) Methods (Najafi, 2005)

TT Method	Advantages	Limitations
Horizontal Auger Boring	▪ Casing is installed as the borehole excavation takes place, and can be used in wide variety of soil types.	▪ Not successful in sands and unstable soils; requires dewatering under water table and needs initial setup.
Horizontal Directional Drilling	▪ Pipeline installation without serious incidents of hydro-fracture and the alignment can be maintained within acceptable limits. ▪ Large drilling equipment could be precisely located in underground operations with sophisticated tracking systems like GPS and GPR.	▪ Specific geotechnical investigation ▪ Accurate Planning and selection of suitable equipment and preparation of a proper work area is required ▪ Experience and qualifications of the contractor ▪ Three stages and equipment encumbrance difficult to launch in some downtown area.
Pipe Ramming	▪ Applicable to a wide variety of pipe lengths and sizes; can be used for driving vertical piles.	▪ No control over line and grade during ramming and it is a very noisy application.
Pipe Jacking	▪ Used in all types of soils ▪ High degree of accuracy obtained, and correction action is taken immediately ▪ Rapidly manually and electronically inspected ▪ Unforeseen obstacles identified and removed.	▪ Requires a lot of planning and coordination ▪ Pipes and liners should be strong enough to resist jacking forces
Pipe Bursting	▪ Applied to non-ductile types of pipes ▪ Ability to upsize the existing diameter by about 30% ▪ One pass for application, thus reduce cost of labor and time needed for replacement. ▪ Cleaning of host pipes not required	▪ Pipes used to replace the old pipes are HDPE ▪ All lateral services and fire hydrants connected to the host pipe main must be excavated and uncovered. ▪ Pulling force must be less than the new pipe tensile strength and that the outer diameter of the new pipe will not be damaged by the fragments of the host pipe. ▪ Any underground utility close to the host main must be excavated and exposed to avoid any damage to the bursting force.
Underground Coatings and Linings	▪ Minimal excavation space ▪ Can accommodate a variety of diameters ▪ Improves hydraulic characteristics, ▪ Services connections do not have to be excavated	▪ Pipe must be structurally sound, cleaned and dried, ▪ Services must be cleaned ▪ Minor reduction in internal diameter. ▪ Limit on bends less than 45 degrees

Table II.1 Advantages and Limitations of Trenchless Technology (TT) Methods (Najafi, 2005) (Continued)

TT Method	Advantages	Limitations
Cured-In-Place Pipelining	▪ Both structural and non-structural purpose, and without excavation or a little excavation ▪ Fast and simple way to install large pipe diameters ▪ Accommodating bends and deformation of pipes (ex: gaps, holes and cracks) ▪ Grouting required only at manhole and lateral openings if required with high corrosion resistant ▪ Minimal impact on neighborhood	▪ Cannot increase the diameter of the host pipe, and the old pipe alignment may result in structural problems. ▪ The curing process may create styrene, therefore the curing water must be removed from the job site. ▪ Safety measures related to hot water and steam must be considered. ▪ Every project needs different tubes or hoses which may not be available ▪ Bypassing of the existing flow is mandatory during the installation process. ▪ Cost-effective depending on situation.
Slip-Lining	▪ Does not require investment in costly specialized equipment; Simple technique ▪ Jacking pipes and fittings can also be used for SL ▪ Can be used for structural and non-structural purposes	▪ Reduction of pipe diameter ▪ Pit excavation is required for access during installation process ▪ For lateral connections, open-cut excavation is required. ▪ Grouting is generally required.
Thermoformed Pipe	▪ Installation process is faster since the pipe is manufactured at factory (efficient QA) ▪ No impact on the environment, since no use of chemicals. ▪ Reduction of the cross section of existing pipe is minimal. ▪ Can solve the corrosion problem of pipeline.	▪ Large working space is needed for Fused and expanded type. ▪ Diameter range availability is limited. ▪ Large working space is needed for Fused and expanded type. ▪ During the installation Bypassing of flow is required ▪ The location of valves and connections needed to be excavated.
Close Fit Pipe	▪ Efficient QA since the pipe is manufactured in factory ▪ Reduction in existing pipe diameter is minimal ▪ Solution for corrosion and water quality problems ▪ Can be installed up to 1000' and can accommodate 45 degree bends ▪ Possibility for internal lateral connections.	▪ Diameter range availability and installation length is limited. ▪ Large working space is needed for fused and expanded types. ▪ Bypassing of flow is required ▪ Services needed to be excavated. ▪ An insertion pit is required.

