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A Novel Semi-Mechanized Shield Tunnelling Method Based on Hydro-Excavation with Waterjet Technology

Noronha, M.[1]; Faria, P[2]; Taqueda. D.[2]; Gomes, B.[2]; Pierri, L[2]; Santos, R.[2]
[1]Civil Engineering Dept, Federal University of Santa Catarina, Florianopolis, Brazil
[2]BraBo Tecnologia Inc., Florianopolis, Brazil

Today, hydrodemolition with high-pressure waterjet is a well-established technology in construction engineering, especially as a concrete removal technique. However, practical usage in underground construction still remains under-explored, posing a great challenge for new and innovative designs. Compared to conventional excavation tools (based on fracture, friction and wear), hydrodemolition has the advantageous features of higher power-to-weight ratio, faster advance rates and lower wearing of mechanical parts. All these advantages might have significant impacts on the design of a new generation of tunnel boring machines with lower cost and higher efficiency. Another attractive possibility is the development of an incremental design of a low cost, semi-mechanized method of tunnel excavation, with a protective shield which allows soil removal by manual means. The present article briefly describes a novel semi-mechanized tunneling method for soil excavation that uses as cutting principle high-pressure waterjets (soil: hydro-excavation approach). Basically, the proposed equipment comprises a hollowed shield, with an internal movable system of waterjet nozzles and drain pipes. As the equipment advances forward, the soil inside the shield can be safely piled into a stabilizing ramp which can be manually removed, reducing the operational cost of the proposed equipment. The article also shows some aspects of the design and analysis of the proposed shield tunneling method.

Key words: TBMs, micro-tunneling machine, waterjet cutting, hydro-excavation.

1 INTRODUCTION

The Tunnel Boring Machines (TBMs) currently available are not sufficiently accessible to meet the rising worldwide demand for underground projects, especially in the fast developing countries like Brazil, Russia, India and China. In fact, the high capital and operating costs of TBMs are still significant barriers to scale up market penetration of this excavation method worldwide. The underlying TBM mechanism is intrinsically linked to their high costs, due to the high power demand of boring, self-propelling and mucking systems. Another impacting aspect relates to the high customization level of TBMs, since these machines are designed for the specific conditions of each project (geology, diameter, length, rate of advance, application). Therefore, it is often quite difficult to reuse these machines, thereby eliminating the benefits of an economy of scale.

The aforementioned drawbacks are particularly critical in small-diameter tunnels, for which there is a pent-up demand for infrastructure facilities like water, sewer, and other basic public amenities. Actually, the problem is even more severe, since non-mechanized and conventional open trench methods are still common practices in many countries, leading to a large waste of investments, material and other resources. As Figure 1 indicates, cost-efficiency of current technology is not enough to meet the global demand for safe water and sanitation.

