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Precision drilling for D&B and bolt installation: Analysis of relevant case histories

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ABSTRACT: A drilling jumbo is machine that has seen, along the last decades, some major evolutions as the introduction of accurate sensors in order to define the exact boom positioning, everything integrated with an automatic drilling PLC able to find and realize the exact holes, data recording and restitution, data analyser with even geological interpretation of the rock mass worked out, high frequency drifters and heavy duty undercarriage for a long life in the hard environment where frequently are used. The paper presents examples from relevant case histories: the tunnels to be constructed with partial sections in heavy congestioned urban areas as Metro Paris, drilling contemporary steel sub-horizontal umbrellas and radial bolts in faulty zone as in Brenner, installing long cable bolts or CT-Bolts automatically injected as in Sydney, drilling and splitting for launching shafts in granite as in Hong Kong.

1 INTRODUCTION

The new generation of fully computerized drilling jumbos have been designed and built with the intention to provide the Owner and the Tunneling Contractor with an efficient, Industry4.0 and safe tunnelling tool. The main improvements, tested and proved through various worldwide case histories, can be expected as follows:

- More accurate profile, which means less over blast, less damage to the surrounding rock, reduced support work, substantial concrete saving (in case of final lining).
- Excellent tool for drill pattern optimization and subsequent optimization of the explosives consumption.
- Facilitates longer rounds for water drainage and exploration drilling.
- Complete round documentation available through the logging facilities.

In the papers are presented case histories of examples managed with machine produced by Robodrill. The Company is designing and manufacturing "in series" and "highly customized" drilling equipment for the major worldwide tunnelling general Contractors, working in the 5 Continents. Main components are usually coming from CAT for what is related to the undercarriages, Montabert for the drifters, the robotized system is developed in house as the full system electric-meca-tronic engineering.

2 BOLTING, PIPING AND CABLING

Jumbos are especially known for Drill & Blast procedures but the "world of bolting" is so extended that it's difficult to have an idea and probably it so wider just because the modern

Figure 1. Example of different bolt types which can be installed automatically by the drilling system.

machines are nowadays able to realize operation which previously have been impossible, leading to change the design philosophy linked to the support technology.

Normal jumbos are nowadays able to install, under an optic of industrialized tunnelling, in a very safe way, an incredible number of supports as (Fig. 1):

- Pipe umbrellas
- Combination Tube Bolts
- Cable bolts
- Self drilling spiles
- Grouted and resin bolts

3 CONNECTING SYDENY

The NSW Government is building a complete transport solution, including public transport and road infrastructure to ensure Sydney does not come to a grinding halt; one of them is called "Connex". WestConnex is Australia's largest transport infrastructure project, linking Sydney's west and southwest with the city, airport and port; it is critical to delivering an integrated transport solution to tackle congestion across the city and provides the catalyst for urban revitalisation throughout the corridor.

NorthConnex is a 9 km motorway tunnel under construction in northern Sydney, New South Wales, Australia. About 21 kilometres of tunnelling is being carried out for NorthConnex. The two main nine kilometre tunnels will carry motorists between the M1 Pacific Motorway and the Hills M2 Motorway and additional tunnels are being excavated for on and off ramps.

The deepest part of the tunnel will be around 90 metres, passing under the Sydney Metro Northwest tunnel at Beecroft; more than half the tunnel is more than 60 metres deep.

Robodrill delivered tens (ca. 40) new machines for Northconnex and Westconnex, designed for various applications including shaft drilling, face drilling, canopy tubes, roof bolting, long bolts and cables.

For NorthConnex (Fig. 2) the objectives were:

- 15 min travel time savings for Australians
- Better and more reliable trips
- 21 traffic lights bypassed
- Link M1 Pacific Motorway to the Hills M2 Motorway

Important figures are:

- 9 kilometres tunnel motorway with interchanges
- $3 billion project
- Includes $2.65 billion construction budget
- Tunnel height clearance of 5.3 m
- Max depth of 90 m

