Plants and job site organization

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Chapter 6

Plants and job site organization

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6.1 INTRODUCTION

This chapter is aimed at summarizing several topics related to muck handling, concrete pouring systems and technological plants such as ventilation. Other peculiar topics included are special tunnelling excavators, multi-purpose vehicles in combination with the utilization of modern belt conveyors, long-distance injection plants, fully integrated BIM & I4.0 carousels able to produce TBM segment linings and tunnel air handling in particular environments and under Health, Safety & Environment (HSE) requirements.

6.2 MATERIAL AND MUCK HANDLING

Material and muck handling is among the most relevant problematics when determining the layout and organization of plants and job sites.

Any item required for a proper tunnelling operation, such as (but not limited to) rock bolts, steel arches, wire meshes, sprayed concrete and precast concrete segmental lining, is considered a material that must be handled. All other products such as foams, grouting mixes, lubricants, oils, grease, pipes, cables and ducts must be included in the development of a global material handling strategy.

Handling muck implies the choice of which transport system will best carry the excavated material out from the front face to the tunnel portal. This choice depends on the type of excavation technology implied, which is mainly related to rock mass or ground behaviour. Furthermore, conditions such as available site area, final disposal sites and any other existing or defined limitations must be included while studying the muck handling system. For example, different transport systems should be considered if a hard rock, an EPB, a slurry or other type of tunnel boring machine (TBM) is excavating.

6.2.1 Trucks

Trucks are generally defined as "large road vehicles that are used for transporting large amounts of goods". Trucks assume a relevant importance within specific applications related to huge underground excavations (powerhouses, caverns, mines, etc.) or tunnels with a "big" section (mainly road or railway tunnels). Confined spaces in tunnels with small sections could limit the use of trucks to open-air operations within the project.

Trucks are dimensioned to transport very large loads, having heavy-duty bogies with purpose-designed axles in order to take on several tons (up to 40). Moreover, they are designed to be easily set in motion, even when fully loaded, and they are able to secure full power control even at low speeds. They also ensure traction control, thanks to driven front axles, which is fundamental, for example, in steep gradients or in sharp turns. Additionally, the axles can be driven both mechanically and with independent hydraulic motors for each wheel. In mining applications, the market also offers electric-powered equipment.

Electric equipment in tunnelling is a new frontier, whereas industry is hardly working on this concept. The first real results are arriving for piling machines and crawler cranes, MSV and particularly trains and locomotives.

Trucks can be used both in tunnels built with conventional excavation method and in those excavated by TBMs. With conventional excavation method, trucks run directly on the bottom section of the tunnel or on top of a concrete slab if an invert is part of the tunnel lining. They are loaded by backhoe loaders or excavators at the front face; they collect the muck as it is produced by the excavation or, if blocks are too large, after crushing.

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In tunnels whose diameter only allow one-way driving, the truck has to be driven in reverse towards the front face; in long, narrow tunnels, however, a turning bay has to be considered at a certain point, in order to allow the truck to enter face-forward and to only drive in reverse for short distances. Turning bays can also be used to exchange the truck that is entering the tunnel with the one that is leaving it, which would allow the excavation cycle to speed up, reducing the waiting time at the front for empty trucks to be loaded. If the tunnel dimensions are enough for two-way traffic, the muck handling with trucks is much more efficient. This condition is the most suitable for conventional excavation.

With TBMs, muck handling with trucks is only seldom implemented. The configuration of a TBM, considering the presence of backup decks to stock all ancillary equipment, hardly leaves space for trucks. The excavated material must be brought at the rear end of the backup decks with conveyor belts, and it comes out continuously. A quite big hopper must be installed to collect the muck flow, and it must be properly set up to load the trucks. Any delay of trucks presence under the hopper would cause the shutdown of the excavation process. In other words, a "continuous" excavation process such as that of TBMs is preferably associated with a "continuous" muck handling system.

As per conventional excavation, the use of trucks is limited to large-section tunnels, due to space restrictions. Alternatively, trains or modern automatic extendable continuous conveyor belts can be implemented.

6.2.2 Trains

Trains occupy a relevant position within various "continuous" muck handling systems, especially when taking into consideration small- to medium-sized tunnels (i.e. diameter up to 5/6m). In tunnels with bigger diameter, it is common to consider the use of continuous belt conveyor system for muck handling, and therefore a different approach for personnel and material transport, too.

A train is generally composed of three main parts: traction unit (locomotive), muck cars and transport cars (for material and/or personnel).

6.2.2.1 Traction unit

The traction unit is generally a locomotive, with a different solution for the engine and the drive unit. The most common engine is a "standard" diesel-powered one, with a catalytic muffler and any other available device for anti-pollution (for example, water bubbler).

As an alternative to diesel-powered engine, electric drive units are beginning to be seen on the market. The electric drive is constantly developing to reach good standards within operation, mainly with the use of new concepts to allow long-lasting battery with a quick recharge time. A relevant difference between diesel-powered engines and electric drives is the maximum installed power, meaning the highest traction force transferred to the trains. The application of electric drive units could be limited by the maximum weight carried both inward and outward from the tunnel. However, big steps forward have been made in this industry and application. Clayton, for example, designed long-lasting batteries, fast recharging stations and powerful electric traction (Figure 6.1).

Both diesel-powered and electric-driven locomotives can be associated with mechanical transmission (gearbox) or hydrostatic transmission. A hydrostatic transmission also involves a limited travelling speed (not above 5/6 km/h if unloaded and 2/3 km/h when fully loaded). In other words, this system is to be considered quite a "special" one as opposed to TBM tunnelling.

A hydrostatic transmission is in fact related to high incline (over 3%) where friction coefficient between rails and wheels is not enough to ensure the trains' proper movement. In this case, traction forces are applied with traction boogies. These can work with friction wheels against a steel profile assembled all along the tunnel or on a "rack and pinion" mechanism. The steel profile can be suspended on top of the section (monorail system) or laying on the invert of the tunnel, while the rack and pinion are generally installed only on the invert.

However, the transport capacity of such systems is very limited (<100 tons) and generally not suitable for mucking out in tunnelling. They are commonly used for

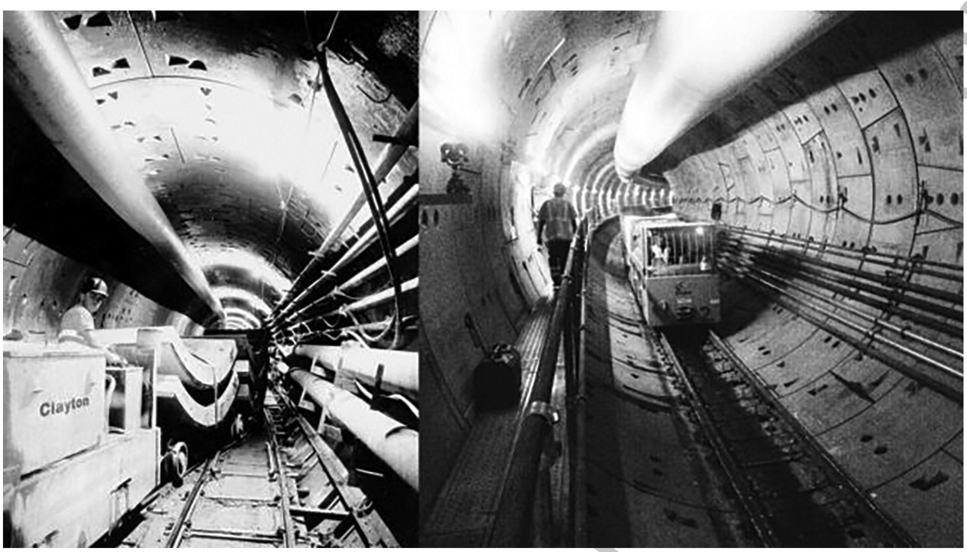

Figure 6.1 Application of electric-driven locomotives in tunnelling.

transport of materials associated with continuous conveyor belt which is fully dedicated to the mucking procedure.

When using mechanical transmission, the capacity load can be quite unlimited, considering the power installed on a single locomotive or the possibility to have a "tandem", with two locomotives coupled together to almost double the traction effort. The coupling of the "tandem" is electronically controlled to grant a smooth drive of the complete system and the full power properly used. Locomotives can be coupled also in a number higher than two. Such kinds of systems can cope with loads up to 400/500 tons, keeping good performances with regard to travelling speed.

A "standard" train can easily reach 20/25 km/h when loaded with segments and other materials running uphill with a smooth gradient (up to 1.5%). Going outward, the train is fully loaded with muck and can reach almost the same speed if running downhill. Clearly, the automatic control of the braking system becomes relevant in order to grant required safety within operations. When the gradient increases, the maximum speed will proportionally decrease. However, it is possible to maintain a range of values that will not affect the TBM advancing speed.

In long tunnels, more than one train may run upwards and downwards at the same time. Any crossing of a train entering the tunnel with one train coming out must be deployed with a proper solution, generally the so-called California switch. This switch is installed on metal works laying in the invert of the tunnel or built in a concrete platform where the section of the tunnel allows the train to run parallel in a short section. For bigger sections, where trains running on two parallel tracks are allowed, there is no need of California switch (Figure 6.2), but exchange points from one track to the other have to be taken into consideration to avoid trains having to stop in case of interruption of one track (for example, trains out of service or other activities performed inside the tunnel).

Figure 6.2 California switch.

The number of trains required at the maximum distance is determined based on the cycle of excavation and in accordance with the TBM backup configuration. The optimal configuration for the backup system generally includes quick unloading systems (for segments and any other material), in order to empty the train quickly and allow it to come back to the portal in the shortest time and to be ready for a new cycle. If the backup system does not foresee quick unloading systems, the train will remain on the backup until all the segments and the materials are unloaded. This arrest will add time to the transport cycle, making it necessary to imply an additional train to cope with the TBM's advance rate at the maximum distance.

If the train is also dedicated to muck transport, the considerations mentioned above will have less relevance, because the leading time will be similar to the loading time of the muck cars. There are two ways to fully load a muck train. The train can either slowly advance under its loading point, or it may be still and have a sliding conveyor or a fixed reversible conveyor running over the full length occupied by the muck cars.

For safety reasons, since the locomotive is located at the rear end of the train (facing the excavation side) and pushes the whole convoy, a camera system is installed on the opposite side, to allow the driver to have a clear picture of the conditions of the tunnel during the ride. Due to the dimensions of such locomotives, it is not possible to let it pull the train up to the backup system. All materials loaded onto the train cannot be taller than the locomotive itself. Subsequently, uncoupling the locomotive from the train and moving it on the other side would require a dedicated switching platform at the rear end of the backup system as well as additional time for the excavation cycle to take place.

6.2.2.2 *Muck cars*

The muck cars may have a single capacity ranging from 3 to 10/12 m^3, according to the tunnel's excavation diameter, or better to its section. The smallest capacity is associated with the smallest width of each car, suitable for running into minimum tunnel diameter of 3.5 m (about 10 m^2), and it is equal to about 1.0 m.

(a)

(b)

Figure 6.3 Muck cars (a) and miners transport car (b).

When the tunnel diameter increases, the muck car's capacity increases; consequently, cars width becomes wider.

As a generic rule, the muck car width may be considered equal to the width of the ring of the segmental lining, which is, in case of shielded TBM, in the range of 1.5m wide muck car for a 6–7m diameter machine. For bigger tunnels, muck cars are implied rather seldom, being difficult to manage very large quantities of muck corresponding to extremely heavy and long trains. In such cases, it is preferred to use continuous conveyor systems.

The muck cars, independently from their dimensions and capacity, are automatically emptied at site area, using specific devices designed to suit the selected type of cars. The most common solutions are the movable/sliding bottoms, or muck cars with rotating/tilting fixed bodies. Figure 6.3 shows classical cars behind (or in front of) a locomotive.

6.2.2.3 Transport cars

The "standard" trains, in addition to muck cars, normally include several platforms associated with specific usages.

In TBM excavation with shielded machines, precast segmental lining is generally used, whereas with open TBMs, an invert segment is generally implied and it can be moved by train rides or multi-service vehicles (MSVs). For this reason, “segment cars” are part of a train, in number and design suited to the different solutions.

With precast segmental lining, the number of segment cars is associated with different possible ring configurations (the number of segments per ring). No more than three segments are carried in one group and loaded on the car. Therefore, a larger diameter of excavation corresponds to an increasing number of segments and, subsequently, cars. In addition, the amount of segment rings carried by one train must be defined every time. This corresponds to the number of advance strokes of the TBM for each muck train. In tunnels of small diameter, e.g. 5–6 m, solutions with one or two rings per train may be taken into account, whereas concerning larger diameters, only one ring per train is generally considered. The segments are carried while laying with the main (longest) axis into the tunnel direction and are rotated 90° in the assembly area just before being picked up by the TBM erector.

Also, when an invert segment must be carried, the quantity is related to the length of the elements as well as the number of strokes mucked out with the train. It is common practice to have the invert segment as long as possible (its weight is the limit), in order to reduce the number of elements along the tunnel. If the cross section of the element is too wide to be carried horizontally, the element will be set on the car with a certain angle.

Any other items to be carried, mainly material or personnel, must have their dedicated car, which will be inserted or removed from the train according to the need. Looking to transport of personnel more in detail, one solution is to have a dedicated car on each train, in order always to allow transportation for workers, engineers, technicians, visitors or others. As an alternative, a personnel car waiting outside at the portal (either with a dedicated loco or motorized) to enter upon request may be used.

Material cars, on the other hand, are specialized, for example, to carry pea gravel hopper, barrels of oil, grease, ventilation cassettes and/or other “standard” materials. Anyway, each train has generally also a flat car to accommodate the transport of any other items required at the TBM and backup, i.e. spare parts, pipes and cables.

6.2.3 Multi-Service Vehicle (MSV)

As stated in Section 6.2.1, the use of trucks is mainly dedicated, perhaps even limited, to muck handling, while materials are transported more efficiently with lighter vehicles. At the same time, as mentioned in Section 6.2.2, trains are mostly suitable for the transport of both muck and materials. In addition to these two solutions, the best compromise is the use of MSVs for the transport of materials combined with the use of continuous conveyors for muck handling.

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MSVs are composed of one or more joined decks, specifically designed to transport precast segmental lining and other materials required to complete a full excavation cycle. Personnel are generally transported by dedicated vehicles. An MSV can reach up to 25 m in length, which is generally limited by the minimum curve radius and must cope into the tunnel or at the site area.

Figure 6.4 Different kinds of MSV.

The MSV is a wheeled vehicle which runs on the bottom of the tunnel lining (Figure 6.4). The diameter of the wheel is as high as possible (up to 1 m or more) depending on the payload of the vehicle and the possibility to run easily into the tunnel, and considering the space allowed into the backup system. When composed of one single piece, the MSV is assembled with driven front and rear axles to better accommodate the drive along curved stretches.

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Looking to the configuration of the MSV for a shielded TBM, the main item to be transported is the precast segmental lining; therefore, the MSV is designed mainly to suit this kind of transport. In fact, the position of the segments on the MSV itself must be associated with the position of the quick unloading device installed on the backup of the TBM. This means that the distance between the different packages of segments is determined by the design of the backup. As an alternative, the MSV must be kept stationary into the backup of the TBM, and the segments are to be unloaded one by one with a dedicated crane.

