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Motivations to swap from trench cutter to hydraulic grab: Case histories from Florence, Rome and Milan

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ABSTRACT: Frequently new Metro lines have to cross their path with existing ones, combined with the frequent need to encounter better geological conditions and preserve archeological heritages; due to this tunnels, stations and technological shafts are often designed to be realized at deeper depth. Another topic is related to the very frequent limited construction space available with space constraint, interferences with existing buildings and infrastructures. In the last 2 decades trench cutter technology evolution has been quite and as a matter of fact the world is looking for something new since a long time. What has been really, technologically speaking, evolving in the last decade is the "marriage" between heavy duty crawler crane and both mechanical and hydraulic grab. The well-known traditional diaphragm wall excavation has experienced new applications also in urban metro projects; deeper depth, higher accuracy, top joint quality, easy and fast mob & demob phases in limited site spaces.

1 INTRODUCTION

For the construction of diaphragm walls, grabs, both mechanical or hydraulic in function of the jaws closing system, are frequently used. It can be named that it is more and more an international practice for the construction of very deep walls (and not only) to use combined systems: crawler excavator and hydraulic grab in its different technical declinations; this combination represents a real modern evolution for the excavation of diaphragms walls.

A lifting and excavating equipment, such as a crawler crane class LWN HD-HS, powerful, silent, with generous, redundant and fast winches, with integrated controls coupled to a hydraulic grab (there are some types worth to mention) may really make a difference in a project that foresees high depths, cutting precision, work in urban environment, minimum pollution (also acoustic) and optimal management of the excavation materials

2 HYDRAULIC GRABS

In general, the diaphragm excavation grab may be of two different types: mechanical and hydraulic. The mechanical grab is the easiest to be manufactured and requires a crawler excavator equipped with 2 winches; the first able to lift the grab body and the second able to operate the mechanical kinematic of opening and closing the grab jaws. The mechanical grab, with freefall winch, although in certain situations can be slightly faster than the hydraulic one and may be efficiently used for repeated chiselling works (particularly resistant materials):

1. Of course requires a heavy duty type crane
2. The grab is particularly mechanically stressed
3. Definitely requires a very experienced operator
4. The operator must always be very concentrated during the entire working phase
5. It can rotate only by using the winding direction of the ropes by manually using the winches
6. It is not equipped with deviation correction systems
7. It cannot manage for high depths deviations
8. It cause excessive ropes consumption

The hydraulic grab, besides, has a whole series of undoubted advantages due to its management through suitable hydraulic circuits that allow it to tighten the excavations jaws, rotate, divert … with safe, controlled, precise and "smooth" manoeuvres. For example, the grab model used for the excavation of some diaphragms walls in the Milan Metro has been equipped with a patented grab rotation device that allows the structure to be swing at 180° on the longitudinal axis. This system can also reduce the excavation deviation and, especially in the case of hard soils, considerably improves the production performance; the device allows to realize panels in narrow spaces or corners where the carrier cannot be perfectly positioned in front of the excavation (Fig. 1).

The asymmetry of the excavation teeth between the two jaws is compensated by the 180° rotation device. This equipment may be supplied with special thrust systems placed in various areas of the grab frame, used for the correction of the grab deviation during the excavation thus in order to allow a constant verticality (Fig. 2). Usually grabs are equipped with two sets of steering plates (flaps, pushing cylinders, …), which may be operated independently. This operation and the effect on the deviation is controlled and monitored by an inclinometer installed on the grab itself and displayed in the operator's cab. It may be directly linked to the crane through different connection systems, depending on the type of carrier, the type of hoses reeling and the size of the panel to be realized. The control system is usually designed to continuously monitor the verticality of the grab during the excavation. The position of the grab is displayed on the operators monitor in real time; an inclinometer

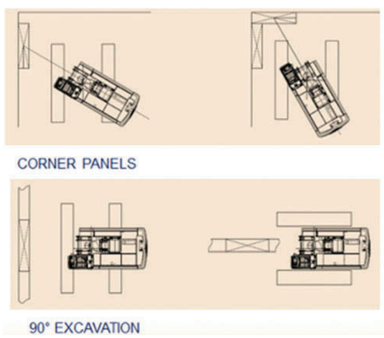

Figure 1. Some usual grab working position.

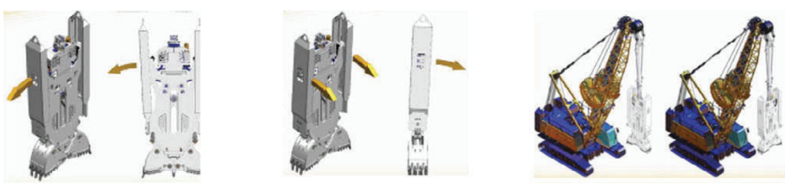

Figure 2. Steering plates and rotating system to drive with the right verticality.

is installed in the frame in order to measure the inclination along two orthogonal axes (x and y).

