Development and Research Trends of TBM Manufacturing Technology in China

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Abstract : Chinese TBM industry has rapidly developed over the past decade, while China can be regarded as the most remarkable TBM market in the world. After sixty years of development, China already has a complete set of technologies in all domains of TBM, including design, manufacturing, operation and tunnel construction, which are still evolving. The growth of the technology is a result of continuous research and development by the industry and academia under the strongly support from Chinese government. In order to complete independent technology development and play a leading role in the global TBM market, the strategy of China has a good reference value for Korea. The history of TBM technology in China was reviewed, and the major research projects and achievements were summarized. Finally, through the implications from the Chinese case, the research and development of TBM technology in Korea and its future research topics were discussed.

Key words : Chinese TBM technology, TBM manufacturer, Shield TBM

Introduction

Along with the booming of China's economy, the rapid urbanization in China has propped up the demand for the development of urban transport systems (Hong, 2015; Hong, 2017; Wang, 2017). Since the first subway was built in Beijing in the 1960s, a total of 32 cities in China opened rail transit operations with a mileage of 4,750 km by the end of 2017 (including maglev and tram). At present, 53 cities have set subway construction plans with a planned mileage of 9,000 km. It is expected that 6,000 km of operating mileage will be achieved by 2020. In addition, to ensure the sustainable development of urban cities, the Chinese Government has actively promoted the construction of utility tunnels. A total of 69 cities in China are building utility tunnels with the total length of 1,000 km, and the construction cost is estimated to be 88 billion (RMB) (Yang and Peng, 2016).

TBM is usually categorized into shield TBM and open (or gripper) TBM. Shield TBMs have been mainly used for soft soils and composite formations, where the applications

are mostly subways and cross-river tunnels. Open (or gripper) TBMs are mainly used for mountain tunnels and diversion tunnels in hard rock formations. This paper will mainly focus on the development of shield TBM manufacturing technology in China.

In the context of huge domestic transportation construction markets, the demand for TBM manufacturing is high and thus, the Chinese TBM industry is growing at a high rate. According to the statistics from the China Construction Machinery Association (CCMA), the total sales of TBM (in number of units) in 2016 increased by 46% year-by-year (Fig. 1). In 2017, China has become the largest manufacturer and the largest market of shield TBM in the world (CCMA, 2018). The Chinese shield TBM market will grow to a scale of approximately 7 billion (RMB) by 2020 (Hong *et al.*, 2013).

Recently, Chinese TBMs have become popularized and have rapidly occupied the domestic market while gradually entering the global market. The TBM industry of China has successfully transformed from "assembled in China" into "made in China" (Chen *et al.*, 2016). The remarkable progress of Chinese TBM technology is based on independent innovation. A number of competitive Chinese TBM manufacturers have emerged including the six-largest TBM manufacturers: China Railway Engineering Equipment Group (CREG), China Railway Construction Heavy Industry

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(CRCHI), Shanghai Tunnel Engineering Co. (STEC), Liaoning Censcience Industry (LNSS), Northern Heavy Industries Group (NHI), and China Communications Construction Company TianHe Mechanical Equipment Manufacturing Co. (CCCCTH). They have captured more than 80% of the Chinese market share. The sales of major TBM manufacturers in 2016 is shown in Fig. 2.

History of TBM technology of China

The development of TBM manufacturing technology of China has gone through three stages (Chen and Zhou, 2017), namely, “early stage (1953-2002)”, “technology innovation stage (2003-2008)” and “rapid development stage (2009 to date)”.

In the “early stage (1953-2002)”, the development of TBM technology mainly focused on several subway construction projects in big cities including Beijing, Shanghai and Guangzhou. STEC played an important leading role in the development of Chinese TBM technology in this period. The hand shield TBM, blade shield TBM, Earth Pressure Balance (EPB) shield TBM were developed in this period.

In the “technical innovation stage (2003-2008)”, with the support from the “863 Program (National High-tech R&D Program)”, some key research projects were funded by the Ministry of Science and Technology of China (Table 1). Furthermore, through the introduction of advanced technology from abroad, China has developed TBMs with fully independent intellectual property rights narrowing

Fig. 1. Total sales of TBM (in units) in China for the period between 2012 and 2016 (from CCMA homepage).

Fig. 2. Total sales of TBM (in billion RMB) by major TBM manufacturers in China in 2016.

Table 1. TBM related research topics supported by the “863 Program” (from Ministry of Science and Technology of China homepage)

Research title	Leading research unit	Research period
Design and manufacture of full-face TBM	STEC	2002-2005
Key technology of cutterhead and hydraulic drive system of shield TBM	China railway tunnel group	2003.01-2004.12
Key technology of cutting and measurement-control system of shield TBM in mixed ground	China railway tunnel group	2005.07-2006.09
Design of large diameter slurry shield TBM	China railway tunnel group	2005.07-2006.12
Design and manufacture of main bearing of EPB shield TBM	LYC bearing	2007.08-2010.08
Design and manufacture of high power reducer of EPB shield TBM	CITIC heavy industry	2007.10-2010.08
Design and manufacture of heavy-duty hydraulic pump in EPB shield TBM	LiYuan hydraulic	2007.10-2010.08
Comprehensive experimental platform of shield TBM	NHI	2007.10-2010.08
Development of the prototype of mixed shield TBM	China railway tunnel group	2007.10-2009.09
Development of the prototype of large diameter slurry shield TBM	STEC	2007.10-2010.08
Research and application of key technology of large diameter hard rock TBM	CRCHI	2012-2017
Study and development on full-face tunnel boring general technology	Zhejiang University	2012-2017

