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Technical–operational comparison between trench-cutters and clam excavators for concrete diaphragm construction in underground works at shallow depths

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The most common excavation methods for the construction of tunnels in urban areas are the ‘cut and cover’ method and the traditional method of excavation at the tunnel face. The first method is usually used for works at shallow depths, even though it frequently involves burdensome deviations and shifting of the existing underground plants and networks. It has been used to realise the Underground Railway Link in Turin (Italy), where excavation was made using trench-cutters and clam excavators. The results of a technical–operational comparison between the two techniques are presented in this work, from which the advantages concerning the use of trench-cutters compared to the use of clamshell bucket excavators have been determined.

1. Introduction

The design and construction of an underground tunnel in a large city presents particular and, in some cases, more sensitive aspects than large roads and railway tunnels outside the cities. For these reasons, the problems related to the construction require an in depth study and an accurate assessment of the effects that could be induced. One important aspect concerns the fact that the work, whether for a road or railway line tunnel or underground station, is almost always close to, if not below, buildings which are often old. Many different elements should be considered in the design and construction of this kind of work: the type of ground, the presence of water tables, the possibility of disturbances on the surface and the presence of other underground structures.

The most commonly adopted methods of excavation for the construction of tunnels in urban environments are: the ‘cut and cover’ method and the traditional method with excavation at the tunnel face.

The ‘cut and cover’ method (Figure 1) consists of only excavating after retaining vertical walls have been inserted along the perimeter of the excavation [1]. This kind of work can involve the insertion of piles or micro-piles, placed side by side, or more

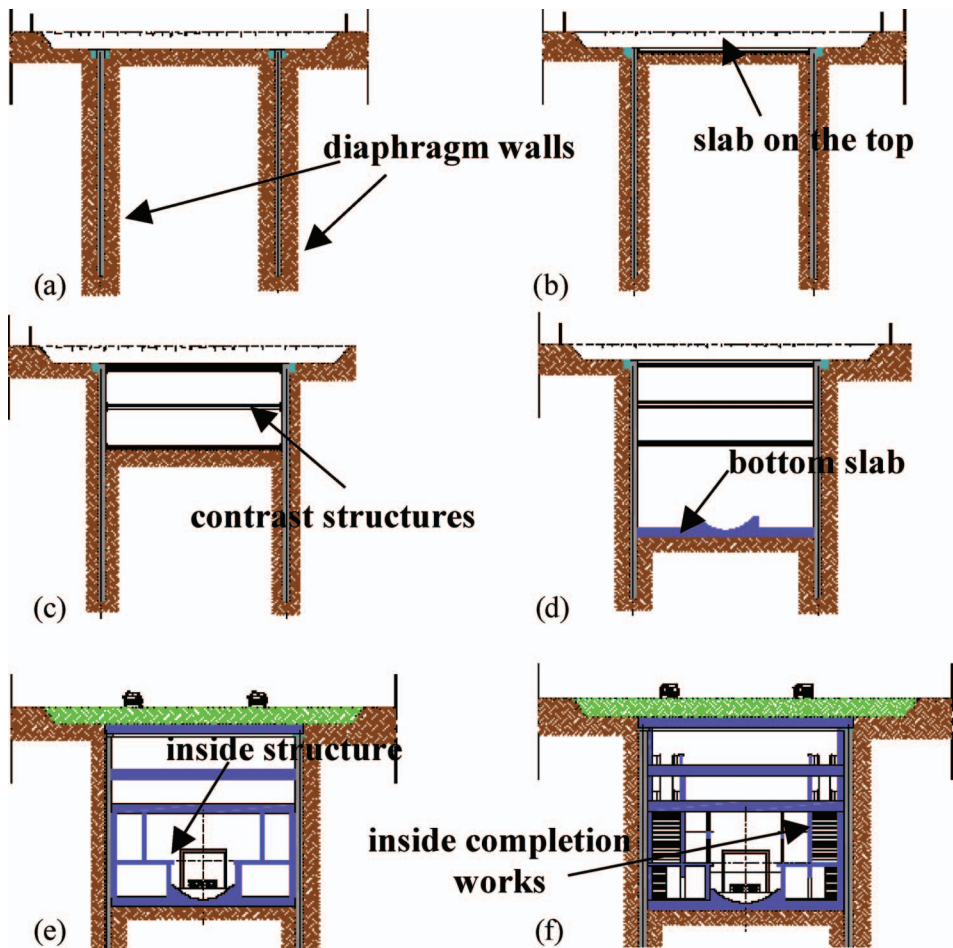


Figure 1. The ‘cut and cover’ method used for shallow excavations in urban environments (for example, for underground stations) [1]. (a) Realisation of the concrete diaphragm walls; (b) realisation of the slab on the top; (c) excavation from the top to the bottom and placing, where necessary, of contrast structures on the concrete walls; (d) completion of the excavation with the casting of the bottom slab; (e) realisation of the inside structure; (f) completion of the work.

frequently concrete continuous walls. The concrete walls are inserted by excavating the ground with a drilling fluid, generally a suspension of bentonite, which is then replaced by concrete, while the mud is displaced and taken up to the surface. In other words, the ‘cut and cover’ method involves the following steps:

- (1) excavation of a trench of reduced height (usually 1 m);
- (2) casting of walls (concrete side walls) to retain the trench;
- (3) filling of the void with bentonite;
- (4) further driving of the excavation until the design level is reached in the presence of bentonite mud;

- (5) excavation of a section of some metres (parallel to the wall) and the subsequent insertion of the steel rod reinforcement;
- (6) casting of the concrete from below, and removal of the bentonite in the excavation (realisation of the primary panels);
- (7) excavation of the zone between the primary panels, insertion of reinforcement and casting of the concrete (realisation of the secondary panels);
- (8) creation of a slab at the head of the walls in order to re-establish the ground surface and to counteract the displacement of the walls;
- (9) completion of the excavation below the slab in the zone between the concrete walls, previously having made the sides and roof of the excavation stable.

