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Productivity and working costs of modern trench-cutters for the construction of concrete diaphragms in an urban environment

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In the excavation of shallow underground works in an urban environment using the ‘cut and cover’ method, the choice is often made to use concrete diaphragms in order to support the side walls, before proceeding with the excavation of the ground. When these diaphragms exceed a depth of about 20 m, trench-cutters are generally used to excavate the panels, using a supply of bentonite mud. A remarkable development of trench-cutters has taken place over the last 30 years and these machines today allow panels to be excavated in any type of ground whatsoever, even when it is highly cemented. The experience that has been gained in Turin (Italy) in recent years can be considered interesting, because of the huge number of diaphragms that have been completed and the varying characteristics of the ground in the urban area, which ranges from loose sand and gravel to highly cemented ones. On the basis of detailed analysis of the *in situ* behaviour of trench-cutters in Turin and of laboratory investigations on the effects of wear on the tools, it has been possible to make a preliminary estimation of the construction costs and the productive times of the concrete diaphragms for the different types of geology.

1. Introduction

Underground works at shallow depths in urban areas are often conducted by means of the ‘cut and cover’ method, which involves installing concrete diaphragms around the perimeter of a structure before carrying out the excavation. This method shows clear advantages over the traditional blind-hole excavation method:

- Lower costs.
- Lower realisation times.
- Fewer risks of subsidence and stress–strain disturbance on the structures and services on the surface.
- Greater safety for the workers during the underground excavation phases because of the absolute guarantee of stability of the roof and side walls.

However, the ‘cut and cover’ method requires that the ground surface reached by the forecasted plan of the underground work is free of structures and that it should be at least temporarily occupied by the excavation work sites. This only happens when a city has a regular street distribution and these streets are wider than the underground work that has to be achieved or when the work has to be conducted in suburb areas of the city where the density of the structures on the surface is low or when there are no structures.

The ‘cut and cover’ method involves a number of steps that must be strictly observed in their sequence [1].

The widespread use of trench-cutters for the excavation of diaphragms has led to the expansion of the ‘cut and cover method’. These machines (Figure 1) conduct the excavation in a bentonite mud bath. This mud is continuously fed in such a way that the bath surface remains coincident with the ground surface as the excavation proceeds. The main function of the bentonite mud is that of making the excavation walls stable before the concrete is cast. It also has the purpose of transporting the debris produced by the excavation to the surface and of cooling the excavation tools.

Bentonite mud is a 5–6% water–bentonite solution. The density of the bentonite can be increased by adding appropriate inert materials (deflocculants or organic products).

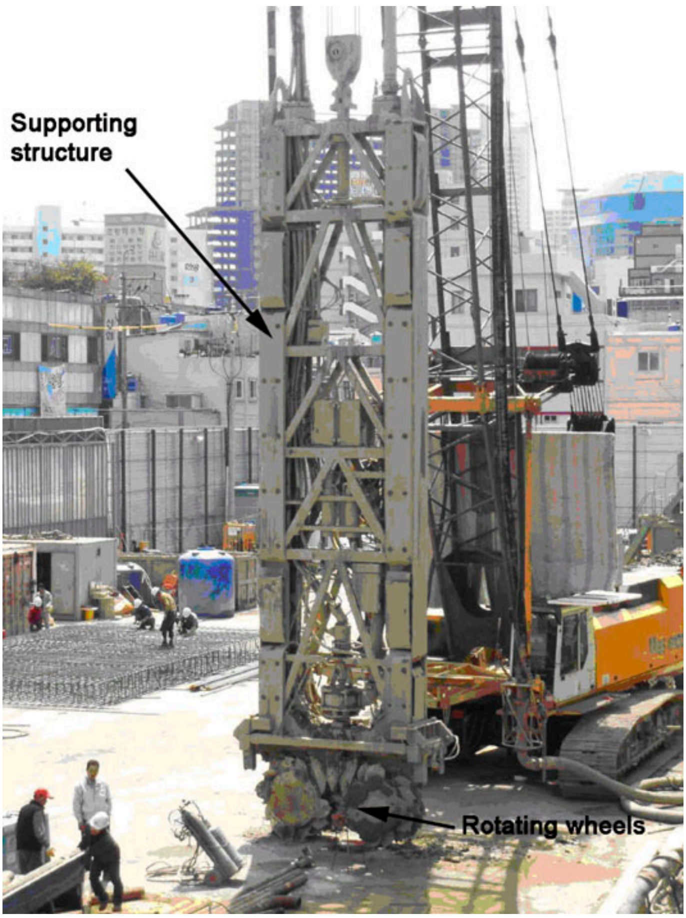

Figure 1. Diaphragm wall electro and hydraulic trench-cutter. Crane: 100 t; height of cutter: 12 m; trench width: 750–2000 mm; trench length: 2800 mm; max depth: 40 m; max torque: 80 kN m; mud-pump hole size: 6 in.; mud-pump quantity: 480 m^3/h; and weight of cutter: 35 t.

