Recent trends and research innovations in pipe jacking and microtunneling

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Abstract. The term "Trenchless Technology" is used to describe a wide array of technologies, processes and techniques for creating holes or renovating conduits without disturbing the surface. Trenchless Technology is the cumulative engineering, equipment and experience that allows making a hole or rehabilitating a conduit between two locations without disturbing the surface above or the environment around the hole. [10]The terms Pipe Jacking and Microtunneling are used to describe an installation methods as well as a concept that is fundamental to a number of Trenchless Technologies. Pipe Jacking can be described as the principle of using hydraulic rams to push preformed sections to line the hole formed by a cutting head or shield. Microtunneling will be defined as those methods that install pipes with an inside diameter of less than 900 mm to a predetermined line and level by remotely controlling the cutting edge. The operations of face cutting, muck removal, monitoring and adjustment all have to be accomplished by remote control. This paper provides a review of the history and development of Pipe Jacking and Microtunneling methods with extensive referencing to the published literature. The application of such methods in comparison with other Trenchless Technologies is discussed and the various planning, design and construction aspects are introduced. The emphasis of the paper is to trace the academic research and field monitoring results covering critical aspects of design and construction with a particular emphasis on jacking force estimation and the effect of lubrication on jacking forces.

Keywords: Pipe jacking; Microtunneling; Design; Construction; Research; Review.

1 Introduction

This paper is intended to provide a review of the development of pipe jacking and micro-tunneling technologies with an emphasis on research and development activities that have been published in the public domain. Naturally, in an equipment intensive field with a substantial competition in terms of ‘‘know-how,” there will be much important R&D that has been conducted and is held privately and only becomes visible as new products enter the marketplace or existing barriers are overcome in the range of projects that can be accomplished. Compared to tunneling technology in general, pipe jacking and micro-tunneling have more specific characteristics but remain difficult to precisely group because various types of hybrid methods have evolved that blur previously adopted definitions. In this paper, the discussions will range across not only specific aspects of pipe jacking and micro-tunneling but also will touch on how these methods relate to other technologies that closely compete. The intent of the paper is to document the increasing level of theoretical research, computer simulation and field monitoring that is being applied to pipe jacking and micro-tunneling methods and to discuss how this research and allied technical innovations are over- coming application barriers. A complementary objective is to give a newcomer to the field a starting point for further study in the field.

1.1 A Brief discussion of methodologies and their history

The emphasis in this paper is on ‘‘pipe jacking” methods of which ‘‘micro-tunneling” is one type. The essential element that distinguishes pipe jacking (as compared to other tunneling methods) is that the lining of the resulting tunnel is pushed through the ground from the starting point rather than being built section-by-section just behind the excavation face or within the tail shield of a tunnel boring machine. Pipe jacking has been identified as being used as early as 1896 to install a concrete culvert under the Northern Pacific Railroad in the USA although the method did not become popular in the USA until the 1950s (Barbera et al., 1993)[7]. Pipe jacking use was also noted in Vienna in the late 19th century (Thomson, 2009). This early form of pipe jacking required person access to the face in order to carry out the excavation work and to load and remove the spoil. Thus, the minimum diameter of such pipe jacking projects was around 1.0–1.2 m. One pipe jacking technique (auger boring) that allowed smaller diameter bores was initiated in the USA from 1936 (Barbera et al., 1993). In this technique, a steel auger and a cutting head are rotated in conjunction with the jacking of a steel pipe. The cutting head excavates the soil and the auger moves the soil back to the starting pit with no personnel access possible or required within the pipe. This technique saw continued development in the 1940s for mining thin coal seams that were uneconomical for person entry tunnels. The limitation of this method was that little control of the excavation face was possible and running ground especially below the water table could flow easily along the auger and lead to large settlements or sinkholes. This restricted the method to suitable types of soils and typically above the water table. The steel pipe that was required to house the auger was usually left in place as a casing to support the ground and a product pipe inserted within the casing. For crossings of road or rail, space is often available at the side of the right of way for preparation and welding of the pipe before the excavation is commenced. The method, however, is not so suitable for pipeline projects following a public right of way because of the large setup areas that would be required for each installation length. Thus, up to the 1960s, pipe jacking was possible in person-entry sized tunnels and auger boring could be used for small to mid size diameter crossing installations in non-flowing ground. In person-entry sized tunnels, support for running ground below the water table could be provided (albeit with difficulty and expense) by compressed air tunneling that was first used around 1910 at almost the same time in New York and Hamburg (Chapman, Metje, & Stark, 2018). No solution, however, yet existed for non- person entry tunneling or pipe jacking. That advance came in terms of the ability to remotely provide support to the excavation face while still accommodating the excavation process in non-person entry diameters. This new ability was given the name ‘‘micro-tunneling” because it allowed a controlled tunneling process in diameters below those permissible for person entry. The characteristics of micro-tunneling (see illustration in Fig. 1) apart from its small size were as a pipe jacking method, with accurate guidance, remote operation and an ability to control the support of the excavation face. The fact that the last four characteristics could also be applied in larger diameter projects has led to some international differences in terminology with North American usage dropping the linkage of the definition to the size of a tunnel and using instead the method characteristics. The various definitions can be consulted in ASCE (2015) [2], ISTT Glossary (www.isttt.com) and Stein (2005) among other sources.