The decision whether to use the 'cut and cover' method or the traditional excavation method is the result of an evaluation of a series of problems, such as: the topographic structure of the city, the urban planning and requalification objectives, the hydrogeology and geology of the area, the geotechnical characteristics of the ground [2], the dimensions of the excavation section and the length of the underground works, the environmental impact of the works, and the construction costs. The crossing underground of urban agglomerates with historic centres of remarkable value and with very irregular urban layouts is almost always only possible using the traditional excavation method; in this case, the usual disturbances connected to sites on the surface are limited to just a few shafts necessary to start the tunnel construction.

The 'cut and cover' method, although offering doubtless advantages in terms of costs, is instead used more easily in less urbanised areas, such as for extensions towards external parts of cities, where the surface restraints are less significant, or where the urban fabric is regular and allows the placement of underground works below the main streets of the city. However, it is a method that is usually used for works at shallow depths in urban areas, even though it frequently involves the burdensome deviation and shifting of the existing underground plants and networks.

In 2000, a group of companies were awarded the right to realise the first section of phase II of the works for the construction of the Underground Railway Link of the City of Turin (Italy), using the 'cut and cover' method. The realisation of the work involved the choice of innovative technologies, as it was necessary to excavate a very long and wide tunnel in which the trains crossing the city of Turin could pass each other. The concrete walls necessary to stabilise the sides of the excavation absorbed a large portion of the resources foreseen for the realisation of the works. The excavation for the concrete diaphragms was conducted using trench-cutters that were designed and built by the German company Bauer Maschinen GmbH (Figure 2).

The use of the trench-cutter method offers prominent advantages compared to the use of conventional techniques, such as clamshell bucket excavators (Figure 3; [3]), with regard to the following aspects: economy, production, accuracy, flexibility, environmental impact and safety. Trench-cutters remove the material from the bottom of the excavation in a continuous manner and reduce it in size to pieces which, when mixed with the bentonite mud, can be taken up to the surface through pipes. The mud, mixed with solid particles of the excavated material, reaches the screening unit, where it is cleaned and returns to the excavation.

The process used to insert the steel reinforcement and the subsequent filling of the excavation with concrete is similar to the one used when clamshell bucket excavation

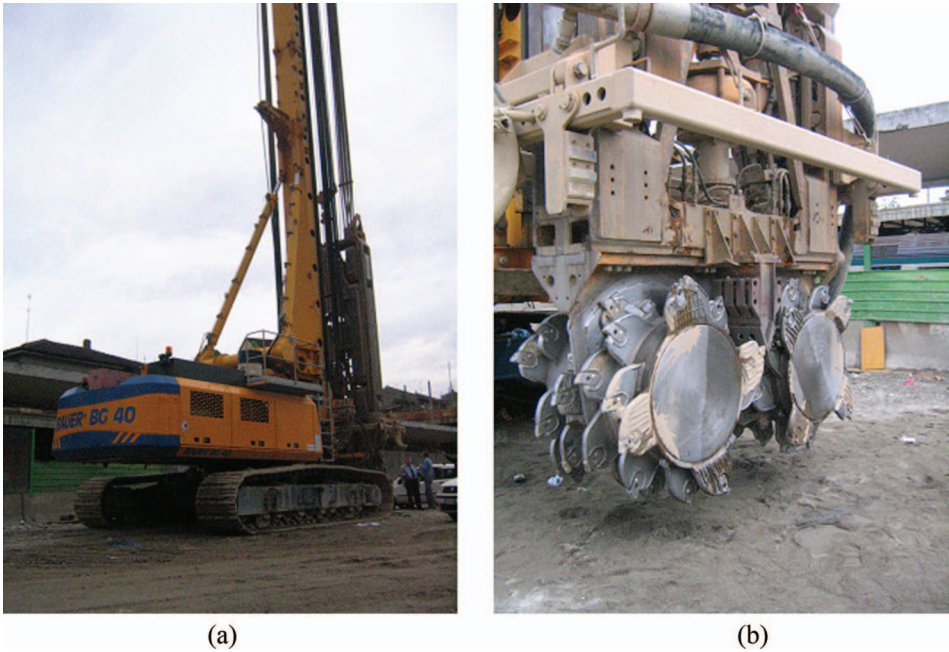


Figure 2. View of one of the trench-cutters used for the construction of the Turin Underground Railway Link (a) and details of the cutting wheels (b).

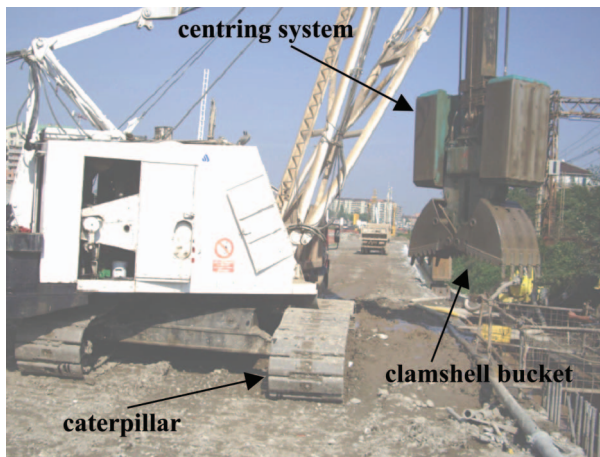


Figure 3. A clamshell bucket excavator and detail of the bucket [3].

technology is adopted. Clam excavators can either function hydraulically or mechanically. The buckets can be manoeuvred through free cables or Kelly type guide rods. The Kelly equipment can be either of a mono-bloc or telescopic type. Furthermore, there are two types of bucket: a valve type with pistons and hydraulic activation and a type with mechanical activation with cables. The bucket itself is used to carry the excavated material to the surface; for this reason, the productivity

(the excavation time per metre) decreases as the depth of the excavation increases (since the equipment has to be removed from the excavation in order to deposit the material on the surface).