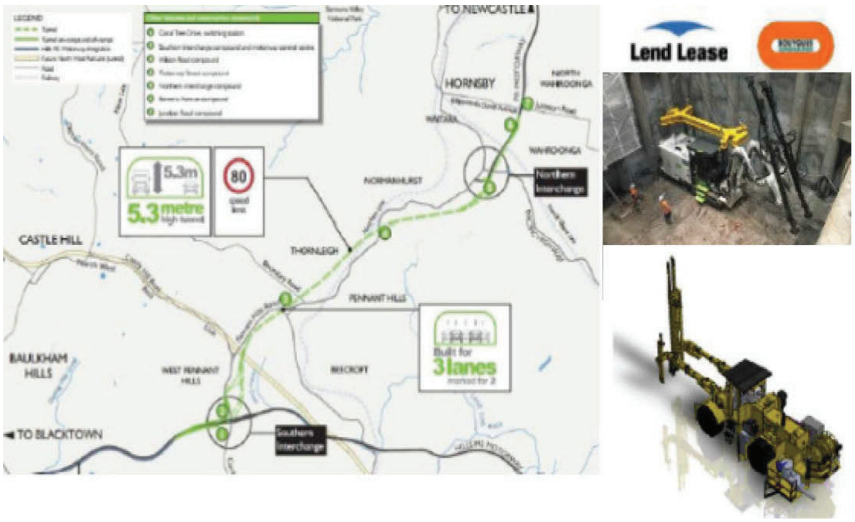

Figure 2. North Connex lay out; shaft jumbo and 3-4-5 m CT-Bolt turret automatic (also injection) jumbo.

Figure 3. West Connex layout; in the pictures the pendular cable jumbo.

For West Connex (Fig. 3) the objectives were:

- Provide quicker and more reliable trips between Western Sydney and the Sydney Airport
- Remove bottlenecks
- Provide a widened M4 from Church Street to Concord Road
- 52 traffic lights bypassed and 40 minutes saved per travel

Important figures are:

- 33 kilometres connection project
- $3.3 billion project

4 NEW YORK: DELAWARE AQUEDUCT BYPASS

The contract will involve excavating a 4 km, 6.7 m diameter, TBM bored bypass tunnel under the Hudson River, between two shafts at Newburgh and Wappinger that are 274 m, 9,14 m finished diameter, and 213 m deep, Φ 9 m, respectively. The tunnel is designed to bypass a damaged section of the Rondout-West Branch Tunnel that is leaking approximately 56 to 130 million

litres of water per day into the Hudson River. The project consists of two contracts, BT-1 and BT-2, for construction of the two new deep shafts and the bypass tunnel to replace an existing section of the Delaware Aqueduct, New York's leading source of drinking water (Fig. 4).

The order is placed by the Kiewit/Shea Joint Venture contractor. The new deep bypass will prevent leakage of up to 20 million gal/day through the fractured limestone geology of the 72-year-old existing tunnel as it runs under the Hudson River. The tunnel conveys more than half of New York City's drinking water. The contracting authority for the US$1 billion project is the New York Department of Environmental Protection (DEP). Design has been completed in-house.

Full scope of works includes TBM excavation of the segmentally-lined 4000 m long bypass of the Rondout Tunnel; installation of 2800 m of steel interliner along the limestone section of the bypass to prevent recurrence of the leaks; excavation by drill+blast of 46m-long tunnels to connect both the TBM launch and retrieval shafts of the new bypass to the existing tunnel; and grouting work during tunnel drain down in another lesser effected section of the main tunnel some 29 km north of the TBM drive, in Ulster County, New York.

Kiewit/Shea, being on target, started drill & blast excavation of the TBM bell-out chamber in summer 2016 (Fig. 5). This follows completion last month (in March 2016), under a separate US$ 101.6 million contract awarded to Schiavone, of the two deep shafts – 5B and 6B – at either end of the bypass. The chamber has been completed in 2017 ahead of arrival later in the year of the Robbins TBM.

The single shield machine has been launched from the shaft 5B which is situated on the Newburgh side of the Hudson River. From here it will pass 600 ft below sea level, some 100 ft below the river under a maximum anticipated hydrostatic pressure of up to 20 bar, through to the reception shaft on the Wappinger side. The shafts will remain in place following the completion of the TBM drives as permanent access structures.

Just like the original tunnel, the new section will include a steel inter-liner. Critically, however, at 2800 m long (70% of the total bypass length) it will be considerably longer than the previous steel liner so as to prevent a recurrence of the leakage problem. "During original construction in the 1940s, tunnel workers dealt with huge inflows of water coming in at them while they were drilling," said Bosch. "Total inflows were recorded at approximately 2–4 million gal/day, with the largest single section of inflow coming in at roughly 1500 gal/minute. This was inflow from both groundwater and river influence, and managing water will also be a major challenge for this project."