Fig. 1. Cut-away illustration of a micro-tunneling project (courtesy Unitracc).

Three main variants of face support (besides compressed air) have been used in micro-tunneling and pipe jacking. One was the introduction of a closed pressurized face within a tunnel boring machine installed ahead of the pipes being jacked with bentonite slurry was pumped into this closed chamber to provide pressurized support to the excavation face as it was being excavated using mechanical cutters. [14]The slurry (mixed with the excavation cuttings) could then be pumped to the surface where the excavated material was separated from the slurry. This is termed a slurry type machine. An alternate mode of face support was first developed in Japan in 1966 (Thomson, 2009) in which (for suitable types of soil), the excavated soil was kept compressed in the excavation chamber to provide support to the face and the pressure control was provided by managing the spoil removal rate compared to the machine advance rate. This is termed an earth-pressure-balance (EPB) machine. Both types of machine are widely used today across a wide range of tunneling applications with EPB machines generally being suitable for finer-grained soils and slurry machines for coarser grained soils. However, due to the size of the soil removal equipment in an EPB machine, it cannot be used for diameters below about 1.7 m. A third type of equipment was used in some earlier micro-tunneling machines with slurry/spoil removal via a small diameter cased auger within the jacking pipe. This was termed an auger-type micro-tunneling machine. Soil removal using augers is still a part of several trenchless excavation methods. It is also worth noting here that micro-tunneling and pipe jacking methods have evolved over time to allow curved alignments for installation. Horizontal curvature allows pipe installation projects to more easily follow curved public rights of way without multiple manholes and short straight segments.[6] Vertical curvature allows shallower launching and reception shafts when installing non gravity pipelines. The ability to accomplish curved pipe jacking has involved developments in terms of understanding the transfer of jacking stresses across pipe joints in a curved alignment and developments in guidance that no longer required a direct line of sight for a laser system.

The use of particular excavation methods and their cost effectiveness depends not only on the development of their own capabilities, reliabilities, productivities, etc. But also whether there is an availability/emergence of competing methods. A few complementary or competing methods will be briefly introduced here and some of them will be touched on further in later discussions where they are providing means of making technological advances. An illustration of the hierarchy of trenchless methods can be seen in Fig. 2. Impact moling is a trenchless method whereby a closed pipe is hammered into the ground and displaces the ground to accommodate the inserted pipe. This is referred to as a compaction method and was first developed in Poland and Russia during the 1960s (Barbera et al., 1993). Because of the need to displace the soil, the method is limited to diameters less than around 200 mm (typically much smaller) and near-surface installations. Various attempts have been made to develop commercial products that can be tracked and steered but almost all field applications today are unsteered over short distances between access pits. These methods serve as a complement to pipe jacking and micro-tunneling methods rather than competition because of the range of diameters suitable for each type of application.