III. Paper Objectives

This research intends to analyze and explore all factors that affect on MT construction equipment productivity taking into account both practical and academic concerns. This research builds up the basics for modeling the micro-tunneling productivity of related projects. It will help micro-tunneling contractors to identify the most affecting factors on micro-tunneling productivity and then building productivity models. Contractors, consultants and infrastructure professionals worldwide might find benefit from this study.

IV. Factors Affecting Productivity

Based on the literature review and Telephone Calls, 22 factors were identified and listed in the questionnaire, which was conducted to validate suggested factors gave the participants the opportunity to add or delete factors (by selecting “1” out of the 1–5 scale).
Furthermore, the questionnaire asked the respondents to rank the importance of each factor. The score for each factor was obtained by taking the average score of responses for each factor. Table IV-1 shows the factors affecting micro-tunneling productivity.

Table IV-1. Proposed Micro-tunneling Productivity Factors:

Factor number	Factors affecting productivity.
1	Cutter head shape
2	Crew/operator experience
3	Soil conditions
4	Drive length
5	Separation equipment
6	Pipe section length
7	Shaft design _size, layout, structural integrity_
8	Slurry flow rate
9	Pipe material
10	Use of IJS
11	Use of high pressure water jets at the excavation faces (jetting).
12	Accurate geotechnical investigations
13	Depth of installation
14	Groundwater conditions
15	Appropriateness of the MTBM
16	Obstruction or unusual soil conditions
17	Restrictions to working hours
18	Straight versus curved alignment
19	Technical support
20	Use of lubrication
21	Thrust Jacking
22	Torque

IV-1. Management Conditions

i- Crew and Operator Skills

The experience of the crew and operator might have a direct impact on the preparation time and finishing time of pipe installation (Hegab, 2003). Skilled operators finish the job faster, avoid losing the connection with pipes and maintain the right pipe track, (Dubey et al., 2006). Therefore, crew experience, harmony and understanding can directly affect project productivity.

ii- (M / T) Type.

A number of micro-tunneling techniques have been used for constructing sewer pipelines, each of which has its relevant advantages and disadvantages depending on the site-specific environment and conditions. Experiences obtained from many different unsuccessful tunneling and micro-tunneling projects all over the world illustrated that selecting the most appropriate construction technique is not an easy task.

iii- Restrictions to Working Hours

Daily working hours have a direct effect on productivity.

iv- Straight versus curved alignment

The major difficulty during pipe jacking is that the entire tunnel is constantly in motion and therefore, not possible to mark stationary points in sections of the pipe conduit which have already been advanced in order to refer to them at a later point in time.

IV-2. Mechanical Conditions

i- ***Cutter head shape Efficiency***

Cutter head: a rotating tool or system of tools that excavates at the face of the micro-tunneling bore.
Cutter shape: the actual teeth and supporting structure that is attached to the front face of the micro-tunneling machine. It is used to reduce the material that is being drilled or bored to sand or loose dirt so that it can be conveyed out of the hole.

ii- Separation equipment

A plant that has a set of equipment (such as shakers, hydrocyclones, and cones) where excavated material is separated from the circulation slurry

iii- Slurry flow rate

Slurry is used during the MT penetration drilling and removal of excavation material. The slurry minimizes the friction between the soil and the drilling head/installed pipe. In addition, it carries the muck out of the drilling hole. Moreover, the slurry acts as a lubricant for the pipe that facilitates its insertion and being laid in its place, and support the annular space around the pipe to prevent earth settlements

iv- Intermediate jacking station (IJS)

A fabricated steel cylinder fitted with hydraulic jacks, which is incorporated into a pipeline between two pipe segments. Its function is to distribute the jacking load over the pipe string on long drives.

v- Use of high pressure water jets at the excavation faces (jetting).

A process using high pressure water to wash out the face of a utility crossing without any mechanical or hand excavation of the soils in the face This process can be used to loosen hard soils in front face of the micro-tunneling machine.

vi- Use of lubrication

Injection of lubricants around the pipeline during

vii- Torque.

The rotary force available at the drive chuck

IV-3. Environmental Conditions.

i- Soil conditions & Accurate geotechnical investigations

The quality and quantity of the available geological information during the design and bidding phase is very important in estimating the production rates, shaft design and maximum drive length for any construction method (Allouche *et al.*, 2001). Geotechnical investigations are used to define the existing soil types and conditions to enable the contractor to make the best arrangement for the MT machine and to choose the most suitable equipment for maximum productivity.

ii- Groundwater conditions

The level of groundwater has little effect on equipment performance ratio. When the depth of ground water increases, the equipment performance ratio increases but with a small rate

iii- Obstruction or unusual soil conditions

Unforeseen ground conditions represent major challenge to the MT machine.