Table 2. Shield TBM related research topics supported by the “973 Program” (from Ministry of Science and Technology of China homepage)

Research title	Leading research unit	Research period
Basic scientific challenges in the design and manufacturing of large full-face TBM	Zhejiang University	2007.7-2011.8
Basic research on the digital design of cutterhead and cutters based on high performance rock cutting	CREG	2010-2012
Basic research on intelligent control and support software for the whole process of TBM safe and efficient tunnelling	CREG	2010-2016
Study on the measurement and control method of electro-hydraulic system and system integration	CREG	2012-2013
Key fundamental issues of Hard Rock Tunneling Equipment	Zhejiang University	2013-2017
Interaction mechanism and safety control between TBM and the deep mixed ground	Wuhan University	2014-2018
Basic research on the safety of shield tunneling in the Yangtze river with high water pressure	Beijing Jiaotong University	2015-2019

the gap between Chinese and international levels Chinese TBM manufacturers developed their own technologies for the design of different types of TBM.

Based on the huge domestic shield TBM market, TBM technology of China entered the “rapid development stage” since 2009. Many research projects on TBM manufacturing and tunneling technologies were supported by the “973 Program (National Basic Research Program)” as listed in Table 2.

For decades of effort and development, major breakthroughs and achievements were successfully made in the

development of key core technologies in shield TBM manufacturing and mechanized tunneling. Some notable shield TBMs made by Chinese manufacturers are listed in Table 3 and shown in Fig. 3.

Research trend of TBM technology in China

In recent years, research on TBM technology has become very popular in China. The number of publications related to TBM technology during the past two decades is

Table 3. List of some notable shield TBMs made by Chinese manufacturers

Manufacturer	Year	Type	Project	Remark
CREG	2015	EPB	Tianjin Metro Line #11	Largest rectangular shield TBM with cross-section (10.42 m × 7.55 m)
CREG	2016	EPB	Baicheng Tunnel, MHT J-3 Section	First horseshoe-shaped shield TBM in the world
CREG	2017	Slurry	Shantou Bay Tunnel Project.	Largest slurry shield TBM in China (φ15.03 m)
CRCHI	2013	Dual mode	Shenhua Xinjie Coalmine Inclined Shaft Project	For long distance and high slope angle of inclined shafts in coal mine, first in the world
CRCHI	2016	Slurry	Yuji Intercity Railway Project	First large diameter slurry shield TBM in China (φ12.77 m)
CRCHI	2016	EPB	Taiyuan Railway Hub Southwest Loop Project	Largest EPB shield TBM in China (φ12.14 m)
CCCCTH	2010	EPB	Shanghai Metro Line #12, Section 26	For Deep buried high water pressure tunnel under Yangtze River
STEC	2015	EPB	Ningbo Metro Line #3	Largest quasi-rectangular shield TBM in the world
NHI	2011	Slurry	Esfahan Cable Tunnel in Iran	First micro slurry shield TBM (φ3.14 m)
LNSS	2015	EPB	Chengdu Metro Line #4, Section #6	Highest tunneling efficiency of 555 m/month in cobble-boulder ground in Chengdu

Dual-mode shield TBM by CRCHI
(φ 7.62 m) (Chen and Zhou, 2017)

Horseshoe-shaped shield TBM by CREG
(11.9 m × 10.95 m) (Li, 2017)

Rectangular pipe-jacking machine by CREG
(10.12 m × 7.27 m) (Li, 2017)

Quasi-rectangular shield TBM by STEC
(11.83 m × 7.27 m) (Chen and Zhou, 2017)

Fig. 3. Some notable shield TBMs made by Chinese manufacturers.

presented in Fig. 4(a). Based on the statistics from the China National Knowledge Infrastructure (CNKI), it can be found that Tongji University, China Railway Tunnel Group, and Southwest Jiaotong University are the most active research institutes in China (Fig. 4(b)). TBM related

journals are listed in Fig. 4(c) and “Tunnel Construction” which is the most widely renowned journal in China. The research subjects in TBM technology are shown in Fig. 4(d), where settlement, cutter, grouting techniques are research hotspots. Although these publications are mostly

(a) Publications related to TBM technology

(b) Number of publications by top 10 Chinese research institutes

(c) Top 10 Chinese journals with the marked number of publications

(d) Nine major research subjects related to TBM technology

Fig. 4. Research trend of TBM technology in China for the past two decades.

published in Chinese which are difficult to access for Korean academics and industries, they are still worth referring to for our future research in TBM tunneling field.