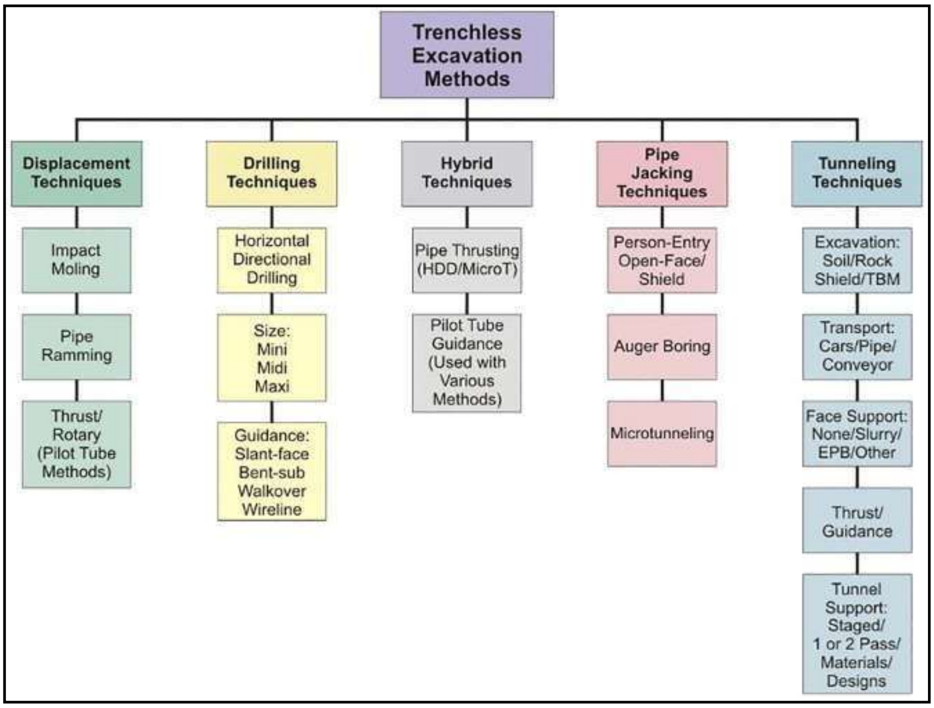

Fig. 2. Example classification of trenchless excavation methods

Pipe ramming also uses a reciprocating hammer to drive a steel pipe into the ground but in this case the soil is allowed to enter inside the pipe as it is forced into the ground thus minimizing the volume of soil that must be displaced to only the cross-sectional rim of the pipe plus any additional thickness provided by a hardened leading edge of the pipe. This change allows much larger pipes to be installed and diameters from around 0.1 m up to around 4.5 m can be driven for distances typically ranging from a few meters to over 50 meters. Early pipe rams in the U.S. in the early 1970s used adapted impact moles. Tools designed specifically for ramming pipe appeared on the market in the US in 1981 (Griffin, 2002). There is little steering capability while ramming pipe but directional control can be improved by combining the method with a steered pilot bore (described below). Pipe ramming is typically used to install casing pipes in road or rail crossings where the large setup area is not a major disadvantage and the soil remaining in the pipe during installation provides security against face collapse. Pipe ramming is also used to assist in other trenchless installation techniques most notably by installing a casing through problem soils when using horizontal directional drilling (HDD). Pipe ramming characteristics overlap only slightly with most pipe jacking and micro-tunneling projects and there is very little research on pipe ramming techniques reported in the literature mainly what can be found are case history papers with few data. Pipe friction during installation in the presence of the vibration due to hammering plus the optimum levels of external and internal overcut provided by the leading edge are among the questions that appear to be addressed mainly by field experience at the current time although Meskele and Stuedlein (2015) have investigated the pipe friction associated with pipe ramming. In loose granular fills, vibration settlement of the overlying soils may also be a concern (e.g. Murphy, & Morera, 2011). Project capabilities continue to increase as larger sized ramming equipment is introduced to the market (e.g. Griffin, 2013).