The data transfer from the inclinometer to the operator's cabin is carried out via a particularly resistant power cable, which to follow the grab movements automatically winded or unwinded by a dedicated hydraulic cable reel. There are interesting variants that involve the information transfer through batteries properly installed on the digging body but which have the drawback of returning the information only at the end of each working cycle. Naturally data are displayed in a touch screen and can be stored and printed.

2.1 *Dragon white*

For some of the M4 Stations (Metro Milan), for example, it has been used an hydraulic grab called Dragon White (design and manufactured by Negrini S.r.l.) specifically configured according to the operational requirements, handled by a new Liebherr crane type HS 8100 HD in order to primarily excavate 2,8 x 1 m diaphragms wall. It is a modular hydraulic grab integrated with the operating machine without having to modify its support structure or having to re-certify the crane boom and neither the boom head. It may be manufactured with several optional accessories to increase its performance and it is mainly composed by a central body and an excavation set divided into: jaws, ejector, jaw supports (by simply replacing jaw supports it may be possible to achieve a wide range of excavation dimensions: from a minimum of about 500 x 2500 mm up to a maximum one of about 1800 x 3600 mm) and hulls. By fitting a special hull handling device, it may be possible to adjust the excavation verticality using the guided hulls. The hulls may be remotely managed (therefore not using electrical cables) directly from the operator's cabin; without getting out of the crane's cabin, by means of a transmitter integrated in the "machine system" and the supplied joysticks, it may be possible to handle all the excavation operations. The receiver is integrated into a suitable enclosure fitted inside the top frame of the grab. All accessories are interchangeable between hydraulic and mechanical grab; a significant economic advantage because different excavation set may be used on both type. A specific extension can increases the grab height, allowing greater verticality of the excavation at high depths. In hard soils or particularly high depths, finally, it may be possible to apply additional counterweights, adding weight and lowering the center of gravity of the grab, resulting – as for the Milan Metro – in an effective and versatile device.

3 THE CRAWLED EXCAVATOR LWN HS 8100 HD

The crane subject of this brief description is part of a range of machines specifically designed for special foundations application. The HS 8100 HD crawler excavator, which for example has been used for the works of the M4 (Metro Milan), has been designed to perform various foundations works such as: trench cutter, dynamic compaction, drag line, several kinds of seaport works, with the help of appropriate "leader": pile, CFA, vibropiling, vibrofloatation, bored piles grab and casing oscillator, application frequently used for the construction of deep piles of large diameter, . . . (Fig. 3)

Figure 3. The HS8100 with oscillator.

3.1 *Operating weight: 115 ton*

This parameter has a significant importance since the stability of the entire working group has a close connection with the mass of the undercarriage and all the components = > greater weight, greater stiffness, less vibrations and consequently less deviations (in addition to minor possible breakages for fatigue)

3.2 *Motor power and consumption: 390 kW*

The engine power is a feature that clearly links all the machine hydraulic functions; having more power means not only be faster in all functions but also to generate spare power in potential critical situations i.e., for example, at high depths. Moreover, the greater power can be useful to manage different kind of works (trench cuter, vibrators, ...). The Liebherr engine is of the latest generation Tier 4i; it is provided with DPF regenerative particle filters, which greatly reduce the environmental impact of machines and allow them to be used in sites particularly environmentally sensitive.

The abundant power available means having an engine that works at a lower rpm, despite having spare power available. LWN has developed low-consumption engine, integrated through the electronics with the hydraulic system, having an innovative concept called ECO-Mode able to limit the fuel consumption; summarizing, it is a new generation 8 cylinders engine with an electronic system that optimizes or disconnects all the hydraulic services when not used. Moreover, thanks to the automatic thermoregulation of the fan system (which allows to work in any climate) helps to reduce fuel consumption. It is reasonable to say that the hourly consumption of the Liebherr combination (Engine-Electronic-Hydraulic) is lower at least of about 20% lower compared to the consumption of comparable machines employed for similar kind of works, per linear meter of excavated panel. For instance, for the Port Said Project, the average consumptions for 100 h of work has been equal to 16,2 l/h!

3.3 *Noise emissions*

With regards to noise emission, it has been developed a specific system called ECO.SILENT-Mode; it is a function that when activated by the operator limits the number of rpm of the engine as well as of the cooling fan, ensuring a significant reduction of noise emission, with a negligent loss of power. This is a very important feature especially in urban areas operation. (i.e. construction works of diaphragms wall for metro stations, such lastly Milan, Rome, Paris, London or Warsaw). In a construction site, it is clearly perceived the difference between HS 8100 HD and all any other machine available on the same site.