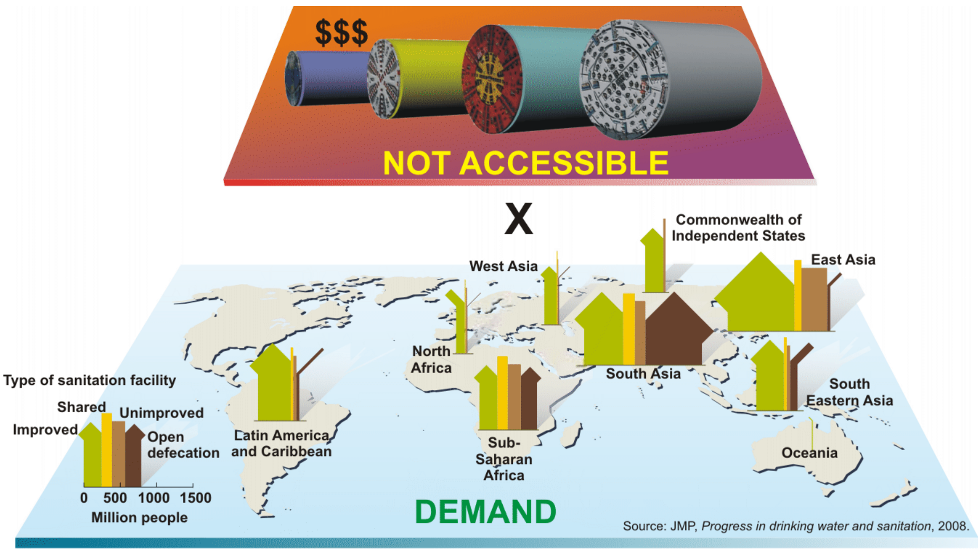

Figure 1. The scarce infrastructure for water/wastewater remains a pressing concern worldwide.

To address the current barriers and opportunities, this article proposes an alternative soil tunneling method based on a semi-mechanized approach which increases efficiency and productivity while reducing overall costs and construction time. The basic idea consists of providing a hollow tubular shield with a water jet cutting system (hydro-excavation) to advance and support the excavation front of the tunnel into the soil layer. The soil in the interior of the shield can be removed either by manual means or by a small tractor loader with a digging bucket. To complete the advance cycle, adequate support must be provided by manual installation of corrugated steel plates (conventional Tunnel Liner Plates) at the rear end of the shield. Due to its innovative design, the proposed equipment offers a more cost effective solution than traditional methods.

Before presenting in more detail the main features of the proposed equipment, the next section will review the existing waterjet technology available for soil excavation.

2 REVIEW OF WATERJET TECHNOLOGY

The historical development of the water jet technology is related to a broad range of cutting and cleaning industrial applications such as precision metal cutting, pipe cleaning, milling, preparation and regeneration of surfaces (Wilson et al., 1997). As Figure 2 illustrates, general applications of the water jet technology can be classified according to the required operating pressure and water volume flow (Momber, 2005).

Figure 2 also indicates that, besides establishing a range of different applications, appropriate settings of waterjet parameters (operating pressure and volumetric flow) are also related to the mechanical properties of the material removed. For civil engineering purposes, water jet technology is usually divided into two branches: hydrodemolition and hydro-excavation, for concrete and soil removal, respectively.

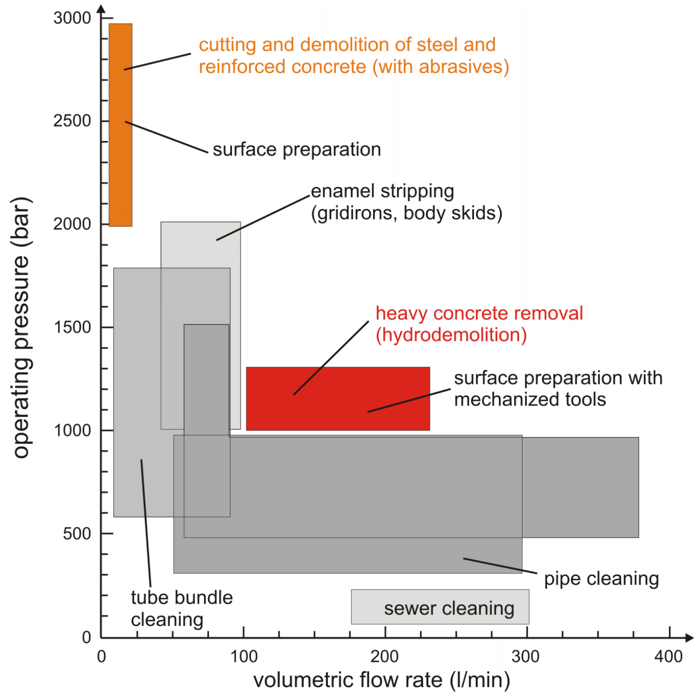

Figure 2. Waterjet applications, operating pressures and volumetric flows.

Table 1 presents the typical range of parameters for the hydrodemolition and hydro-excavation technologies as well as for cleaning and cutting applications.