The results of a technical–operational comparison between excavation with trench-cutters and clamshell bucket excavators used on the site of phase II of the Turin Underground Railway Link are presented in this work.

2. The Turin Underground Railway Link

The Turin Underground Railway Link project, which is unique in Italy because of the importance and complexity of the work, foresees the total transfer of the surface railway underground, through the creation of a north-south railway link (Figure 4) and of new stations, including the new *Porta Susa Station* which has been located underground and which is to be the station that is used for long-distance trains [4].

The purely urban section of the rail link runs from the *Lingotto Station* to the *Stura Station* over a distance of 12 km, of which 7 km are in tunnels, in part excavated using the ‘cut and cover’ method and in part using the traditional method. The integration of these development programmes of the railway node of Turin,

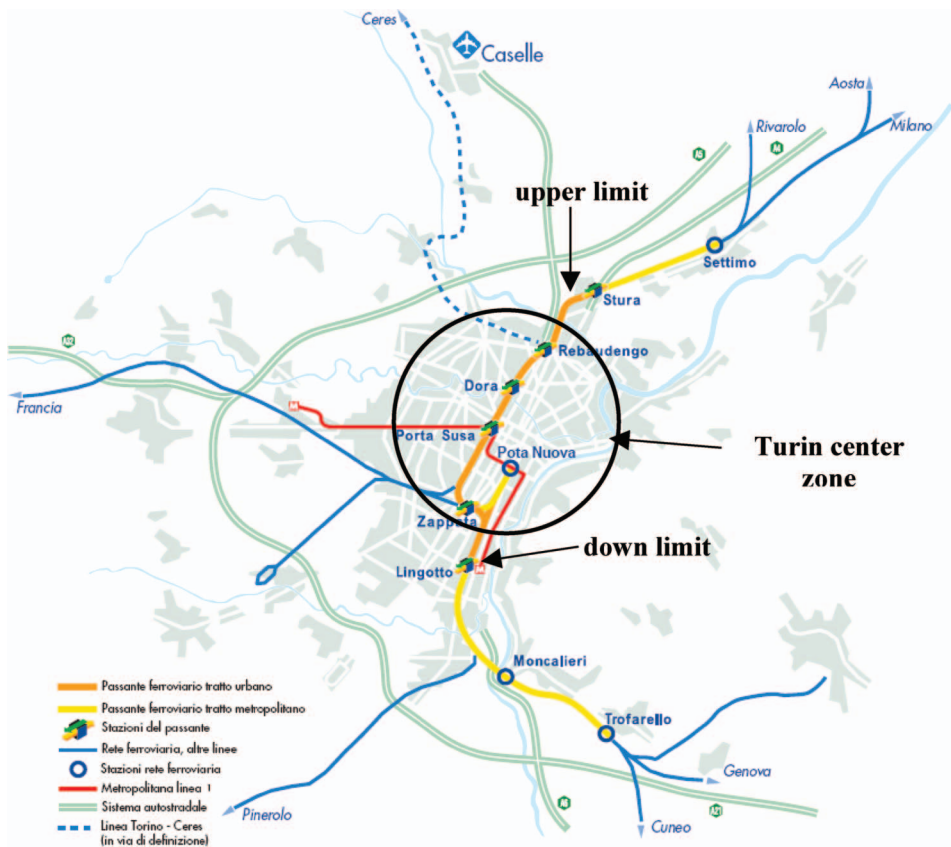


Figure 4. Map of the Turin transport network with indications of the route of the Turin Underground Railway Link [4].

together with the requirements of the city, has also highlighted the strategic nature of the Underground Railway Link as part of a complex urban renewal project. The project foresees the covering of the railway lines and the creation of a large avenue, as part of the urban renewal of a large zone of disused industrial areas along the border of the historical railway line.

There are seven stations involved in the railway link project, two of which are new (*Zappata* and *Rebaudengo*), and another three are to be rebuilt (*Porta Susa*, *Dora*, *Stura*), while the *Lingotto* and *Porta Nuova* stations will not undergo any significant changes.

The doubling of the anticipated railway lines of the new Underground Railway Link arises from the necessity of functionally separating medium and long-distance connections from local transport connections; at present, there is only one network, on which goods trains, local trains and long-distance trains all have to pass [4]. As is known, each train passes along the railway lines at a different speed, and the routes are organised on the basis of different stops; an inevitable result of this is that the interference between the trains and the problems of circulation dictate the train timetables and number of trains are concerned over the needs of the travellers.

The second phase oversees the development of two separate tunnels running side by side with the railway tracks at the same level. From an altimetric point of view, the new tunnels will generally be at a lower level than the ground surface and the original Turin-Milan line. This will allow the *Spina Centrale* (a new main street) to be built above the railway tunnels, in a very central zone. This large road artery will have side roads and crossroads on the ground surface and will allow the area above the tunnels to be reconnected.