For TBM diameters up to 6 m, the MSV is composed of one single piece supplied with a "standard" diesel-powered engine, with a catalytic muffler and any other available anti-pollution device (for example, water bubbler). Concerning tunnels of bigger diameter, the MSV is preferably still a one single piece, but, due to the dimensions of the segments ring, it sometimes has two joined decks. The same configuration is required when the MSV must be used in tunnelling with small curve radius (less than about 200 m). A dedicated design for each specific tunnel is required in order to take into consideration the vertical and horizontal alignments. The vertical alignment with curve radius <500 m can determine the choice of a vehicle composed of joined deck, so as the horizontal alignment with curve radius <200 m. Both figures are mostly related to the diameter of the tunnel. In tunnels with small diameter (up to 4/5 m), a solution with tilt of wheels (camber) is preferable, so as not to face difficulties while driving and in order to avoid excessive wear of the wheels external side.

The MSV has two driver cabins. It is driven from the front end (looking to the direction of tunnel drive) pulling the vehicle, when entering the tunnel, and from the other side when coming out. The front-end cabin can be tilted or collapsed, in order to allow the discharge of segments and the other materials moving at the same level of the deck. There is no need to lift items to overpass the cabin, and the space in height is limited to the height of the deck of the vehicle. So, even within tunnels of small diameter, it is possible to easily unload materials. The driver has a perfect control of the vehicle, unlike the locomotive driver on trains, for they must look directly into the tunnel pathway in both driving directions.

The maximum travelling speed of the MSV is related to its transport capacity, and it is not higher than 10 km/h when loaded in small incline. Clearly, the speed is substantially reduced if a steep incline is provided in the tunnel (for example, in metro projects, with incline up to 5%).

Each MSV, contemporary with the segmental lining, will transport all other materials required for an excavation cycle (for example, pea gravel for backfilling). Materials needed for excavation, such as grease and oil barrels, pipes, ventilation ducts and high-voltage cables, are transported separately during maintenance. All these items are to be accommodated on the same decks of the MSV, using specific supports (reels), boxes or fixing hooks.

6.2.4 Belt conveyors

Belt conveyors enable cost-effective, low-emission transport of bulk materials across long distances. They belong to the family of continuous conveyors and are also called conveyor belt systems. Belt conveyors are reliable transport systems with a high level of operational safety. This is why belt conveyors have also been used in underground mining and in industry for decades to transport bulk materials.

6.2.4.1 Conveyor systems' effectiveness

Unlike other transport systems, belt conveyors are characterized by low energy and personnel requirements and high availability. High conveying capacities with relatively low space requirement are also a further advantage. Conveying capacities of up to 2,500 t/h are common in underground mining. However, far more would also be possible.

One disadvantage is the limited ability to convey heavily sticky or liquefied material, and investment costs are rather high as well. Despite the high investment costs, conveyor systems are often the most cost-effective transport solution for large transport quantities. Because of this, they are mainly suitable for continuously conveying bulk materials over long distances, or in case large conveying capacities are needed. It is not uncommon to have conveyor lengths of 2–10 km (in Brenner Base Tunnel, BBT Lot Mules 2–3 project, more than 30 km in one single belt) and a height of several 100 m. However, belt conveyors are used for shorter transport distances as well, e.g. if great height differences or individual obstacles need to be overcome (such as gorges, rivers, streets or railway lines).

6.2.4.2 Construction types

Due to continuous conveying, belt conveyor installations have a relatively low line load, even with large conveying capacities. This enables the routing to be extensively adapted to the local conditions. The conveyors can be suspended or supported, or they can even be made to float. Accordingly, there is a wide variety of belt conveyors. In tunnelling, a distinction is generally made between the following construction types:

- *Belt conveyors with a fixed axle base*: this includes belt conveyors both above ground and underground, and they can have axle bases from one metre to up to several kilometres. In the case of interurban belt conveyors, special design types are often required for street crossings, railways or gorges (Figure 6.5).


(a)
(b)

Figure 6.5 Belt conveyor over a gorge (a). Belt conveyor crossing railways and streets (b). (Courtesy of Marti Technik.)

- *Extendable belt conveyors*: extendable belt conveyors are used in both mechanized and conventional tunnelling. On these belt conveyors, the axle base changes while the system is in use. Depending on the type of tunnelling, the conveyors may be continuously or gradually extended.
- *Belt conveyors that are continuously* extended are typically equipped with a belt storage and are primarily used in TBM tunnelling. The advantage of such a system is that the conveyor can be continuously extended while the TBM is excavating, with no need of arresting the conveyor. The system must only be stopped when the belt storage is empty and needs to be refilled. Conventional belts have a storage capacity of ~400–500 m, thereby allowing advancing of the tunnel for 200–250 m without interruptions. Horizontal or vertical belt storages are implemented according to space conditions on the construction site (Figures 6.6 and 6.7). The belt

Figure 6.6 Horizontal belt storage. (Courtesy of Marti Technik.)

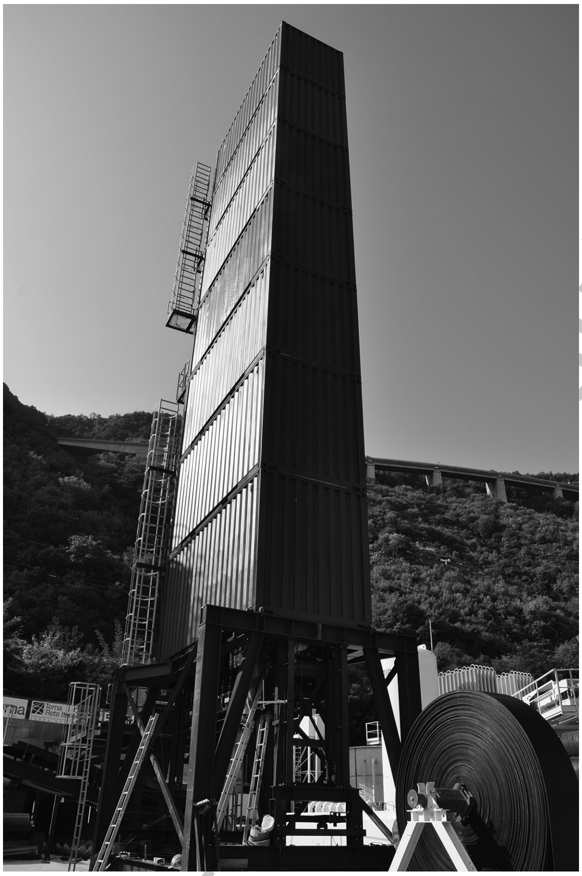

Figure 6.7 Vertical belt storage. (Courtesy of Marti Technik.)

conveyor structure is extended on the TBM backup, where an extension station is installed. Renowned conveyor manufacturers provide an extension station with safety equipment that ensures the belt conveyor chassis can extend when the belt is running (Figure 6.8).

- *Belt conveyors that are gradually* extended are mainly used in drilling and blasting headings. Most of the time, a mobile crusher is placed in front of such belt conveyors, in order to allow material to be placed on the belt conveyor and carried out properly. In this case, the crusher and the belt conveyor's return station are relocated in stages. The stages are individually determined according to the construction site. Such belt conveyors are often extended between 100 and 200 m at once.
- *Dumpsite conveyors*: there are several special installations which allow to fill and/or manage dumpsites, such as tripper cars, radial stackers, bidirectional conveyors and semi-mobile skid conveyors. The choice of which belt conveyor is more suitable depends on the geometry of the dumpsite, as well as its required volume.
- *Vertical conveyors*: steep or vertical conveyors are used whenever great height differences need to be overcome within confined spaces. In such cases, sidewall

Figure 6.8 TBM backup extension station. (Courtesy of Marti Technik.)

conveyors or double-belt conveyors are often used, particularly in shaft construction sites. Whereas the sidewall conveyors are mainly used for grainy excavated material, double-belt conveyors are used for heavily sticky conveyed material instead. However, in the case of heavily sticky carried material, a belt conveyor solution will reach its limit, one way or the other. This is primarily the case in the transfer chute area, where heavily sticky material can cause blockages. Conversely, if the material is too liquid, vertical conveyors – especially those with double-belt conveyors – cannot be used. The proper choice and safe operation of a vertical conveyor is very challenging and heavily depends on the geology and, in the case of EPB tunnelling, on how the excavated material was treated beforehand.

6.2.4.3 Belt types

Different belt types may be used according to specific requirements. For construction site installations, the following criteria are crucial when selecting a belt type: the maximum slope, horizontal curve radii, maximum grain size, consistency and type of the conveyed material. As long as the maximum slope on a belt conveyor is not >16° (~28%), belts without surface profiling are mainly used in tunnelling. Belts with surface profiling are seldom used when mucking excavated material, because in this case it is not possible to clean the belt with a scraper. Washed gravel is an example of an application for such belts. Sidewall belts or double-belt conveyors are used to vertically convey the excavated material.

Other than different belt types, there are also different belt qualities. The belt quality must meet all safety requirements, especially for underground belt conveyors. Fire protection standards have become continuously stricter over the past few decades (European standard EN 14973 must currently be adhered to).

6.2.4.4 Control system for conveyor systems

A system control unit is required in order to allow conveyor systems to be optimally and safely operated. Controlling and monitoring the installation is a crucial success factor, especially for complex installations. With the right control system, even complex installations can be operated with minimum personnel levels from a central control room. To achieve this, information from video cameras, sensors and other monitoring instruments must be analysed and visualized in the central control room. This gives the installation operator information about the current state of the individual conveyors at all times, and the operators can direct the flow of materials accordingly, as well as locate and eliminate any malfunctions.

6.2.4.5 Conveyor systems' advantages

Transporting materials via conveyor systems offers many advantages over alternative transport solutions such as trains or tyre vehicles.

- *Continuous conveying*: conveyor systems enable continuous removal of the excavated material. This is a major advantage for TBM tunnelling in particular. Due to the continuous conveying, the TBM performance is not limited by the removal of the excavated material. Conveyor systems with conveying capacities up to 2,500 t/h and more are implemented in tunnelling. Conveyor systems can also be used to overcome greater differences in height. For instance, the excavated material can be transported directly from the tunnel face to the dumpsite without reloading, even in shaft construction sites or in rough outdoor topographies.
- *High availability*: if the installations are professionally built and if the conveyed material is in a transportable condition, installation availabilities (running time without stoppages) of >95% can be achieved, even in a tunnelling environment. This requires regular and professional maintenance for the installation. It is possible to plan the replacement of wear parts during the appropriate maintenance shifts.
- *Less personnel requirements*: conveyor systems can be operated with low personnel levels, thanks to central control stations. If the installation is regularly and professionally maintained, the maintenance work can be performed during the planned maintenance shifts, and the personnel levels can be limited to a minimum during tunnelling shifts.
- *Low-emissions operation*: suitable measures can be taken to reduce noise and dust emissions to an absolute minimum; conveyor systems can be fully cased if needed. By doing so, excavated material can be transported in inner city areas with practically zero emissions. Conveyor drives generally operate without emissions, which is a major advantage, especially underground. As a result, ventilation systems can be smaller.
- *Work safety and health*: Belt conveyor transport significantly reduces traffic within construction sites. Furthermore, standard-compliant conveyor systems have a high safety performance and therefore ensure safe and environmentally friendly transport of the excavated material.

As previously mentioned, belt conveyors are often the most cost-effective transport solution for large transport quantities and distances, in spite of the high investment costs. To ensure that this is the case, materials transport via belt conveyors should be considered and planned mainly taking time into consideration. Planning conveyor installations according to time is particularly recommended in both external and dumpsite installations. Doing so prevents cumbersome and correspondingly expensive alignment.

6.3 EXCAVATORS, LOADERS AND SPECIAL HAULING EQUIPMENT

Tunnel excavators and loaders are special machines that can be used in all conventional tunnelling applications. They are always used in conventional tunnelling when a mechanical excavation process is not foreseen. They are also frequently used after a TBM bore to create the cross-tunnels, in the drill and blast operations in order to muck out as well as for front face profiling (for safety reasons). Particular features of these machines are economic operation, high performance and reliability. For conventional equipment, the market is offering a big range of choices, but for special and tunnelling machines, there are only few manufacturers, which are really specialized with dedicated high-productivity products.

6.3.1 Excavators

Tunnel construction is one of the toughest existing environments for excavator operations. The operation of a tunnel excavator becomes efficient when the machine, despite harsh conditions, can cut out the required tunnel profile as rapidly as possible, without leaving economical factors behind (safety, rate, preciseness and low operational costs). This means that a tunnel excavator has to produce a high hydraulic capacity and, above all, must be provided with operational fittings that are tailored to the particular application (Figure 6.9).

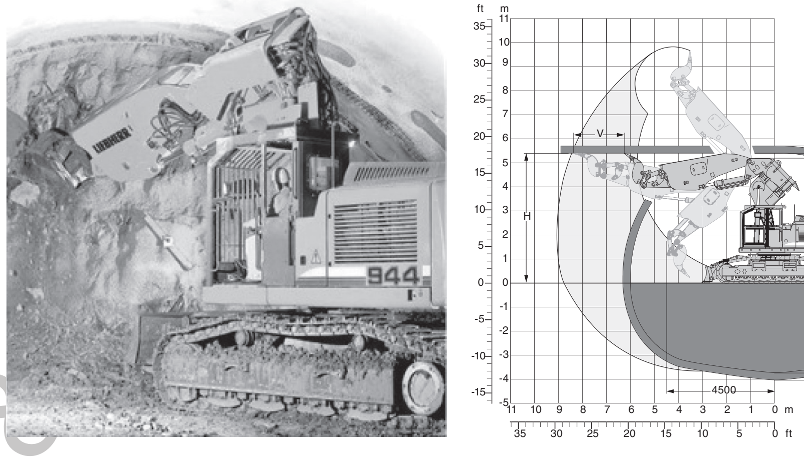

Figure 6.9 Example of an excavator working on a tunnel face and its operational area. (Courtesy of Liebherr.)

The hydraulic system used for tunnel excavators has to be optimized for milling. Tunnel excavators are the result of decades of practical experience in the development of reliable special equipment for demanding situations. All the materials used should have undergone intensive, long-term tests and meet high-quality standards even under hardest conditions, in addition to being extremely robust.

Special cabs are often safeguarded with rollover protection structure (FOPS) and Fast Geophysical Positioning Solution (FGPS) standards. To prevent damage from falling rocks, all hoses in exposed locations are additionally secured with protection plates. Another important characteristic of the special cab on a tunnel excavator is the ergonomic design and the high standard of operating comfort and convenience. The windows on the right and at the rear should be fitted with polycarbonate panes, which are resistant to scratches and impacts, and with extremely good visibility properties.

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6.3.1.1 Special equipment for excavators

The advantages associated with the use of hydraulic excavator crawlers are the possibility to use and interchange different operating "tools".

One of these is the hydraulic clamp (Figure 6.10), which allows to erect and set the steel arches with a safe operation. The main advantages in using this device are the following:

1. Less time of erection, for the machine must not be stabilized. The decreased erection times are connected, above all, to a greater level of security. The latent danger situation persists for a shorter time in the front face. Furthermore, it is not necessary to exchange different equipment at the front face through rapid coupling on the excavator for the clamp device.
2. Complete stability against overturning and smaller operating dimensions in the tunnel.
3. Less or no spare parts; excavators only consist of a hydraulic cylinder system coupled on the clamping machine, thereby reducing the risk of mechanical damages (lower operating costs due to the simplicity of the equipment).
4. Lower purchase cost and shorter procurement times for new equipment.