1.2 Focus of this paper

Advances that allow a wider use of pipe jacking technologies include both technical issues and issues related to the selection of the technology compared to other options (including both other trenchless methods and open cut installation). Since the full range of topics is too broad to cover in this review, the categories are outlined below with some direction for further reading but with the core of this review reserved for some key issues that concern much of the research literature relating to micro-tunneling and pipe jacking.

2 Method components

2.1 Project planning and design

As micro-tunneling and pipe jacking increased in usage, a number of guidance documents were developed. Without trying to be comprehensive, English language guidelines and standards as micro-tunneling and pipe jacking developed have included: USNCTT (NRC) (1989), Yorkshire Water (1990), TTC/NUCA (Iseley and Tanwani 1992), TTC/WES (Bennett et al., 1995)[12], Pipe Jacking Association (1995, 2017), Najafi (2005), EN (2000) and ASCE (2001, 2015)[3][4]. Japanese guidelines have included JSTT (1994) and JMTA (2000) and were part of early recommendations from ISTT (e.g. ISTT, 1994). Various other European and German standards apply and can be found according to their applicability to different aspects of the design process in reference books such as Stein (2005). A number of reference books have been written to aid in the design and construction of micro-tunneling and pipe jacking projects. These have included: Stein, Mollers, and Bielecki(1989), Thomson (1993), Stein (2005) and Chapman et al. (2018).

Nido, Knies, and Abraham (1999) analyzed micro-tunneling construction from an operational simulation perspective and Wilkinson (1999) provided a review of the issues that must be effectively addressed in a pipe jacking project to achieve success. Bennett (2006)[13] also provided a summary of potential design, construction and equipment problems for micro-tunneling projects.

Project planning and design for micro-tunneling and pipe jacking projects has at its core the balancing of meeting project geometric and performance constraints while minimizing the cost and risk of the project by careful selection of the vertical and horizontal alignment, location of shafts, choice of equipment, etc. Due to the uncertainties involved in predicting the geological environment for the tunneling works and the lack of access to the face (for many micro- tunneling projects), this may require substantial judgment rather than definitive analysis. The various aspects involved in a project are reviewed in turn below with references provided to pertinent research and guidance in that area.

2.2 Geotechnical investigation, uncertainty and alignment selection

While many aspects of the geotechnical investigation for pipe jacking projects are similar to those for tunneling, they have some specific differences. Also, many utility micro-tunneling projects may evolve from designs that envisage open cut installation that would require far less attention to geotechnical investigation. In non-person entry sizes, the machine and pipe once launched need to be able to reach the arrival shaft (depending on issues such as cutter wear, change of ground type, higher than expected friction, etc.).

A micro-tunnel covering the same distance as a large tunnel requires the same length of geology to be categorized but the percentage of the project budget that is often allocated to site investigation means far less money available for the micro-tunnel project.

How to fairly apportion the risk between the project owner and the contractor and to decide when project conditions have materially changed from those on which the bid was made. In this regard, the approaches are similar to those that have been adopted in conventional tunneling.

For guidance on geotechnical investigation, risks and contractual issues, papers such as Lyman and Camp (2006) and the manuals/guidelines referred to above provide a more detailed discussion of the issues and suggested approaches. The evolution in contractual practices to manage tunnel risk and litigation starting from early work by the US National Committee on Tunneling Technology (USNCTT) of the US National Research Council (NRC) through its broader application in guidelines from the American Society of Civil Engineers (ASCE)f and the Inter- national Tunnelling Association (ITA) can be traced in the publications: USNCTT (NRC) (1974, 1978, 1984), ASCE (1997, 2007)[1][5] and ITA (1988), ITA (2011). Many case study papers also address these issues but are too numerous to list individually. Such papers can be found by searching for microtunneling as a keyword on the technical paper resources of the ISTT (www.istt.com) or the NASTT (www.nastt.org). (Note: when searching internationally, both the British spelling ‘‘microtunnelling” and the American spelling with only one ‘‘l” should be tried).