3.4 *Winches and depth*

The winches are outstanding in their compact design and easy assembly. Clutch and braking functions on the free-fall system are provided by a compact designed, low wear and maintenance-free multi–disc brake (Fig. 4).

Figure 4. Well known LWN high quality double winches.

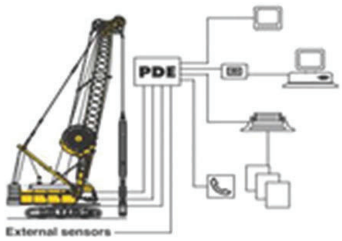

Figure 5. The communication net system Li-tronic + PDE.

Figure 6. Some of the main brand of foundations rig with grab.

The drag and hoist winches use pressure controlled and variable flow hydraulic motors. This system features sensors that automatically adjust oil flow in order to provide max. winch speed depending on load. The rated speed of the 2 synchronized winches (stnd. 25 ton capacity) is equal to 88 m/min with approx. 40 m of rope in the first layer. It is reasonable to be said that the pure speed of the LWN HS 8100 HD is at least 20-30% higher when compared to similar machines and the winch speed is one of the key points for excavation productivity! The depth achievable in standard configuration is equal to 120 m.

3.5 *Telematics System for assistance*

The integrated Li-Tronic + PDE system allows not only the transmission of operational data but also the remote assistance from the manufacturer headquarter; this "architecture" apart from being a modern feature is also an important operational advantage in the construction sites and a great savings in case of problem occurrence, easing a fast assistance service knowing in advance the cause of any problem, frequently been able to remotely fix it (Fig. 5).

3.6 *Crane's boom and compatibility with any kind of grab*

The duty cycle crane's boom, which is mainly used with grab and other multifunction tool for deep foundation works (Fig. 6), shall be able to withstand significantly higher loads of a standard crane boom. The loads are generated essentially by the horizontal forces due to the lateral grab acceleration, by the potential lateral flexion forces, by the dynamic forces connected to the operation of the grab itself and by the auxiliary tools applied to the boom; the lateral stresses components are also added to the axial forces generally stressing the boom. The structure is therefore dimensioned for heavy loads thus in order to absorb all these actions. For the record, it is worth to mention that the LWN system is compatible with any kind of grab: mechanical, hydraulic, kelly and semi-kelly.

4 INTEGRATION OF DUTY CYCLE CRANE AND GRAB

It should be noted that there is an important integration between the excavator and the excavator tool (the grab, in this case); in short, there is a hydraulic and electronic dialogue platform that transfers information, commands, data returns (in visual, graphic and system

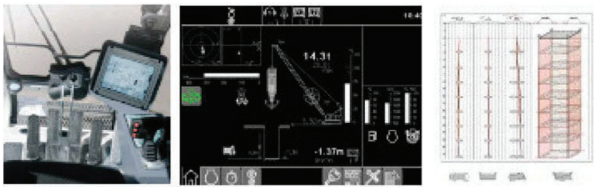

Figure 7. Li-Tronic System on board.

format) and can transmit them to the User and to the Mother House with the other potential related analysis and active interventions, such as maintenance, if needed.

4.1 *Integration, control and data management*

The crane/grab system can be integrated with the LWN electronic system called Li-Tronic. The crane management system is the centerpiece for precise and reliable crane operation (Fig. 7). Li-Tronic is a unique one-system-solution which unites the best technologies available for reliable crane control; it is the one-level interface between crane and driver. Various analysis tools provide relevant information on the operation. The system empowers the driver to efficiently control the crane and to optimize turnover.

4.2 *Grab chiseling*

Chiseling with an hydraulic grab is not really a usual practice, nevertheless LWN system provides a specific integrated function allowing to perform chiseling with grab operating in free-fall at a certain height. This option can be used in various scenario, for instance: breaking through supporting slabs, excavating lenses of compact material at variable depths, headings in the bed rock . . .

4.3 *Grab safety and double winch availability*

The fact that these machines work with 2 synchronized winches and consequently with 2 ropes simultaneously guarantees a redundant system not only for the loads lifting but also providing a high degree of safety for the grab itself. It has occurred more than once, having a single grab lifting block (i.e. crane equipped with a sole winch only) that rope got broken subject to excessive fatigue or wearing, particularly in the area of the return pulley on top of the grab lifting block (the lower pulley, very delicate zone!). Moreover, these types of machines are first of all cranes; their system, manufactured considering the strict referred design standards, takes care of monitoring the lifting loads as well as the position of the boom, putting them in closed relation. There are excavation machines suitably designed for such operations (lifting), which may not be provided with any load safe indicator when used just as excavators (it's also an accuracy and integrated stress calculation problem) and not as lifting equipment, a clear limit and a safety issue handling extraordinary unbalanced loads at high depths.

