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Revista Ingeopres. Año 2000

Publicación:

"La excavación mecánica de túneles en terrenos blandos y su evolución histórica"

(inglés)

TUNNEL MECHANICAL EXCAVATION IN SOFT GROUND AND ITS HISTORICAL EVOLUTION

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SUMMARY: This report presents several historical notes about the technological revolution accomplished by mankind all along its development, in order to reach higher efficiency in the excavation of rocks and grounds in order to build tunnels. The great technological impulse begins in the Industrial Revolution (18^{th} and 19^{th} centuries). The first Brunel circular shield appears in 1818. During the 1860s we come across an important development in slurry and earth pressure shields in Japan (IHI, Mitsubishi and also European manufacturers such as Wayss Freetag, Herrenknecht). At the beginning of the 21^{st} century the use of the pressure shields is widely developed.

1. INTRODUCTION

Right from the beginning, people have come across the need of using the natural subterranean places as their habitat.

The small rural societies that developed mainly in Egypt and Mesopotamia (3,000 B.C) needed for their development, mainly agricultural, to accomplish water canalization works in order to carry this water to the cultivated areas and to dry great marshy ground extensions. Therefore, they faced the need of excavating not only hard rocky materials but also soft clay ones.

2. HISTORICAL EVOLUTION

All throughout its evolution, mankind has developed and used, according to its level of development, different techniques of increasing efficiency in the excavations of rocks and grounds.

Within this technological evolution we focus on several advances:

- **8^{TH} CENTURY:** The Arabs discover the gunpowder.
- **1690.** Widespread use of gunpowder for civil uses until 1850 approx.
- **1814.** First steam locomotive.
- **1844.** First air hammers (Brunton).

- **1847.** Discovery of nitroglycerine.
- **1861.** Use of hammer drills in Mont Cenis tunnel (12.8 km).
- **1875.** Discovery of gelatine dynamite (Alfred Nobel).

Simultaneously, the Industrial Revolution, which originated in the 18th century in England, takes place in Europe and the United States in the 19th century,. It is a technological and scientific revolution.

- **1818**. We see the appearance of the first patent of a circular shield by M.I.Brunel, covered with bolted cast iron segments. It was used in the first tunnel under the river Thames in London, (Table 1). As it was an underwater tunnel built in soft ground, its construction brought about several problems derived from the instability of the front, and the flood of the tunnel as a consequence of the water filtration through surrounding ground of the river Thames.

Table 1.- PRESSURE SHIELDS HISTORICAL EVOLUTION

YEAR	INVENTOR/ MANUFACTURER	TYPE OF MACHINE	PROJECT	REMARKS
1818	M.I. Brunel	Circular shield, lining with bolted cast iron segments.	1st tunnel under the river Thames.	Technical problems. Water inflow in tunnel.
1828	Colladon			Proposal of compressed air instead of Brunel shield. Compressed air properties still unknown.
1831	Lord Cochrane			Proposal of using compressed air to stabilize the front.
1861		Use of airlift drills.	Mont Cenis tunnel (12.8 Km.).	
1864	P.W. Barlow			Patent space injection between ground and segment.
1874	J.H. Greathead			Proposal of transportation of hydraulicly excavated products, previously converting them into mud.
1874	J.H.Greathead	Design of a shield that uses compressed air to stabilize the front in its upper part.		Never used.
1874	H. Lorenz			Proposal of stabilisation of the excavation front, applying pressure on this, a mixture of bentonite and water.
1879	De Witt Haskins		Tunnel under the river Hudson. New York.	First use of compressed air without shield. 5.5 m x 4.9 m section. Air section: 2.4 bar. Air leaking through the upper mud.
1879	De Witt Haskins		Antwerp Docks Tunnel.	First use of compressed air without shield. 1.5m x 1.20m section. Cast iron segments.
1959/60	C. Gardner	Slurry shield "Teredo".		
Años 60		Development of modern partial face machines and road heading machines.		
1961	Campenon Bernard	Use of compressed air confined to be the front compartment of a rotary mechanized shield.		The staff does not work in a pressurized atmosphere.
1963	Sato Kogyo Company	First design of earth pressure balance shield.		