2.3 Method selection

Appropriate method selection is a key step in ensuring a successful and cost effective project but it is rarely a straightforward issue. Guidance has been developed to assist in trenchless method selection including guidance manuals, chapters within trenchless reference books and computer decision support software (e.g. Russell, Udaipurwala, and M. Alldritt and K. EI-Guindy (1999), Leu,Adi (2011), Matthews and Allouche (2012), Jafarimoghaddam, Hamidi, and Najafi (2013) and Matthews, Allouche, Vladeanu and Alam (2018)). However, as the capabilities of methods change and hybrid or new methods emerge, such guidance can quickly become outdated aspects. [8] Method selection also brings into play the question of how closely to define the method in the design specifications and/or whether to pursue a design build approach. Such issues are not discussed in this paper.

3 Pipe friction assessments

3.1 Background to discussion

As identified earlier, the key characteristic of pipe jacking and micro-tunneling compared to conventional tunneling is the need to slide the pipe or tunnel support structure through the ground as the tunnel is advanced. The thrust that will be required to complete a pipe jacking drive and the ability of all the components of the thrust system to withstand the forces that will need to be applied are key elements for success of a project. The interaction of the pipe with the surrounding ground, the effect of intended and unintended curvature of alignment, the impact of over- cut and the friction reduction by lubrication are factors that complicate the assessment[9] As a key aspect of pipe jacking and one that crosses the concerns of designers, con- tractors and equipment manufacturers, it is an area of strong interest for methods of better estimation of expected forces but without falling strongly into the purview of specific companies. It is also a topic that offers aca- demic challenges. For all the above reasons, the estimation of jacking force represents the main body of research literature for pipe jacking and micro- tunneling and hence is covered in more detail in this paper.

3.2 Overview of jacking force assessment

Many of the practical approaches to jacking force estimation are based on relatively simple physical models coupled with experience on prior projects and informed in some cases by laboratory testing. Figure 3 illustrates the several components that contribute to the overall jacking thrust required for a pipe jacking project. Firstly, thrust is required to provide the necessary face pressure to support the face, to balance the groundwater pressure and to enable the appropriate force on the cutters to excavate the ground. Since this force will remain relatively constant over a length of pipe jacking (unless the geology changes radically along the alignment), it becomes a smaller percentage of the total jacking force as the drive extends and is typically not a critical issue in terms of total jacking force estimation for long drives. Another component of the jacking force results from the need to slide the shield or tunnel boring machine through the ground. The machine/shield is of a fixed weight and length and hence contributes a constant contribution to the total jacking force as the drive extends. The remainder of the components of the total jacking force all act based on the length/surface area of the pipe string and hence get larger as the drive extends. In a dry stable hole, the weight of the pipe will cause a frictional resistance to sliding. In a hole below the water table, buoyancy effects from the empty pipe below the groundwater surface will counter- act and often exceed the weight of the pipe (in which case, the pipe will try to float within the hole and the friction will act along the upper surface of the pipe). The previous two components are easy to calculate for specific pipe sections and depths below the groundwater table. However, the pipe will only rarely slide through a stable hole created by the shield or TBM ahead of the pipe string. Typically, the overcut made by the machine results in an annular gap that can close or collapse on the pipe string behind the machine allowing some proportion of the full ground pressure at the level of the micro-tunneling drive to act against the surface of the pipe. The actual contact area between the pipe and the soil, the contact pressure exerted, the effect of changing the annular gap, the influence of lubrication mud pumped into the annular space and the friction coefficient that is appropriate to be used are all difficult to assess. To add to this already complex problem, bores may not be exactly straight (even when intended to be), curved alignments are common, pipe and joints may have geometrical defects that cause dragging in the soil, pipe jacking is not continuous over time (allowing adhesion to occur), etc.