4.4 *Ropes tensioning and wearing*

The load indicator device is also used to calibrate the pressures of the winches in order to keep the rope in tension (without affecting the grab) during the excavation phase; this ensures no loosening, unloading of the pulleys, irregular wear, offload operation of the winches, tears, undesired turbulence along the panel walls, ... This specific function aims to reduce the deviation tendency during the operational phase, a further factor minimizing the danger of deviation from the design verticality. A further consideration on the ropes wearing shall be made on the geometry of the reeling drums of the winches; the greater is the drum length or the diameter, the greater will be the reeling length in the first layer of the rope, the less will be the wearing.

Therefore, it is essential, in order to optimize the useful ropes lifetime, to provide larger winches (as well as powerful and reliable). The useful life of a lifting rope is in direct function of the type of material to be excavated (presence of stones hanging on the pulleys, anomalous wearing cause by friction, ...) and of the excavation depth (numbers of reeling cycles and multi-layer reeling, ...). Considering the mechanical grab, the technology foresees 2 ropes having 2 different tasks: the first winch bears the full weight of the grab (while with the hydraulic version the weight is equally distributed on both ropes), being this element particularly stressed. The second rope is engaged for the excavation jaws opening and closing procedure; it passes through a series of suitably dimensioned pulleys and through a numbers of referral mechanism (with short curvature radii) as well as the presence (quite frequent) of soil between the groove of the pulley and the rope itself, resulting in a reduced useful life. Moreover, the ropes consumption is not symmetrical, being subjected to anomalous strains. It is reasonable to say that the ratio of the ropes lifetime for the mechanical grab vs the hydraulic grab is 1:5 (indicatively 500 h: 2500 h); steel ropes not only have a cost and are related to operational safety, but also provide long stop for their replacement ... at the expense of production.

5 THE FLORENCE HIGH SPEED RAILWAY LINK PROJECT

The works related to the Florence High Speed Railway Link (Fig. 8) and the realization of the new high speed train station represents a kind of urban revolution of the famous city; it provides for a vertically distributed development (a "negative" skyscraper), more like a large metro stop than a railway station. The new structure has been designed by Norman Foster & Partners; the platform level in the new station is located 25 meters below ground. The station chamber consists of a single volume, 454 meters long and 52 meters wide, built using cut-and-cover techniques similar to those deployed at Canary Wharf Station in London. The station will be linked to the existing Santa Maria Novella station, 2 km to the south, with the aim of realizing a multimodal hub sensitive to its historic location, but looking forward in its use of energy and other resources, offering a model for contemporary rail travel.

The diaphragms walling has been realized providing complex reinforcement having the slab rebars directly link to the bulkheads, the latter working in the entire structure and, by virtue of that choice, no longer having the need to build a foundation supporting wall, but more likely a make-up lining of the existing one.

For the realization of the diaphragm walls n. 5 duty cycle cranes, LWN HS-HD class, have been deployed, owned and operated by SAOS S.r.l., a well-known company specialized in deep foundation works; three working crews has been arranged for the excavation of 40 m deep diaphragm walls handled by two HS 855 HD (450 kW power) and one HS 845 HD both equipped with hydraulic grab, while a HS 833 and a HS835 cranes have been employed as service cranes, handling the 36 ton rebar cages. The site manager, Geom. Fabio Rossi, reported: "Negrini has provided us with special bucket jaws and grab shoulders for the existing grabs and with Liebherr we have designed and implemented a new software solutions with the aim to increase the effectiveness of the diaphragm slurry walls realization. We may say

Figure 8. Florence High Speed Railway.

that it has been possible to pursue a wide range of experimentation benefitting of the unlimited horizons provide by Liebherr's research and development on the heavy cycle machines. Without this assumption, we could not have been able to give such a decisive impetus to the planned intervention times of this works."

6 METRO LINE 4 IN MILANO AND SAOS COMPANY

For some years, the city of Milan is increasingly projected into a European scenario, particularly from the point of view of services designed to ensure the best sustainable mobility. One of the latest improvements involving the city infrastructure is Metro 4 (M4 or "Blue Line"), which will allow the Lombard capital to compete with other European capitals in terms of transport as well (Fig. 9). Among the stated goals of M4 S.p.A. - the company that manages the works and which was set up in 2014 by the Milan City Council as a majority shareholder - is the decline in wheeled traffic for the benefit of public transport, with a forecast of 30 million moves in less annually and reducing pollutant emissions by 2%, about 16 million ton less fuel (figures which, however, also include the contribution provided by the new M5 service).