The area involved is characterised by a high density of buildings, some of which are of historic interest, and which are located close to the planned railway tunnels. This leads to complex problems as far as the placing of work sites is concerned since, as will be explained later on, it is necessary to carry out the work whilst at the same time guaranteeing the normal services of the Turin-Milan railway service. Furthermore, the work has to be carried out in a very restricted area in which it is necessary to guarantee access to the existing residence buildings and commercial activities.

The vertical walls of the tunnels are concrete diaphragms systematically cast into the ground. Three different basic dimensions for these diaphragms have been found necessary: rectangular 120×280 cm sections, rectangular 100×280 cm sections and T sections with a length and an overall height of 240 cm. In order to create a continuous wall, the adjoining panels are interpenetrated by about 10 cm along the contact edges. The internal tunnel walls are always of rectangular section, while for the external walls, in direct contact with the ground, T section panels have also been used due to the particular static requirements deriving from the depth of the internal excavations and from the necessity of reducing horizontal displacements at the top. The entire local public transport system will therefore have a significantly upgraded railway service, thanks to the convenient interchange stations that are connected to the new metro line and to the other public transport services on the surface [5]. Some of the characteristics of the Underground Railway Link once completed are:

- length of railway line: 12 km;
- maximum depth with respect to ground level: 18 m;
- overall covering to the old railway lines: $260,000 \text{ m}^2$;

- concrete used: 180,000 t;
- open excavation: 2,000,000 m³;
- length of new tree lined avenue between *Corso Turati* and *Corso Grosseto*: 7.5 km;
- maximum width of the new tree lined avenue: 90 m;
- passengers transported in a year: more than 50,000,000;
- trains in transit each day: 520;
- daily frequency of the trains in both directions: during rush hour one train every 5 min;
- overall cost of the work: 1,299,511,104 Euros.

3. Evolution and functioning of trench-cutters for concrete diaphragm wall excavation

No other innovation has been able to change the construction procedures of concrete diaphragms as much since the development of trench-cutter technology in 1980s. Although excavation techniques with clamshell bucket excavators had already demonstrated an enormous potential for the construction of diaphragm walls, the ever increasing need to reach greater depths and to obtain better waterproofing of the structures soon highlighted the limits of clamshell bucket excavators.

The idea of constructing concrete diaphragms walls with the use of trench-cutters came from Japan, where the first machine was built back in the early eighties. When, in 1984, the need arose to create concrete walls for the *Brombach basin*, part of the *Rhein-Main-Donau project* in Germany, Bauer Maschinen designed the first BC 30 trench-cutter. This prototype worked successfully for the construction of diaphragm walls some 40 m deep in moderately hard sandstone. Over the following years, the machine was continuously improved, with the main innovations involving the design of an absorption system to counteract the impact between the cutting wheel and the reducers as well as the development of a system of balancing teeth [6]. The technology was further developed when, at the end of the 1980s, the first work in hard rock was undertaken. This innovation involved replacing the fixed drilling tools with rotating button cutters.

At the beginning of the 1990s, a trench-cutter was constructed in Japan that was able to excavate 80 m deep diaphragms and, in 1993, diaphragms as deep as 150 m were constructed. The subsequent introduction of guiding hydraulic plates in the frame of the trench-cutter made it possible to limit the vertical deviations of the walls (only 2 cm at a depth of 100 m). The main element of the trench-cutter is the cutting head [8], which is usually called the 'cutter'; it is made of a heavy steel structure in which cutting wheels are installed in the lower part that rotate in opposite directions around a horizontal axis [7]. The cutting wheels, which are specifically designed for the material that is to be excavated, are installed in pairs on two reducers. Each reducer has an independent hydraulic circuit so that the cutting heads can be manoeuvred separately and at different speeds. As they rotate, the material in front of the wheel is removed in a continuous manner, mixed with the bentonite suspension present in the excavation and moved towards openings in the suction box.

The cutting heads can be modified or substituted to excavate panels of different sizes [8]; the suction box and the frame have to be modified in order to be suitable for the dimensions of the excavation. The ejector plates, which are assembled on the

suction box, guarantee the passage of the maximum sizes permitted, allow blind spaces to be covered and have the function of fragmenting the larger pieces.

The reducers are protected by special elastic shock absorbers, which are installed between the cutting wheels and the reducers themselves, in order to protect them from knocks caused by impact with the material that is being excavated by the cutting structure.

The cutting heads are usually equipped with long tool holders; these allow any type of material to be excavated, including plastic clays, without the wheel being plugged. The cut produced by the tool, which usually has an insert of tungsten carbide, covers the entire width of the tool holder. Different types of tools can be used depending on the type of material. In very hard formations, with strengths above 100 MPa, the cutter heads must be equipped with special rotating cutter tools supplied with button inserts (like those utilised in oil drilling). The trench-cutter allows high performances to be reached in almost all geological formations. Maximum productions of 60 m³/h of excavated material have been obtained. The body of the trench-cutter can be equipped with additional ballast to increase the drilling thrust; with this kind of system it is possible to create diaphragms with thicknesses of up to 1.2 m.

In the case of geological formations that have relevant blocks of rock, such as some alluvial deposits, the rotating wheels supplied with rotating cutters can reach similar productions to those obtained in soft soils; the advantage of this type of excavation over that of clamshell bucket excavators is that it is no longer necessary to demolish these blocks with high-powered hydraulic hammers, which are necessary when clamshell bucket excavators are used.