Obstructions, buried utilities, old foundations and unexpected soil conditions might cause a loss of connection with the drilling head and delay the whole pipe installation process. MT drilling bits are used according to soil type and pipe length. Machine performance might drop dramatically as the number of boulders exceeds the drilling head capability limit. In addition, slurry system may be damaged by rock fragments (Hegab, 2003).

IV-4. Pipe Conditions.

i. Pipe section length & Shaft design (size, layout, structural integrity)

The pipe section length affects preparation time and entry shaft size for pipe installation. By increasing pipe section length, both construction cost of entry shaft and construction time increase (Hegab, 2003). Hence, it is concluded that pipe section length through both aligning of drilling segments and preparation time affects MT process.

ii. Pipe material

The effect on productivity by pipe material is realized as a result of friction between pipe and soil. However, slurry flow acts as a lubricant to facilitate pipe alignment. Therefore, as long as the pipe material is well fabricated and properly installed, material should have no major effect on productivity (Hegab, 2003).

V. Micro-tunneling Questionnaire

A questionnaire was distributed to micro-tunneling contractors, engineers, and manufacturers to investigate the factors affecting micro-tunneling productivity. The questionnaire was divided into four sections. The first section contained questions about respondents' contact information and type of business. The second section asked about productivity factors and respondents' work related experience. In the third section, the respondent was asked about the possible dependency between the various productivity factors. The final section addressed favorable soil conditions for the micro-tunneling operation, as depicted in figure (V-1).

The questionnaire was sent to 50 micro-tunneling contractors, engineers, and manufacturers across the Dubai and Abu Dhabi (UAE) by e-mail. A copy of the questionnaire is shown figure (V-1). The questionnaire asked the participants to rank the factors that affect productivity of micro-tunneling machines. The ranking was scaled from 1 to 5, where 1 is not important and 5 is extremely important. The questionnaire asked also a question about the ranking of the favorable soil conditions in micro-tunneling operations. Similarly, the ranking was scaled from 1 to 5, where 1 is least favorable condition and 5 is most favorable.

Eight responses were received, representing a response rate of 16%. Accordingly, the experience of the respondents in the micro-tunneling industry ranged from 3 to12 years with an average of 5 years.

The respondents to the questionnaire were eight contractors; Contractors had comparable responses, which came from their experience as all the respondents had at least 3 years' experience in the micro-tunneling field.

VI. MT- Productivity Factors Rank

The purpose of establishing the input factor ranking is to highlight the relative importance of the factors used to model MT productivity. The AHP technique using (expert choice – software program) is utilized to determine the relative importance of each of the previously investigated MT productivity factors. The investigated factors that affect MT productivity are divided into four major levels. A pair-wise comparison matrix was developed considering the twenty two factors, as shown in Table (IV.l). In order to assign priorities, the AHP methodology is applied to these matrices in order to determine each factor's weight.

The eigenvector or weighting vector (Wj) for each pair-wise matrix is then established using Saaty's methodology (1982), as shown in the output data from (expert choice software program) in figures (VI-1, VI-2), and the average weight values shown in table (VI-1) Each of these weights represent its relative importance among the other factors, therefore the total weight value of each matrix is equal to one.

Questionnaire

Appendix I. Microtunneling Questionnaire

This questionnaire is conducted for the purpose of a MSc. research. All the data will be confidential. Thank you for your participation. Your valuable experience in microtunneling is greatly appreciated. If you have any question regarding this questionnaire, please do not hesitate to contact me by e-mail (ahmed_eng121@yahoo.com).

The respondent:

Name:

Company:

Address:

Telephone:

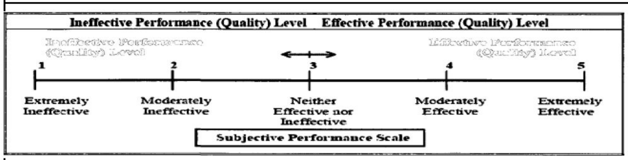
Fax:

E-mail:

Position:

Company type: ☐ Contractor ☐ Subcontractor ☐ Owner ☐ Engineer

1. How many years have you been dealing with microtunneling?



2. According to the above scale, please, rate the effect of the following factors on the microtunneling (M/T) productivity.