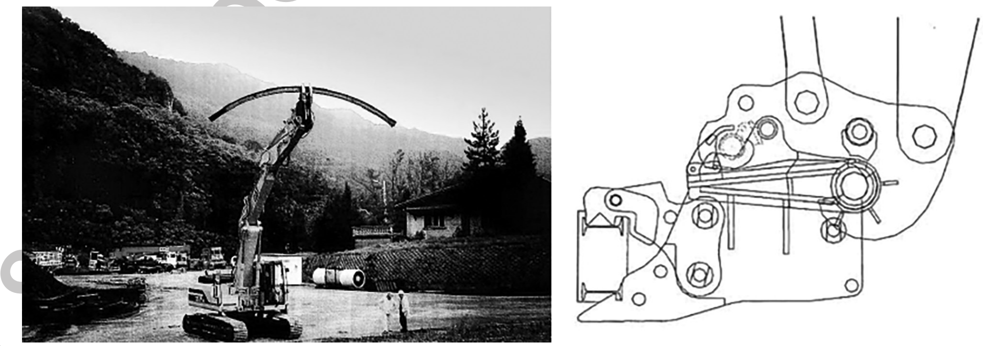

Figure 6.10 Clamp for setting steel ribs.


(a) (b)

Figure 6.11 Hydraulic breaker (a) and ripper bucket (b).

A further tool is the hydraulic milling cutter which may be fixed to an excavator in spite of the bucket. The milling cutter has a simple and compact design and is almost maintenance-free, with the exception of pick changes. Hydraulic excavators of any type, having the corresponding service weight and diesel power, are suited for this purpose. The milling cutter mainly consists of a gearbox and a pair of transverse cutting heads, which are fitted with round shank picks. It is driven by a hydraulic motor, which is fed with oil pressure from the excavator hydraulics. An adapter is required for attachment to different excavator types. The position of the milling cutter, which is mounted to the adapter, even allows cutting of narrow trenches (when turned 90°).

Hydraulic breakers (Figure 6.11a) are an effective method for excavating tunnels featuring geological profiles and sizes that make blasting a difficult or uneconomical solution. Ripper buckets (Figure 6.11b) are especially suitable for rock outbreak and ripping, due to the bucket's special form and digging behaviour.

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6.3.2 Wheel loaders and load, haul, dump (LHD)

By nature of the work environment, mechanized tunnelling can't offer big-picture visibility of large-scale truck and shovel surface operations; open space necessary for typical multi-truck loading patterns just isn't available underground. However, the basic elements of surface-fleet equipment selection – such as appropriate size for site conditions (Figure 6.12), correct pass-matching between loaders and trucks and proper machine configuration for optimal safety, reliability and maintenance – are valid and perhaps even more critical in underground operations, where fleet and individual equipment size and capacities are often constrained by workspace limitations.

The operator must take into account not only the dimensions of the machine's usual workspace, but also spaces in which it may have to pass through. In addition, the actual height of underground work areas must be taken into consideration, including any hanging ventilation or mine-service structures that could interfere with machine's operation. Bucket selection should consider the machine's primary use as well as the characteristics of the material that will be loaded (Figure 6.13); a standard

Figure 6.12 Example of wheel loader and LHD. The L566 is loading dump trucks with a capacity of up to 45 ton (a) and the largest loader in Cat's LHD line-up, the R3000H (b). (Courtesy of Bringiotti.)

Figure 6.13 GHH diesel (can be also electric-driven) LHDs are particularly compact with a good operator's position (a) and a crawler Liebherr L634 (b).

bucket design may work well in many applications, but a high-penetration design will be needed for others. If a high-penetration bucket is required, load spillage will somehow increase.

The conditions encountered at the work site may require specific optional equipment, which can range from a choice of open or closed cab styles, remote control-ready configurations or ride-control systems, to integrated machine-recovery attachments for stranded equipment. It is very likely that in tunnelling, the future in conventional operations lies within electric-driven motors, which already is reality in various mines, and allows to reduce pollution and ventilation costs. Surely, this market is not mature yet; however, it is evolving, indeed.

6.3.2.1 Dumpers

As for loaders, a similar approach should be used to size and prepare underground trucks. What are the drift dimensions? Will trucks be loaded by loader, LHD or chute? What's the density of the material that will be loaded? If trucks are loaded by LHD, will they be loaded from their side or from their rear? Is the cab open or closed? Which optional features and accessories will be implemented to improve productivity and

Figure 6.14 Kiruna Truck K350.

safety, such as a payload management system, on-board fire suppression equipment or fast-fill fluid service system?

Once loaders and trucks are purchased and commissioned underground, it is crucial to figure out how to make the best out of them in terms of productivity. When planning any improvement program, there are two main points to consider: minimizing costs and maximizing loads, as well as keeping any productivity enhancement efforts simple. It is possible to observe any inefficiency or delay by sitting on the trainer's seat of the vehicle for half a shift. Alternatively, simply observing the machine's activities from outside the cab can allow noticing particular conditions within the whole working area. Technology may assist in evaluating operations; for instance, Enterprise Content Management (ECM) data, load factors or idle time. Develop "measurements", such as best cycle times, draw-point and haul road conditions and payload accuracy, and then validate and quantify the improvements.

The ideal solution for high productivity in mining and tunnelling are articulated, heavy-duty, low-profiled trucks able to reach an optimal ground contact, which is guaranteed even at high speeds and bad road conditions, regardless of whether the vehicle is loaded or not (Figure 6.14). Sometimes a bidirectional operating cabin may be able to quickly move the truck in both directions, without the need to turn the vehicle around in narrow cross sections or tunnels.

6.3.3 Rail-borne loading and transport in tunnels

Häggloaders for rail-borne loading are manufactured in two different sizes. The smaller one is called 8HR2, and the larger, 8HR5. These can handle tunnel widths from 5.0 to 6.2 m. Both loaders are equipped with a particular digging arm system, which, connected to the built-in conveyor, allows the Häggloader to load continuously. Both machines may also be fitted with a backhoe digging system, which is particularly useful when handling soft rock or when cleaning the tunnel floor prior to erecting arches or installing linings.

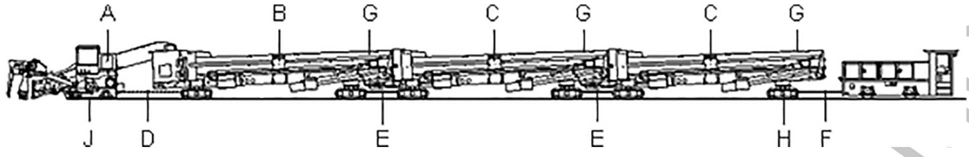

Figure 6.15 Shuttle cars system. A = Häggloader 8HR-2 or 8HR-5; B = Load car HRST-CLE; C = Train cars HRST-CTE; D = Drawbar for towing; E = Drawbar between shuttle cars; F = Drawbar for towing/unloading; G = Wear plates 500 HB; H = Track gauge determined for each application; J = Voltage/frequency of electrical system determined for each application.

6.3.3.1 Shuttle cars

Shuttle cars are designed to work together with rail-borne loaders (Figure 6.15) to allow continuous loading. Muck is loaded onto the shuttle train by the Häggloader and subsequently transferred from car to car via built-in conveyors. Shuttle cars come in several sizes, from 9.0 (HRST90) to 14.0 m^3 (HRST140). Up to eight shuttle cars can be coupled together, allowing excavation of more than 100 cubic metres of muck without switching cars. For confined rail tunnels, the high-speed tunnelling method includes a rail-borne drill rig and Häggloader with shuttle train. The choice of shuttle cars depends on the height of the tunnel. A separate service set can be used for roof-bolting, shotcreting, ditching and track-laying purposes. The Häggloader is a multi-purpose machine, which may also be used to lift rails into place, to handle an Omega rail extension system and to dig trenches in the tunnel floor.

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The shuttle train is designed for transport in tunnels and drifts and is composed of several shuttle car units linked together. A conveyor at the base of each car transfers rock along the train, from the loader on the front until the last car, in order to fill the whole train. No car-shunting is needed. By matching the number of cars in one train to the volume of the blasted rock, the complete round can be removed by one train set.

6.4 SLIDING AND LIFTING PLATFORM LOGISTIC SYSTEM

High-performance drill and blast methods for tunnel construction require that each individual working element that makes up the construction process be optimized and considered as a system of sequential and parallel activities. In order to increase production, it is necessary to improve the drilling, explosive loading and temporary ground support installation, such as rock bolts, steel mesh, shotcrete, steel sets, lagging, mucking and logistics. Moreover, the drill and blast (or in general "conventional") method is characterized by operations that occur in a repeated cyclic sequence. The level of automation and mechanization of these tasks is low and there is a high degree of hard manual labour involved.

6.4.1 Suspended platform system

The suspended system has been used by contractors in long tunnels with excavated cross section dimensions for single-track rail lines such as the Vereina South, or

Mitholz in Switzerland. The Mitholz consisted of a 9.4 m diameter drill and blast tunnel section 2 km long. The Vereina South drill and blast section was 7,474 m in length. Two kilometres of the drive length included twin-track tunnels with an excavated cross section of 70–86 m^2; the subsequent 5.4 km long section was a single-track tunnel (40 m^2). Good success was recorded on this heading, thanks to the use of a 230 m long suspended platform with an integrated conveyor belt. The use of a suspended system made it possible to increase the production of the drill and blast excavation.

Through the application of such system (Figure 6.16), it was possible to run working processes parallel to one another and to uncouple material flows affecting supply and muck disposal. The shiftable infrastructure carriers are suspended platforms riding on rails that hang from rock bolts from the tunnel roof. On each side of the platform, pushing jacks with locking grips are installed to move the platform forward. It is mandatory that the pushing jacks move simultaneously.

The front area of the suspended platform is protected against flying rock debris during blasting by a chain curtain. A crawler-mounted travelling rock crusher is installed in front of the inclined feeder conveyor and advanced for mucking purposes up to roughly 30 m behind the face (Figure 6.17). The entire support infrastructure for the drilling and blasting is transported on the suspended backup platform. This includes electrical transformers, compressors, emergency power, shotcrete aggregates, explosive storage containers, crew and foreman lounges, workshop, toilets, utilities and vent duct storage.

Two different material flows must be coordinated at the end of the furthest platform from the face. Materials for temporary ground support construction and other work supplies must be carried beyond the invert construction zone and through the equipment-parking zone. This process takes place under the platform and is accomplished with the overhead rail crane. At the same time, the muck must be carried away from the face. A belt conveyor located on top of the suspended platform accomplishes this task; therefore, the muck movement is separated vertically from the parking, storage and invert construction. At the loading bridge, muck is transferred to the tunnel transport system, which is typically either a muck train with locomotive, or a muck

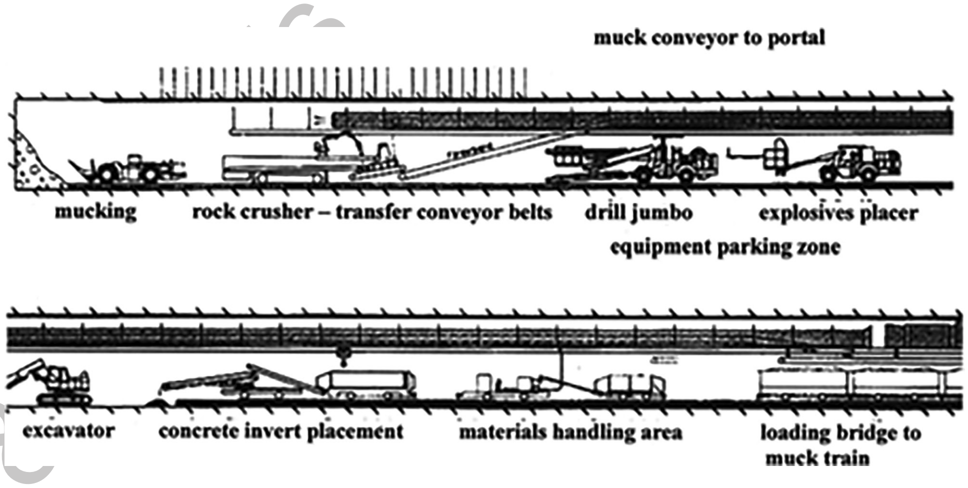

Figure 6.16 Backup system, Vereina South Tunnel, Switzerland.

Figure 6.17 View of equipment from tunnel face; crusher and hanged conveyer belt.

conveyor system. Either method can be used to complete the movement of the muck to the tunnel portal.

6.4.1.1 The Ceneri Base Tunnel

The Ceneri Base Tunnel is the continuation of the Gotthard Base Tunnel southwards. It completes the new flat rail link across the Swiss Alps towards Italy. Similar to the Gotthard Base Tunnel, the Ceneri Base Tunnel system consists of two single-track tubes, which lead from the Northern portal at Vigana/Camorino to the Southern portal at Vezia, connected with cross-passages about every 300 m.

All infrastructural installations may be placed onto the 135 m long platform. These consist specifically of a de-dusting unit with a 1,200 m^3/s performance, ventilators for expiration and suction, an air compressor, a water pressure booster system, an emergency generator (with a capacity of 200 kVA), a transformer for medium-voltage conversion (16,000 V) to 380 V as well as a high-voltage cable drum. A container for the management, one storage container both for electricians and for mechanics, lifting devices, air-duct cassettes for expiration and suction ventilation, as well as a maintenance area for the monorail are also installed onto the platform. Below the heading platform on the invert, tunnel constructors have a second working level and free floor space for working, manoeuvring and parking (Figure 6.18). Working safety has substantially been increased, thanks to effectively arranged space conditions, the rationalization of work flows and the generous illumination.

The supply of the heading with rock support material, shotcrete in mixing containers, wear and tear material as well as explosives is guaranteed by the monorail, which bridges over the invert construction site and the heading installation (Figure 6.19). The monorail moves on an additional lift track, suspended with chains on eye Bellex 240 friction rock bolts. Bracings absorb induced acceleration and deceleration forces.

Simultaneously with the heading operation, a self-moving formwork fits the entire width of the invert (Figure 6.20). The in situ concrete casting system is supplied with a truck and transported to the installation site by a 15 t heavy-duty crane suspended from the invert platform. Heavy replacement parts for the construction equipment can

Figure 6.18 Telescopic ventilation platform for fresh air supply, allowing efficient suction ventilation of blasting fumes as well as increased working safety, thanks to free floor space for working and parking.

Figure 6.19 Monorail for direct supply of the heading area.

Figure 6.20 The 15 t heavy-duty crane in the invert construction area. The 66 m long invert platform may be moved accordingly to the heading platform.

also be carried across the invert construction site with the crane. The 66 m long invert platform can be moved with a total of eight friction drives. The relative traverse path to the heading platform amounts to ~50 m, thereby considerably reducing the interdependencies between the two construction sites.

6.5 AGGREGATE AND CEMENT PLANTS, GROUT, CONCRETE AND FORMWORKS

6.5.1 Concrete plants in underground

More and more often, in tunnel excavations, trend is to install underground systems. This approach certainly has important advantages over some negative aspects that need to be evaluated.

The main *advantages* are the following:

- Protection from thermal shocks and potentially adverse weather.
- Shorter distance from the concrete casting front and, consequently, fewer number of concrete mixers in motion with the same production due to the shorter distance. A lower number of concrete mixers is equivalent to a reduction in kW in operation in the tunnel and therefore to a reduction in the size of the ventilation.