The trench-cutter is lowered into and removed from the excavation via the use of winches, which are assembled on the base machine. In some cases, the advancement of the trench-cutter cannot be controlled by a simple conventional winch, as it may not be sufficiently sensitive to the heterogeneous ground. Nowadays, the precise regulation of the thrust of the cutter on the bottom of the excavation can be obtained through a thrust cylinder that is assembled on the frame of the trench-cutter or through the use of a highly sensitive winch. Both of these systems are controlled electronically and can therefore be easily regulated by the operator.

A centrifugal pump, which is installed immediately above the cutter wheels, withdraws the bentonite mud together with the excavation material and sends it to a treatment plant. The productivity of the excavation, in the presence of loose material and when heavy mud is used, is determined by the capacity of the pump. Pumps with a nominal capacity of up to 700 m³/h can be used with the trench-cutter.

An inclinometer is installed inside the body of the trench-cutter in order to measure the vertical deviations on both levels; this information is shown, in a continuous manner, on the control monitor that is found in the cabin, supplying information on distance (cm) and dip (°). If the trench-cutter deviates from its vertical axis, the relative position can be regulated with the help of steerable sliding blocks.

The bentonite mud loaded with the excavation material is sent to the de-sanding unit, where all the solid particles are removed, and the thus cleaned bentonite can then be recycled back into the excavation. Sieves, cyclones, vibrating tables and centrifugal separators are used to mix and regenerate the mud. The main features of the de-sanding plant are:

- (a) the entire structure is constructed in modules, and this allows the de-sanding unit to be adapted to the capacity of the trench-cutter;
- (b) secondary separation is also possible through the use of conventional or centrifugal de-sanders;
- (c) the unit is compact for limited bulk volumes;
- (d) very little time is required to assemble and dismount all the units.

The de-sander discharges fine sands and pebbles outside the structure as it has two fine sieving modules on the side and a coarse sieve in the centre.

4. Analyses of the performances of the trench-cutter and the clamshell bucket excavator in the sites of the second phase of the Turin Underground Railway Link

4.1. Geological–technical characteristics of the area

Numerous geognostic investigations were carried out in the scoping work of the Turin Underground Railway Link before excavation work started. These investigations included continuous boring mechanical surveys, SPT (standard penetration test) tests, plate load tests, seismic tests, geo-radar prospecting, permeability tests, continuous assessment and laboratory tests (grain size and Atterberg limit analyses) in order to conduct geotechnical characterisation of the soils, also in relation to their excavation properties. The data obtained made it possible to identify the following stratigraphy of the Turin subsoil in the area involved in the project, from the top to the bottom:

Undifferentiated alluvial deposits (Holocene) represented by coarse gravel and sands of various degrees of coarseness, sometimes cemented, originating from the meandering of the *Dora Riparia* and the *Stura di Lanzo* riverbeds, with a thickness of up to 50 m;

Fluvial-glacial deposits (Middle Upper Pleistocene) with gravel and sands, sometimes very cemented, with subordinate silty-clayey levels, of depths up to 70 m from ground level;

Fluvial-lacustrine deposits (Upper Pliocene – Lower Pliocene), alternances of sediments from a fluvial environment (gravel and sands) with those from a lacustrine-palustrine environment (silts and clays with remains of vegetation);

Pliocene marine deposits, fossiliferous sands passing to blue clay deposits.

The section of the city involved in the second phase of the Underground Railway Link affects two areas: the first (Zone 1) from *Corso Vittorio* to *Piazza Statuto*, where coarse fluvial-glacial deposits prevail, with the presence of cemented levels of a thickness of 20 m; the second zone (Zone 2) is from *Piazza Statuto* towards the *Dora Riparia River*, where alluvial and fluvial-glacial deposits from the *Dora Riparia River* are present with cemented levels with thicknesses of up to 10 m.

From an analysis of the investigations, it can be observed that the presence of cemented layers is significant in Zone 1, but less relevant in Zone 2. Mean parameters, obtained from in situ and laboratory tests, were attributed to the different aforementioned types of ground.

In zone 1: γ : 20 kN/m³; φ' : 38°; c' : 0-20 kPa; E: 240–360 MPa.

In zone 2: γ : 20 kN/m³; φ' : 35–40°; E: 50–240 MPa.

These geotechnical evaluations were also used to determine the most appropriate excavation technology to adopt; on the basis of this knowledge, it was considered that the ground in the second phase could be excavated with rotating tools equipped with teeth (trench-cutters). In fact, numerous in situ tests showed how the performance of the clamshell bucket excavators is influenced to a great extent by the state of the cementation of the ground, which prevents the teeth of the bucket entering the ground.

4.2. *The adopted trench-cutters*

A Bauer BC 40 trench-cutter mounted on a Sennebogen BS 6100 wagon and a Bauer BC 30 mounted on a Sennebogen BS 670, equipped with an external power pack, are two of the types of trench-cutters that have been used in the Turin Underground Railway Link sites. The basic difference between these two machines concerns their weight and power. Moreover, the BC 40 has positioning and vertical control blocks, but these are not present on the BC 30 structure, which is instead equipped with a thrust piston. However, the two machines generally work in the same manner.

The cutter bearing structure, which is about 12 m high, is suspended from the mast of the machine; the overall system weighs about 40 tons. The structure supports the cutting group. This is made up of two hydraulic engines that supply the movement to the four wheels into which the cutting tools are inserted.

The overall cost of the machines is about three million Euros.

The production of the trench-cutter used for the rail link reached levels of 4 panels/day for a long work shift, that is about 200 m³/day of excavation. The mean value is in the region of more than 2 panels/day for each machine. In terms of hours, it is possible to obtain excavation speeds of 11 m/h in soft ground.