With the increasing and wide application of TBMs, the TBM tunneling techniques have greatly evolved in China (Wang, 2014). The relevant content of TBM tunneling techniques will not be covered in this paper. However, some typical cases where key techniques of TBM tunneling in difficult (or complex) ground conditions can be found such as for mixed ground (Liao, 2012; Wang, *et al.*, 2016), cobbly-bouldery ground (Yang *et al.*, 2011; Le *et al.*, 2012; Sun *et al.*, 2017), super long tunnel with large diameter TBM (Deng, 2016; Wang, 2017), high geo-stress region (Fang *et al.*, 2013; Song and Zhao, 2017), and underwater tunnel with high water pressure (Xiao, 2018; Zhu *et al.*, 2018).

State Key Laboratories (SKLs) in China

To solve the technical challenges and ensure efficient TBM tunneling in complex geological conditions, China has increased the investment for TBM manufacturing and tunneling technology. Some specialized and professional research institutes have been established to carry out relevant research projects of TBM technology funded by the government.

Two state key laboratories have been established for the development of TBM technologies. The ‘State Key Laboratory (SKL) of Full-Face Rock TBM’ which belongs to NHI was founded in 2004. This laboratory has a series of advanced test facilities including a multifunction test system of TBM (Fig. 5).

The ‘SKL of Shield TBM and Boring Technology’ operated by CREG was set up in 2010. Since then, the laboratory has won a total of 35 scientific and technological achievements, including the first prize of State Science and Technology Progress Award in 2012. Some experimental facilities of the laboratory are shown in Fig. 6. Currently, three main research topics have been set:

- (1) Cutterhead and cutting tool technologies: to make the design of cutterhead and cutting tools to accommodate different geological conditions; to study the key technologies of cutter geological adaptation; to establish the theory of high-efficient rock breaking for cutterhead and cutters; and to develop industry

standard for cutting tool design and manufacturing.

- (2) Control technology of shield TBM tunneling: to establish the information management system of shield TBM tunneling which can provide technical advice and technical service for tunneling projects.
- (3) System integration technology: to develop the machine integration and control technology; and to develop remote automatic diagnosis system and intelligent decision system.

Unique achievements and future plans of Chinese TBM technology

Through the consistent effort from the Chinese TBM industry and academia, many unique advanced technologies have been developed including (1) New driving technology (such as permanent magnet synchronized driving technology and electro-hydraulic driving technology), (2) cutterhead and cutter repair technology (such as replacement of cutter tools under atmospheric pressure and robot-assisted detection and repair technology), (3) rapid muck removal technology (such as high-efficiency crushing technology of large boulders), and (4) adaptive technology for non-circular sections (Zhao and Chen, 2013; Chen *et al.*, 2016; Wu *et al.*, 2016; Chen and Zhou, 2017; Li, 2017).

The main development trends in the future are as follows:

1. Chinese TBM manufacturers are developing miniature TBMs for a build-up type shield TBM (several miniature TBMs to be assembled together). CREG has already applied a prototype machine to the construction of an underground parking lot.
2. TBMs for great depth with high geo-stress, high water pressure, and for large-diameter tunnels are under development to accommodate diverse demand for efficient tunnelling.

The adaptability of TBMs in the complex and difficult geological conditions, robustness of TBMs, and reliable cutter life would be even more demanding in the future (Wang, 2014; Liu *et al.*, 2015). The long-term vision of Chinese TBM technology is to realize more efficient and automatic design, modular manufacturing, remote and intelligent monitoring, controlling and maintenance of TBMs.

(a) Multifunction test rig

(b) Multifunction testing TBM ($\phi 3.2$ m)**Fig. 5.** Multifunction test system of TBM in the State Key Laboratory (SKL) of NHI.

(a) Experimental platform of engineering structure

(b) Rotary cutting platform

(c) Disc cutter testing platform

(d) Comprehensive experimental platform

(e) Intelligent big data platform for TBM tunneling site

Fig. 6. Experimental platforms in the State Key Laboratory of CREG.

Conclusions

China is the country that has the most tunneling projects in the world at present. Based on the diverse projects, the TBM manufacturing industry of China has rapidly grown in the past decades. Narrowing down the technological gap with advanced countries, the Chinese TBM industry still has tasks in enhancing the reliability of TBMs, independent technological innovation, and development of more intelligent design and manufacturing methodologies.

From the Chinese history of TBM technology development, some implications and beneficial enlightenment can be attained. TBM industry is technology- and capital-intensive. It requires huge initial capital investment and many engineering projects to apply its technologies. The Belt and Road Initiative (BRI) and strong governmental support made the Chinese TBM industry viable. Manufacturers have been working together with research institutes and universities in many projects. It is worth noting that the technical development could not be made without diverse tunneling projects, feedbacks from job sites, and modifications of the technologies.

TBM industry of Korea is small in size due to the limited number of national tunneling projects and the preference of cost-effective drill-and-blast tunneling over TBM tunneling in many cases. On the contrary, the Korean government has supported R&D projects for the development of core technologies in TBM design, subsea and utility tunnels by TBMs. In case that the government and the potential manufacturers are interested in TBMs, the Chinese history of TBM technology development will make an excellent case to refer to.

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