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YEAR	**INVENTOR/ MANUFACTURER**	**TYPE OF MACHINE**	**PROJECT**	**REMARKS**
1964	Robbins Company	Shield with rotary star head, 10.30m diameter, with air compressed Pressure front chamber.	Paris underground.	The staff does not work in a pressurized atmosphere.
1965		Slurry shield, partialy pressure machine.	Research project.	
1966	Ishikawajima-Harina Heavy Industri Co. Ltd. (IHI)	Construction of the first earth pressure balance shield. Prototype shield.		
1967	Kajima-Kensetu	Prototype slurry shield.	Built and tested	
1967	Markham	Shield with pressure water, up to 3 bar, mixed with excavated mud.	Mud sewage tunnels under Mexico D.F. Diameter, 6 m.	
1970	Mitsubishi Heavy Industries	Slurry shield, 7.29 m diameter.	Rail tunnels in Tokyo Bay.	The first machine started to drill in 1969. Works stopped. The second machine strarted to drill in 1970, in 40m it was trapped and abandoned.
1971	Robert L. Priestley Ltd.	Experimental slurry shield, 4.10m diameter with a maximum pressure of 2 bar.		Start mass-production of slurry shields (SS).
1974	Wayss and Freytag. Aktiengesellschaft	Construction of 1st hydroshield, 4.80m diameter.	Sewage tunel, Hamburg. 4.6 Km.	
1981	Mitsubishy	First articulated earth pressure balance shield, 3.68 diameter.		Sand and gravels under hydrostatic pressure of 1.6 bar.
1984	Kawasaki	Slurry shield to excavate ground with hydrostatic pressure, and in rocks.		
1984	IHI	First rectangular tunnel.		
1985	Wayss and Freytag. Herrenknecht	Mixshield.	HERA project, Hamburg, 6.3 Km and 5.95 m. diameter. Sandy ground of thin and medium grain and pebbles.	
1985	Mitsubishi Heavy Industries	First earth pressure balance shields to excavate also in rocks.		Hydrostatic pressure: 1.2 bar. Performance: 18m /day; 6m /day with pebbles.
1987	Kawasaki	Multiface slurry shield, with partial overlapping. (H/V type).	Double-way rail tunnel, Tokyo.	
1987	IHI	First double "o" tube slurry shield.		
1988	IHI	Articulated slurry shield designed to excavate inclined and bend tunnels with 5.24 diameter.	Electric wiring tunnel, Tokuichi-kansen.	Length: 2395m. Inclination: 15°. Minimum radius: 20 m.
1989	Herrenknecht AG	Convertible mixshield slurry shield. Rock/ground. Diameter: 11,60 with retractable head (600 mm).	Grauholz rail tunnel, Bern, 5.5. Km.Túnel ferroviario de Grauholz, Berna, de 5,5 Km.	