Table 1. Typical parameter values for different applications of waterjet technology.

Application	Operation Pressure [MPa]	Volumetric Flow [m3/h]	Output Energy [kW]
Cleaning	≈ 50	≈ 5.0	≈ 70
Cutting	≥ 250	≈ 1.5	≈ 90
Hydrodemolition	≤ 100	≈ 10.0	≈ 270
Hydro-excavation	≤ 70	≈ 7.0	≈ 140

Although there is a large range of Civil Engineering applications for hydrodemolition and hydro-excavation, such as construction of underground openings and subsurface utilities, application of these technologies in tunnelling still remains largely untested.

To explore this gap, the proposed design promotes waterjet technologies tailored to cut out only the boundary of the tunnel section. From a technical perspective, our investigation indicates that the proposed waterjet cutting system is highly feasible. Based on the removal rates of commercially available waterjet nozzles, which ranges from 0.3 m^3/h to 1.5 m^3/h for rock and up to 10 m^3/h for soil (per nozzle), the proposed equipment could offer advance rates > 60 m/day (Noronha *et al*, 2012).

On the other hand, the financial feasibility of the proposed equipment is closely linked to the level of water reuse rate during the excavation of a tunnel. Our estimates are that between 70% and 80% of water reuse would be necessary to guarantee low cost and reliable water supply, with practically no impact on the global costs. Therefore, besides hydro-excavation nozzles, for the particular case of soil tunnels, a hydraulic circuit shall comprise water supply, pumping circuit and draining, filtering and separation subsystems. The pumping circuit would require power ratings between 250 kW and 500 kW. This input power is enough to feed the high-pressure pumps and the auxiliary subsystems (centrifugal pumps, compressors, fans, etc).

In order to guarantee the maximum service life of the waterjet nozzles, only clean water, free from fine particles, must flow on the circuit and a suitable filtering system has to be provided. The hydro-excavation process results in slurry with sand/silt/clay content, which is sent to the separation system for treatment in the proposed equipment. The separation system comprises a protective screening, with sieves for coarse and fine particles, and a clay separation tank based on gravitational or centrifugal sedimentation. Usually just a part of the flow is channelled to the clay separation tank, since it has performance limitations and might be highly energy-consuming. To close the circuit, the treated water is then pumped to the feed pipe, mixed with the water from the supply system. Figure 3 illustrates a simplified hydraulic circuit for the proposed design.

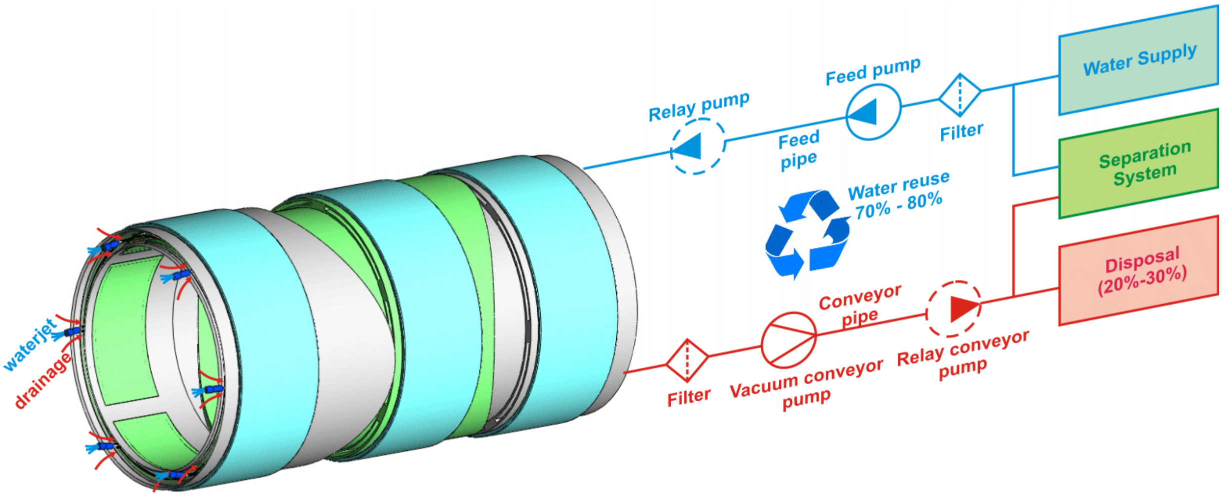

Figure 3. Schematic diagram of the hydraulic circuit.