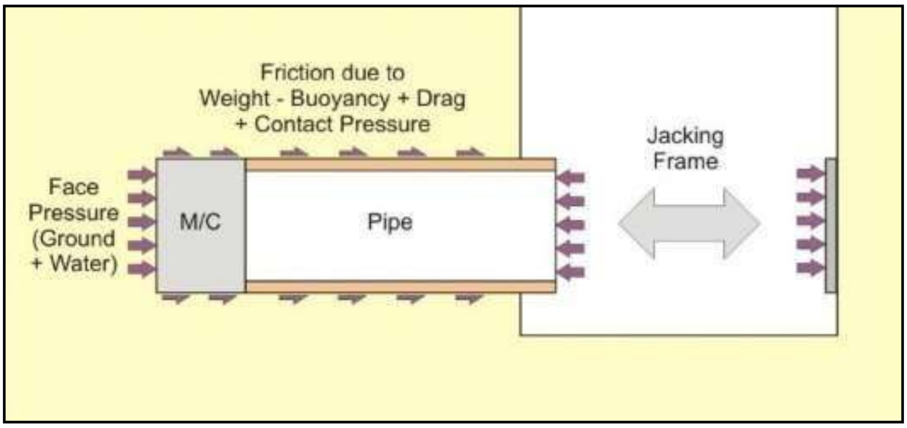

Fig. 3. Basic force diagram for pipe jacking.

The development of more detailed analytical, empirical and semi empirical models plus the quantification of the above effects form the core of much of the academic and industry based research into jacking force calculation.[15] The literature is too extensive to provide a detailed review of all the individual contributions but the research areas will be discussed in terms of their general research themes and methodologies with references to individual papers for detailed study.

3.3 Field test bed studies and laboratory-scale experiments

The issue of pipe-soil friction has also been studied in specially prepared field test beds and in laboratory scale experiments in soil boxes.[16] Such work has mostly been undertaken by research institutions in the field and typically involving Ph.D. Dissertation research.

In US studies, a test bed constructed at the Waterways Experiment Station of the US Army Corps of Engineers in Vicksburg, MS consisted of several different soil type sections with the capability of varying the ground water level within a test section. The test facility was 104 m long, 4.9 m wide and 4.0 m deep (Iseley and Bennett, 1993; Staheli and Bennett, 1996)[11]. In the same time period, a test bed was also constructed at the Trenchless Technology Center at Louisiana Tech University. The test bed was used to test a new Japanese micro-tunneling system in addition to other uses for trenchless technology field studies (Najafi et al., 1993). In the UK, Yonan’s Ph.D. Dissertation research used reduced scale testing in the laboratory to study pipe jacking forces in sand (Yonan, 1993).

3.4 Assessment for curved pipe jacking alignments

Micro-tunneling on a curve can significantly increase jacking loads since the machine and the following straight sections of pipe are deflected along the curved alignment by the reaction forces on the wall of the tunnel. Researchers studying this problem through analysis and/or 3-D numerical modeling include Broere, Faassen, Arends, and van Tol (2007), Shou and Jiang (2010) and Shou and Yen (2010). Nanno (1996) discussed the development and use in Japan of an adjustable four-point load transfer system between the sections of pipe jacked along a curved alignment (applicable to person-entry diameters). Sugimoto and Asanprakit (2010) combined geometrical analysis, a ground reaction spring model and finite element modeling to study the behavior of pipes and the friction force during curved pipe jacking. Chen (2008) carried out physical modeling and jacking force analysis for curved pipe jacking.