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YEAR	**INVENTOR/ MANUFACTURER**	**TYPE OF MACHINE**	**PROJECT**	**REMARKS**
1989	Herrenknecht AG	Mixshield slurry shield, articulated and convertible, ground/rock, 11.60m diameter.	Grauholz rail tunnel, Bern, 5 Km.	Innovations: -Crushes central rock. -Retractable head. -Bentonite primary treatment plant located inside the tunnel.
1990	Kawasaki	Start of development of shields with several heads.		
1992	Herrenknecht AG	Convertible mixshield slurry shield. Ground/mud. Diameter: 8.30 with independent central microshield, diameter 1.20m.	Essen Underground, length 2x2.1 Km.	
1992	IHI	First earth pressure balance shield with rotating shield technology.	Sewage tunnel under the river Kannon, Kawasaki.	Clayey ground.
1993	IHI	Design and construction of earth pressure balance shields. Design: NOMST and DPLEX.		NOMST. DPLX to excavate rectangular or oval sections.
1994	IHI	Slurry shield. "Nesting parent-shield" method.	Teito Rapid Transit Autohority Subway Line 7	Shield of 14.18m and 9.70 m diameter.
1994	IHI	"Kurun" method	Nippa-Sueho sewage tunnel, 4435m and 9.45m diameter.	To excavate long and deep tunnels with strong hydrostatic pressure.
1994	IHI	"Derun" method		To make inclined or vertical drillings from an existent tunnel.
1994	Mitsubishi Heavy Industries	Slurry shield with three circular heads of 17,44 m. x 8,85 m.	Lidabashi station. Line 12. Tokyo Underground.	Hydrostatic pressure: 5 bar. Sand and gravels with artesian waters. Clay.
1994	Kawasaki	Multi circular slurry shield with three heads.	Lidabashi station, Tokyo.	Excavation total width: 17.440 m. High: 8.84 m.
1995	IHI	Earth pressure balance shield with high performance mud injection; diameter: 5.81m.	Hydraulic tunnel, Kasunigaura.	Efficiency: 20 m./day, excavation and segments placement simoultaneously.
1995	Kawasaki	"Parent-shield". Slurry shield.	Takai-Matsubara cable tunnel. Bashi, Tokyo	Main tunnel: 7.27 m diameter. Secondary tunnel: 5.00 m diameter.
1996	Miitsubishi Heavy Industries	Multi-head circular slurry or earth pressure balance shields.		
1996	IHI	Multi-micro shield (MMST)		For very large rectangular excavations.
1996	Kawasaki	Detachable three section slurry shield	Tokyo underground. Line 7	Width: 15.84 m. High: 10.04 m.
1997	Kawasaki	Multi-micro-slurry shield (MMSST)	Air-conditioning tube for the road tunnel undert Tokyo bay.	
1997	Kawasaki	"Twister" slurry shield with joint circular heads.		Contiguous sliding shields of variable relative position.
1997-1998	Kawasaki	Murticircular slurry shield with four heads.	Tokyo underground. Line 7	Width: 13.18 m. High: 7.06 m.

Consequently, this posed the difficulty of building tunnels in soft ground under hydrostatic pressure.

While building the first tunnel under the river Thames, it was considered the use the compressed air to counteract the hydrostatic pressure and avoid water filtration (Colladon-1818, Lord Cochrane-1831).

From the construction of the first shield, we see the need of a technological development towards a shield that allows the excavation of tunnels in unstable ground under hydrostatic pressure.

The historical evolution of pressured shields is shown in chart 1. Its most important milestones are:

- **1874,** J.H. Greathead designs the first shield which uses compressed air as front stabiliser fluid. This shield would never be used.
- **1874,** De Witt Haskins uses compressed air at 2,4 bar for the first time to build the tunnel under the river Hudson, in New York and the Antwerp Docks tunnel, using bolted cast iron segments.

Simultaneously to the use of compressed air, other front stabilisation techniques will be taken into account:

- **1874.** H. Lorenz suggests using bentonite mud against the excavation front.
- **1896.** H.H. Dlarymple. First use of clay in order to stabilize the front in non-cohesive ground. This idea is considered to be the forerunner of earth shield designing, very much developed, especially in Japan.

From the end of the 19th century until the 1960s, the development of pressure shields, had a sudden halt of more than 70 years. From this date on, new shield designs with the latest technological advances emerge.

- **1959-1960.** A giant leap in design and construction of pressure shields is achieved, accomplishing the building of the slurry shield "TEREDO", designed by C. Gardener, and used in the excavation of a tunnel in Houston, Texas.
- **1963.** Nevertheless, the biggest technological advance in the design and construction of pressure shields is made in Japan, from 1963. Japanese techniques develop methods of stabilisation by means of bentonite mud applied under pressure against the front –this technique is used in the slurry shields; and also by means of the pressure put on by the materials excavated against the front, with a mechanical confinement of those materials, and by the controlled evacuation of the working camera of these materials – this technique is used in the earth pressure balanced shield.
- **1966.** The company Ishikawajima- Harina Heavy Industry Co. Ltd (IHI) builds the first Earth Pressure Shield (research phase).
- **1967.** The company Kajima- Kensetu builds and tests slurry shields (SS).
- **1970.** Mitsubishi Heavy Industries starts the mass production of slurry shields.
- **1984/1998.** Biggest rise in the production of earth pressure shields in Japan, manufacturing 332 shields.