3 PROPOSED SOLUTION

The proposed solution, called BraBo (Brazilian Borer), derived from our analysis of the high demand and of the waterjet technology suitability for tunnelling applications. The present study also resulted from a thorough search for potential innovations to enhance the current TBM technology. The guiding principles for the BraBo solution were based on the concepts of simplicity and innovation. One of the most important innovations of the BraBo proposal refers to the excavation process, which is now based on a two-stage process (peripheral cut followed by removal of the soil mass cylinder) instead of a full face excavation of the conventional approach. Despite being relatively simple, this new arrangement offers a solution that reduces costs (almost half) and increases the excavation advance rate (almost double). Figure 4 illustrates the main parts of the proposed equipment. For the present version, we designed an articulated, three-segment tubular shield with an outer diameter of 3 m and inner diameter of 2.6 m and a total length of 5.8 m.

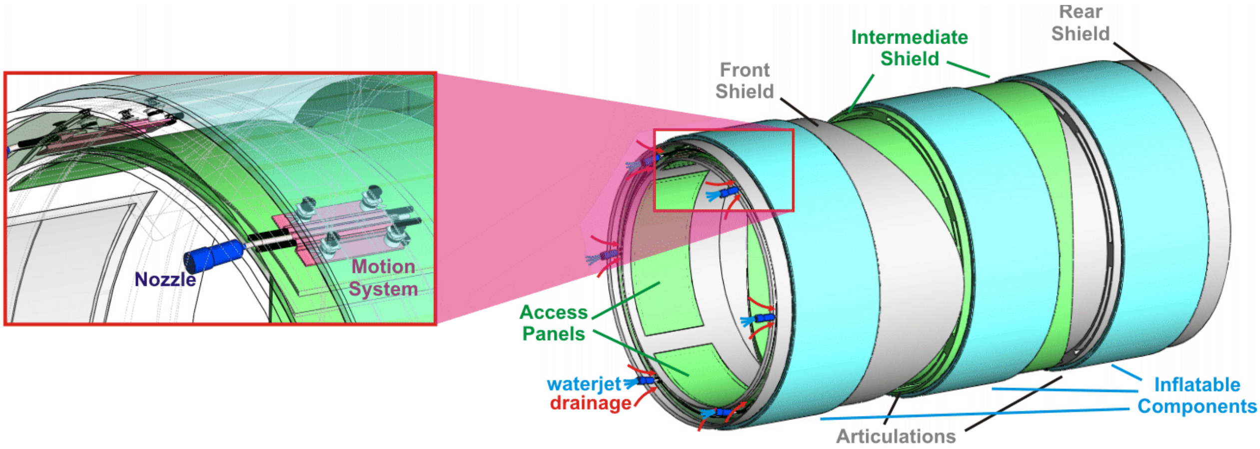

Figure 4. Overview of the proposed BraBo machine.

As the flow chart of Figure 5a visually depicts, the proposed BraBo machine works in four phases. The first phase consists of a hydro-excavation process with waterjets, cutting a circular ring of thickness 20 cm at the soil mass while providing the drainage requirements with drain pipes inside the hollowed shield. The resulting annular opening allows the forward movement of the machine, comprising the second phase. This movement is accomplished by means of an innovative system with a set of internal thrust jacks and three external segments of inflatable components (Fig. 5b). The innovative motion system also requires an auxiliary source of pressurized fluid (bentonite slurry) and a circuit unity for the controlled expansion sequence of the inflatable components.