The consumption of the teeth registered on the trench-cutters resulted in very low values, thanks to the level excavation technology that has been adopted (electronic control of the drilling parameters) and to the high quality of the cutting tools that have been used. The mean tool substitution incidence, under normal working conditions, without considering any initial inconvenience caused by interference with metallic objects, is currently equal to 0.05 teeth/m³ of excavated ground, which in practice means 2.5 teeth/panel. Each single panel has a mean dimension of 2.75–2.8 m width and of 1–1.2 m thickness.

The wear on those parts in direct contact with the material at the bottom of the excavation and in the movement in the pipes towards the de-sanding unit resulted in being medium–high, due to the high abrasiveness of the mixture of bentonite and the high quantity of pebbles (some with sharp edges), quartz sand and sometimes even metallic objects.

Trench-cutters are normally used to create diaphragms at great depths and/or when the excavation touches the substrates of a lithoid consistency. In this case, the site plant is more complex than the plant relative to a clamshell bucket excavator; the extraction and removal of the excavation material is entrusted to the circulation of bentonite mud which takes the excavation material up to the surface in a continuous manner through a pump and specific pipes.

Excavation with trench-cutters requires a pre-excavation (which should be conducted with clamshell bucket excavators) until a depth is reached at which the mud circulation pump that is incorporated in the machine can be used (about 4 m). Only after having reached such a depth can the trench-cutter be used to reach the

final depth determined in the design. After the excavation of the panel, about 40 min of de-sanding is necessary, leaving the suction pump for the mud and debris functioning without using the cutters.

Maintenance of the trench-cutters at the Underground Railway Link sites (control of the levels in the hydraulic circuits and repair of worn parts, such as the teeth holders and protection plates, through electrode welding) has been relegated to the weekends in order to avoid delays in production during the working week.

The workforce used to excavate with the trench-cutter is made of a team of five: one specialised worker to guide the trench-cutter, one worker to manoeuvre the crane and to move the metallic reinforcements and three workers to carry out the operations around the excavation.

Before proceeding with the excavation, it is necessary to dig short trenches: these usually have a depth of 80 cm. They have the purpose of guiding the excavation and are dug for several panels at a time (Figure 5). Finally, the consignment and return pipe systems are connected to the de-sander unit and the trench is filled with bentonite.

The excavation with the clamshell bucket excavator is then carried out for a depth of at least 4 m. This operation lasts about 60 min, considering the levelling of the clamshell bucket excavator before excavation, the excavation itself and the final movement of the excavator to leave space for the trench-cutter.

The trench-cutter is then positioned on the basis of the points established by the topographers, and the two consignment and return pipes are connected to the de-sanding unit.

After excavation, the reinforcement is installed inside the diaphragm and the concrete is cast (Figure 6).



Figure 5. View of the short trench made initially to allow excavation of a panel in order to begin the construction of concrete diaphragm walls.

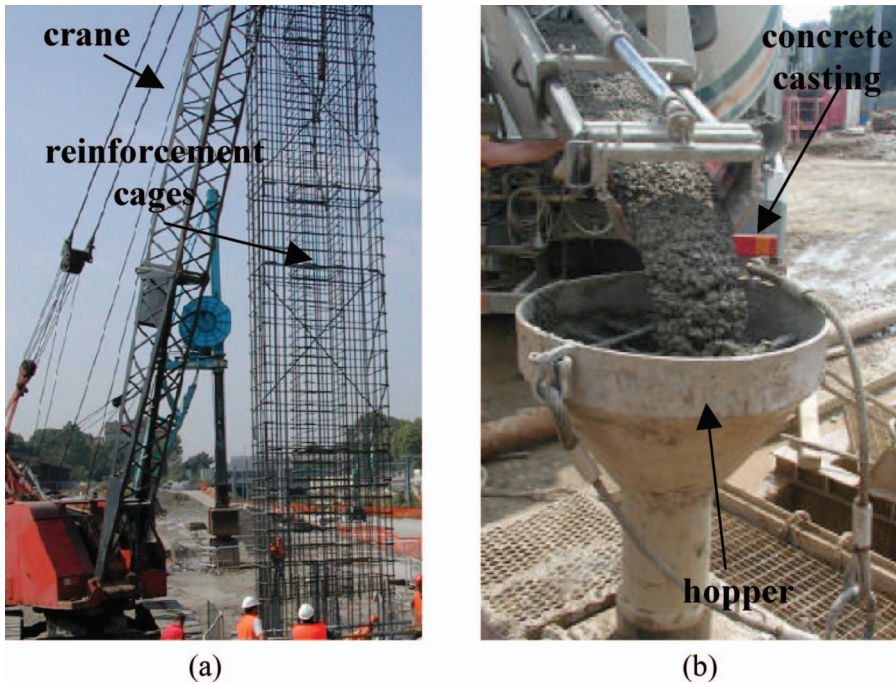


Figure 6. Positioning of the reinforcement cages of a panel (a) and the subsequent casting of concrete through a hopper and the casting pipe below (b) [1].

In order to optimise the work, every fourth panel is excavated by the trench-cutter so that the cast concrete in the preceding panel has time to harden before the adjacent panel is excavated.

4.3. Characteristics of the clamshell bucket excavators

The clamshell bucket excavator used for the Underground Railway Link has a mean bucket capacity of 2 m^3 . The bucket excavates a little less than 0.5 m of diaphragm for each passage. Maximum depths of concrete walls of 26.5 m have been obtained with this machine, a value that represents the limit as far as the admissible tolerance of the vertical deviation of the panels and the regularity of the side walls themselves are concerned. The weight of the bucket varies, according to the dimensions of the panel, between 6 and 10 tons. The weight of the bucket obviously allows the teeth to penetrate well into even the most compact ground.