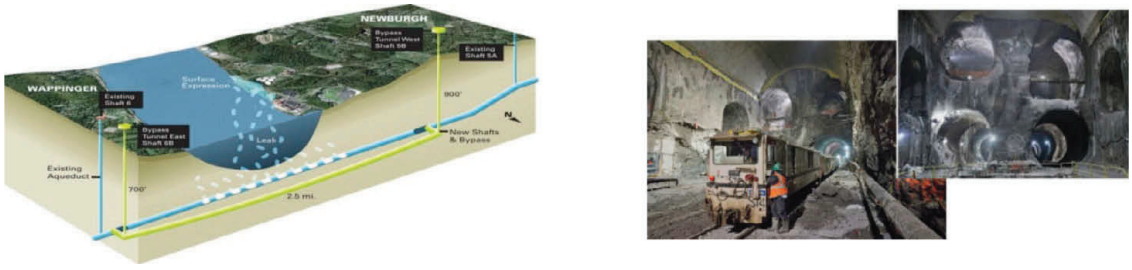

Figure 4. Delaware Aqueduct Bypass Tunnel cross section alignment (at right NY metro, Long Island East Side Access CM019, powered as well by RBDR).

Figure 5. Shaft jumbo able to perform vertical and horizontal drilling operations.

To handle these expected inflows a grout curtain will be installed ahead of the TBM and the contractor will also be prepared to pump out water where necessary. Despite the highly pressurized conditions at the face, hyperbaric interventions are not expected. "We will be relying on drill probes of the ground ahead, installing a grout curtain where necessary ahead of the face, and there are expected to be adequate sections of competent rock in which the contractor can perform maintenance to the cutterhead and the cutting tools in free air," said Bosch.

5 ATLANTA: WATER SUPPLY PROGRAM PHASE 1

PC-Russell, a Joint Venture, has awarded Atkinson Construction an $81 million contract for the Atlanta Water Supply Program Phase 1 Extension. The Phase 1 Extension connects the old Bellwood Quarry (Fig. 6) to the Hemphill Water Treatment Facility. At the Bellwood Quarry site, Atkinson has constructed four shafts, approximately 1,000 linear-feet of adit connections joining the shafts to each other, and one main 400-foot deep tunnel. The main tunnel will run approximately 5,500 linear-feet northwest to the Hemphill site, where the project team will construct five additional small-diameter well shafts.

Atlanta's water supply program will transform a quarry into one of the largest reservoirs in North America. The average North American public utility has only a three-day back-up supply of clean drinking water. The overtaxed system, paired with the increasing risk of drought, prompted the city's Department of Watershed Management into action. In 2006, the Department took steps to purchase the Bellwood Quarry from Vulcan Materials Co., a 300 ft (91,4 m) deep, vertical-sided behemoth of a quarry where granitic gneiss was mined for a century to become structural blocks for Atlanta's buildings as well as crushed stone aggregate for roads. The USD 300M project would turn the inactive quarry into a 2.4bn gallon (9bn L) raw water storage facility, bolstering the city's emergency water supply to 30 days at full use and to 90 days with emergency conservation measures. To make the program a reality would require excavation of Georgia's deepest tunnel (more than 400 ft, 122 m), starting at the quarry and running under two treatment facilities for 5 miles (8 km) to an intake at the Chattahoochee River. It would also require construction of two pump stations at the Quarry and Hemphill Reservoir, five blind-bored pump station shafts at the Hemphill site up to 420 ft (128 m) deep, as well as two more pump station shafts, one riser shaft, and one drop shaft (Fig. 7). The quarry would ultimately store raw water before it is withdrawn for treatment at the Hemphill and or Chattahoochee water treatment plants, connecting the Quarry to the Hemphill Water Treatment Plant (HWTP), the Chattahoochee Water Treatment Plant

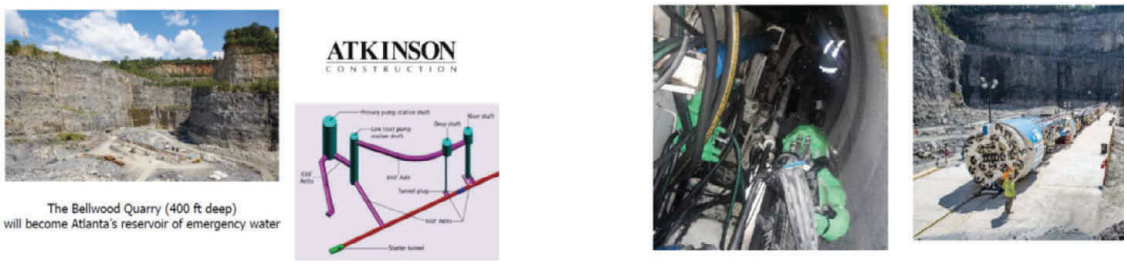

Figure 6. Job lay out and TBM assembly with Robo-drilling probe & bolt holes equipment.

Figure 7. Shafts excavation equipment for primary and lower level pump station.