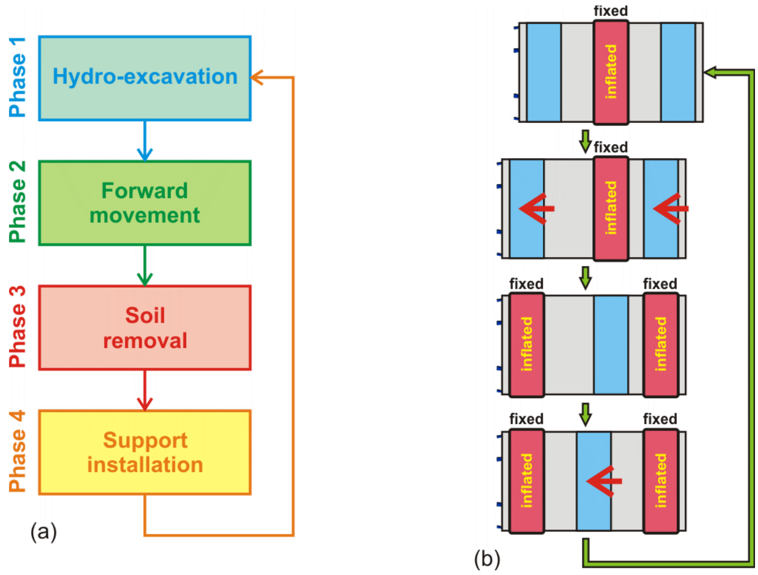

Figure 5. BraBo machine: (a) operation flow chart and (b) sequence of motion.

The third phase consists of the removal process of the soil in the shield. To reduce costs, the present version considered a simplified removal procedure by manual means or by a small tractor loader with a digging bucket. The soil in the shield has to be safely piled into a stabilizing ramp (slope stabilization). To complete, the fourth phase consists of providing the adequate support to the tunnel by manual installation of corrugated steel plates at the rear end of the shield. As the shield moves forward leaving the bolted steel plates behind, the resulting void must be filled with grouting concrete. This can also be manually achieved by injecting pressure grout into the perforated plate openings. Figure 6 illustrates both the soil removal and the support installation processes.

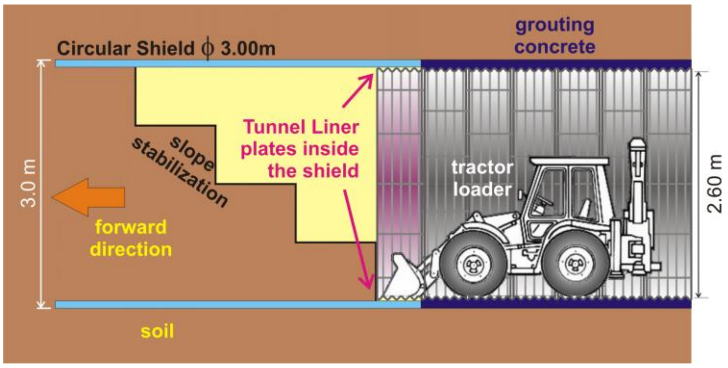

Figure 6. Soil removal and support of the tunnel.

The proposed three-articulated design offers a flexible steering capability to maintain both vertical and horizontal alignment for tunnel excavation in small radius curves. This steering system can also be easily integrated into the design of the equipment, since it can use the already existing internal thrust jacks. Figures 7a and 7b illustrate, respectively, the movement of the set in the horizontal and in the vertical direction.