4 Summary and conclusions

This review paper has been written to provide an introduction to the development of pipe jacking and micro-tunneling and to describe the key components of practice and research in the field. Extensive citations are provided to allow readers to identify early work in the field, expansion of capabilities over time and the recent areas of research and development. A particular focus of the paper is to categorize the research into the assessment of jacking loads which is the most extensive body of research in the field. Because of the variety of research findings and estimation procedures, it is difficult to provide a concise overall summary from the literature review. It can be said, however, that progress is being made on understanding the implications of such factors as soil type, overcut, stoppages and most importantly lubrication on the friction load for pipe jacking. Effective lubrication activated as soon as possible behind the machine and with sufficient volume and pres- sure to reduce the effective stress at or near the pipe inter- face have been shown to allow pipe jacking with very low unit frictional resistance. Pipe jacking and micro-tunneling continue to evolve in terms of capabilities for distances jacked, increasingly challenging alignments, use in hybrid technologies and in handling more challenging geological conditions. Equipment development, courage of designers and constructors the increased understandings from research all contribute to these developments.

Future research directions will no doubt continue to include studies on how to model the complex interactions of pipe, soil, annular space and lubrication mud injection and how jacking loads are affected by curved alignments in various types of ground conditions.

References

1. ASCE. Geotechnical Baseline Reports for Underground Construction: guidelines and Practices. American Society of Civil Engineers Reston, VA (1997).
2. ASCE Standard Design and Construction Guidelines for Micro- tunneling, ASCE/CI 36-15. American Society of Civil Engineers Reston, VA (2015).
3. ASCE Standard Practice for Direct Design of Precast Concrete Pipe for Jacking in Trenchless Construction, ASCE Standard 27-00,62 (2001).
4. ASCE. Standard Construction Guidelines for Micro-tunneling, ASCE/CI 36-01. American Society of Civil Engineers Reston, VA (2001).
5. ASCE. Geotechnical Baseline Reports for Construction Suggested Guidelines. American Society of Civil Engineers Reston, VA (2007).
6. Atkin, R: Mechanized Curved Pipe Jacking by Giro-Compass. Proc. Pipe Jacking and Micro-tunneling 91, 1st Intl. Conference, Oct. 23-24, London, Pipe Jacking Association, London, 17.1–17.6 (1991).
7. Barbera, L., Iseley, T., & Tanwani, R. Historical Development of Trenchless Construction Methods and Equipment in the United States. Proc. Trenchless Technology: An Advanced Technical Seminar for Trenchless Pipeline Rehabilitation, Horizontal Directional Drilling and Microtunneling, Vicksburg MS, 139–160. (1993).
8. Barla, M., & Camusso, M. A method to design micro-tunnelling installations in randomly cemented Torino alluvial soil. Tunnelling and Underground Space Technology, 73–81 (2013).
9. Barla, M., Camusso, M., & Aiassa, S.: Analysis of jacking forces during micro-tunnelling in limestone. Trenchless Technology Research, Tunnelling and Underground Space Technology, 21(6), 668–683 (2006).

10. Beckman, D., Stein, R., Fabri, T., & Uhlenbroch, A.. CoJack – A new statics method of computing and controlling pipe jacking, Tunnelling and Underground Space Technology, 22(7), 587–599 (2007).

11. Bennett, D. Jacking Forces and Ground Deformations Associated with Microtunneling, Ph.D Thesis. University of Illinois (1998).

12. Bennett, R. D., Guice, L. K., Khan, S., & Staheli, K. :Guidelines for Trench- less Technology: Cured in Place Pipe (CIPP), Fold and Formed Pipe (FFP), Mini-Horizontal Directional Drilling (mini-HDD), Microtunneling, TTC Technical Report No. 400, Technical Report CPAR-GL-95-2, (1995).

13. Bennett, D. From one extreme to the other: Challenges with microtunneling in very soft soils and hard rock. In Proc. NASTT No- Dig Nashville. (2006).

14. Biggart, A. Closed face decisions – slurry or EPBM?. Tunnelling Journal (February), 32–37 (2011).

15. Bobylev, N. Comparative analysis of environmental impacts of selected underground construction technologies using the analytic network process. Automa- tion in Construction, 20(8), 1030–1040 (2011).

16. Borghi, F. X. Soil conditioning for pipe-jacking and tunnelling (PhD thesis). Department of Engineering, University of Cambridge (2006).