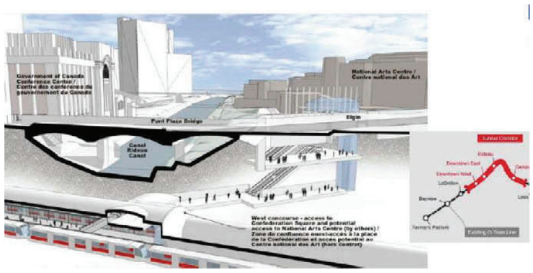

Figure 8. Project idea and road header + bolter impression.

(CWTP) and the Chattahoochee River. After construction, the area around the Quarry would then be turned into Atlanta's largest park totalling 300 acres (1.2km^2) complete with hiking and biking trails, baseball fields, and an amphitheatre.

The project schedule, primarily driven by the condition of the city's existing water infrastructure, compelled the city to consider Alternative Project Delivery (APD) instead of traditional design-bid-build. The project schedule required a start date for construction of January 2016 and a substantial completion date of September 2018. The method selected was construction manager at risk (CMAR), where the contractor acts as a consultant to the owner during the development and design phase and as a general contractor during the construction phase. The setup resulted in a unique process to start TBM manufacturing, in particular, before the tunnelling subcontractor was mobilised at the site. The decision to use a new TBM by the City of Atlanta was primarily risk-based. The PC Construction/HJ Russell (PCR) JV was selected as the CMAR for the project, who then purchased a 12.5 ft (3.8 m) diameter Robbins Main Beam TBM for the tunnel. The designer for the construction works including tunnel and shafts, JP2—consisting of Stantec, PRAD Group, Inc., and River 2 Tap—specified the hard rock TBM.

6 OTTAWA: LIGTH RAIL TRANSIT

The Confederation Line of the OLRT System is a 12.5 km east-west Light Rail Transit Project through the heart of Canada's national capital. The project will replace, enhance and extend the existing Bus Rapid Transit service corridor, and will serve over 9 million passengers annually. The project (Fig. 8) includes 13 new stations, 2.5 km of twin tunnels (with 3 of the 13 stations located underground through Ottawa's downtown business core), and possessed a capital construction of cost of nearly $ 2.1 Bn.

Its principal feature is a 3 stations and 2.5 km tunnel running underneath the downtown core.

The tunnels are excavated by mean of 3 road-headers backed by 5 bolting rigs supplied by Robodrill. The track-type bolters are used for roof bolting and installation of 12 m canopy tubes (tube diameters ranging from 139.7 mm to 168.3 mm).

The machines comply with the Canada CSA standards. They are fitted with a drilling boom with HC108 drifter and a 2 person basket-boom. They are operated and maintained by local operators and fitters who were initially trained by a Robodrill technician. In Fig. 8 project lay out and job site picture.

7 TORONTO: EGLINTON CROSSTOWN LIGTH RAIL TRANSIT

ECLRT is commonly referred to as Crosstown, is a 19 km light rail transit (LRT) line being constructed from Kennedy Station to Mount Dennis (Weston Road) in Toronto, Canada. Approximately 10 km of the line will be located underground and up to 26 stations will be built along the stretch. Pre-construction works for the project commenced in mid-2011 and