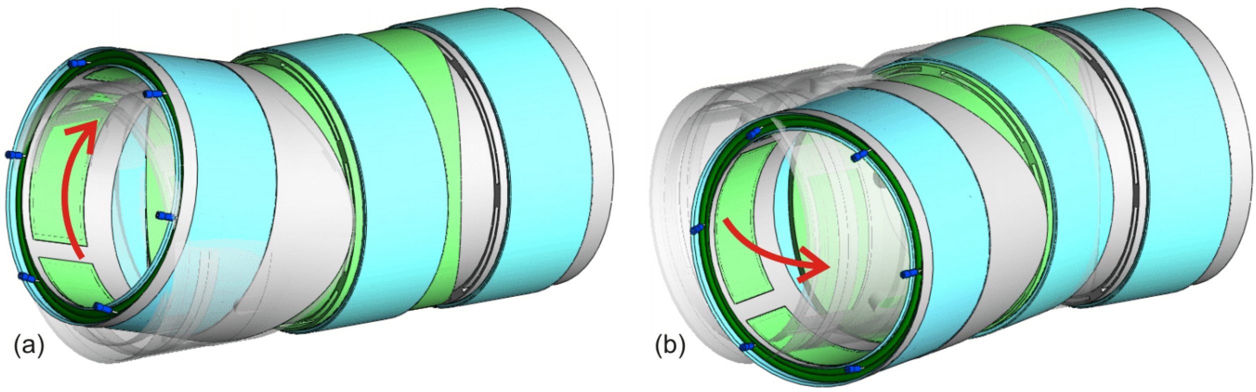

Figure 7. Three-articulated design: (a) vertical movement and (b) horizontal movement.

The hollowed structural body of the BraBo shield has many advantageous features as it provides enough internal space to install the waterjet nozzles and all necessary hoses, connections and electro-mechanical devices for the motion systems. For the particular case of the waterjet motion system, the proposed design consists of a set of six evenly spaced motorized robots to move and rotate the nozzles along the circumferential direction led by a guiding track (thin-walled curved beam with T-shape section). Also, in each motorized robot two drain pipes are mounted alongside the nozzle (Fig. 8a). A specific operating system shall control not only the movement of the robots but the flow rate, pressure and angular position of the waterjet nozzles. Also, the front part of the shield is equipped with a set of four removable maintenance panels, providing access to all internal components (nozzles, jacks, connections, etc) for inspection and repair.

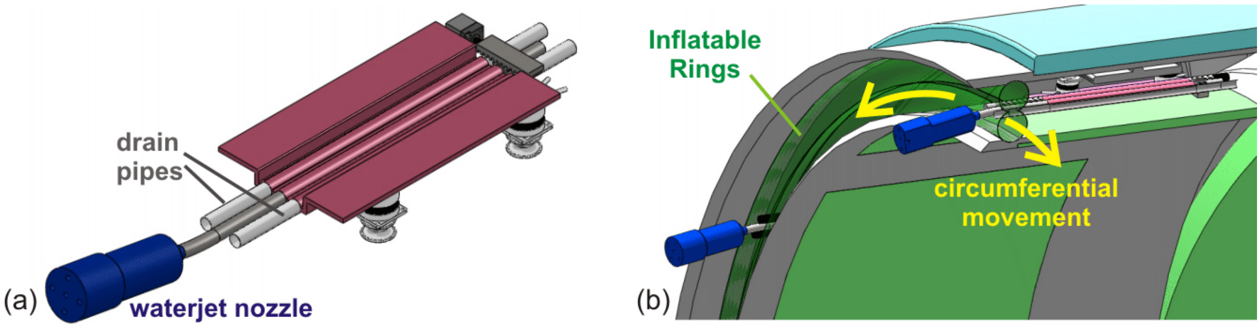

Figure 8. (a) Waterjet motion system and (b) sealing inflatable rings.

To prevent water and debris infiltration from entering the hollowed shield, the proposed design comprises two concentric inflatable rings with pressurized water to close the gaps at the front edge (Fig. 8b). This sealing system provides a cost-effective solution while still allowing the waterjet and draining pipes freely slide along the joint of the two rings.