Table 1. The physical and chemical properties that bentonite mud should have during excavation of the diaphragms and before the concrete is cast [2].

	New mud	Recycled mud	Before casting
Unit volume weight	<1.10 g/ml	<1.25 g/ml	<1.15 g/ml
Marsh viscosity	32–50 s	32–60 s	32–50 s
Filtration value	<30 ml	<50 ml	–
pH	7–11	7–12	–
Sand content	<3%	<6%	<4%

The EN 1538 regulation [2] suggests periodic controls of the bentonite during work procedures, with reference to the parameters given in Table 1.

Once the excavation of the panels has been finished, the next steps involve the insertion of the reinforcement cage (Figure 2) and then the casting of the concrete. The latter operation is very delicate as it is essential to avoid the mixing of the concrete and bentonite mud inside the panel. The casting, therefore, takes place, through the use of casting pipes, from the bottom of the excavation, and the mud that moves to the surface is gradually collected. At the end of the casting step, the upper portion of the concrete is demolished as it is contaminated by the bentonite mud and a head beam is cast after the iron reinforcement has been positioned.

The head beam has the purpose of making the concrete diaphragms that have been installed during the different phases, along the perimeter of the underground work, homogeneous.

Once the construction of the concrete diaphragms along the perimeter of the underground work has been completed, it is possible to proceed with the head slab, which is placed upon the previously created diaphragms. It is then possible to open the area on the surface to the transit of traffic and the underground excavation operations can proceed as there is now a stable roof and side walls.

At present, two important underground infrastructures are being completed in Turin (the Underground railway link and Line 1 of the Underground metro system) and a

Figure 2. Diaphragm reinforcements in the site area of the Turin railway link ready for insertion into the panels excavated by means of trench-cutters.

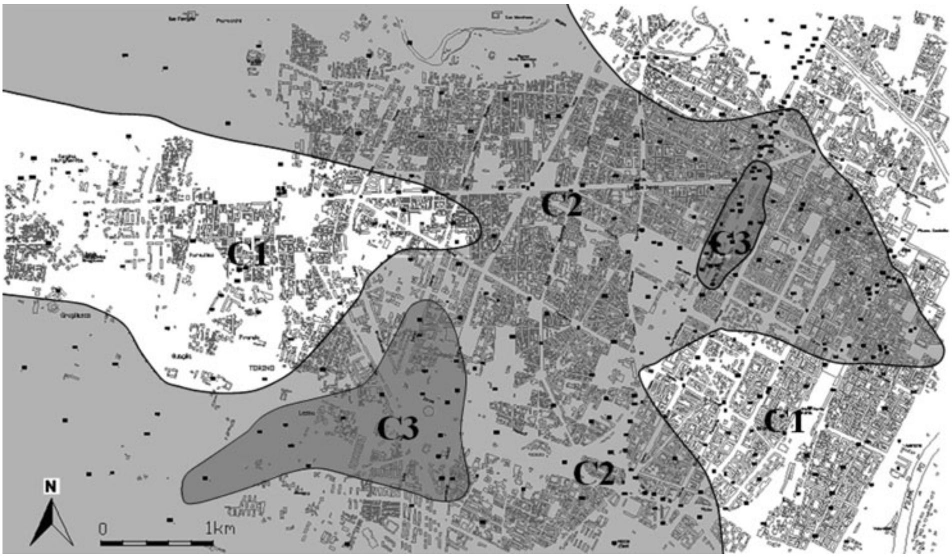

Figure 3. Degree of cementation (C1, C2 and C3) of a horizontal section of the Turin subsoil at a depth of 15 m from the surface [3–5].

third is at the design stage (the Corso Marche multi-modal corridor). All these large infrastructures, which will radically change the characteristics of the city's mobility system, have relied on the 'cut and cover' excavation method and the creation of several kilometres of concrete diaphragms for the support of the excavation side walls (http://www.italferr.it/cms/v/index.jsp?vgnextoid=dd8eec38bea0a110VgnVCM10000080a3e90aRCRD).