Line 4 crosses the city transversely by connecting the east and west boundaries and passing through the historic center along the Cerchia dei Navigli; by importance of the connected and crossed areas can be compared to Line 1. Given its track and intersections with the other lines and the Passive Railroad will be of fundamental development at the metropolitan and regional TPL. By 2022 the metro network in Milan will be the sixth in Europe; with M4, the metro of Milan will have a total of 118 km of line, 136 stations and an increase in the network in 10 years by 34 %, a pace of development among the highest in Europe.

The main features of the M4 are: 15 km of extension, 21 stations, 86 million passengers a year, 6 interchange points (Sant'Ambrogio M2, San Babila M1, Crocetta/Policlinico Sforza M3, Bypass Dateo, St. Christopher FS, Forlanini FS), 1 workshop in San Cristoforo; frequency in peak/hours 90 seconds, maximum speed 80 km/h, automated without driver.

The features of the "center" stations are (Fig. 10):

- Central Stations are defined as "deep typological stations" (about 30 m in depth)
- Located in the city center, in the oldest and most urbanized part, these stations have greater constraints than those of the outer trails

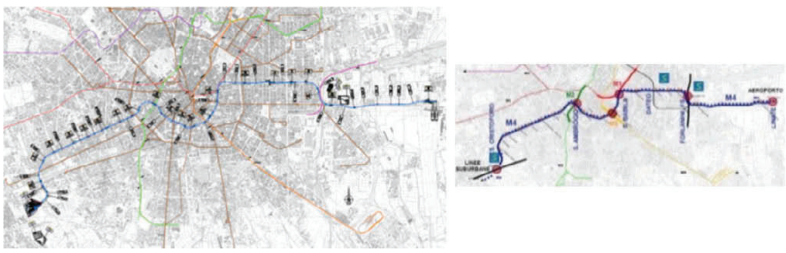

Figure 9. The Line 4 in Milan.

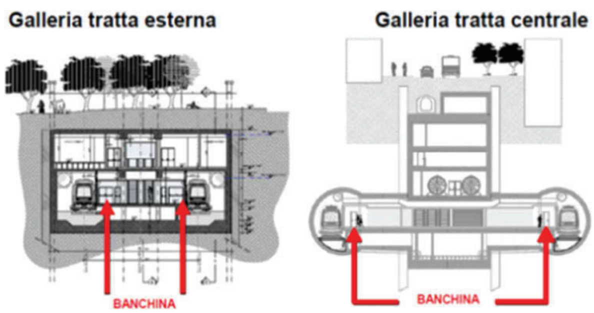

Figure 10. Typical view section of the Line 4.

– The solution adopted combines the small spaces on the surface with the necessary distance of the galleries where the trains run, through the creation of a deep central shaft between the two tunnels
– Inside the tunnels they find the train travel routes and the related platforms.

To carry out this kind of intervention, the Contractor has entrusted an important number of foundational works to S.A.O.S. (Società Appalti Opere Specializzate) S.r.l. - a company specialized in foundations and which plays a role as interlocutor of large general construction companies for the creation of special foundations.

SAOS used its existing LWN diaphragms crane fleet and also purchased a new HS 8100 HD crawler excavator and a special hydraulic grab from Negrini.

7 DIAPHRAGM WALLS AND JOINTS FOR THE BLU LINE

The project of the Metro Milan Line foresees the construction of reinforced concrete diaphragms walls, side by side eventually bonded by struts and tie back rods, as supports structures for the excavations of deep shaft stations and line tunnels, or in any case, in general, for underground works. The drilling technique is normally based on the use of bentonite slurry (Fig. 11). “Dry” excavation, without the use of stabilization slurry, is not allowed. Excavation shall not, in any case, compromise or worsen the mechanical characteristics of the ground surrounding the diaphragm; therefore, it shall be avoided or at least minimized: any possible variations of the groundwater levels, the reduction of the relative density of the incoherent layers, the decrease of the effective horizontal tensions of the natural soil state and the adhesion reduction between the diaphragm and surrounded ground due to an improper use of the bentonite slurry. Realizing diaphragms slurry walls in urban area, means operating: in presence of road traffic, close to existing buildings and their foundations, balconies, canopies and any other protruding structures, street lighting, electric overhead lines, sewer pipeline and any other subservice, it is therefore required to conduct such a works by using proper equipment taking care of ensuring the full functionality of these services, constantly monitoring them during the whole the duration of the works. The employed equipment shall also comply with the stringent regulation and standards related to noise emission and vibration transmission to the surrounding environment. Diaphragm walls shall be realized bearing into consideration their precise geo-localization and in compliance to the parameters and tolerances given by the designer (with exception of stricter limitations indicated in particular situations) such as:

– Floor plan: ± 3cm
– Diaphragm head: ± 5cm

Figure 11. Excavation with slurry grab in down town Milano.