At the same time, the production of pressure shields starts in Europe, although in a lower scale. These are the most important landmarks:

- **1967**. The British company Markham builds a slurry shield, made by the mixture of materials excavated with water at a pressure of 3 bar. Two of these machines even worked in the drainpipes of Mexico D.F.
- **1971**. The British company R.L. Priestley builds an experimental slurry shield, working at a pressure of 2 bar.

However, the real inrush of the European technology in the building of pressure shields takes place in 1974.

- **1974.** The German company Wayss Freytag Aktiengesellschaft builds the first hydroshield, successfully used in a sewer in Hamburg.
- **1985.** The German companies Wayss-Freytag/Herrenknecht build the first mixshield. This type of shield conveys an important contribution, embodying all the techniques available at that time (compressed air, mud and the excavated ground itself).
- **1989.** The company Herrenknecht, following the development of the mixshield, builds the first convertible shield which can work in different varieties as earth pressure shield, slurry shield, compressed air shield and tunnel boring machine. It is a very versatile shield that allows to change the mode of operation with small modifications made in the same tunnel. **(Figure 1)**

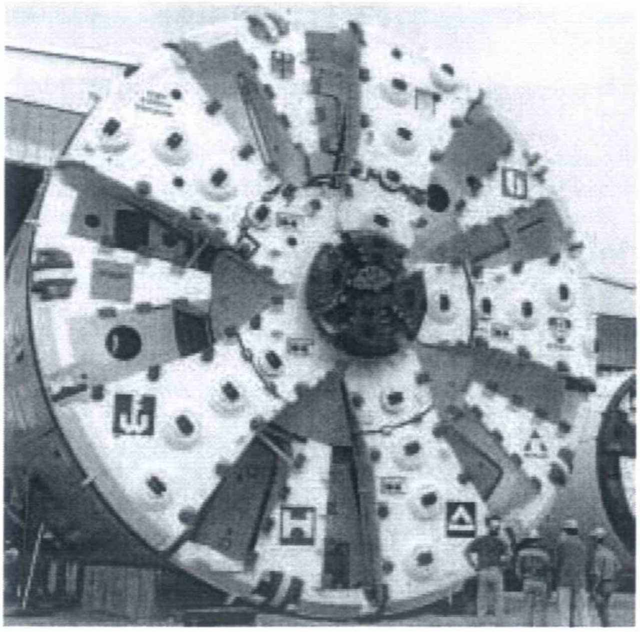

Figure 1. MIXSHIELD (Ø14.20 m.), 4° ELBE TUNNEL

- **End of the 1980s.** In the developed countries and in Europe in particular, the projects related to the construction of underground lines in cities with more than 1 million inhabitants increase considerably.

In 1990, the use of pressure shields reaches the excavations of stations and sewer networks, cable networks and service galleries.

One of the main objectives is to lower the price of the subterranean works, increasing their level of safety at the same time.

The main stages in the recent development of pressure shields during the last decade are shown in table 1. Among them we may find:

- **1987.** First double "o" shield (DOT), manufactured by the Japanese company IHI.
- **1990.** Design of multi-head circular shields in Japan.

* **1994.** Mitsubishi and Kawasaki build three-head circular shields for the construction of stations in the Tokyo underground.
* **1992.** A new generation of pressure shields starts being made in Japan in order:

  a) Allow new applications
  b) Use a basic machine design with several detachable elements that make it easy to extend the field of application, economising on the inversions.
  c) Improve the safety in unstable ground with hydrostatic pressure.
  d) Increase the excavation outputs and the resistance to the detrition of the different elements of the machine. This new technology has been devised by the Japanese company IHI, with the following fulfilments.