The experience gained over these last 10–12 years in Turin has made it possible to fully evaluate the expansion of trench-cutters and also to estimate the costs of the work and the productivity of these machines in order to have precise comparisons for the planning and programming of future work.

The Turin case has proved to be very interesting, not only because of the relevant number of concrete diaphragms constructed, but also because of the great variability of the mechanical characteristics of the ground, which goes from loose sand and gravel to very cemented sand and gravel of a stony consistency (Figure 3 and Table 2).

In this work, after having described the main characteristics of the modern trench-cutters that have been used in Turin, the constructive costs and excavation productivity of these machines have been estimated on the basis of a detailed analysis of the times of the various operative phases obtained on the sites. In addition, the results of an analysis carried out in the laboratory on the interaction between the components of the

Table 2. Geotechnical parameters of the cementation classes [3,5].

	C1 class	C2 class	C3 class
Cohesion (MPa)	0.01	0.03	0.1
Friction angle (°)	36	38	40
Elastic modulus (MPa)	150	190	230
Poisson ratio (–)	0.25	0.25	0.25
Specific weight (kN/m^3)	20	21	22

subsoil of Turin and the trench-cutter tools are provided, in order to point out the performance in terms of wear.

2. Main characteristics of modern trench-cutters and of the desanding plant

The idea of constructing concrete diaphragm walls using trench-cutters originated from Japan in the early 1980s when the first machine was built. Bauer Maschinen designed the first BC 30 trench-cutter in 1984 when the need arose to create concrete walls for the Brombach basin, part of the Rhein-Main-Donau project in Germany. This prototype worked successfully to construct diaphragm walls some 40 m deep in moderately hard sandstone. During the following years, the machine was continuously improved and the main innovations involved the design of an absorption system to counteract the bumps between the cutting wheel and the reducers as well as the development of a system of balancing teeth [6].

At the beginning of the 1990s, a trench-cutter was constructed in Japan that was able to excavate 80 m deep diaphragms and by 1993, diaphragms as deep as 150 m were created.

The main part of the trench-cutter is the cutting head (Figure 4), which is usually called 'cutter'; it is made of a heavy steel structure in which cutting wheels are installed in the lower part, which rotate in opposite directions around a horizontal axis [6]. The cutting wheels, which are specifically designed as a function of the material to be excavated, are installed directly in pairs on two reducers. Each reducer has an independent

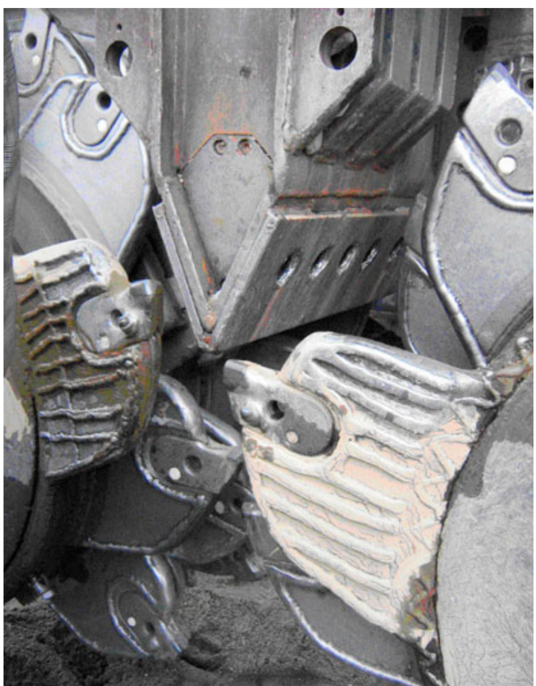

Figure 4. The trench-cutter Bauer BC 30 used to realise the Turin underground railway link: details of the rotating excavation head.

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 way, mixed with the bentonite suspension present in the excavation and moved towards the openings in the suction box.

Cutting heads are usually equipped with long tool holders; these allow all types of material including plastic clays to be excavated, 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 as a function of the type of material.

Cutter wheels can rotate with a maximum velocity of 30 rpm and can develop a maximum moment of 100 kN m. The dimensions of the excavation for the Turin underground railway link are: length 2.8 m, width 1–1.2 m and depth of up to 34 m, with a mean value of about 22 m.

The trench-cutter is lowered into and removed from the excavation through the use of winches, which are assembled on the base machine. The advancement of the trench-cutter in some cases cannot be controlled by a simple conventional winch, as it may not be sufficiently sensitive to the heterogeneous ground. The precise regulation of the thrust of the cutter on the bottom of the excavation can be obtained through the use of 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 regulated easily by the operator (http://www.sifspa.it/lavoro.aspx?l=ITA & id_lavoro=20).