Finally, the semi-mechanized proposed design also requires a backup system locally or remotely mounted to provide hydraulic and electrical power supply. However, since it demands less energy than conventional tunnel boring machines (about half), the proposed design requires a greatly simplified backup system.

4 CONCLUSION

The ever-increasing demand for effective and economical construction methods of tunnels is now a firmly established guiding principle for the development of efficient and well-planned urban and regional strategic infrastructures, which directly impact our quality of life and environmental issues. Technological innovations are inevitable in this scenario.

After identifying the waterjet technology as one of the most promising innovative and cost-effective alternatives for tunnels, the present study has focused on the development of a novel semi-mechanized tunneling method for soil excavation. Basically, the proposed design comprises a four-phase life-cycle approach:

Phase 1 – Hydro-excavation system (soil);
Phase 2 – Forward movement of a hollowed shield equipment;
Phase 3 – Removal of the soil enclosed in the shield;
Phase 4 – Installation of corrugated steel plates.

The last two phases involve manual procedures, providing the semi-mechanized character to the proposed equipment.

The design presented herein is particularly suited for 3 m diameter micro-tunnels for water, sewer, and other basic public amenities. In this case, the resulting device comprises a three-articulated, hollowed shield with an outer diameter of 3 m and inner diameter of 2.6 m and a total length of 5.8 m. Our calculations indicate that the proposed equipment is highly feasible. Due to the removal rate of approximately 10 m^3/h of the hydro-excavation system, the BraBo machine could offer advance rates higher than 60 m/day.

To conclude, the BraBo proposal might offer significant improvements in the current TBM performance and costs, opening new perspectives for impacting projects and helping to address the world's pent-up demand for strategic infrastructures.

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REFERENCES

Corcoran, E., C. Nellemann, et al. (2010). Sick Water? The central role of wastewater management in sustainable development. A Rapid Response Assessment. United Nations Environment Programme, UN-HABITAT, GRID-Arendal, Birkeland Trykkeri AS, Norway.

Crow, S.C. (1973). A Theory of Hydraulic Rock Cutting, Int. J. Rock Mech. Min. Sci. and Geom., pp. 567–584.

ITA-AITES (2002). Why go underground? Contribution of the Use of Underground Space to Sustainable Development", International Tunnelling Association, TRIBUNE, Special Issue, March 2002.

Jeng, F., T. Huang, S. Hilmersson, S. (2004). New Development of Waterjet Technology for Tunnel Excavation Purposes, Tunnelling and Underground Space Technology 19, pp 438-439.

Kolymbas, D. (2005). Tunneling and Tunnel Mechanics, a Rational Approach to Tunneling, Springer Verlag.

Liu, S. Y. (2010). Slurry Dewatering in Pipe Jacking Industry, PhD Thesis, The University of Leeds School of Civil Engineering, UK.

Momber, A. W. (2005). Hydrodemolition of Concrete Surfaces and Reinforced Concrete Structures, Elsevier.

National Research Council (2013). Underground Engineering for Sustainable Urban Development. The National Academies Press.

Noronha, M., Gomes, B., Santos, R., Taqueda, D. (2012). On the Development of a Micro Tunneling Machine with Water Jet Technology, 30th International no-Dig Conference and Exhibition, São Paulo, Brasil.

Noronha, M. (2010). Technological Innovation in Mechanized Tunnelling: Towards the Establishment of a New Industry of High Performance Tunnel Boring Machines, World Tunnel Congress, Vancouver, Canada, 2010.

Philips, N. S. (2012). The Optimisation of Slurry Separation Within Pipe Jacking, MSc dissertation, The University of Leeds School of Civil Engineering, UK.

Wilson, J.W., Summers, D.A. and Gertsch, R.E. (1997). The Development of Waterjets for Rock Excavation, 4th International Symposium on Mine Mechanisation and Automation, Brisbane, Australia.

(WSDTI) 2009. Mechanised Tunnelling and Segmental Lining: For safe and environment friendly tunneling. German-Czech Scientific Foundation.