The main *disadvantages* are as follows:

- More excavations required for the installation of the systems (large rooms, widenings, etc.).
- Need for a localized ventilation study: normally, the system is installed in special chambers with a larger section of the tunnel; the return air from the tunnels tends to slow down and drop below 0.5 m/s. Additional ventilation must be provided for the personnel present at the plant.
- Greater care in controlling dust emissions.
- Greater number of vehicles in the tunnel for loading aggregates and cement with consequent greater ventilation requirements.

At the Mules site (BBT Lot 2–3), it was decided to install a concrete plant directly at the foot of the adit (2 km long and 10% slope) in an expressly built large cavern (Figure 6.21).

The plant is installed in an area of about 1,100 m^2. It is a double plant to ensure continuity of production, mainly composed by: (a) two mixers of 5 m^3 with a yield of 3.3 m^3 and hourly production in continuous of 130 + 130 m^3/h, (b) aggregate storage hoppers (four types) for a total of 630 m^3, (c) eight cement silos of 65 m^3 each, (d) dosage for two additives, (e) high-pressure automatic washing system and (f) control cabin.

The plant is installed in a special cavern connected to the main chamber: only the mixers protrude into the main chamber to facilitate the logistics of the truck mixers. The packaged products are both shot-concrete and concrete with various mixtures depending on the needs of the single casting. The mixers are arranged staggered and

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The term can be changed with "shotcrete"

Figure 6.21 Underground batching plant located in a logistic cavern. (Courtesy of BBT-SE.)

not in line to allow, in some phases of the work, the loading of both the truck mixers and the trains.

For concrete mixers, the following average cycle can be considered: a call 1–2 hours before the casting; placement of the truck mixer in 3 minutes; truck mixer loading with 10 m^3 of concrete; and three cycles for a total of 8 minutes. The average time for delivery to the unloading point over a length of 5 km is around 45 minutes (including truck mixer placement).

The supply of aggregates normally takes place through a double-function belt conveyor: the muck is transported on the upper belt (600 ton/h) and sent to the crushing plant installed outside, while the aggregates are transported on the lower belt (250 ton/h) from the crushing plant to the batching plant. With this system, the truck traffic is reduced with advantages for ventilation system. The system has been engineered and built by Marti Technik (Figure 6.22), and it is fully automatic: when an aggregates hopper to the batching plant marks a low level of aggregates, the necessary aggregate is automatically loaded from the crushing plant (also automatically). The system calculates the operating time to fill the hopper with the missing aggregate and then moves on to load the next aggregate type.

At the crushing plant, the aggregate loading system is made with vibrating screens located under various aggregates stocks: when the concrete plant is needed, the screens begin to vibrate, loading the related aggregate onto a belt system that will arrive directly to the concrete plant (Figure 6.23a and b). This automatic belt loading system has reduced the transport in the tunnel (supply of aggregates to the concrete plant).

The concrete plant is also equipped with an emergency loading system (Figure 6.23c): a hole where the trucks are unloaded by overturning the body and a belt that loads the aggregates hoppers. This additional system ensured both work continuity in the event of a technical problem with the conveyor system and the immediate start of the concrete plant when the conveyor system was not yet installed.

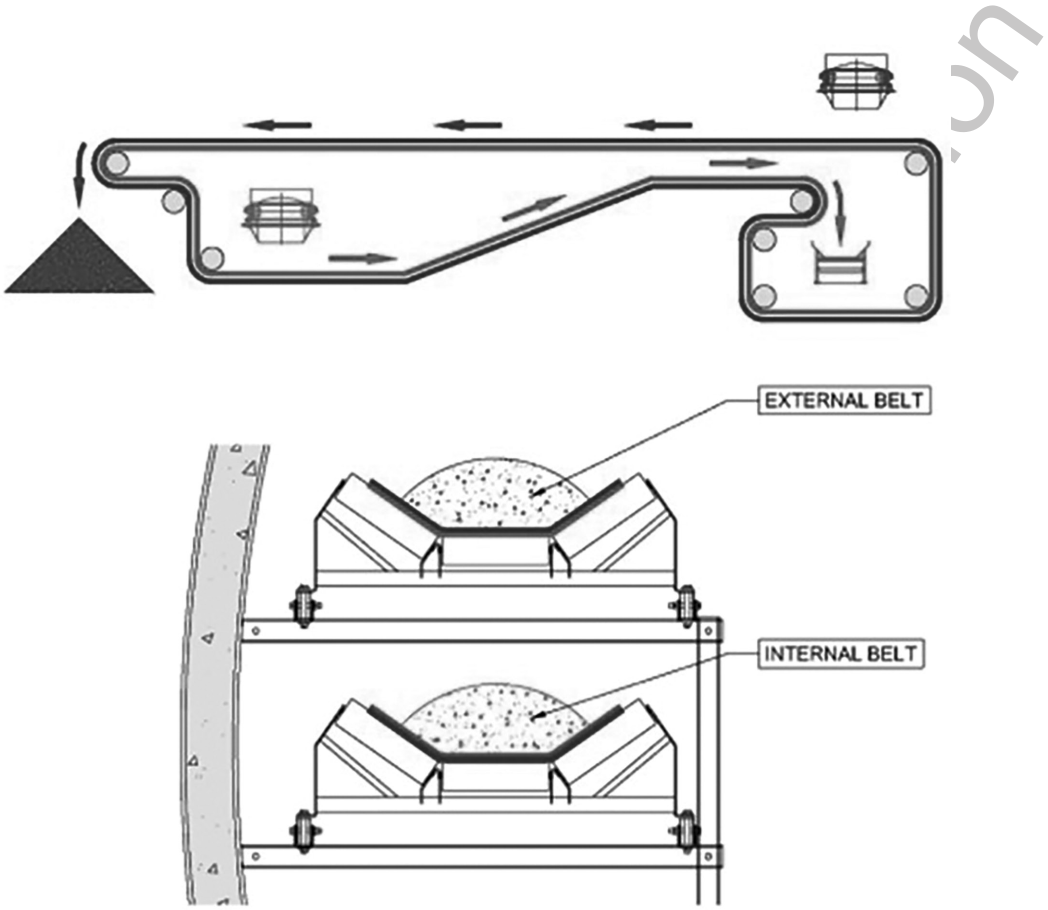

Figure 6.22 Double-function conveyor. (Courtesy of Marti Technik.)

(a) (b)

Figure 6.23 Automatic load system for aggregates (a and b). Emergency loading system for aggregates (c).

Figure 6.24 Layout crushing plant.

For aggregates production, a crushing plant is located in the outdoor external area that directly receives the spoil from the excavation fronts, both mechanized and traditional.

The plant crushes 250 tons/h and covers about 2,500 m^2 (Figure 6.24).

Sizes produced are typically those needed for shot-concrete and concrete for on-site castings. Aggregate sizes are: 0–4, 4–8, 8–16 and 16–22 mm; max. diameter can go up to 32 mm. The system is fully insulated for noise reduction and has various nebulizers for dust suppression.

6.5.2 Injection plants

The filling of the annular gap created by the excavation between the extrados of the segmental lining and the cutting profile of the TBM cutter head is a relevant aspect when it comes to guarantee the correct positioning of the lining, the uniform distribution of loads on the segments, the reduction in induced surface settlements and the hydraulic tightness. The backfilling material, generally low-density cementitious mixes, allows a controlled injection in order to completely fill the gap and to ensure high and constant quality of the injected product.

The backfilling materials must be characterized by fixed parameters in terms of workability, setting time and mechanical properties. Bi-component mixes are those which better satisfy such criterion. Such mixes successfully combine the pumpability of the fluid from the mixing plant, generally located outside of the tunnel, to the excavation face where they are injected (even at a distance of several kilometres), with their almost immediate solidity.

The bi-component mix is composed of two separate fluids: Component “A” (cement, bentonite, water and retarding agent) made to inhibit the setting during transport and Component “B” (accelerating additive), which is added at the injection point to reach the gelling of the mix within a few seconds.

A mixing plant is dedicated to the preparation of Component A and later transfers the final product to the injection plant, installed on a deck of the TBM's backup system. The maximum flow rate can reach more than 40 m^3/h, and the maximum distance allowed is up to 7–8 km in normal conditions (in sub-horizontal tunnels). The dosing and mixing operations are controlled via programmable logic controllers (introducing percentages of different products). The production of the cementitious mix is obtained with a colloidal mixer, a grout mixing device that shears or separates cementitious particles with a high-speed blade in order to break surface tension and enable complete contact between the particles and the mixing water.

The mixer is assembled with load cells that are able to weigh each product entering the tank according to the established dosages for the bi-component mix. The first to be introduced is water, by means of a pump; when the correct quantity is reached, the pump is automatically arrested, and the second component, the bentonite, is added. The bentonite is driven into the tank via a screw conveyor located under its respective silo, and it is automatically stopped once the programmed weight is reached. Finally, the cement is brought into the tank. Same as for the bentonite, the dosage of the cement is obtained, thanks to a screw conveyor. In the same way, if the mix treats this component in addition to the cement, fly ash is introduced into the tank. The last component to be put in the mix is the retarding agent: it is dosed separately in a dedicated small tank and later transferred into the mixer. After having combined all the components, the mixer works for the predetermined time and then transfers the mix into the agitator.

The produced mix is kept as a suspension (which means the particles have not settled) through an agitator, which then transfers the mix to the pumping unit. The pumping process is carried out with more than a single piston pump, forming the pumping unit. The flow rate of each piston pump and the related pumping pressure are monitored continuously: the limit values are fixed and automatically controlled.

An independent pumping system can be dedicated to the transfer of Component B to the plant, which is installed on the same deck as the backup system of the TBM. Alternatively, the most common solution is to transfer Component B on the backup system's deck in a plastic tank, which is relocated through a train platform or with the MSV.

In conclusion, the plant is composed of three main zones (Figure 6.25): **Zone 1**: cement, bentonite, additive silos and water tank; **Zone 2**: container with colloidal, mixer and agitator; and **Zone 3**: container with pumping unit.

Another plant, installed on the deck of the backup system of the TBM, is necessary to pump Component A of the cementitious mix into the chamber through dedicated lines manufactured inside the tail (rear) shield of the TBM. Component B is pumped into the same chamber through other dedicated lines (which join the ones of Component A at the end section).

6.5.3 Concrete transportation machines and performance

Delivery implies carrying the concrete (or shotcrete) to any equipment (formwork, spraying robot and/or TBM) in adequate quantities whenever required. It is an essential phase, especially within underground spaces. Operators often use standard on-road transport to get the concrete where needed, but these vehicles are usually not agile or robust enough for the unique conditions in underground job sites.

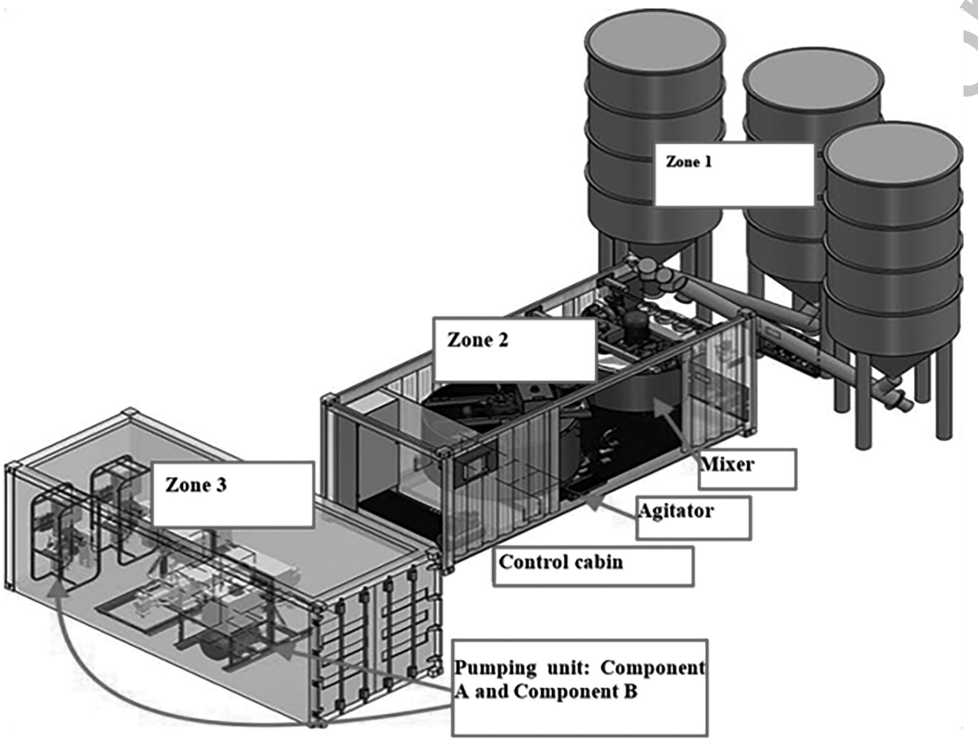

Figure 6.25 Typical injection plant. (Courtesy of Lorenzetto S.r.l.)

Vehicles specially designed for underground concrete transportation and pumping procedures offer the safest and most efficient solution, providing better protection for personnel and a more convenient operation cost for project owners.

There are many ways to carry the shotcrete on-site, including truck-mounted or rail-based concrete mixers (or agitators), slick-lines, boreholes and dry-bulk bas. The choice of delivery method mainly depends on accessibility, material handling systems, location of working places and demand of concrete per shift. Handling concrete from the mixing plant to the casting point must be carried out preventing segregation, loss of material and premature stiffening.

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Whenever traditional mixers are not adequate or authorized, the ideal alternatives are mining mixers, off-road truck-mounted mixers or trans-mixers. These machines have small dimensions, which allow them to easily move in narrow spaces, and a capacity up to 4–5 m^3. Modern tunnelling machines have control systems and checks like those currently used on the most advanced surface truck mixers, such as the drum rotation control during the vehicle's movement and safety systems that block the drum while carrying out maintenance inside it.

In case of a high demand of concrete, alternative solutions such as train mixers or agitators may be implemented. Train mixers have two main functions: mixing and agitating, and their application depends on the type of concrete plant in the job site. Train mixers can carry up to 12–14 m^3 of concrete and can be coupled in two or more units, driven by a locomotor and joined with a stationary pump (Figure 6.26).

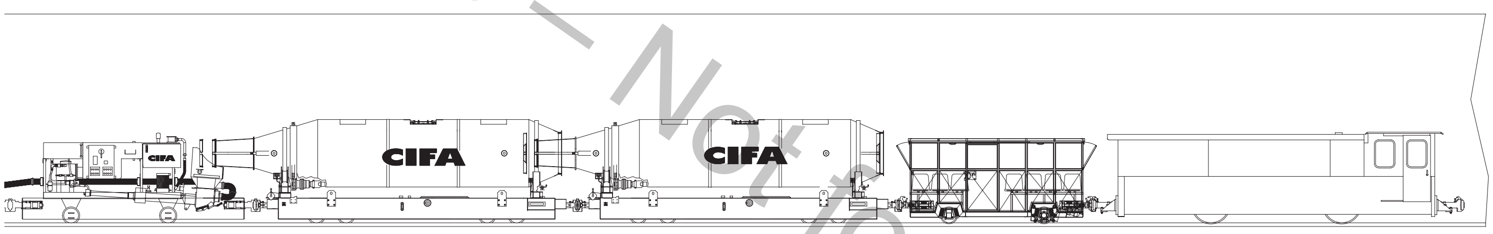

Figure 6.26 Concrete transport set composed of locomotor, utility wagon, train mixers and pump. (Courtesy of Cifa.)