A centrifugal pump, which is installed immediately above the cutter wheels, pumps the bentonite mud together with the cuttings to a treatment plant. The productivity of the excavation, in the presence of loose cuttings and heavy mud, is determined by the capacity of the pump.

In order to avoid blockage of the excavation mud pipe system, the openings of the suction boxes, which are positioned close to the rotating wheels, are reduced to 50% of the pipe diameter. The trench-cutter can reduce the cuttings to a maximum dimension of 40–120 mm depending on the type of trench-cutter.

The pump, which has a diameter of 6″, sucks the material that is mixed with the bentonite and pumps it to the desander, which has a processing capacity of up to 450 m^3/h. The replacement of the bentonite is guaranteed by the presence of another analogous pump (booster pump) which sucks clean mud from the large basins and pumps it to the excavation void so that it is always full of mud.

Some hydraulic data (oil flow rate and power) of the pipe system tank, of the thrust cylinder, of the mud removal pump and of the cutting wheels are reported below for the three types of Bauer trench-cutters that have been used in the construction of the Turin underground railway link:

BC 25 Bauer model, pipe diameter 5″

- Pipe tank: 100 l/min, 42 kW.
- Thrust cylinder: 110 l/min, 40 kW.
- Mud pump: 200 l/min, 100 kW.
- Excavation wheel: 200 l/min, 100 kW.

BC 30 and BC 40 Bauer model, pipe diameter 6″

- Pipe tank: 120 l/min, 50 kW.

- Thrust cylinder: 110 l/min, 40 kW;
- Mud pump: 300 l/min, 150 kW; and
- Excavation wheel: 300 l/min, 130 kW.

BC 50 Bauer model, pipe diameter 8″

- Pipe tank: 120 l/min, 50 kW.
- Thrust cylinder: 110 l/min, 40 kW.
- Mud pump: 550 l/min, 300 kW; and
- Excavation wheel: 300 l/min, 160 kW.

The desanding system has a modular structure and is programmed for the treatment of a large quantity of any type of mud (Figure 5).

The system is made up of two fine sieve/desanding modules and a coarse sieve/separator module. The suspension is made to flow in the coarse sieve module and then passes into the two connected fine sieve/desanding modules. Each module can be made to work separately.

The dimensions of the eliminated particles in the desanding process depend on the following properties: the viscosity of the mud, the percentage of solid material, the pressure of the cyclone and the capacity of the pump.

Desanding systems can treat water–bentonite, water polymer or water–cement and bentonite suspensions. The recycling or cleaning capacity of a desanding system is determined on the basis of the system's contaminated suspension intake capacity, which is defined in m^3/h. The recycling efficiency, or the 'significant cut-off point' – d50 – indicates the smallest particle size in microns with at least 50% removed from suspension

The main components of all desanding plants are: a coarse screen for intercepting stones larger than 5 mm; a storage tank of the coarse screen; a cyclone with a cyclone

Figure 5. General view of the desanding system of the bentonite mud used for the Turin underground railway link.

feeder pump for removing fine particles from the suspension; and dewatering screens for abstracting further water from the solids discharged by the cyclone.

The system employed in Turin has the following characteristics:

Max water feeding capacity (m^3/h)	500
Installed Power (kW)	122
Max mud density (t/m^3)	1.18
Capacity of the main tank	4.4 m^3
Sand percentage	<18%
Weight (kg)	14,000

The material obtained from the desanding process is accumulated in the front part of the system where it is collected by a mechanical shovel; the separation between gravel and sand can be considered a very opportune process for the recycling of the material as inert for concrete.

3. Metal-rock pair characterisation for the evaluation of wear, productivity and costs

Because of the importance of trench-cutting, the microhardness of the cutting tools (picks) was tested, both with new and worn tools from the Turin subway station excavation, to study the possible decrease in metal cutting and crushing performance, considering the mixture of limestone and gneiss encountered during the excavation cycles (Figure 6). The circles in the figure highlight the areas on the tools where microhardness tests were conducted. Five samples were obtained from the carbide tools (i.e. one new and four used) and polished in the laboratory. The microhardness distribution diagrams are given in Figure 7, according to [7]. Higher microhardness values are noticeable for the new tool (N) than for the used tools (U1 – 4), as expected. The two most common rocks encountered in the Turin subsoil (limestone and gneiss) were also tested and their microhardness distribution diagrams are given in Figure 7. The characterisation of the metal-rock pairs is shown in Figure 8.