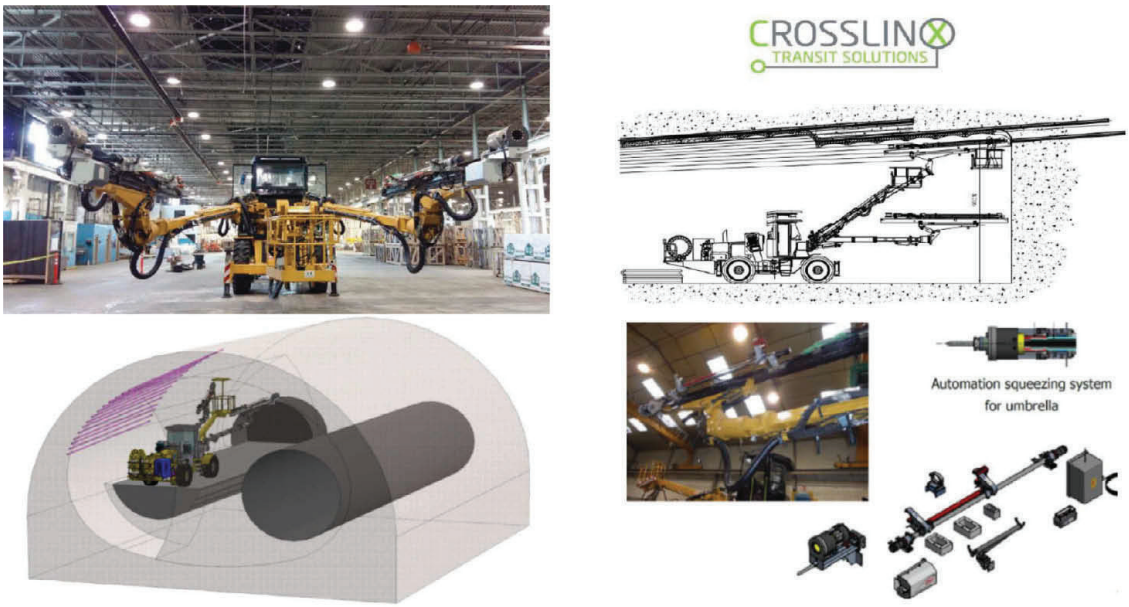

Figure 9. Jumbos provided with drifters and automatic squeezing system for DSI pipe umbrella.

tunnel boring started in June 2013. The 10 km twin tunnels are located between Keele Street and Laird Drive, while the remaining sections of the LRT will include 1.5 km of cut-and-cover tunnels, 0.5 km of elevated guideway and 7 km of at-grade right-of-way surface transit guideway, with signalling provided at intersections. Up to 54 bus routes, three subway stations and several GO Transit lines will be connected to the Crosstown.

Of the overall 26 stations, 13 stations will be located underground. A maintenance and storage facility for the line's rolling stock will be located at Mount Dennis Station and emergency exit buildings will be located on certain sections of the tunnels.

The tunnels will have an internal diameter of 5.57 m and are being bored using four EPB tunnel boring machines (TBMs) each measuring 81 m in length. The TBMs, named Dennis, Lea, Don and Humber, were supplied by Caterpillar. The twin tunnels are being constructed under two separate sections, which were awarded to two different contractors. The first section covering 6,2 km will stretch from the west launch shaft area at Black Creek Drive to Yonge Street in the east section, and is being bored by the Dennis and Lea TBMs. The Eglinton Crosstown LRT will cut across central Toronto for 19 km, with about 10 km of tunnels and 25 stations or stops. The tunnel alignment runs close to more than 1200 existing buildings, as well as buried and surface utilities and equipment. A very narrow right-of-way requires us to pay close attention to issues of private property, treatment of utilities, and traffic management.

Special bolting equipment has been delivered especially for umbrella roof operation; DSI & Robodrill have developed in JV an automatic pipe squeezing device able to install with a continuous operation, fast and safe, long protection sub-horizontal tubes after the hole drilling procedure (Fig 9).

8 HONG KONG: MTR SHATIN TO CENTRAL LINK – CAUSEWAY BAY TYPHOON SHELTER TO ADMIRALTY TUNNELS – CONTRACT NO. 1128

Dragages was selected to construct one of Hong Kong's most technically challenging tunnels – part of the 6 km extension of the ongoing Shatin to Central Line – from Kowloon to the transit hub on Hong Kong Island. The main scope and challenge of the project is to construct the Eastern Tunnels (2 x 680 m) and Western Tunnels (2 x 480 m) by Tunnel Boring Machine (TBM), as both tunnels go through the city's busiest districts. Meticulous project planning is essential in aiding the TBMs to navigate through a large volume of pile obstructions and utilities with zero interruption of services to citizens. To cope with the complex geological

Figure 10. View of the complex down town job site location.

conditions, two different types of TBMs are being employed for excavation – a slurry TBM and an Earth Pressure Balanced (EPB) TBM.

The construction of the South Ventilation Building requires careful effort as well, as the existing Police Officers' Club (POC) needs to be demolished and re-provisioned on the top of the South Ventilation Building. Delicate drilling operations through shafts and in very narrow sections have been successfully performed (Fig. 10).

9 HONG KONG: HATS SEWAGE CONVEYANCE SYSTEM

Mainly Gammon Company has performed this huge job (Fig. 11), using 10 drilling jumbos. In few words:

- Approximately 12 km of tunnel by Drill & Blast
- 4 Production shafts North Point, Wanchai, Sai Ying Pun & Stonecutters' Island
- Tunnels are at ~ 160 m underneath the Victoria Harbour
- Tunnel area varies 12 – 26 m², 1600 – 2600 m long drives (size varies depending on support class)
- Mainly solid granite
- Typical rock support is steel fibre reinforced shotcrete with epoxy resin rock bolts
- Some fault zones may require pipe roof and arches
- Stringent water ingress requirement – significant pre-excavation grouting is foreseen
- The water that leaks into the tunnel is very corrosive

Excavation has been be done by rail mounted gear, typical equipment per face is:

- 2-Boom rail jumbo (Fig. 12)
- Haggloader with excavator arm (single) and hydraulic scaling hammer
- Hagglund shuttle-cars 1×3 nos
- Rail-mounted Meyco shotcrete robot

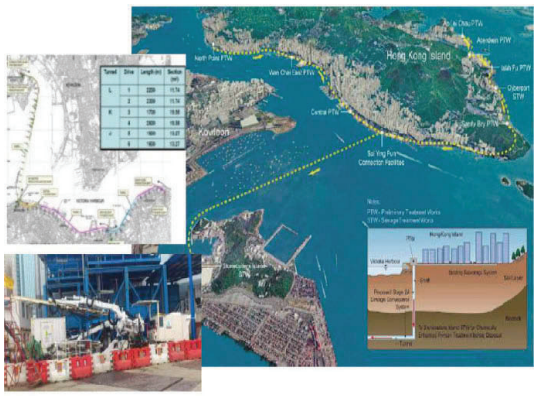

Figure 11. Lay out of the "in the sea" tunnels.

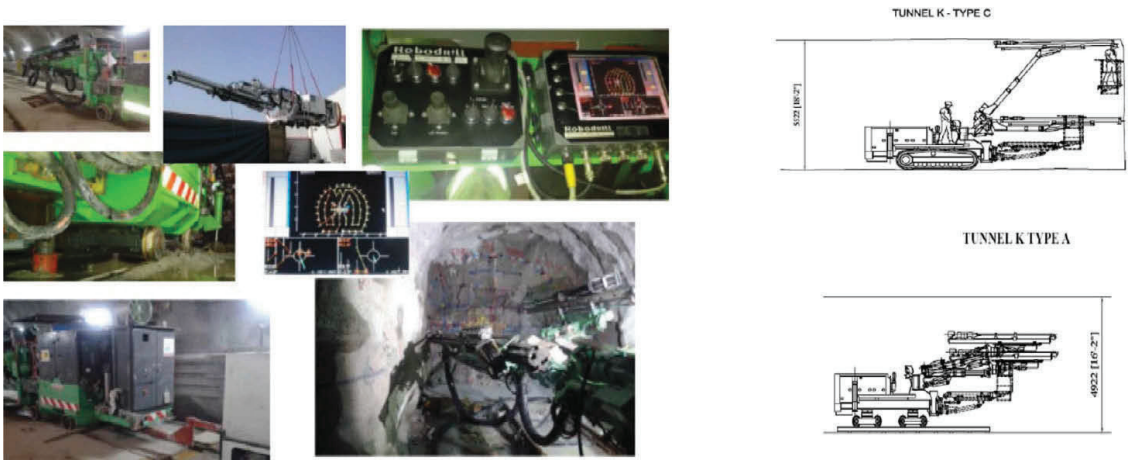

Figure 12. Jumbos switchable from wheels to rail undercarriage.

– Rail-mounted grouting platform
– Schoema locomotives, flatcars and man-rider car

A fully equipped workshop at each shaft bottom has been provided, included inspection recess and wash basin.

The construction works has taken place 24 hours a day and 7 days a week, typically on 6 days on/3 days off scheme.

Explosives can only be delivered on normal working days (Monday to Saturday 9 a.m. to 6 p.m.), Sundays and statutory public holidays excluded. Explosives charging can only be done by local shotfirers; bulk emulsion explosives and Nonel detonators have been be used.

10 ROCK SPLITTING IN HONG KONG

In urban sites can be frequent the impossibility to use hydraulic hammer or road header for vibration or no production motivations (too hard rock in function of the excavation section), for similar reason drill & blast as well. From these consideration a new technology has been developed, called Drill & Split. In few words a dedicated jumbo is used to perform short (1-1.5 m) and closed axis holes (20 - 50 cm) in order to be enlarged by a suitable hydraulic rock splitter. The working principle of the rock splitter is based on two fixed matching steel probes being inserted into a pre drilled hole. A hydraulic cylinder mounted on the attachment pushes out a hardened steel wedge between the probes thereby causing the assembly to expand in the hole forcing the rock to crack and break away.

Of course high drilling precision is required, enough boom cinematic is necessary, fast drilling positioning procedure as well correct rock splitter handling are the key of the production success.

Robodrill has also designed a special jumbo with a view to providing an increased and varied range of articulation to aid the rock splitter (usually called Super Wedge) to be positioned for entry into pre drilled holes at the rock face. In this kind of equipment an horizontal slideway designed and manufactured by Robodrill has been incorporated into the design so as to give parallel advance and retract of the Super Wedge, thereby reducing jamming in the hole as would be expected if that movement was facilitated by the telescopic boom only.