If the batching plant includes a concrete mixer, the truck mixer only needs to agitate the concrete mix so that it does not disaggregate while being conveyed to the spraying area. If a dosing plant is used, the truck mixer must mix the shotcrete while loading it and then agitate the mix during transport. During transportation, the mix should only be agitated. Agitating requires a lower rotation speed of the concrete drum than mixing.

6.5.4 Concrete pumping; equipment and performance

Since pumping can be the quickest and most economical solution for the handling of concrete, stationary pumps are used to convey such material through a pipeline to the casting point. Common concrete pumps consist of a receiving hopper, two pumping cylinders and a valving system called the “S” valve, which alternatively directs the flow of concrete into the pumping cylinders and into the pipeline. Pistons are driven by a hydraulic system using either closed-loop or open-loop designs. A closed-loop electronic switching system allows better fuel efficiency, minimized heating of the fluid as well as faster switch actuation; primary power is provided by diesel or electric motors.

The pumping units are rated for a maximal theoretical output in m^3/h, based on the diameter and length of the concrete cylinders multiplied by the maximum available frequency of pumping stroke.

The pumping of concrete over a long distance requires a special preparation of the pumping infrastructure. The basic issue that must be considered by technologists while designing a concrete mix is the concrete’s pumpability. The basic parameters of pumpability are the amount of cement, ash contents and plasticizers contained in the mix: any admixture that increases workability usually improves the pumpability, too. While pumping, the concrete cannot get dehydrated, because it would cause the pipeline to clog. Pumping of concrete over a long distance therefore requires a proper preparation of the pipelines. It is essential that the entire pipeline system is strong, because exceeding the working pressure of concrete over 85 bar would not allow the use of standard flange systems on pipeline connections. It is necessary to use high-pressure pipelines with hinged-type couplings by cam-lever closure handle. The preparation of pipelines for long-distance pumping requires pipe anchoring. The movement of the pipeline resulting from the pulsation of the concrete pumping system is definitely to avoid leaks on joints.

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6.5.4.1 Feeding systems

Concrete is normally poured with a concrete pump when a formwork system is used. The concrete may be placed directly through the pump delivery line or via a distributor, depending on the size of the tunnel cross section, formwork type and working conditions.

A hydraulically operated distributor delivers concrete to the concreting points at the windows or grouting pipes at the vault crown, without any heavy manhandling and with the possibility of remote control. A pantographic pipe system allows the distributor to move forward along the equipment from one casting position to another.

A modern alternative to casting consists of an automated filling system regulated by a set of valves which is integrated in the formwork's structure and connected by a single delivery line that joins all casting points in sequential rows. The operation of the valves can be automatized through radio-controlled steered hydraulics.

6.5.5 Mobile formworks

A mobile formwork system can be defined as a self-propelled, free-standing temporary instrument used to cast tunnel cross sections (rings), walls or slabs in one operation during a daily cycle. It mainly consists of:

A. A steel portal structure that allows the form to move forwards along the tunnel and set up for casting. The portal is equipped with motorized systems for travelling (wheels on rails, pneumatic tyres and a walking system with hydraulic feet).
B. Backing structures that are all the structural components that support the forms, made up of curved, straight and ribbed steel components.
C. Form liners that are the surfaces in contact with the concrete, generally sheet steel or plywood and metal sheets.

The equipment is a reinforced structure, the surfaces of which have a high enough quality to only require minimal finishing. It combines the speed, quality and accuracy of factory/off-site production with the flexibility and economy of in situ construction. A mobile system is more complex than a modular system, but it does shorten the cycle time. Formworks for secondary or final linings must provide some essential functions, such as:

a. Withstanding all actions without damages or structural deformations and reproducing the design geometry without deforming.
b. Protecting fresh concrete (for example, against strokes or water loss), promoting the efficient hardening of concrete and producing what is required for exposed surfaces, avoiding leaks when pumping concrete under pressure.
d. Allowing passage underneath for service vehicles and internal systems (ventilation).
e. Avoiding the application of any deleterious/unpredictable load to nearby structures.

Mobile formwork systems can be divided into the following main typologies described below.

6.5.5.1 Self-reacting formwork

These are formworks with an articulated structure (self-reacting struts) able to withstand the loads due to the concrete casting (Figure 6.27a). The devices for moving and positioning the formwork are mounted on the portal frame and provide for all longitudinal, transverse, height and banking adjustments. The skirt movement is supplied by oblique struts with powerful hydraulic cylinders. The bottom of formwork is forced against foundation by the oblique struts. The alignment of struts is performed by a beam hydraulically moved. It is the compressive force that provides the seal and transmits the pressure from fresh concrete to the system. The hydraulic cylinders apply heavy loads to the formwork and foundations, a fact which must be given due consideration in the design.

The advantages deriving from the use of self-reacting forms are the following:

a. Avoidance of the use of any anchoring system at piers and kickers;
b. The reacting force is absorbed by reacting struts and not by pier or kicker, enabling higher resistance against concrete load pressure;
c. Manpower savings for set-up and dismantling operations and safety increase;
d. Small kicker and little concrete thickness permitted (compared with formworks with tyloop/rods anchoring).

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6.5.2.2 *Turret-type formwork*

The wide formwork is supported by a special latex structure (turret) mounted on a truck or on a wheeled carrier. The equipment can rotate on the turret axis, allowing the passage of the wide section inside the main tunnel section (Figure 6.27b).

The turret consists of a series of carpentry frames, sliding on wheels and handled by hydraulic jacks to allow transverse and longitudinal adjustments of steel form sections. A frame with a fifth wheel allows the horizontal rotation of the forms.

The forms are only supported by the turret during the transportation, set-up and dismantling phases. The forms must be detached by the support beams of the turret during the casting phase, because the turret is not able to support the casting loads. The turret may be used to transport two or more formworks.

6.5.5.3 *Cut and cover formwork*

The cut and cover formwork is a shed positioned externally from the lining formwork so as to simulate the tunnel profile and create an artificial one, or to cast portal structures. Both the internal and the external formworks can translate mechanically: this

(a) (b)

Figure 6.27 Self-reacting formwork (a) and turret-type formwork (b).

Figure 6.28 Cut and cover formwork.

solution is convenient when the length of the artificial tunnel is over 50 m. The two sheds are connected by anchor rods along all the surface or at the top and bottom parts (Figure 6.28).

Alternatively, special panels may be moved by cranes. This is an economical solution; however, it is only suitable for short cut and cover sections. Measures of standard panels are 0.6–0.7 m × 2.0 m. Alternative solutions are often obtained with plywood panels (light structure).

6.5.5.4 Light and multi-section formwork

Light formworks may cast large sections (enlarged section/cavern, big chamber for hydropower, subway stations, etc.). This solution is used with sections with a transversal width over 15 m. This type of formwork has an average longitudinal length of 4/6 m, and the carrier is integrated in the latex structure of the vault. This allows to implement the same system for both transport and withstanding the concrete loads, reducing the overall weight of the equipment and consequently reducing costs (Figure 6.29).

Multi-section formwork: this type of formwork is used to follow modification of the geometry along the tunnel, in order to avoid the use of a formwork for each section. The variation occurs by inserting portion of vault. Additional variations of geometry can be achieved by means of shims or inches. Additional trellis structures may be necessary to support the formwork during the casting phase, such as vertical props.

Figure 6.29 Light formwork.

6.5.5.5 Cycling time and job site organization

The average cycle time for a self-reacting formwork with 12 m length and advancement speed 6 m/min ranges from 20 to 22 hours (varying according to the conditions of the project, the site's layout and cross section). A calculation example is reported in Table 6.1.

In conditions of narrow sections, as well as in case of overlapping phases, interferences may occur between the transit of mixer trucks and dumpers carrying rebars, muck and other equipment.

The initial erection of the equipment can be performed outside the tunnel or in separate caverns inside the tunnel or again in the main tunnel: interferences in case of equipment erection inside the tunnel have to be well considered. The main services required are as follows: compressed air for vibrators (~1.8 m^3/min per vibrator, usually up to 4 at the same time), water for cleaning, electric power for hydraulic motors and concrete feeding with an average volume of 18–35 m^3/h.

Table. 6.1 Self-reacting formwork cycle time example

AU: Please check and approve the edit made. Also please check subsequent occurrences.

Operation	*Average time*	*Affecting factors*	*Min. operators Number*
Cleaning	30′	Dimensions	1 + 1
Set-up	40′–50′	No. of props, form length	2 + 2
Stop-end erection	40′–90′	Typology, waterstop	2–3
Casting	5–6 hours	Distribution, project conditions	2–3
Curing	12 hours	Type of concrete, specifications	-
Dismantling	30′–40′	Manpower	2 + 2
Transport to next position	15′		1 + 1
Total	20–22 hours		

Note: The number of operators considered is: 3 trained operators + 1 skilled and experienced chief.

6.5.6 Full round equipment

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the term can be changed to "full-round"

The type of on-site full section and single-phase casting currently called "full round jet" was created for the final lining of hydraulic tunnels with circular sections with radii from 2 to 5 m. Generally, these very long tunnels (over 1 km) require a full section lining with the least possible number of cold joints and step-less surfaces so as to avoid turbulence in the water flow and consequent risk of early damage to the coating. All these requirements led to the development of formwork systems with telescopic movement, which allows the continuous casting of the lining. The installed formwork provides the correct hardening of the casting, while another part of the formwork with hardened concrete allows its dismantling and telescopic advancement. At the end of the transportation to the advancement face, the element of the formwork is set up, avoiding any interference with the casting operation. The concreting operations progress with a continuous pumped inflow through a long steel pipe fixed to the excavation cap. This pipe slides forwards with the same advancement rate as the casting front (Figure 6.30).

The complete circular or polycentric formwork normally consists of six articulated elements: a vault formwork, two pier elements, two end-toe elements and one invert element, which is equipped with rails to allow sliding. The formwork ring is supported inside the excavation section by suitable mechanical conical props, which will be partially dismantled once the casting is completed, and others removed during said casting operations.

This type of telescopic multi-element formwork may be used for both continuous and step-by-step casting solutions. In continuous casting solutions, the total number of elements is defined as a function of the daily progress of the casting (between 24 m and maximum 50/60 m/day), the minimum curing time (12/14 hours) and the natural angle of the cast concrete (variable between max. 19° and 15°).

With an average advance of 50 m/day, a required maturation time of 12 hours, 5.6 m diameter of the tunnel and 16° natural angle of the concrete, the two areas that affect the formwork during the casting phase are defined as follows: (a) the length of natural slope of the concrete starting from the tunnel crown will be 19.5 m (5.6/tan 16°) and (b) the area of formwork affected by the curing will be 25 m [(50/24) × 12].

With this information, a 6 m element is always required to allow the form advancing, another four 6 m elements affected by the natural slope of the casting, four 6 m elements affected by the curing of the concrete and a further element of 6 m in dismantling and transfer. Therefore, usually the minimum length of the formwork is 60 m. It consists of ten elements of 6 m, with three additional 6 m long elements, one at the back and two in front, to allow the proper movement (Figure 6.31a).

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An alternative solution, in tunnels with diameters >9/10 m, is the so-called "full round American type", which provides short-distance handling with portals and wheels inside the form element without additional invert form for the functionality of the movements. The classic typology of these formworks involves cantilever beams to

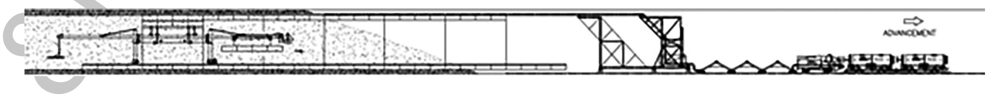

Figure 6.30 Full round formwork in lining progress.


(a) (b)

Figure 6.31 Full round formwork (a) and continuous casting full round formwork (b).

allow lifting and translating of the arch-reversal formwork with the rails. This concept has not changed much over the years, except for structural updates and mechanical components. The only important variant launched is the solution of the wagon portals with a "frog-type" structure, which allowed lifting and translating of the invert formwork in its horizontal position. These quick operations allowed better safety, avoiding the manual rotation of the invert formwork and consequent risks of materials falling on the ground (Figure 6.31b).

The average cycle time for a full round equipment, step-by-step casting, consisting of five elements of 6 m each (with one overlapped element in curing and four elements in casting) ranges from 40 to 42 h (according to the conditions of the project, the layout of the site and cross section), as shown in Table 6.2. The average daily advancement of the casting is 14.4 m (or 0.6 m/h).

6.5.7 Self-launching formwork: principles, cycling time and job site organization

In addition to the classical full round telescopic solution, there is the full round single-element-type solution. This single form element is moved by a traveller with the front carriage sliding on the excavation floor and the rear carriage sliding on the invert casting profile. This solution, which includes a single element from 6 up to max. 15/18 m with a full round casting, requires long curing times in order to achieve a resistance of the concrete able to avoid deformation with the rear sliding of the traveller wheels (Figure 6.32).

The best production performance with this type of equipment is one casting every two days for the casting length of 6 m, or two castings per week with lengths >10 m.

To avoid the difficult movement of the traveller on the invert, a double-length traveller with alternate mutual movement between formwork and traveller has been created. In this solution, the traveller does not have wheels at the base of the legs of

Table 6.2 Full round formwork cycle time example

Operation description	*Average time*	*No. of operators*
Cleaning	60′–65′	3–5
Dismantling of the last formwork element in overlapping	50′–60′	3–5
Advancement by traveller supporting vault; lifting the last invert	25′–30′	3–5
Telescopic advancement of the traveller up to the front	25′–30′	3–5
The element of formwork is installed by connecting it to the first reinforced section of the last casting	90′–100′	3–5
Invert element is moved from rear to front, and it is installed to restore the two additional front invert elements	50′–60′	3–5
Repetition of the cycles from 2) to 6) for all the elements	210′ × 3	3–5
Stop-end erection and pumping/distribution system set-up	90′–100′	3–5
Casting (~150 m^3)	480′ (8 hours)	3–5
Cleaning of distribution system	80′–90′	3–5
Curing phase for 24 m (overlapped to previous)	12 hours	-
Total	40–42 hours	

Note: The number of operators considered is: 5 trained operators + 1 skilled and experienced chief.


(a) (b)

Figure 6.32 Formwork detail (a) and self-launching formwork (b).

the end portals. The legs rest directly on the excavation floor at the front and on the previous invert casting surface at the rear. When the formwork articulations have been locked and the stop-end closure with external support props is installed, the traveller legs can be lifted and the entire traveller supported by the formwork can be moved forwards. In this way, a new casting cycle starts after a regular curing of the previous casting, which is not affected by the traveller legs support during the advancement phase.

Moreover, this solution allows the use of the equipment for longitudinal slopes of tunnels when higher than 3% or 4%. These types of equipment have already been used for tunnel inclinations of 80% and 100% and for vertical shafts. With such extreme slopes, it is mandatory to prepare suitable pockets for the insertion of anti-fall pins.

Numerous lining sections of metro tunnels have been created with such self-launching full round formworks. In this case, the presence of the long traveller beam forwards facilitated the installation of the reinforcement without requiring additional equipment.

The production cycle with these single-element full round formworks (with length from 6 to 15 m) allows one casting per day with minimum curing time of 12 hours (Figure 6.33). Dismantling and repositioning equipment is simple, as there is only one central longitudinal flange positioned in the invert or in the cap. All the elements are connected through the appropriate hinges.