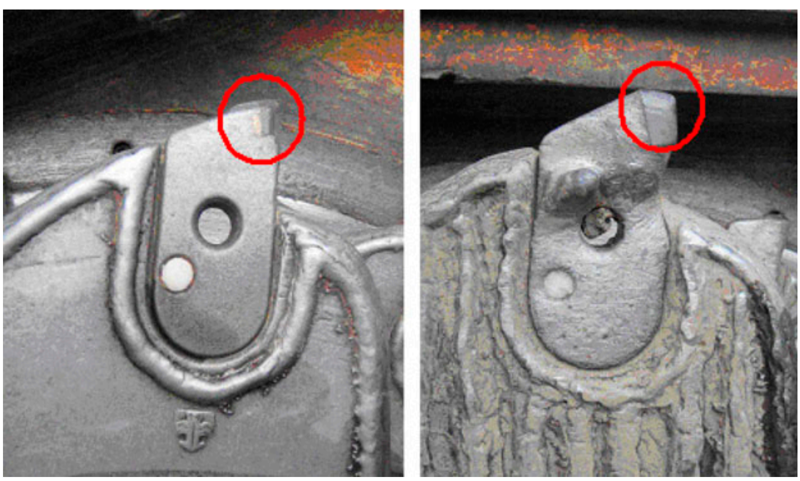

Figure 6. Comparison of a new (left) and a worn (right) cutter. The circles highlight the details of the carbide tool.

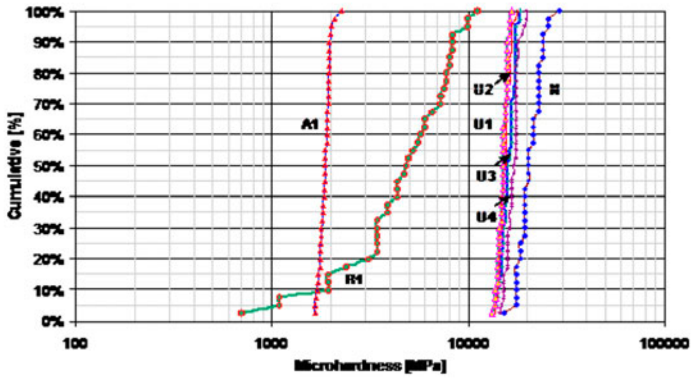

Figure 7. Rock and metal hardness distribution diagrams: limestone (A1); gneiss (B1); hardness distribution of five polished carbide samples taken from trench-cutter tools: new (N), used (U1, U2, U3 and U4).

The carbide tool samples showed lower microhardness fluctuation compared to the tools tested in some of the prior case studies or to the new pick, i.e. the microhardness diagram distributions are almost vertical. From this observation, two conclusions can be drawn:

- The cutting tool material is very homogeneous;
- Wear does not significantly affect microhardness compared to that of a new tool: Figure 7 shows that the microhardness of the most degraded used pick (U1) is only 21–42% less than the microhardness of the new pick. Furthermore, from the analysis of the ratios, it can be seen that in both cases (metal-rock pairs) the carbide picks were appropriate for the application and, not surprisingly, excavation proceeded without difficulty.

A tool consumption rate of 0.05 tools/m^3 has been calculated from a rough estimation of wear on the cutters, which means that nine cutters/day had to be replaced. Given the microhardness data reported above, this rate does not appear to have been

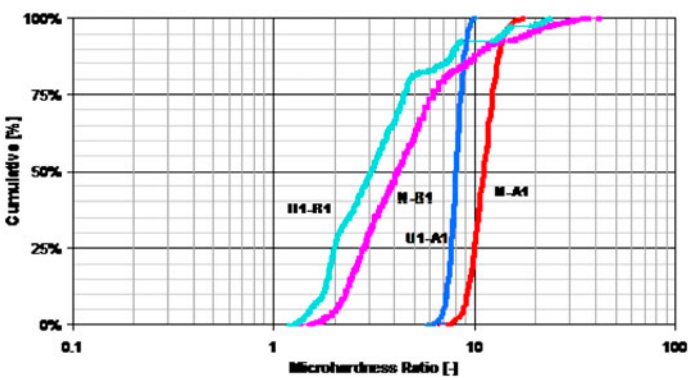

Figure 8. Microhardness ratio distribution diagrams. N-A1: new carbide tool (N) with limestone (A1); U1-A1: used carbide tool (U1) with limestone (A1); N-B1: new carbide tool (N) with gneiss (B1); and U1-B1: used carbide tool (U1) with gneiss (B1).