* **1992**. Construction of a rotating shield. (Table 1.3.).
* **1993**. Construction of earth pressure shields, NOMST and DPLEX design, (table 1.3).
* **1994**. Construction of nesting parent shields which allow excavations in right angle or in the same direction with a different diameter. **(Figure 2).**

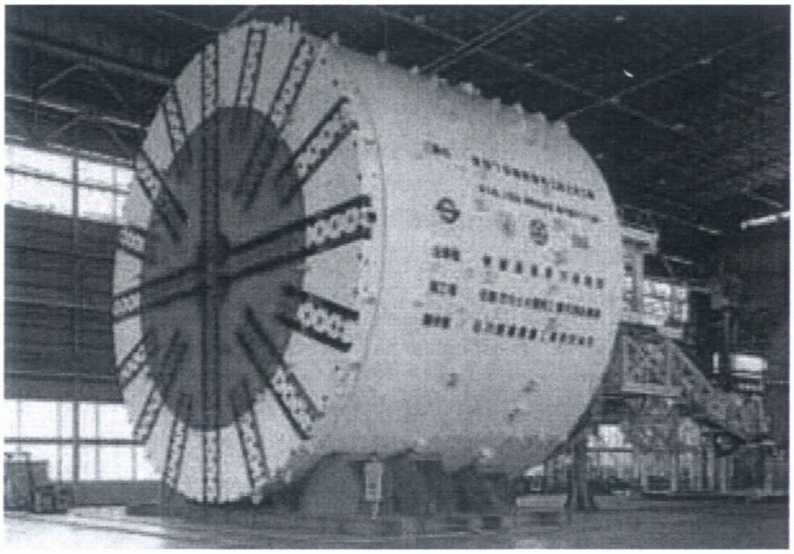

Figure 2. PARENT-SHIELD TYPE. (Ø14.18/9.70 m.), TOKYO METRO

* **1994**. Development of shields "Kurun" and "Derun" (Table 1.3).
* **1995**. Development of earth shields, with mud or polymer injection, high performance, designed to get a high rhythm of advance and lining placement. As regards the last four years of the 20th century there have been many designs of earth pressure balance and multi-head circular slurry shields that allow the fulfilment of rectangular excavations, and contour excavations of subsequent ones. The shape of these shields can be adapted to the specific needs, using shields and microshields of different diameters.

Some examples of this are:

* **1996**. Mitsubishi and Kawasaki build multi-head circular slurry and earth pressure balance shields. **(Figure 3).**

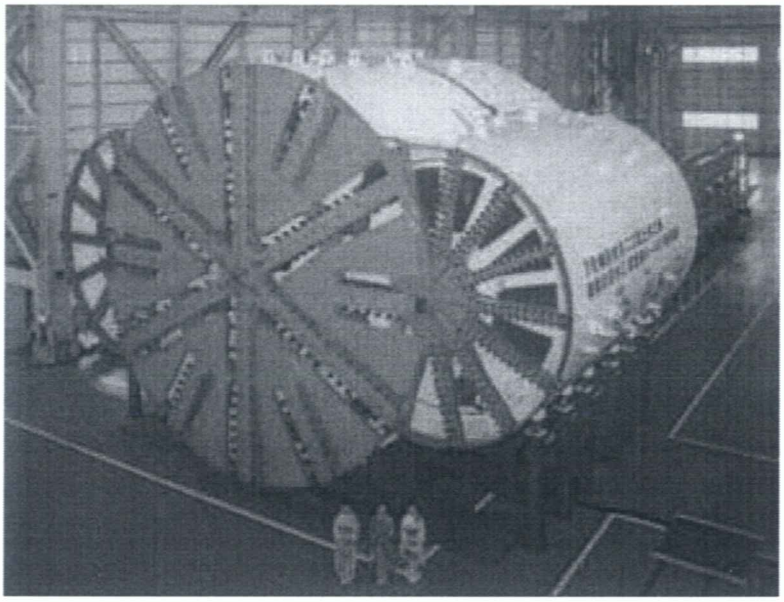

Figure 3. TRIPPLE-HEAD SHIELD (15.80x10 m.), MEGURO STATION, TOKYO METRO

- **1996**. The company IHI builds a multi-microshield (MMTS).
- **1997**. The company Kawasaki builds "Twister" type shields which slide one over the other, being able to adapt any position in space.