6.6 TBM SEGMENT PLANTS

This section explains the different technologies implemented during the production of segments, including driving parameters involved in the choice of the best type of production (Figure 6.34). In addition, an analysis concerning the deep impact of automation, robotics and data transfer on one of the most industrialized processes in the underground infrastructure construction will be shown.

Segment production represents one of the key processes within mechanized tunnel construction. Some crucial aspects that can grant the project's success as well as the durability of the infrastructure are a precise manufacturing of the moulds, the correct choice of precasting technology and precise data collection.

AU: Please confirm whether the usage of the term 'pre-casting' is OK.

The typical production supply chain consists of reinforced concrete material (cement, reinforcement, raw materials, etc.), a batching plant, accessories (dowels, guidance rods, gaskets, etc.), a precasting plant, pre-storage and storage areas and segment transport vehicles on-site or directly to the TBM. Precasting may be operated on-site or through existing facilities nearby the site (Figure 6.35).

6.6.1 Moulds and tolerances

Before mentioning precasting methods, it is important to focus on the influence of tolerances, which is a fundamental aspect that must be taken into consideration during manufacturing and assembling of the moulds (Figure 6.36). The accuracy of the dimension of the segment affects the following:

- Stability of the tunnel lining.
- Tunnel tightness against prevailing groundwater.
- Acceptance of the prevailing ring loads (earth and water pressure, grouting pressures, support loads, etc.).
- Acceptance of driving loads from the machine thrusts.

In particular, the side and head shutter welding and annealing process as well as the mould assembly represent the most critical phases (Figure 6.37).

For a worldwide reference for the rules related to tolerances, see Table 6.3.

Once the mould is assembled, a dimension check is required. The measurement of the said moulds is carried out by determining their 3D geometries and checking whether the divergences of these figures from the design data comply with the required tolerances. A laser tracker is normally used. A weather station measures the temperature, pressure and humidity of the air within the whole measurement system, so as to

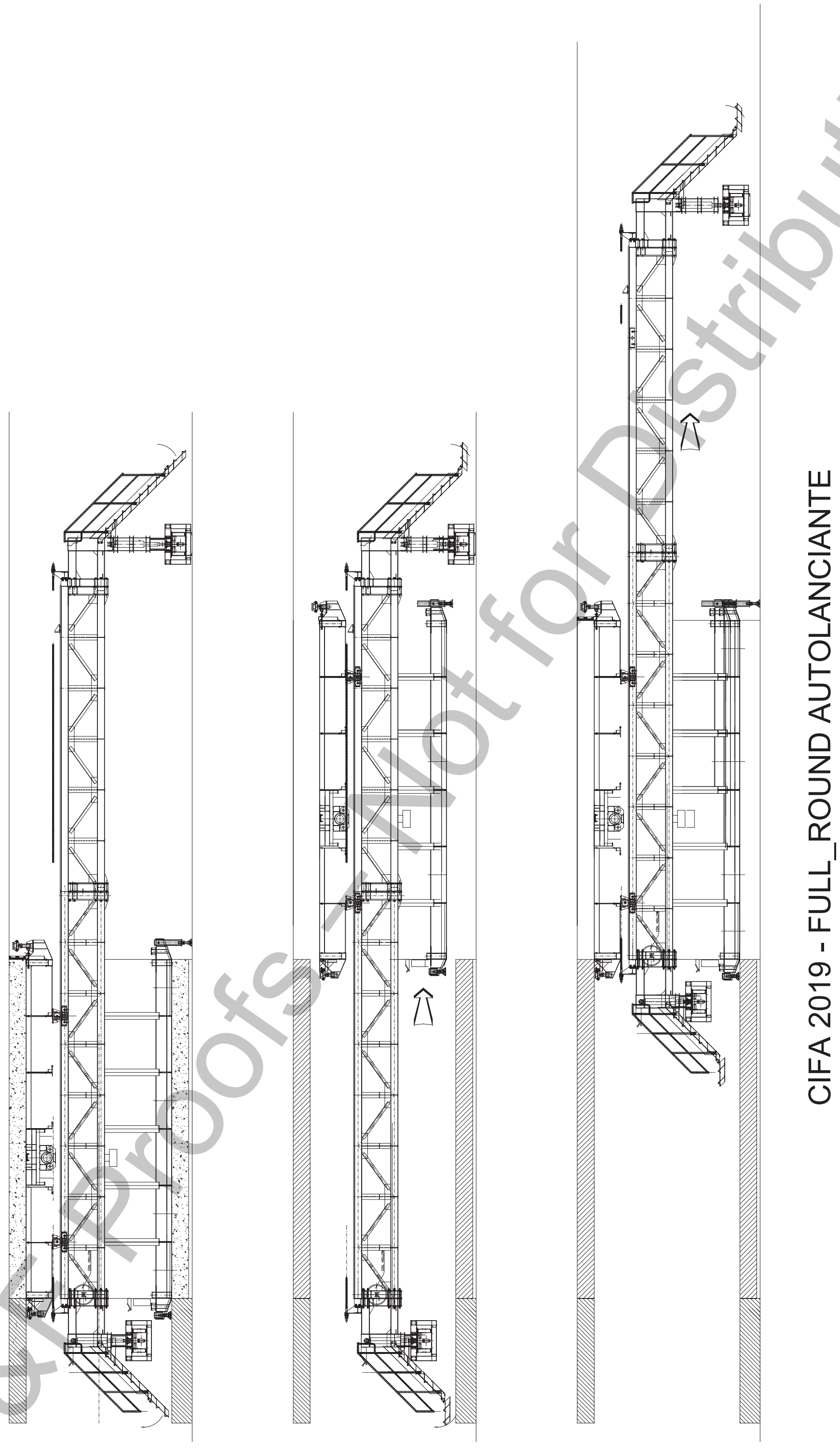

Figure 6.33 Self-launching formwork sequence.

Figure 6.34 Various processes involved in the construction of infrastructure.

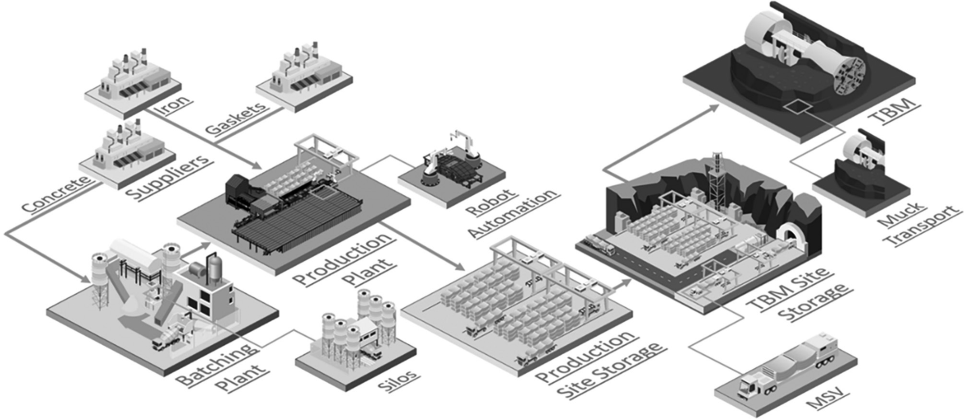

Figure 6.35 Design of the complete supply chain.

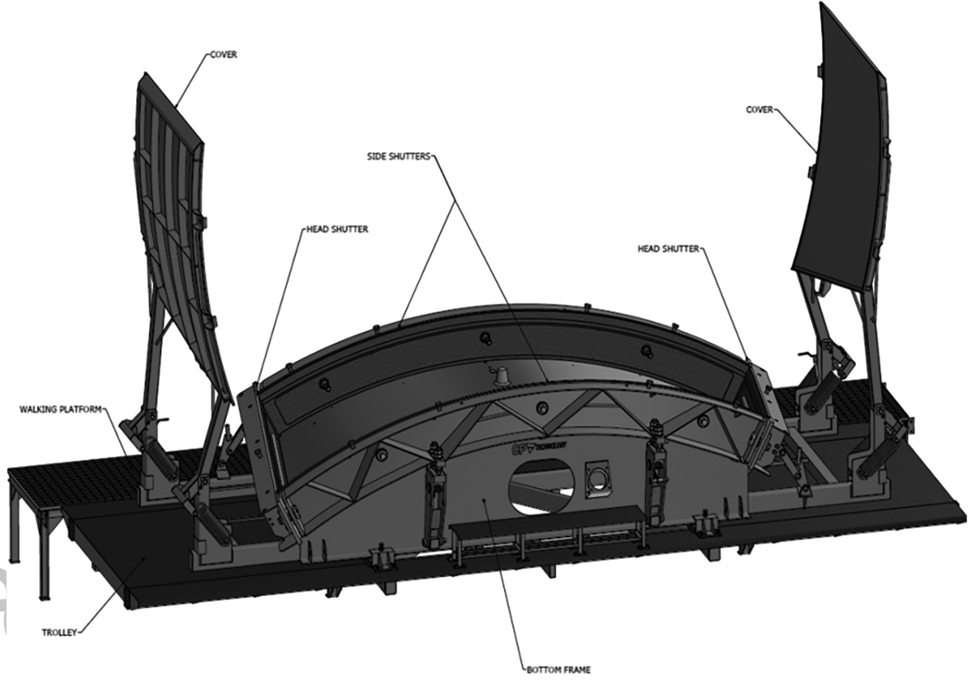

Figure 6.36 3D typical mould configuration.

Figure 6.37 Example of robotized alternate side shutter welding process to distribute tension effects.

Table 6.3 Tolerance reference

Guideline 853, Module 4005 – Lining with Segments, Deutsche Bahn – 01 March 2011 (left column); ZTV ING Part 5, Section 3 – Germany Highway Institute (BAST) – 12/2007 (right column)		
Angle deviations		
Segment distribution angle (large segments)	Inapplicable	±0.01
Segment distribution angle (small keystone)	Inapplicable	-
Angle of twist in the longitudinal joints/twist in the longitudinal joints	±0.3 mm	±0.3 mm
Angle of longitudinal joint conicity/longitudinal joint conicity	±0.5 mm	±0.5 mm
Linear dimensions		
Segment width	±0.5 mm	±0.6 mm
Segment thickness	±3.0 mm	±3.0 mm
Segment arch length (large segments)	±0.6 mm	-
Segment arch length (keystone)	Inapplicable	-
Inner radius (individual segment)	±1.5 mm	±1.5 mm
Outer radius (individual segment)	Inapplicable	±2.0 mm
Sealing groove axis	± 1.0 mm	±1.5 mm
Contact area axis	Inapplicable	-
Evenness and plane parallelism of contact surfaces		
Longitudinal joint evenness	±0.5 mm	±0.5 mm
Annular joint evenness	±0.5 mm	±0.5 mm
Tolerances on closed ring		
Outer diameter	±10 mm	-
Inner diameter	±10 mm	-
Outer circumference (measured at three heights)	±30 mm	-

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make sure that the laser beam is not influenced by any conditions within the surrounding environment. However, since the temperature of the concrete which composes the segments as well as the temperature of steel may vary, the measurement results could be compensated for with the thermal expansion coefficient for concrete and steel at a required reference temperature, thereby allowing an appropriate comparison of the dimensions of the moulds and segments in different conditions.

Once the measurement is completed, a measuring report is filled out and returned to the job site management team. This operation is carried out with predefined frequency during the whole tunnel segments production. Furthermore, the approval procedure requires the measurement of the full set of segments which compose the first ring to be produced.

6.6.2 Segment precasting methods

The key factors in the evaluation of the equipment and the needed logistic quality level are as follows: the respect of dimensional tolerances of the moulds; vibration method; curing system; segment logistic system; segment traceability; and health and safety approach.

Two are the major production methods to be identified: stationary precasting and carousel precasting. For both systems, the production follows the steps as shown in Figure 6.38. The key parameters that influence the correct choice of the precasting technology may be identified as listed: (a) the overall number of segments, (b) cost of manpower, (c) work required during the demoulding stage, (d) TBM speed and (e) available area.

A small amount of segments, low manpower cost or low TBM speed could imply stationary precasting.

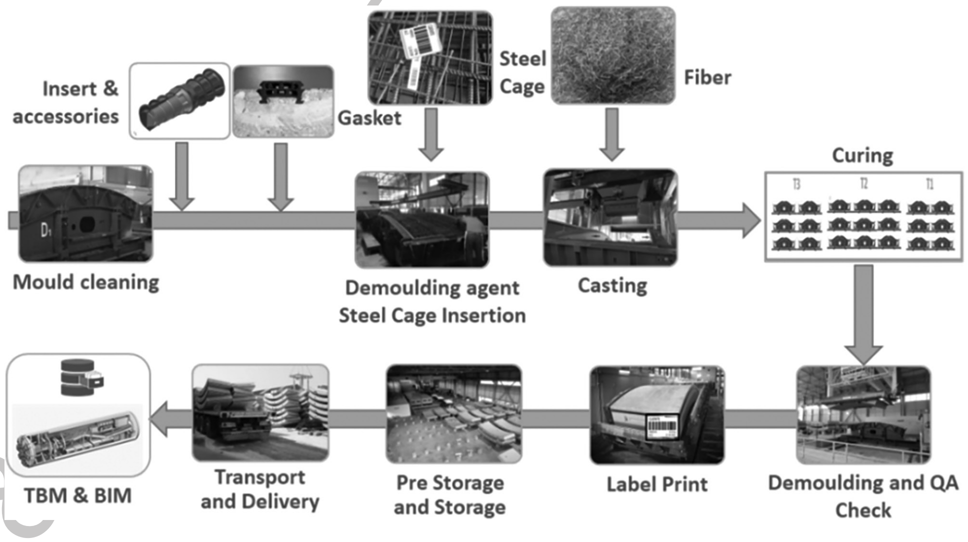


Figure 6.38 Steps in the precasting process.

Nowadays, the use of a carousel is the most used method, thanks to the following features: (a) higher efficiency, (b) better control of traceability, (c) higher operators' safety, (d) usability and (e) possibility of robotization.

Nevertheless, there are some contexts in which stationary production still is the ideal choice. In a stationary production line, the moulds are fixed on the factory slab and the workers move from one mould to the other (Figure 6.39). The curing line is distributed throughout the facility in order to carry heat and steam to each mould. Also, the vibrator supply system requires distribution of air and electricity to all the moulds. The concrete can be provided either by a concrete truck or by a travelling hopper.

In a carousel production, moulds move on rails, and workers remain in the same position, following an industrial-like approach. All the moulds movements are automatic.

The latest development in the production technology consists of a "universal carousel", a highly effective solution that allows to produce rings for different projects within the same carousel by changing the moulds on trolleys and therefore making it possible to reuse the carousel, making a small impact on costs and allowing an exponential growth in terms of efficiency (Figure 6.40).

The carousel is usually composed of a working line and a curing room. On the side of the carousel, a pre-storage area is normally located, where the segments are stocked for 24 hours in a reduced stack configuration. Then, the segments are moved to a "normal" storage area for up to 30 days (Figure 6.40). Both the pre-storage and storage timings are indicative and can be cut in case the required resistance is reached early. In case of dry environment, a water curing tank may be used.

A carousel system can operate with 6–20 workers, depending on the level of technology implemented and the cycle time can also vary in a range between 5 and 15 minutes.

Figure 6.39 Stationary precasting line layout.