– Depth: ± 25cm
– Verticality: ± 0,5% and, in any case, not to involve, by the work performed, an off-axis of the internal line of the plane in relation to the vertical one through the path of the track exceeding 10 cm (for total diaphragm length ≤ 20 m)
– Joints complanarity: ± 1% which implies a restriction in the permissible tolerance for the absolute verticality of the panels; if a panel vertical offset is equal to 1%, the adjacent panel shall bear the same vertical offset following the same direction, or it shall be perfectly vertical.

During the excavation of the diaphragm panels, the machine systems and operators shall be able to monitor and record verticality, stratigraphy, the actual depth reached by the excavation tool, bentonite slurry consumption (thus in order to record any slurry loss due to anomalous ground condition) and as well as any other relevant information. The excavation technology could be chosen by the Client and the Contractor between the various types of grabs or trench cutter; of course, with high depths (> 50 m), potential presence of resistant hard materials, proximity to existing (historical) buildings, space and environmental constraints as well as the need to comply and guarantee high construction tolerances, it could have driven Everybody to the trench cutter technology; this has not happened!

The typical phases for the realization of diaphragm walls are as follows (Fig. 12):

– Preparation of the ground surface
– Topographic alignment
– Realization of guide walls
– Consolidation injections where required
– Preparation of the stabilizing fluid (bentonite slurry)
– Excavation with grab in bentonite slurry
– Installation of the rebars cages;
– Concrete placing and retrieval of the bentonite slurry
– Diaphragm wall top level cropping
– Head concrete beam construction

The diaphragms walls shall be realized assuring a perfect hydraulic seal (in Milan the spring line is everywhere at very low level); all its elements shall be perfectly in contact and seamlessly compenetrating. Therefore, realizing a waterproof diaphragm to ensure a perfect hydraulic joint, before the casting at both ends of the primary panel, a stop-end shall be placed, which usually consists in a:

– Form pipe (stop hand) with diameter equal to the diaphragm thickness
– Suitable shaped elements (semicircular, sheet pile, etc.)

Project's specification requires that these elements are to be removed after the pouring (after concrete setting), leaving in the casted element their semi-circular footprint, interfacing groove. During the excavation of the secondary panels, it is necessary to clean the groove of both panel ends, thus is order to produce a rectangular shaped groove in order to have a perfectly matching joint during the casting of the secondary panel. Alternatively, different types of joints may be

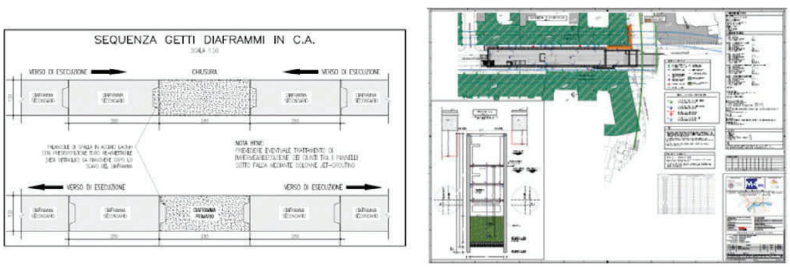

Figure 12. Usual phases to realize panels by diaphragm method.

realized, i.e. by fitting tubes or plastic formwork panels. In this case, during the excavation of the secondary panels, the plastic material of the formwork needs to be taken out by the grab; this will result in a concave impression similar to that described above.

Diaphragm wall cannot be realized continually for a very long section due to various limitations; the wall is usually constructed in alternative section. Two stop end tubes will be placed at the ends of the excavated trench before concreting; the designed technology foreseen that the tubes are withdrawn at the same time of concreting so that a semi-circular end section is formed. Wall sections are formed alternatively leaving an intermediate section in between. The in-between sections are built similarly afterward but without the end tube. At the end a continual diaphragm wall is realized with the panel sections tightly joined by the semi-circular groove.

7.1 *MM Line 4: Usage of GFRP Rebar Cages for Tunnel Boring Machine "Soft-eye" openings*

Metro Line 4 will be serving the densely populated areas in city center of Milan. In order to minimize disruption caused by construction activities, it has been designed to be compatible with other modes of transport and maintain sufficient groundwater level. Metro Line 4 will have twin tunnels with single tracks in each direction. Extensive use of tunnel boring machines (TBM) will be required. Metro Line 4 will have a total of 21 stations, including interchange stations on Lines 1, 2 and 3. The 21 stations, including the terminal, are San Cristoforo FS, Segneri, Gelsomini, Frattini, Tolstoi, Washington-Bolivar, Foppa, Parco Solari, S. Ambrogio, De Amicis, Vetra, S. Sofia, Sforza-Policlinico, San Babila, Tricolore, Dateo, Susa, Argonne, Forlanini FS, Q.re Forlanini and Linate Airport. The future stations will be built in open construction pits: An open central shaft and blind-hole side tunnel technique will be implemented to facilitate passage of the TBM and minimise excavation.