The verticality of the excavation tool is made possible thanks to the biaxial inclinometers that are mounted on the bucket and to the sensors that are mounted on the movement cable.

Verticality of the machine is usually guaranteed by the correct balancing of the weight of the machine, except for when boulders are encountered. Excavation with the clamshell bucket excavator is performed in the presence of resting bentonite mud.

During the excavation, the level of mud is kept constant in respect to the work level, and small quantities of mud are added to balance the portions lost inside the ground or trapped in the ground extracted by the clamshell bucket excavator.

The bucket itself is used to carry the excavated material to the surface; for this reason, the productivity (excavation depth in m/h) is prolonged with an increase in depth of excavation (the clamshell bucket excavator must be removed from the excavation in order to deposit the excavated material at the surface). The mean trend in the productivity of the clamshell bucket excavator, with variations in excavation depth and of the dimensions of the bucket, is shown in Figure 7 [9].

When blocks or boulders are encountered, they have to be broken up so that they can be removed. This process can be carried out with hammers or explosives. In both cases, the operation, apart from causing delays in the excavation of the panels, can also induce significant over-excavations and therefore a greater consumption of concrete during the casting phase.

The team of workers on site using a clamshell bucket excavator is composed of four individuals: one specialised worker to guide the clamshell bucket excavator, one worker to manoeuvre the crane in order to move the metallic reinforcements and two workers to carry out the operations around the excavation.

The machine used for the excavation weighs about 500 q and costs about 750,000 Euros.

4.4. Analysis of the excavation times of the panels for the Turin Underground Railway Link

The behaviour of four different types of trench-cutter, of BC 30 and BC 40 types, operating on sites of the second phase of the Turin Underground Railway Link have been analysed in order to evaluate the productivity of these modern excavation machines for the realisation of concrete walls. The first and fourth machine have been used in front of the *Dora Station* (Zone 1), while the second and third have

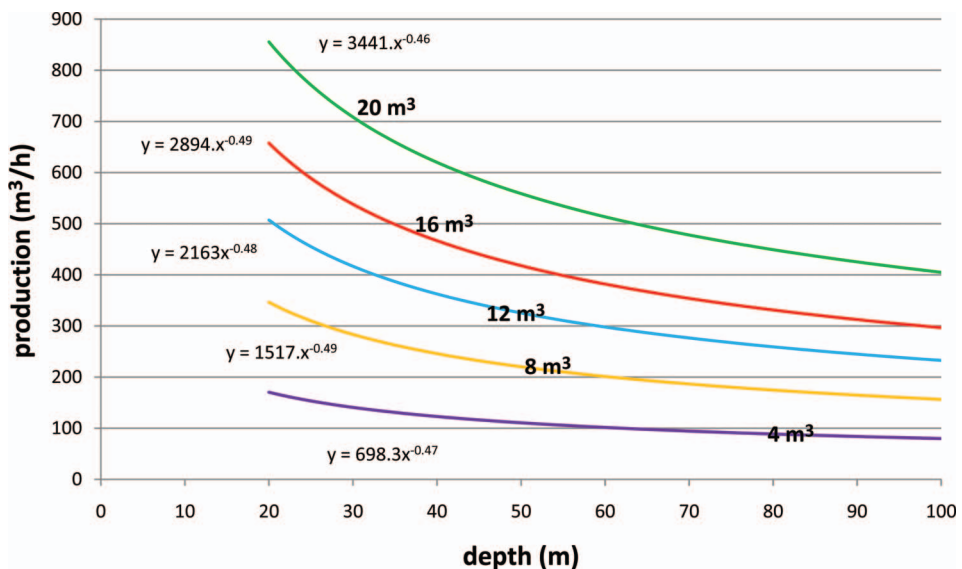


Figure 7. Productivity of a clamshell bucket excavator as a function of the capacity of the bucket [9].

worked close to *Corso Principe Oddone*, halfway between *Corso Regina Margherita* and *Piazza Statuto* (Zone 2).

In the four cases examined, the panels that had to be created with the trench-cutters had a depth of 32 m and plan dimensions of 2.8×1 m. The time necessary to excavate the first 4 m of the panels was always about 1 h, with the use of clamshell bucket excavators.

The following times were necessary for the excavations using the trench-cutters for the remaining 28 m: about 2.5 h in case 1, about 5 h in case 2, about 8 h in case 3 and about 3.2 h in case 4.

In the case of the clamshell bucket excavation, the panel had a total height of 26.5 m (the technical limit for excavation with this type of machine) and plan dimensions of 2.75×1 m. The excavated ground had poor geotechnical characteristics and cemented levels of negligible thickness.

The productivity of the excavations, in terms of depth reached with respect to time, for the four cases excavated with the trench-cutters and for the case of the clamshell bucket excavator, is shown in Figure 8.

It can be observed in the figure how the excavation speed of the trench-cutters varies greatly from case to case: the trench-cutters even seem to proceed more quickly in the more cemented grounds (Zone 1 – cases 1 and 4) compared to the less cemented grounds (Zone 2 – cases 2 and 3). The specific excavation times for the type of panel considered (plan dimensions of 2.75–2.8 m) varies between 5.5 and 17.2 min/m or between 0.09 and 0.29 h/m, and it remains constant with depth. The productivity of the excavations examined varies between 0.16 and 0.51 m³/min as a function of the type of ground encountered. The data concerning case 3 have to be considered rare and due to the particular aspects of the site. For this reason, the interval of values of the specific excavation time equal to 5.5–11 min/m (0.09–0.18 m³/min) and of excavation productivity equal to 0.26–0.51 m³/min as a function of the type of ground encountered can be considered valid.