the result of an inappropriate metal-rock pairing [8]. Alternatively, the wear may have been due to other tool performance aspects, which implies the need for improvement in this area, i.e. by reduction of tool consumption. The steel tool-holder in particular undergoes extensive wear because of its contact with the rock. The degradation of the tool on the right in Figure 6 should be noted. Tools had to be replaced as a result of this degradation. Thus, some reduction in tool wear could be achieved by modifying the overall tool geometry. This change in the tool geometry due to wear could also give rise to a decrease in excavation performances leading to increased costs.

An analysis of the microhardness ratios, as shown in Figure 8, is of fundamental importance because it permits the verification of the suitability of a trench-cutter to

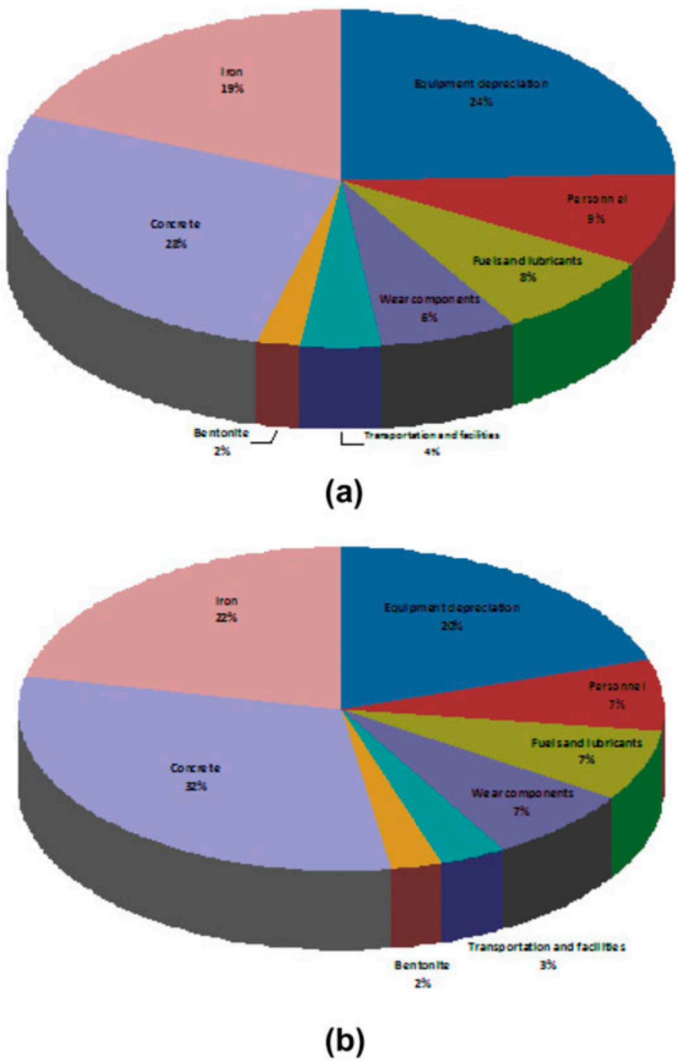

Figure 9. Percentages incidence of the cost items per m^3 of panel. Key: (a) daily productivity of about 100 m^3 (sand and gravel with intercalations of conglomerate or cemented layers) and (b) daily productivity of about 140 m^3 (loose sand and gravel).

excavate the soil present in a given site. In the case in which these ratios drop, even just partially below the unit value, the wear of the tools can increase in a significant manner. Under such circumstances, it is necessary to stop the machine frequently to replace the tools, and the production costs increase due to the greater consumption of tools and the lower productivity from repeated stops. A technical-economic limit exists beyond which it would be inconvenient to use the trench-cutter due to wear. When such a limit is reached, it would be appropriate to use a clamshell excavator and hydraulic hammer to demolish the more compact or cemented portions of ground or any rock masses encountered within the ground.

4. Evaluation of the construction costs and times of panels made with trench-cutters

On the basis of verifications conducted in excavation sites of concrete diaphragms in the city of Turin (Underground railway link and Underground metro system), it has been possible to estimate the construction times and costs.

The main expense items that can be used to estimate the cost of a trench-cutter panel are listed below (the reported data are indicative of investments for new equipment).