(a) (b)

Figure 6.40 Example of the carousel layout.

The resistance required during the demoulding phase is the driving parameter within the calculation of the carousel configuration, which depends on mix design and curing cycle.

Most times, a long working line with even/flat industrial work level platforms is preferred, for safety and productivity reasons.

A general list of the different activities on the working line is given below:

1. Head and side shutter unbolting and head shutter opening (manual or robotic).
2. Cover opening and segment demoulding (demoulding and tilting table or vacuum).
3. Mould cleaning (manual or robotic).
4. Demoulding agent placing (manual or robotic).
5. Dimension check and sealing gasket installation (manual).
6. Rebar cage fitting and blocking installation (manual).
7. Cover closing or installation (manual).
8. Concrete pouring and vibrating (manual).
9. Cover opening or removing (manual).
10. Segment smoothing (manual/robotic).
11. Mould cleaning (manual).

Each operation requires extreme attention to detail in order to reach the quality requested to have the segments approved. Clearly, robotics plays a role in the production process.

6.6.3 Cover opening/closing

The opening and closing operation represents one of the most delicate operations during the process, which is why the state of the art is represented by removable covers on moulds. These covers may be removed either inside the casting room, or in the subsequent position, depending on the concrete slump. This allows access to all areas of the mould in order to clean and guarantee an easy installation of the gasket. This solution grants a reduction in the required manpower, lower water consumption during cover cleaning and, moreover, safer working conditions.

6.6.4 Mould cleaning

If the moulds are not properly cleaned, the remaining parts of concrete in the gasket groove will cause problems when fitting the new gaskets. At the same time, concrete stuck between the head shutters and the side shutter could compromise the respect of the required tolerances.

Once the mould is closed, after a check with a mechanical template, a dismantling agent is applied on all mould surfaces. Sometimes, grease may be applied on the erector cones and other mechanical parts inserted to avoid damage on the segment. For this reason, the quality of the dismantling agent is crucial.

Nowadays, the state-of-the-art foreseen gasket installed in the mould before casting (embedded or anchored gasket).

AU: Please check and confirm the clarity of the sentence 'Nowadays, the state-of-the-art foreseen … before casting'.

6.6.5 Segment demoulding operation

The demoulding operation also represents a critical step inside the precasting cycle. A wrong technology might create cracks or bring inefficiency. With regard to the first point, it is fundamental that the concrete reaches a minimum strength to avoid damages to the segment. The proper latest developments are the use of various sensors and software systems to provide an automatic alert whenever the requested resistance is not reached.

Concerning the logistic efficiency, demoulding systems nowadays include a tilting function, avoiding inefficient multiple segments movements with the risk of damages (Figure 6.41). Different technologies can be taken into consideration, such as a jack on the side of the segment (a system that reflects the TBM thrusting concept) or a vacuum (requiring a good surface smoothing).

For the transport from the pre-storage to the storage area, normally a hydraulic or mechanical clamp (Figure 6.42) or a forklift is used.

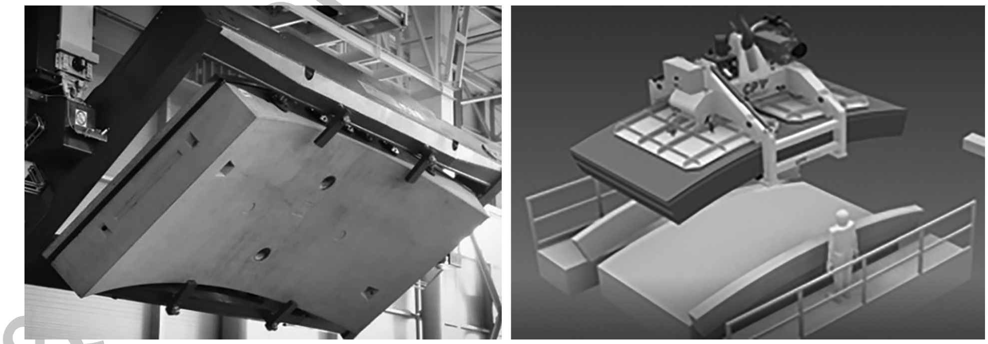
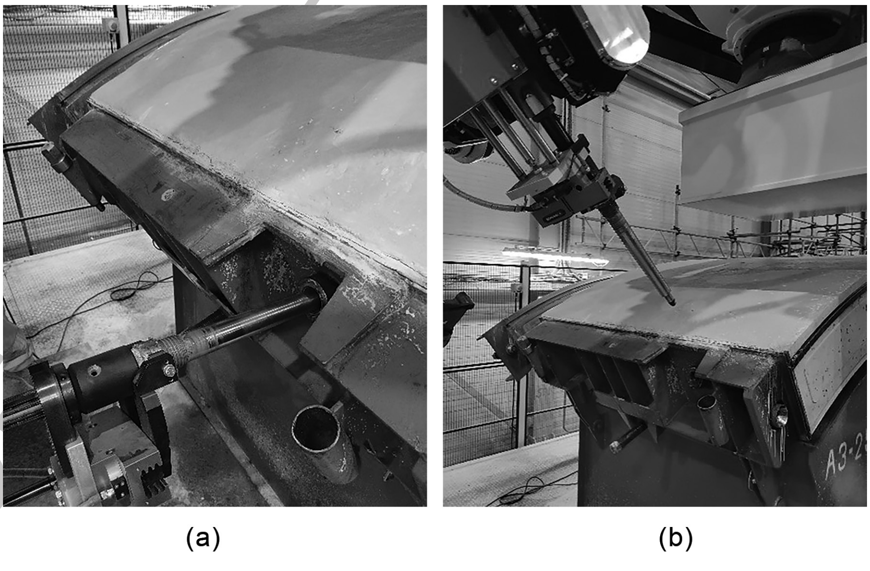


Figure 6.41 Demoulding devices and stress FEM diagram.

Figure 6.42 Pre-storage area and evacuation to storage area.

6.6.6 Robotics and automation

Over the last few years, automation and robotics have been breaking into the world of infrastructure. With a new technological perspective, the carousel production system may be the perfect springboard for the introduction of robotic technology in this area. Construction companies could become confident with this type of technology and pull the trigger for continuous innovations. Robots can take the workers' place in difficult tasks that may be hard or dangerous for humans within a carousel system, increasing safety and quality of life in the worksite. For example, robotics may be applied to: (a) unbolting (Figure 6.43), (b) side and head shutter openings, (c) mould cleaning, (d) side and head shutter closing and € dismantling oil spraying.



(a) (b)

Figure 6.43 Robotic unbolting process.

It has been proven that the exposure of the hands/arms to vibration can cause hand vibration syndrome due to impact wrenches. Considering an average tunnel length, which roughly requires the production of 65,000 segments, the bolting/unbolting operation is repeated up to 650,000 times, which is equivalent to 1,800 hours of vibration, without taking into consideration the lifting of wrenches and the AC-DC effect "noise pollution", which sum up to the health risks within the plant. In fact, the weight of the bolt is 5 kg, its relative strength of sound can reach up to 100 dB, whereas robotic electrical guns do not need to be lifted and do not reach such levels of noise.

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The introduction of robotics in the world of construction represents an inevitable industrial shift within the field. Moreover, the high TRL (technology readiness level) of new manpower available on the market must be considered. It has become clear that robots increase safety in the workplace: workers are moved to supervisory roles where they no longer need to perform dangerous jobs. Another development that is foreseen is the robotic production of the steel cages.

6.6.7 Traceability system

As mentioned, every tunnel project represents a complex chain of processes, in which many single phases must lead to a general plan. Constant monitoring of production progress as well as real-time information is therefore extremely important. To satisfy these needs, a traceability system plays a critical role in the management of production, quality and storage of a prefabrication plant. Some of the features of the most innovative traceability systems available on the market (Figure 6.44) are the following:

- Real-time management of information concerning segments.
- Traceability of all phases of the process: from production to shipment to the TBM.
- Production dashboard for real-time monitoring of productivity systems, including performance indicators.
- Data integration among batching plant and PLC according to the production.
- Integration with the main management system (ERP), prefabrication and batch systems.
- Documentation and management of nonconformities in production.
- Transparency of data collection guaranteed from equipment integration with software.
- Transmission of data to the digital building information modelling (BIM) model.
- Management of different projects with a unique platform.
- Monitoring the curing temperature to certify the quality of segments.
- Knowing the exact position of each segment in all stages of the project.

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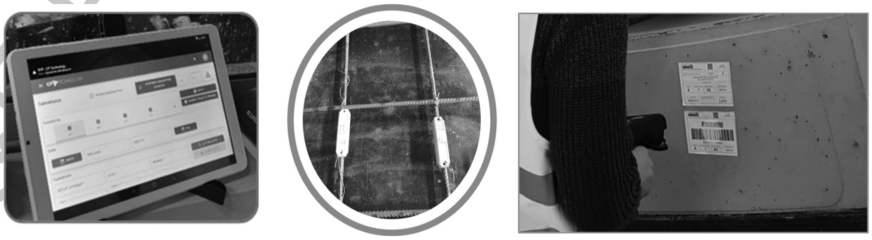

Figure 6.44 Traceability system example.

To implement these functionalities, a traceability system must be supported with the best modern technologies. Sensor technology is experiencing a new wave of innovation linked to the miniaturization of components, new protocols and communication systems. Thanks to the introduction of a variety of sensors, industrial objects become "smart", as they begin to interconnect with each other and transmit data and information through the network. Sensors are able to measure just about anything; for example, in the industrial field, IoT (Internet of things) sensors are mainly used to instrument machinery, detect working parameters in real time and support traceability systems so as to automatically collect data and information.

One of the emerging technologies in the market is the LoRa (long-range frequency), a wireless technology that allows the transmission of data over long distances and at low power, allowing long-lasting solution (3–5 years) with low consumption. The transmission distance can reach up to 2 km for high-density urban environments. For this reason, LoRa qualifies as the best technology for "hostile" environments such as those of construction and tunnelling. Some examples of the use of LoRa technology related to the construction field are given below, all without going through expensive physical wiring, simply by correctly positioning the sensors, even on moving objects:

- Measuring the temperature of concrete during the curing process, both inside and outside the formworks (in fixed and carousel prefabrication plants).
- Measurement of the filling levels of silos and tanks.
- Geolocation of machinery and mobile equipment.

Lastly, thanks to its interoperability, the monitoring system is able to communicate with both the management and application systems already present in the company, considerably reducing installation times due to the communication and security protocols for data protection.

6.6.8 BIM design & tunnel modelling in the Industry 4.0 (I4.0) supply chain

Building information modelling (BIM) is a process that creates and manages all the information within a project, throughout the infrastructure's lifecycle. The output is a digital information model that contains all information on the infrastructure.

BIM represents a method which optimizes planning, creation, and management of constructions by means of software. For instance, simply by using the software, all relevant data of a building can be collected, combined and connected digitally (Figure 6.45). The virtual construction is also available as a 3D geometric model.

I4.0 (Industry 4.0) is the current trend of automation and data exchange in manufacturing technologies. It includes cyber-physical systems, the IoT, cloud computing and cognitive computing. I4.0 is commonly referred to as the Fourth Industrial Revolution (Figure 6.46).

I4.0 fosters what has been called a "smart factory". Within modular-structured smart factories, cyber-physical systems monitor physical processes, create a virtual copy of the physical world and make decentralized decisions.

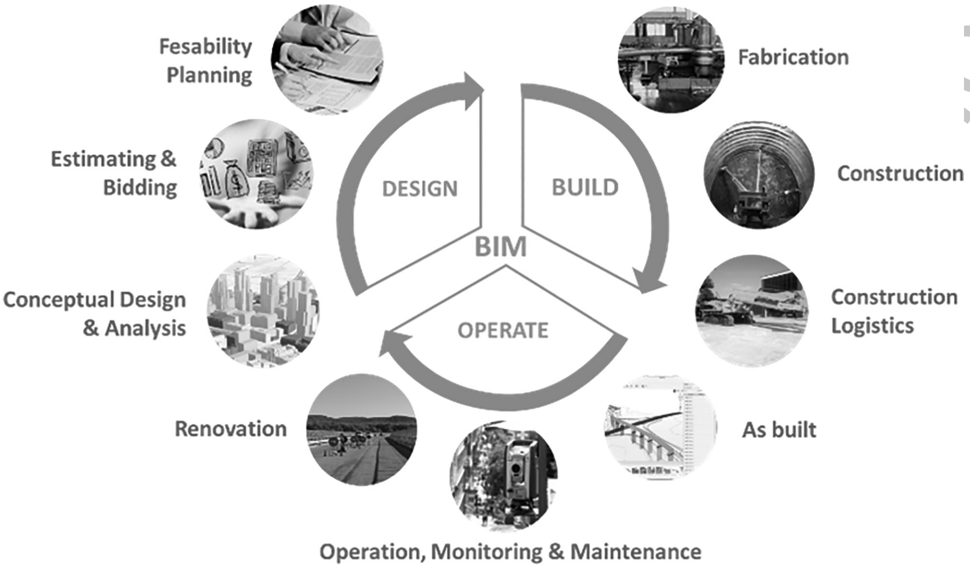

Figure 6.45 Tunnel continuum construction.

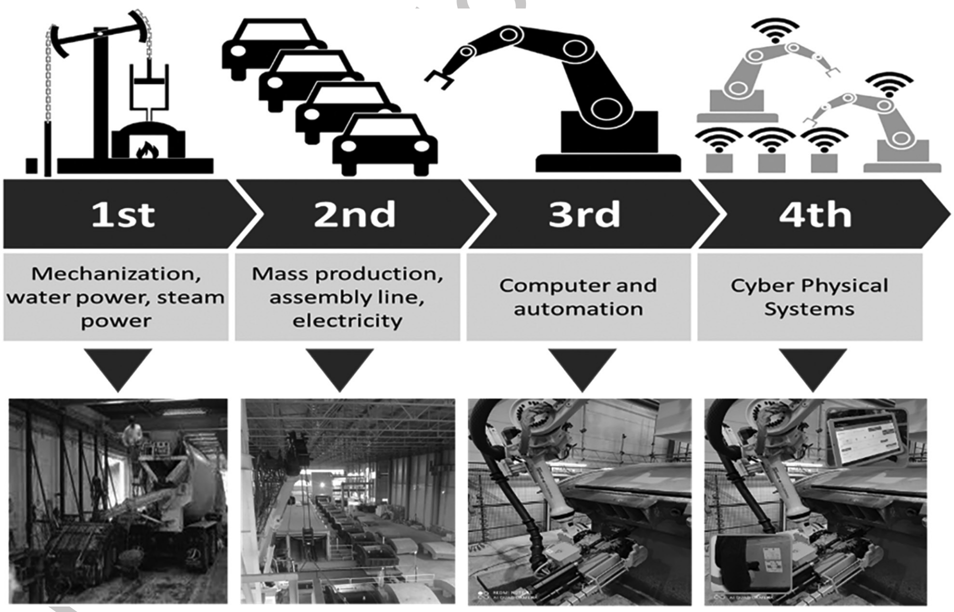

Figure 6.46 Industrial revolution in construction world compared to TBM segment plants evolution.

Over the IoT, cyber-physical systems communicate and cooperate with each other and with humans in real time, both internally and across organizational services used by members of the evaluation chain.

How does the explosive mixture of these two approaches generate a revolution and a winning strategy in the construction industry? The analysis of processes and different technologies involved has shown that relevant results can be obtained by supporting BIM models, thanks to interoperability I4.0, with a view of total transparency and automation, during both the construction and the maintenance phases of the infrastructure.