	1	2	3	4	5
1. Cutter head shape					
2. Crew/operator experience					

	1	2	3	4	5
3. Soil conditions					
4. Drive length					
5. Separation equipment design					
6. Pipe diameter					
7. Shaft design _size, layout, structural integrity					
8. Slurry flow rate					
9. Pipe material					
10. Use of intermediate jacking station					
11. Use of water jets at the excavation face _jetting					
12. Accurate geotechnical investigations					
13. Depth of installation					
14. Groundwater conditions					
15. M/T type (slurry, EPB, pilot)					
16. Obstruction or unusual soil conditions					
17. Restrictions to working hours					
18. Straight versus curved alignment					
19. Technical support					
20. Use of lubrication					
21. Jacking thrust					
22. Torque					
23. Other					

3. Please mention the dependency between the factors. If any of the following factors depends on another factor, please write the number(s) indicating the dependent factor in front of each one (multiple selections are acceptable).	
Example.	
1. Cutter head shape	3
2. Crew/operator experience	
3. Soil conditions	1
(There is dependency between cutter head shape and soil condition or, in other words, there is an interaction between them)	
1. Cutter head shape	
2. Crew/operator experience	
3. Soil conditions	
4. Drive length	
5. Separation equipment design	
6. Pipe diameter	
7. Shaft design (size, layout, structural integrity).	
8. Slurry flow rate	
9. Pipe material	
10. Use of intermediate jacking station	
11. Use of water jets at the excavation face (jetting)	
12. Accurate geotechnical investigations	
13. Depth of installation	
14. Groundwater conditions	
15. M/T type (slurry, EPB, pilot)	
16. Obstruction or unusual soil conditions	

17. Restrictions to working hours					
18. Straight versus curved alignment					
19. Technical support					
20. Use of lubrication					
21. Jacking thrust					
22. Torque					
4.In your opinion, please, rate the soil conditions according to it's effect of Microtunneling productivity as ⟹(1 is the least favorable soil condition and 5 is the most favorable one).					
	1	**2**	**3**	**4**	**5**
_ Hard clay					
_ Silty clay					
_ Soft clay					
_ Silt					
_ Sand					
_ Boulders and rocks					
_ Backfill					

Figure V-1 Proposed Questionnaire.

Model Name: Respondent 1 (Microtunneling Questionnaire)

Treeview

- **Goal: Productivity Factors**
  - **Cutter Head Shape (L: .069)**
  - **Crew/operator Experience (L: .069)**
  - **Soil Conditions (L: .069)**
  - **Drive Length (L: .025)**
  - **Separation Equipment Design (L: .025)**
  - **Pipe Diameter (L: .069)**
  - **Shaft Design (L: .025)**
  - **Slurry Flow Rate (L: .025)**
  - **Pipe Material (L: .012)**
  - **Intermediate Jacking (L: .025)**
  - **Jetting (L: .025)**
  - **Geotechnical Investigation (L: .025)**
  - **Depth of Installation (L: .007)**
  - **Groundwater Conditions (L: .025)**
  - **M/T Type (L: .069)**
  - **Obstructions (L: .069)**
  - **Working Hours (L: .025)**
  - **Straight/Curved Alignment (L: .069)**
  - **Technical Support (L: .069)**
  - **Lubrication (L: .069)**
  - **Jacking Thrust (L: .069)**
  - **Torque (L: .069)**

Model Name: Respondent 1 (Microtunneling Questionnaire)

Numerical Assessment

Cutter Head Shape	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	Crew/operator Experience

Compare the relative importance with respect to: Goal: Productivity Factors

	Cutter Heac	Crew/opera	Soil Condit	Drive Lengt	Separation	Pipe Diame
Cutter Heac		1.0	1.0	3.0	3.0	1.0
Crew/opera			1.0	3.0	3.0	1.0
Soil Conditi				3.0	3.0	1.0
Drive Lengt					1.0	(3.0)
Separation						(3.0)
Pipe Diame						
Shaft Desig						
Slurry Flow						
Pipe Materi						
Intermediat						
Jetting						
Geotechnic						
Depth of In:						
Groundwat						
M/T Type						
Obstructior						
Working Hc						
Straight/Cu						
Technical S						
Lubrication						
Jacking Thi						
Torque						

Figure VI-1 Tree view for the factors affecting productivity percentage as respondent 1.

Figure VI-2 Numerical assessment comparison for the factors affecting productivity as respondent 1.