TBMs cannot cut through steel-reinforced concrete drilled shaft walls as the steel bars get caught in the shovels of their shield. In addition, the steel bars cannot be cut into pieces small enough to allow their transport by the TBM's conveyor belt system. As a result, the conventional construction method with steel-reinforced drilled shaft walls needs the manual removal of the steel reinforcement in the path of the TBM. Not only is this time-consuming and expensive in itself, it also required the stoppage and retraction of the TBM in front of each shaft wall. Finally, to ensure that neither the soil nor potential groundwater outside the shaft wall would collapse into the opened hole, complex and expensive soil stabilization measures are required outside the wall.

All these time-consuming and costly measures are not required when the areas of the launch shaft head walls to be penetrated by the TBM are reinforced with glass fibre-reinforced polymer (GFRP). Even though these bars have a much higher tensile strength than steel rebars, they are easily machined and can be broken down into small bar segments by the cutter head of the TBM (Fig. 13). These segments can then be transported by the machine's conveyor system together with the excavated soil. The TBM does not have to be stopped, and soil

Figure 13. Using the Maplad i-BAR glass fibre reinforced polymer bars.

stabilization measures are not required, as the soil is always stabilized by the TBM. The resulting savings in the overall construction time and cost are substantial. Construction of the first two shafts for the project, at Argonne and Frattini Stations, was opened for bids in January 2015. In both cases, GFRP reinforcement was specified in the bid documents. In early July 2015, MAPLAD was awarded the contract to deliver the soft-eyes GFRP rebar cages.

8 THE ROME METRO PROJECT EXPERIENCE AND THE JOINTS MODIFICATION FOR THE MILAN METRO PROJECT: GRAB VS HYDROMILL

After a careful analysis of the excavation methodology and process specifications for the construction of the "Lot T4 - Line 4 Milan Metro" and been familiar with the Milan's ground morphology, SAOS has proposed an alternative construction method stated, keeping the same quality standards, beneficial time and economically wise. SAOS with a consolidated experience particularly in the construction of diaphragms walls at considerable depths, proposed a solution, which has been accepted, able to ensure a successful result; this technology was already used by SAOS for the "WHSD" in St. Petersburg. The equipment indicated for the excavation of the diaphragms wall is an hydraulic operated grab manufactured with a special long frame; this device allows to reach high depths (over 60 m), guaranteeing speed and verticality comparable to a trench cutter.

The willing of using a grab in place of a cutter was referred to the previous experience in Rome where, for the construction of Metro Line C San Giovanni Station (diaphragms 2,8x1,2 m, depth 56 m), in order to avoid leakages of bentonite slurry and ground collapses (such as the one occurred during the construction with the trench cutter of the neighbor Lodi Station), it has been successfully chosen the grab option.

Here following the report draft prepared in collaboration with Metro C Roma Metropolitane: "... the choice of using an *intelligent grab* have been taken after the experience gained during the construction of the slurry wall central panels of Lodi station. As reported, during the excavation with cutter, a rapid loss of bentonite slurry occurred within a layer of sands and gravel. This phenomenon is attributable to the presence of confined groundwater with reduced hydrostatic pressure within the gravelly layer not sufficient to counter balance the vertical pressure of the bentonite. To make the situation worse the use of the cutter it has been required a continuous recirculation of slurry not properly mixed with correct amount of bentonite affecting the chiseling capability of the cutter. The diaphragms, of the new San Giovanni Station, has a height of about 56 m and crossing entirely a sand and gravel layer with a thickness of about 13 m, heading for about 10 m in a layer of Pliocene's Clays. Given the geometry of the diaphragm walls and the geological nature of the ground, the phenomenon, observed at Lodi's jobsite, would be amplified in San Giovanni jobsite. The design choice pursued involves the use of an "intelligent hydraulic grab" to replace the trench cutter, in order to limit the bentonite slurry recirculation therefore reducing the risk of leakages of the excavation stabilizing fluids, having the benefit of using thicker slurry mix without affecting the excavation capability ...".

Excavation verticality is guaranteed by the considerable length of the grab, approx. 10 m, and the ability to rotate by 180 degrees, while the speed control is given by the crane's lifting configuration. A key feature of this type of equipment is the heavy weight (in configuration 2,8x1,2 m it is about 20 tons), easing the excavation at high depth. The verticality of the diaphragm, in this case, has been constantly monitored in the operator's cab also by means of a dedicated Jean Lutz monitoring device. At the end of each excavation cycle, it has been possible to print reports, having most of the time excavation verticality in a good range minor of 0,5%.