Total investment: 3,990,000 €
Trench-cutter and tracked waggon: 3,000,000 €
Desanding system: 350,000 €
Service crane: 300,000 €
Bentonite mixing system: 80,000 €
Electric generator: 100,000 €
Compressor: 80,000 €
Silos, containers and pipe system: 80,000 €
Personnel: cost per month per worker: ~4500 €/month; total: 36,000 €/month
One person in charge of the site, 2 machine operators, 1 mechanic and 4 unskilled workers.
Fuel: 1800 l/day; total cost: 1400 €/day
Trench-cutter: ~1000 l/day
Service crane: ~200 l/day
Compressor: ~200 l/day
Generator: ~400 l/day
Lubricants: total cost: 140 €/day
About 10% of the fuel costs.
Worn parts
Cutting teeth and trench-cutter patches: ~4 €/m^3;
Other parts: ~8 €/m^3.
Other costs
Transport: 50,000 €
Installation of site plant: ~50,000 €
Bentonite: ~20 kg/m^3, ~4 €/m^3
Concrete: ~50 €/m^3
Iron: ~60 kg/m^3; total cost: 35 €/m^3
Driving walls: limited incidence that cannot be evaluated per m^3.

Assuming 22 working days per month, the production data relative to a minimum of 100 m^3/day panels can be considered; the estimation of the daily productivity refers to difficult work conditions in the presence of compact conglomeratic ground with sands and gravel. In order to estimate the total production costs, amortisation of equipment at 2.5% per month of their value and a total work time of six months have been assumed.

Using the data above, the incidences per m^3 are:
Amortisation of equipment: 2.5% × 3,990,000 €/22 days/100 m^3 = 45.3 €/m^3
Personnel: 36,000 €/22 days/100 m^3 = 16.4 €/m^3
Fuel and lubricants: 1400 € × 1.1/100 m^3 = 15.4 €/m^3
Transport and installation: 100,000 €/6 months/22 days/100 m^3 = 7.6 €/m^3
All this leads to an outlay cost (excluding indirect costs, risks, etc.) of about 185 €/m^3 of diaphragm.
Should the geology be composed of loose sand and gravel, the daily productivity could rise to about 140 m^3/day panels. In this case, the incidences per m^3 would be:
Amortisation of equipment: 2.5% × 3,990,000 €/22 days/140 m^3 = 32.4 €/m^3
Personnel: 36,000 €/22 days/140 m^3 = 11.7 €/m^3
Fuel and lubricants: 1400 € × 1.1/140 m^3 = 11.0 €/m^3
Transport and installation: 100,000 €/6 months/22 days/140 m^3 = 5.4 €/m^3
All this leads to an outlay cost of about 160 €/m^3 of diaphragm.

The incidence percentages of the costs for the two examined cases are shown in Figure 9. It should be pointed out that the considered ground (the Turin subsoil) produces limited wear of the excavation tools. In the presence of greater wear, both the overall costs per m^3 of panel and the percentage incidence could change considerably.

As far as the construction times of the panels are concerned, it has been possible to show that about an hour is necessary to reach a depth of 4 m with clamshell bucket excavator, a depth from which it is possible to initiate working of the trench-cutter. The excavation mud-debris suction pump requires minimum hydraulic head to function. In all the examined cases, the trench-cutter continued the excavation with an almost constant advancing speed, which depended on the type of ground encountered.

It was observed that the trench-cutter advances more quickly in heavily cemented ground (type C3 in Figure 4 and Table 2) and less quickly in loose or weakly cemented ground. In the examined cases, the trench-cutter maintained a mean excavation speed of about 9 m/h in heavily cemented ground and 5.4 m/h in loose ground with cemented level intercalations.

The latter value is in fact in line with the values recorded by [9] in mixed ground (conglomerates with sand and gravel) during the excavation of the diaphragms for the construction of the underground works for the Intesa-San Paolo skyscraper in Turin (Figure 10). They noted a speed of just over 5 m/h for the primary panels (those excavated with ground on both sides) and of about 4.5 m/h for the secondary panels (those excavated between two main panels) in this type of ground.

A primary panel of the type constructed for the Turin underground railway link (length 2.8 m; thickness 1–1.2 m) would require the following times for the excavation:

- For a depth of about 20 m: about 140–160 min in homogeneous cemented ground and 230–240 min in loose ground with more consistent intercalations.
- For a depth of about 25 m: about 170–200 min in homogeneous cemented ground and 280–300 min in loose ground with more consistent intercalations.