In Hong Kong similar systems have been used in different projects as, for example, MTR contract 703, to drill shafts and tunnel lines in the hard granite (Fig. 13).

Figure 13. Rock splitting in HK.

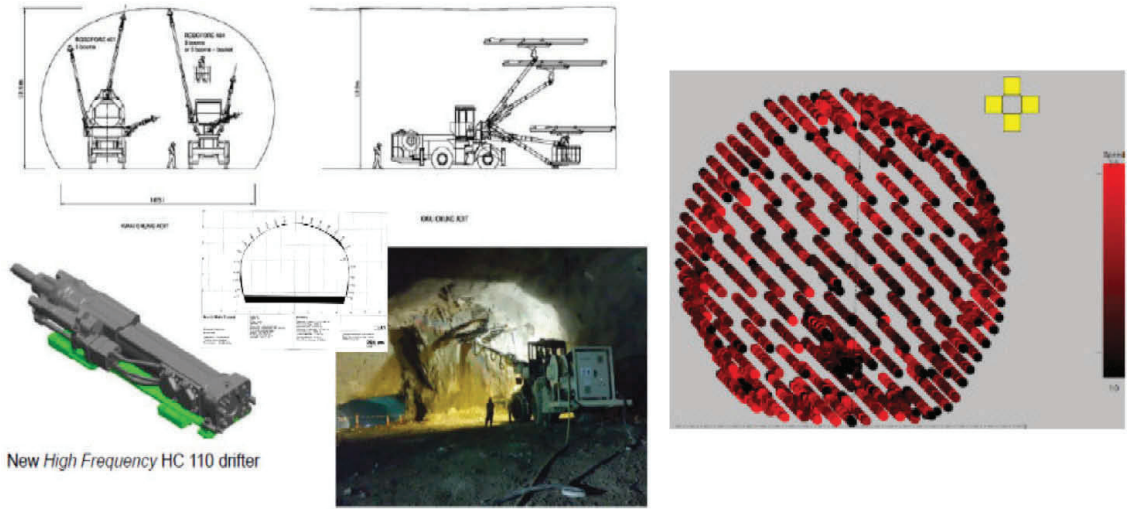

Figure 14. Drilling in granite in Hong Kong.

11 HIGH FREQUENCY DRIFTERS IN HONG KONG

Of course talking in general about hard granite, very frequently have been as well used high frequency drifters, the new Montabert HC110.

Example in HK can be referred to MTR - XRL Contract 820/821 (Fig. 14).

These drifters have performed as expected with a very fast drilling cycle, optimum excavation profile, and are as well presently used in Brenner, Italy in combination with a sophisticated and performing PLC system.

12 BRENNER BASIS TUNNEL: USAGE OF SPECIAL DRILLING JUMBOS FOR LONG PROTECTION SELF-DRILLING REINFORCEMENT AND UMBRELLA

The Brenner Base Tunnel is a central element of the Corridor AV/AC Berlin-Monaco-Verona-Bologna-Palermo, crossing 10 regions of Italy, passing by the Brenner Pass, continuing along the Tyrrhenian regions, to arrive to Sicily; it represents a fundamental connecting route for transporting goods at long distance N-S Europe.

Figure 15. Long holes in faulty zones with 4 booms robotized jumbo and self-drilling bolt carousel.

The Brenner Base Tunnel, about 55 km long, will consist of two single-track main tubes, connected by a tunnel cross every 333 m, with a distance between 40 and 70 m, with a circular cross section of ca. 4.05 m radius. The speed of the project, in line with European standards for the high speed lines, will be 250 km/h.

When fully operational, it will be crossed by at least 400 trains per day, of which 320 loaded with goods.

The north portal of the Brenner base tunnel is located just before the entrance station of Innsbruck, while the south portal is located at the entrance of the station Fortezza, in Italy. The portal of Mules is one of the lateral adits. It's a natural tunnel with a length of 1.8 km that reaches a maximum coverage of more than 1200 m, with a slope of about 8%. Along the tunnel line the structure of the rock is mainly massive granite which does not constitute a problem about the advancement as the excavation has been realized by Drill&Blast, using high performance Montabert drifters (when not excavated by TBM).

A heavy fault of ca. 250 m has obliged to use a particular consolidation technique constituted by protection umbrellas plus radial and front face R38 and R51, 12-18 m long, self-drilling anchors. Robodrill SA provided several conventional and robotized jumbos with 2/3 booms for the granite drilling operations to various Companies as Salini & Strabag, PAC – Oberosler – Cogeis, Europea 92 and CIPA S.p.A. In the fault some special jumbos, 4 booms (2 for face drilling, 1 for radial drilling + basket) have been supplied; the 2 front face feeds have been equipped with special rod handling systems in order to automatize the entire drilling procedure for the 12-18 m length operations. The system engineered have optimized drilling operations and speed up the fault passage in a considerable way (Fig. 15).