Table VI-1 Average Weight Values for All Respondents

Factors	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Respondent 5	Respondent 6	Respondent 7	Respondent 8	Average Weight
	Weight (Wi)	Weight (Wi)	Weight (Wi)	Weight (Wi)	Weight (Wi)	Weight (Wi)	Weight (Wi)	Weight (Wi)	
1. Cutter head shape	0.069	0.05	0.058	0.02	0.102	0.033	0.129	0.046	0.063
2. Crew/operator experience	0.069	0.05	0.058	0.052	0.102	0.087	0.129	0.104	0.081
3. Soil conditions	0.069	0.118	0.139	0.114	0.102	0.087	0.129	0.104	0.108
4. Drive length	0.025	0.02	0.058	0.02	0.017	0.015	0.025	0.01	0.024
5. Separation equipment design	0.025	0.009	0.007	0.01	0.017	0.015	0.011	0.01	0.013
6. Pipe diameter	0.069	0.118	0.058	0.058	0.043	0.033	0.025	0.104	0.064
7. Shaft design _size, layout, structural integrity	0.025	0.008	0.011	0.02	0.009	0.033	0.026	0.01	0.018
8. Slurry flow rate	0.025	0.01	0.022	0.01	0.017	0.033	0.025	0.02	0.020
9. Pipe material	0.012	0.02	0.058	0.01	0.017	0.033	0.011	0.01	0.021
10. Use of intermediate jacking station	0.025	0.02	0.022	0.022	0.017	0.015	0.025	0.02	0.021
11. Use of water jets at the excavation face _jetting	0.025	0.05	0.022	0.052	0.043	0.033	0.025	0.046	0.037
12. Accurate geotechnical investigations	0.025	0.05	0.058	0.052	0.043	0.087	0.063	0.104	0.060
13. Depth of installation	0.007	0.05	0.058	0.05	0.017	0.008	0.025	0.047	0.033
14. Groundwater conditions	0.025	0.05	0.022	0.02	0.017	0.087	0.011	0.02	0.032
15. M/T type (slurry, EPB, pilot)	0.069	0.02	0.058	0.027	0.017	0.087	0.025	0.02	0.040
16. Obstruction or unusual soil conditions	0.069	0.05	0.058	0.114	0.102	0.087	0.063	0.104	0.081
17. Restrictions to working hours	0.025	0.02	0.011	0.052	0.043	0.033	0.011	0.046	0.030
18. Straight versus curved alignment	0.069	0.05	0.058	0.057	0.102	0.008	0.025	0.046	0.052
19. Technical support	0.069	0.118	0.058	0.114	0.043	0.087	0.063	0.046	0.075
20. Use of lubrication	0.069	0.02	0.022	0.05	0.043	0.033	0.025	0.02	0.035
21. Jacking thrust	0.069	0.05	0.022	0.022	0.043	0.033	0.063	0.02	0.040
22. Torque	0.069	0.05	0.058	0.055	0.043	0.033	0.063	0.046	0.052

VII. Factors Importance

To be able to further analyze the results, the studied factors were categorized under four categories: underground conditions, operator's experience, mechanics of the system, and others. As concluded from the questionnaire responses, the most important category was found to be the underground conditions followed by the operator's experience, Pipe conditions and finally the mechanics of the system.

Underground conditions include accurate geotechnical reports, soil conditions, and obstructions. Operators' experience can be a major factor in productivity improvement because many of the problems can be overcome consequently. Pipe conditions include Pipe diameter and alignment. The mechanics of the system was represented by the cutter head shape; cutter head torque can be included in this group because it is mainly used to overcome the soil friction.

Other factors, which come next, can enhance the performance of the project but their impact is less than the first four groups according to the survey.

Table VII-1 the most effective factors with its Average weights.

	Factors	Average Weight
1	Soil conditions	0.169
2	Crew/operator experience	0.128
3	Obstruction or unusual soil conditions	0.127
4	Technical support	0.118
5	Pipe diameter	0.100
6	Cutter head shape	0.100
7	Accurate geotechnical investigations	0.095
8	Torque	0.082
9	Straight versus curved alignment	0.082

VIII. Conclusion

The productivity of micro-tunneling operations depends on a large number of factors. Soil conditions, accurate geotechnical investigations, operator's experience, obstructions, use of lubrication, and the capacity of main jacks have the most impact on the productivity of micro-tunneling. Accordingly, the contractor should study these factors well in the bidding phase of the project because they are the keys for profitability. Most of productivity factors are interdependent, and ignoring one of them can affect the project dramatically. Knowing that sand is the most favorable soil condition for micro-tunneling while boulders is the worst one can help contractors recognize the difficulty of the project and adjust the bid and schedule accordingly.
These questionnaires highlighted the main factors affecting the productivity of micro-tunneling operation. This paper has examined the level of importance of the factors based on expert opinion and examined the importance of their relationships.
Contractors, engineers, and owners should consider these factors when looking for enhancing the project productivity. This questionnaire was a step in modeling the productivity of micro-tunneling projects under different soil conditions

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