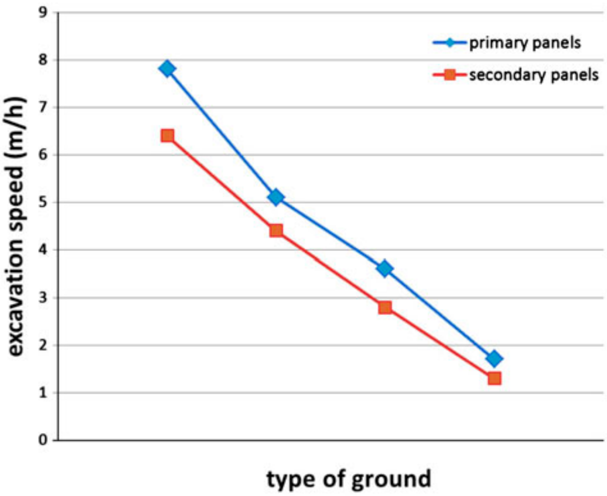

Figure 10. Trench-cutter excavation velocity recorded for the construction of concrete panels to support underground excavation for the Intesa-San Paolo skyscraper in Turin [9].

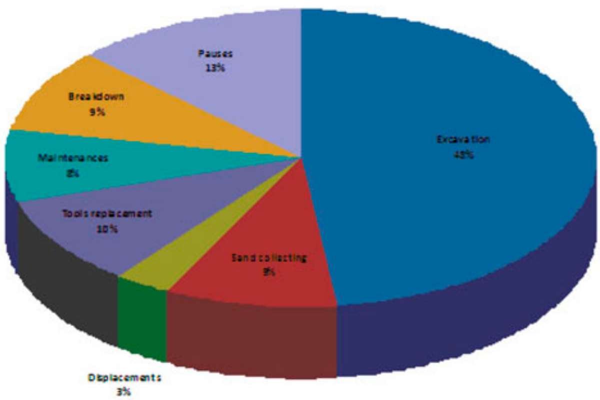

Figure 11. Percentage incidence of the times of the various site operations recorded for the trench-cutter excavation of concrete diaphragms for the support of the underground excavations of the Intesa-San Paolo skyscraper in Turin [9].

- For a depth of about 30 m: about 200–220 min in homogeneous cemented ground and 330–340 min in loose ground with more consistent intercalations.

Manassero et al. [9] also identified mean values of the percentages of time occupation of the various site operations during a work shift (Figure 11). The recorded values refer to the same work site for the construction of diaphragms to be used for the excavation of the underground works for the *Intesa San Paolo* skyscraper in Turin. It is interesting to note how trench-cutter excavation accounts for about 50% of a work shift; the other operations (desanding, movements, substitutions of the trench-cutter tools, maintenance, interruptions for break downs and stops) take up the other 50%. The substitution of the trench-cutter tools requires about 10% of the work shift. This percentage is typical of types of ground that cause a relatively low wear of excavation tools.

5. Conclusions

The 'cut and cover' method is commonly used for the construction of underground works in urban environments, both because it is competitive, from the economic point of view, compared to the traditional blind-hole method, and because it allows the traffic on the surface to restart immediately after the head slab has been cast, even before excavation procedures start. The degree of safety that can be attained for workers is also very important. This degree of safety is due to the fact that the underground operations take place in presence of support structures on the roof (head slab) and on the sides (concrete diaphragms) which has been specifically dimensioned to bear the loads that are present.

When diaphragms reach depths greater than 20 m, it is common practice to use trench-cutters to excavate the panels, with a supply of bentonite mud. A trench-cutter is a very complex machine that allows panels to be excavated at sustained speed from both consolidated and unconsolidated geologies.

In recent years, important underground structures have been built, and still underway within the city of Turin (Italy) are structures that will radically change the mobility system of the city. These infrastructures have made use of the 'cut and cover' method, and the concrete diaphragms have been made using trench-cutters.

The function of trench-cutters has been analysed in depth in this paper, with reference to the characteristics of the necessary plants and to the excavation times of the panels for the different types of ground present in the Turin subsoil. Results of laboratory experiments on the effects of wear on equipment have also been presented to address the impact of wear on both the productivity and the working costs of the trench-cutters.

The study was used to develop preliminary estimation of the construction cost of panels (considering only outlay, amortisation and installation costs of plants) as well as of the construction times in different types of geology. It has been possible to show how trench-cutters proceed faster in homogeneously cemented compact ground than in mixed ground that comprises intercalation of loose ground, and more compact and/or cemented layers. In mixed geologies, the desired perfect verticality of the panels requires continuous compensation by an operator and, therefore, results in lower tracking speed.

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