13 GRAND PARIS EXPRESS METRO

It consists in a fundamental rethink, redesign and focus on the public transport network on the scale of the metropolitan area. The purpose of this exercise is to avail Grand Paris with multimodal transport solutions, more integrated transport services, hence supporting a model of polycentric development. Grand Paris Express in main figures can be so defined:

- 4 additional lines
- 200 km of new railway lines
- 68 brand new interconnected stations
- 2 million passengers every day
- a train every 2 to 3 minutes
- a 100% automatic metro system
- 90% of lines will be built underground

Grand Paris Express, as an automated transit network, is the new metro of the Capital Region. With its 68 new stations and 200 kilometres of additional tracks, Grand Paris Express consists of a ring route around Paris (line 15) and lines connecting developing neighbourhoods (lines 16, 17 and 18). Additionally, Grand Paris Express also involves the extension of existing metro lines. Its 4 new lines circle the capital and provide connections with Paris' 3 airports, business districts and research clusters. It will service 165,000 companies and daily transport 2 million commuters.

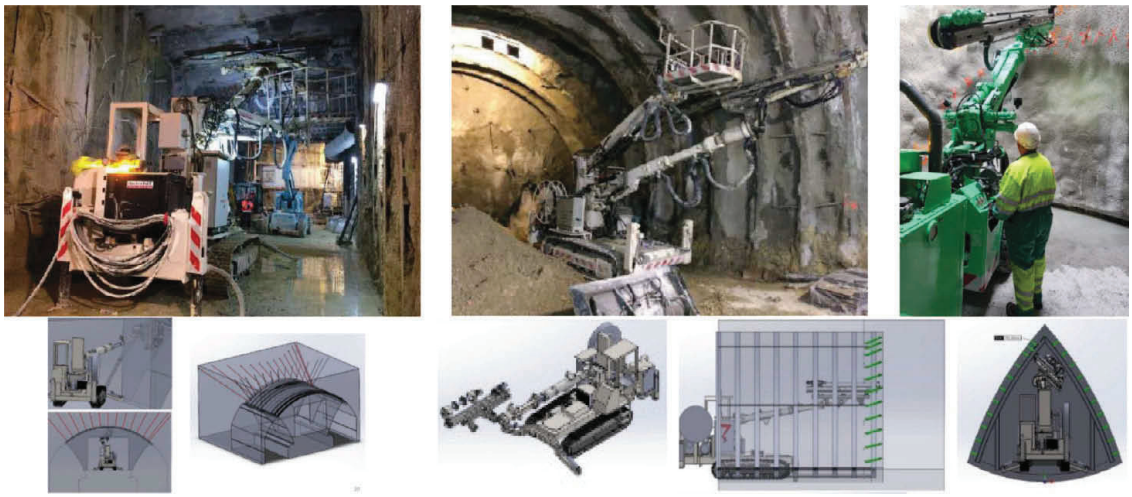

Figure 16. Customized jumbos for special application in Gran Paris.

At the moment of the paper submission Robodrill is working in the following sites:

- Prolongement du Métro Ligne 11 à l'Est – GROUPEMENT ALLIANCE
- EOLE – Prolongement du RER E vers l'ouest - Tronçon Saint-Lazare – Nanterre la Folie – Gare la Défense – Groupement EDEF
- Prolongement du Métro Ligne 4 – Lot T01 Montrouge Bagneux
- Prolongement du Métro Ligne 14 - Lot T02
- Ligne 15 - Puits de reconnaissance – ZAC Seguin Boulogne
- Eole Entonnement GC Haussmann Saint Lazare (HSL)
- Grand Paris Express/Ligne 15/Gare FIVC/Clamart

Works to be done have been various, as can be imagined; especially the drilling experience has been in the field of supports being them in fiber glass GFRP (mainly produced by the Italian MAPLAD) and in steel (DSI).

Special jumbos (Fig. 16) have been designed also for long injection holes, umbrella canopies or tunnel excavated per partial sections. Usually all the equipment have been calibrated in order to work in very narrow spaces; down town working procedures, metro access shafts between old historical buildings, tunnelling in weak materials (from the geological point of view but also for the potential existing foundation interferences) is part of the daily job.

14 CONCLUSIONS

The use of a modern drilling technology is a key for modern tunneling. The presence of a specialized drilling company is the key of the success not only for a complex job site; customizations capacity, flexibility, hardware & software top quality and perfect service are the necessary qualities for reaching a successful project.

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