Experience in the long story of Metro of Roma Linea C (Fig. 14) has therefore foreseen 4 different technologies; panels excavated with trench cutter, primary panels with grab and secondary with cutter and then diaphragms solely excavated with grab, mechanical first, hydraulic afterwards. In terms of precision, productivity, cost and time the experience has slowly indicated the hydraulic grab excavation methodology as the most reliable one.

Figure 14. The "Eternal City" frequently under heavy grabbing .. . .

Figure 15. Positioning of joints.

8.1 *Operational methodology for the joints realization*

Given the considerable height of the diaphragms walls to be constructed in Milan (50 m depth) and the need to realize a water tight joint, it has proposed the "virgin-interlocking" methodology with sheet pile stop-end (Fig. 15). This methodology consists in realizing "virgin" or "primary" panels by installing at both ends trapezoidal 36 m long sheet pile in one go. Two cranes of suitable capacity have been used to lift them.

The first one, supporting vertically the sheet pile placed on end and the second, which acting as a support, placed at about 2/3 of the sheet pile length. The sheet pile head is equipped with a dedicated lifting anchor, while the second crane is using omega shaped clamp. Once the two cranes are in position, the lifting operations are carried out; the tail of the sheet pile acts as a fixed point resting on the ground and the second crane holds the sheet pile in position, in order to avoid the bending. The first crane moves forward lifting the sheet pile by keeping its position perpendicular to the lifting point until it is fully lifted in a vertical position. When the lifting operations are finished, the sheet-pile is then lifted into the bore-hole. Once two adjacent primary panels have been completed, the "interlocking" or "secondary" panel are excavated. After the excavation phase, the two sheet piles previously installed are removed with the help of a vibrator. The demolding operation is very fast (ca. 4 minutes per sheet pile) without causing any damage to the realized structure. The advantage of this operation is to guarantee the absolute cleanliness and integrity of the hydraulic coupling, result not easily obtained by using extraction type sheet or pipe stop ends.

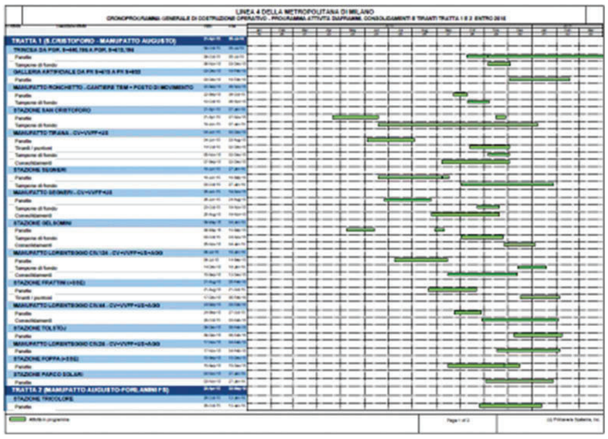

Figure 16. Job time schedule; target achieved!

8.2 *Compliance with the project schedule*

The works part of SAOS subcontract for the M4 Metro Line foreseen the realization of various size of diaphragm walls having thicknesses ranging from 600 up to 1.500 mm, at a depths up to ca. 50 m.

Given the variety of works to be realized, versatile and modular/adaptive equipment has been required; the collaboration between Liebherr LWN & Negrini has shown its strength. The time schedule of the contractualized foundation works has been successfully achieved: technological Building San Vittore: 56 days, Station San Ambrogio: 60 days, Technological building de Amicis: 73 days, Station de Amicis: 120 days, technological building Ticinese: 76 days, station Vetra: 116 days, technological Building Vettabia: 68 days, Stazione Santa Sofia: 60 days, technological building San Calimero: 70 days, station Sforza Policlinico: 125 days, technological building Augusto: 57 days, station San Babila: 78 days and technological building San Damiano: 18 days.

The synthetic schedule of the previous lot is reported (Fig. 16), just to give a picture of the working phases complexity, especially from the organizational point of view and of simultaneous workings activities to be conducted with suitable equipment in a cost effective and punctual manner.

9 CONCLUSIONS

The first SAOS experience in the Metro of Rome line C has taught us that in many of the Italian soil, at even high depths (> 50 m), diaphragms walls can be realized with hydraulic grab with excellent results in terms of cutting precision, productivity and costs; the Florence Railway link and the Metro of Milan are the clear successful evidence. Nevertheless, it is pretty clear that in order to achieve such a result Contractors shall be equipped with state of the art machineries and tools as well as supported by experienced technical operators.

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