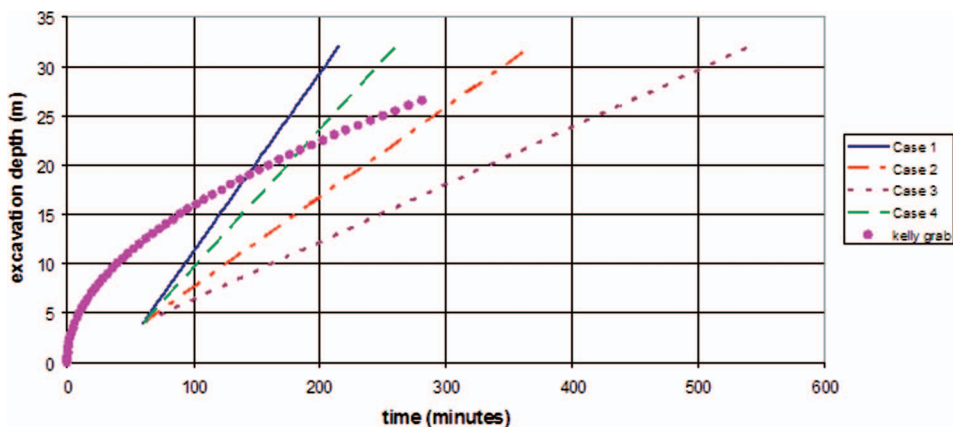


Figure 8. Depth reached with respect to time by the trench-cutter for the four cases examined and for the clamshell bucket excavator at the Turin Underground Railway Link sites. In the first 60 min or so of excavation with the trench-cutter, it was necessary to excavate the first 4 m of panel using the clamshell bucket excavator, this is in order to reach the necessary depth to be able to start the pump to circulate the mud together with the excavation debris.

The excavation speed of the clamshell bucket excavator obviously varied with depth. The specific time changed from 0.2 min/m at the start of the excavation to 21 min/m at a depth of 26.5 m (mean value of 10.6 min/m). The productivity of the excavation ranged from 825 to 7.8 m³/h (mean value of 15.6 m³/h). These values are generally independent of the type of ground and are valid for non-cemented ground (incoherent or weakly cohesive) without boulders (large blocks of rocks). If the clamshell bucket excavator encounters layers of cemented ground, or areas with large boulders, the productivity of the excavation is drastically reduced as it is necessary to temporarily substitute the excavator with other means in order to demolish the compacted material and then proceed with its removal using the clamshell bucket excavator.

In Figure 8, it can be noted how the comparison of the excavation times always points towards the clamshell bucket excavator being the most convenient for depths below 18–20 m. In some cases, when trench-cutters do not seem to be very productive (for example, in cases 2 and 3), the clamshell bucket excavator seems to be more competitive up to the limiting depth of 26.5 m (technical limit in relation to the tolerance required concerning the verticality of the concrete walls).

Once the excavation is complete, the reinforcement is installed and this is followed by casting of the concrete. The reinforcement cage is inserted in two parts for depths greater than 12–15 m: first, the lower part of the reinforcement is inserted and then the upper part. About 20 min are necessary to lift each part of the reinforcement with a crane. After the first part has been installed and the second is placed in position, about 5 min are required to weld the two together. Another 10 min are necessary to install the second part. The total time necessary for the installation of reinforcement composed of two parts is therefore in the region of 1 h.

The concrete is then cast. The preparation for the casting lasts about 20 min, and this should be added to the time necessary for the concrete mixer to be available. About 3.6 h were necessary to cast concrete for a panel of 32 m, while 3 h were necessary for a panel of 26.5 m.

Nine concrete mixer loads were necessary to fill a diaphragm of a height of 32 m with concrete, while 7.5 concrete mixer loads were necessary to fill a diaphragm of a height of 26.5 m.

Once the time necessary for the hardening of the concrete has passed, the panel can be considered finished and it is possible to proceed with the next panel.

5. Conclusions

In order to draw practical conclusions from the comparison between trench-cutters and clamshell bucket excavators, it is possible to state that a clamshell bucket excavator requires 4.5 h to excavate a panel of a height of 26.5 m in ground without any particular excavation or stability problems, while a trench-cutter only needs 3.5 h to excavate a panel of a height of 32 m.

However, several additional operations can slow down the excavation: a typical example is that of the maintenance operations that are necessary for the clamshell bucket excavator. The most frequent of these is the substitution of the cable that supports the excavation apparatus. This becomes worn during excavation and it is usually by precaution replaced at every 20 panels for excavations in the ground with medium geological and geotechnical characteristics. This operation lasts about 1 h. The maintenance operations for the trench-cutter, excluding particular cases, are not

performed during excavation activities. They are usually performed at weekends or on holidays in order not to interrupt the production of the machine.

The main advantages concerning the use of trench-cutters in sites compared to the use of clamshell bucket excavators can be summarised as:

- (1) the excavation speed: up to two panels a day were excavated with the trench-cutter in the Turin Underground Railway Link sites compared with only one excavated with the clamshell bucket excavator;
- (2) the depth and the precision of the excavation: greater excavation depths are reached with the trench-cutter (beyond the technical limit of the clamshell bucket excavator of 26.5 m) with very high precision of verticality;
- (3) the quality of the walls is usually better when trench-cutters are used and there is therefore less concrete is lost due to over-excavations;
- (4) there are no risks of interruptions or lengthy hold ups in the excavation in the presence of very compact (or cemented) grounds or boulders, as trench-cutters can excavate under these conditions without problems.

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