Finally, in **table 2** we can find the complementary techniques that have had a bigger influence in the technological development of pressure shields.

Table 2.- HISTORICAL REFERENCE:
INCORPORATION OF MOST IMPORTANT TECHNIQUES
IN THE TECHNOLOGICAL DEVELOPMENT OF PRESSURE SHIELDS

YEAR	INVENTOR/ MANUFACTURER	ELEMENT	REMARKS
1864	P.W. Barlow	Proposal of filling the annular space between lining and ground.	
1869-1870	J.H. Greathead	Invention of transversal diaphragm, lock and segment erector.	
1896	H.H. Dalrymple-Hay	Use of clay for the first time to stabilize the front.	Forerunner in earth pressure balance shield design.
1973	Tekken Kensetu. Const. Comp. Ltd. and MitsubishiI	Automatic system in slurry shields control.	
1975	Mitsubishi	Incorporation of a trommel in a slurry shield, 3.55m diameter.	To excavate a hydraulic tunnel in gravels in Tokyo.
1976		Mud injection in earth pressure balance shields.	Research phase.
1979	Mitsubishi	Stone crusher added to a slurry shield.	Excavation of gravels and ground with rocky areas.
1980	Mitsubishi	Use of cutter disks in slurry shields.	
1980	Kawasaki	Electric drive in a slurry shield.	

Table 2.- HISTORICAL REFERENCE: INCORPORATION OF MOST IMPORTANT TECHNIQUES IN THE TECHNOLOGICAL DEVELOPMENT OF PRESSURE SHIELDS			
YEAR	**INVENTOR/ MANUFACTURER**	**ELEMENT**	**REMARKS**
1980	Kawasaki	Slurry shield head with intermediate beam system.	
1981	Kawasaki	"Rotary feeder" in an earth shield.	
1981	Kawasaki	Type 150 sealing system of shield head central bearing.	
1981	IHI	Earth shield with mud injection.	
1982	Kawasaki	Double body rotatory stone chrusher.	
1982	Kawasaki	"Copy cutter" cutters.	
1983	Kawasaki	"Over cutter" cutters.	
1984	Mitsubishi	Use of thick mud in earth shiels.	
1984		Earth shield with foam injection.	
1984	Kawasaki	"Ribbon" screw feeder, rotatory discharge.	
1985	IHI	Segment erector automatic system.	
1985	Kawasaki	Electric drive in earth shields.	
1986	Kawasaki	Articulated earth shield.	
1986	Kawasaki	Control automatic system in earth shields.	
1986	Kawasaki	Design of dome heads.	To excavate in gravels area.
1987		Use of polymers in earth shields.	Research phase.
1990		Use of foams in earth pressure balance shields.	Lubricant effect. Floor conditioning effect, increasing impermeability.
1990	Mitsubishi	"Docking movable hood"	When using two shields simultaneously from the two external entrances.
1993	Nishitake et al		
1994	Reda	Use of polymers and conditioners.	Extension of the utilities of earth pressure balance shields.
1995	Ishimoto et Al.		

3. CONCLUSION

The historical evolution of the technological development applied to the pressure shields has been continuous since 1818, although in some periods of time this technological development has been more intense. It originated in 1963 in Japan, and kept consolidating since 1970, reaching its first peak between the years 1984 and 1998.

Simultaneously in Europe, this technological development originates in 1967, although the periods of a faster technological advance are the years 1974 (hydroshield), 1985 (mixshield) and 1989 (convertible shield).

The consolidation of a European technological development is produced from 1985 when the German company HERRENKNECHT plays an important role in the mass production of its pressure shields.

In this last decade, from the year 1990, the technological development has improved considerably with the inclusion of multi-head shields.

In the beginning of the 21st century we are witnessing a rising demand of pressure shields as the consequence of the different subterranean projects, mainly urban which are being developed or planned to be so in a near future.

This demand of machines guarantees a continuous technological development in the following years that, with no doubt, will allow us to use more efficient, versatile and security-effective machines.