These tools combined allow an intelligent process or project management, with the aim of:

- having an overall view of the actors and entities involved;
- having a real-time view of the whole situation;
- gathering historical data in order to carry out in-depth analysis;
- cutting human intervention in operational activities related to the management of operations, safety and quality control.

All the enabling technologies involved in this digital acceleration are related to the sphere of the I4.0, specifically:

- 3D design collaboration tools;
- sensors on-board of machines or environmental sensors;
- automation systems and PLCs;
- devices that allow people to record information digitally (smartphones, tablets, barcode readers, etc.);
- traceability systems for objects and people based on RFID (radio frequency identification) technologies, Beacon, LoRa, etc.;
- cloud platforms that collect and share information;
- monitoring, analytics and artificial intelligence solutions that support decision-making processes.

In addition, the cases where the greatest benefit has been achieved are those in which the "digital twin" involved several factors in the same supply chain, allowing better integration of processes as well as the exchange of data in real time (e-Supply Chain Collaboration and e-Supply Chain Execution).

AU: Please confirm the capitalization and usage of the term.

Having a "smart management" of a production chain allows better knowledge of all those processes that occur during the creation of a product or service, also available and accessible on a virtual level in order to view all the actors or subjects involved in the supply chain: from suppliers to customers (Figure 6.47).

Focusing on a specific case related to the construction of a tunnel, such technologies allow us to:

- provide results of the design to builders and construction managers in a collaborative perspective;
- simultaneously gather the evidence of the executive process by recording the deviations from the initial project;

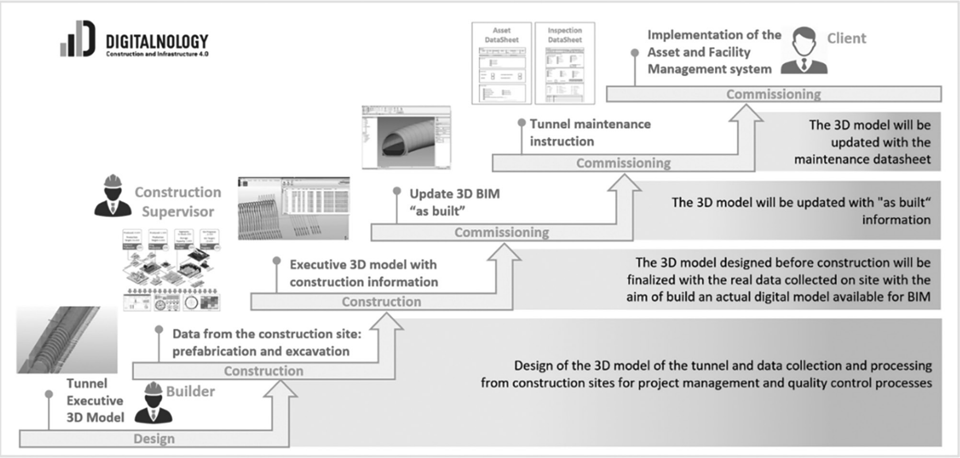

Figure 6.47 The phases of the creation of a digital twin for a tunnelling project.

- deliver the finished work, including all the necessary documentation for commissioning and for its future maintenance (both ordinary and extraordinary).

By applying what we have seen so far to a TBM precast lining tunnel, the following steps should be taken.

1. The design studio delivers the executive 3D information model of the tunnel to the builder and the construction supervisor.
2. During construction, excavation and prefabrication of the segments, the construction company is responsible for monitoring all execution processes as well as collecting data and key documents through digital tools in a ramified manner in order to facilitate project management. The availability of the required information, which is able to enrich the 3D model, will be useful to the client. During construction, there are mainly three types of real-time information:
    a. *Productivity*: evidence of the progress of the work as a whole and, in more advanced cases, management of all documentary aspects, risk management and correlation with the economic and financial impacts.
    b. *Quality*: tracking of:
        i. raw materials used through the periodical tracking of goods, so that the bill of materials is always complied;
        ii. production/executive process through dynamic monitoring of sensors and reading of data from machines (PLCs), in addition to the compilation of digital work.
    c. *Security*: the real-time visibility of:
        iii. location of vehicles and people;
        iv. correct use of PPE (personal protective equipment);
        v. video surveillance systems, traffic lights and emergency communication;
        vi. air quality sensors.

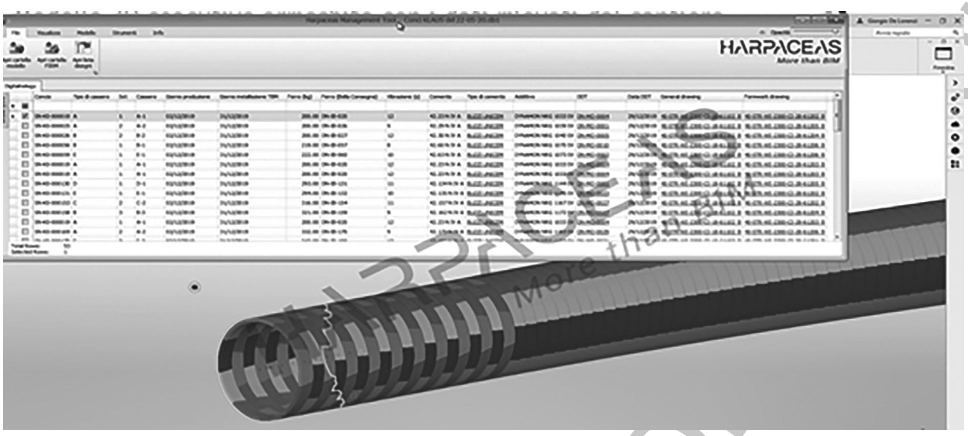

Figure 6.48 TBM tunnel as built with segment data automatically collected. (Courtesy of Harpaceas S.r.l.)

3. While the construction progress advances, the association of information from the production and execution of all the physical parts to the 3D drawing is automatically carried out, creating the "as-built" model, a virtual representation of the finished tunnel (according to a logic Open BIM). This modelling can be automatically carried out starting from the excavation and positioning data of the TBM segments, thereby saving a lot of time (Figure 6.48).
4. Finally, all information related to the management of the entire tunnel's maintenance is entered: database which includes all parts of the job is created, including the inspection files linked to the master data of the assets in the tunnel, a preventive maintenance calendar and corrective measures to be applied in case of intervention.

   Once the digital twin has been created, it is delivered to the client for the commissioning of the "physical twin" and the information entered will be the result of the selection work started many years earlier with the collection of construction data on-site that will allow knowing who manufactured each single part, the installation date and the recommended maintenance frequency, even after years.

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6.7 VENTILATION SYSTEMS DESIGN FOR TUNNELLING DURING ITS EXCAVATION

Ventilation is one of the most important systems, provided during tunnel excavation works, to ensure safety conditions for those involved in the underground environment. The goal of this system is to provide clean, fresh air to the excavation face or working areas. The airflow, under normal working conditions, must ensure the dilution of waste gas emitted by vehicles and machines and guarantee a sufficient oxygenation to personnel working underground. Therefore, the preservation of an acceptable air quality is linked to the correct sizing of the ventilation system, as well as its construction and operation.

There are various kinds of ventilation systems, and the air inside the tunnel may be distributed, for example, through ducts, shafts or chambers. Ventilation is always carried out by means of a circuit consisting of a series of two sections crossed by air without interruption. The first one goes from the entrance to the excavation front, while the second one connects the tunnel face to the entrance. Air is forced through the circuit by one or more fans, so the ventilation systems can be classified according to the position of the fan along the aerial circuit, and therefore, there will be suction, pushing and mixed or combined systems. In suction ventilation, the exhausted air is removed from the final tunnel section through a duct. The suction effect produced by the fan placed near the face draws healthy air from outside. With this system, air travels through the tunnel, arrives at the tunnel face and is then pushed outside the tunnel through a duct. A negative effect of this kind of approach is that the air flowing through the entire length of the tunnel meets excavation areas that may be already partially polluted, making it necessary to move fans continuously to follow the advance of the excavation face. On the other hand, in case of pushing (blower) ventilation, the fan is installed outside of the tunnel and the excavation face is always lapped by fresh air coming directly from the outside through a duct that ends in the working area. Then, polluted air flows back through the tunnel to the exit portal, which is the only negative aspect, because workers in tunnel are hit by the dirty airflow. However, generally it doesn't represent a critical problem. In mixed ventilation, the two systems described above are combined. In this case, it is necessary to avoid short circuits of contaminated air by ensuring a sufficient overlap of the suction and pushing ducts.

6.7.1 Underground ventilation criteria

Tunnel construction consists of two main excavation methods: drill and blast and mechanized tunnelling through TBMs. The choice of excavation method depends on various factors – e.g. route length, nature of the rock mass, economic context conditions and planned construction period. For both methods, all the ventilation techniques previously mentioned may be applied, and the implementation of one system or another depends on the method of carrying out the work and local conditions. Generally, mechanized tunnelling implies the use of conventional blower ventilation with external fans and flexible ducts directly connected with the TBM's backup. In traditional excavation, blower or suction ventilation may be applied, but blower ventilation is often preferred; exceptions are made for some particular applications (Figure 6.49).

As mentioned, when using mechanical ventilation, the rate of the airflow must be sized in such a way that the gases and dust concentration inside the entire tunnel do not affect the air quality, in terms of both hygiene and safety (oxygen content and concentration of CH_4). In terms of sanitary ventilation, air pollutants, noxious elements, humidity and temperature must always maintain their levels under the admissible values, while in terms of safety, ventilation must guarantee higher levels of oxygen possible. Furthermore, in case of CH_4 detection, ventilation level must adjust its flow rate in order to keep concentration levels under dangerous limits (lower explosive limit – LEL). The designer has to determine the most suitable system configurations for the adopted excavation scenario, sizing ventilation according to performance criteria defined above.

Figure 6.49 Blower external ventilation in underground works.

Generally, the most common ventilation systems used in underground works are blower, consisting of one or more fans installed in front of the tunnel entrance, and one or more ventilation ducts that convey the air outside pushed outside towards the processing area. The air jet coming out of the duct near the excavation face widens and slows down, mixing with the air inside the tunnel; thanks to this mixing, the dilution of the polluted air and its removal are guaranteed.

6.7.2 Design flow rate

6.7.2.1 References

The main references concerning underground ventilation requirements are the following: Swiss Standard SIA 196:98 "Ventilation of Underground Structures" and British Standard BS 6164:2011 "Code of Practice for Health and Safety in Tunnelling in the Construction Industry".

Both standards may be used as a reference for good practice within tunnel construction; the British Standard is strictly applied to Anglo-Saxon countries excavation works, while Swiss Standard is conventionally used as a universal reference guideline. Definitions and concepts associated with the ventilation of underground works may be found within the said standards, as well as the design of ventilation systems and its sizing, including design equations, underground airflow, operating pressures and supervision and control of ventilation systems.

6.7.2.2 Airflow demand

In order to ensure the correct dilution of pollutants produced during the work phase, the air demand has to be estimated carefully, considering every pollution source involved, as well as operating machines, trucks and other engined vehicles. The amount of ventilation air will be calculated mainly according to the total diesel power at work inside the tunnel. It can be easily foreseen that not all (and not always) the working vehicles will actually be present in the tunnel; for this reason, correction factors are considered so as to determine the actual average diesel power employed.

As previously mentioned, it is common practice to use calculation parameters of the Swiss Standard SIA 196; this regulation implies that the total flow rate of fresh air must be calculated as the product of a unitary flow rate times the total power actually used in the excavation face/working area. The unitary flow rate varies as a function of the nature and type of the vehicles working inside the tunnel as well as the number of people/personnel involved in tunnelling operations. In particular, a unitary flow rate for fresh air is required for:

- 4 m^3/min/kW of diesel power employed during excavation stages (or in the presence of excavation vehicles) [please note: BS 6164 only provides for one airflow rate of 3 m^3/min/kW in any working scenario];
- 2 m^3/min/kW of diesel power during loading and transport of materials or lining;
- the values of the unitary flow rate rise, respectively, to 6 and 3 m^3/min/kW with the use of vehicles/equipment without control of waste gas;
- in the presence of working personnel, the flow rates are increased by unitary flow of 3 m^3/min/person in order to ensure adequate environmental conditions (oxygen level).

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In order to ensure efficient transport of polluted gas from the excavation face to the tunnel exit, it is necessary to check that, under normal working conditions, the return air velocity from the excavation face is not under 0.3 m/s. This value represents the conventional design reference; however, in case of impossibility to prevent CH_4 from flow out of the rock mass, this value should be increased up to 0.5 m/s (according to SIA 196 standard).

Therefore, the calculation of air demand is given by the following equations:

$$Q'_0 = q' \sum\left(\text{power } 0.5 F_c\, F_s\right) + q''\, pax \tag{6.1}$$

$$Q''_0 = w A_T \tag{6.2}$$

where

- q' is the unitary renewal airflow rate m^3/min/kW defined by standards;
- F_c stands for the simultaneity factor; the quantity of air ventilation is calculated during the most critical phase of the process. It must be taken into account that the processing can be simultaneous or subsequent; if different works are simultaneous, an adequate coefficient of contemporaneity must be introduced within the calculation;
- F_s represents the safety factor for the calculation of airflow ventilation (assuming equal to 1);
- q'' is the unitary fresh airflow per person involved in tunnelling operations, equal to 3 m^3/min;
- pax stands for the number of workers present in the tunnel during the processing phase;

- w is equal to the tunnel return design velocity;
- A_T represents the net cross section of the tunnel, measured at a certain distance from the tunnel face (i.e. five to ten tunnel hydraulic diameter).

In other words, the final flow rate design is given by solving equations (6.1) and (6.2) and by using the maximum result value:

$$Q_0 = \mathrm{Max}\left(Q_0';Q_0''\right) \tag{6.3}$$

6.7.2.3 *Ventilation scenarios analysis example*

The demand of ventilation must be evaluated considering all possible scenarios that may occur during working phases. Below is the examination of a real example of a work cycle, predicted during TBM excavation of a long underground railway tunnel.

Two different excavation scenarios are taken into account: for example, in case of tunnels excavated by TBM, a change of the working approach, or simply an increase in the number of service vehicles considered in the calculation analysis.

The increase in production rates requires a larger number of MSVs, as well as people involved in the working operations.

The amount of power equipment is evaluated for each scenario and results in:

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- *Ventilation Scenario 1*: 2 MSV TBM logistic (MSV 85); 1 Vehicle People transport (PSV 20); 1 TBM safety generator (J250K); 2 MSV Service and cross-passage (MSV 35); and 1 MSV concrete for invert (MSV 120).
- *Ventilation Scenario 2*: 3 MSV TBM logistic (MSV 85); 2 Vehicle People transport (PSV 20); 1 TBM safety generator (J250K); 2 MSV Service and cross-passage (MSV 35); and 1 MSV concrete for invert (MSV 120).

In Tables 6.4 and 6.5, the results for airflow calculation for both reference scenarios are listed.

6.7.2.4 *Fan flow rate*

The above-calculated flow rate values refer to the flow turnover required at the excavation front; in order to compensate for all the distributed losses along the ducts (due to vents or rips), fans positioned at the beginning of the network must ensure a flow rate higher than Q_0. For this reason, the fans' airflow at the entrance of the tunnel must be suitably sized; the increase in the flow rate is calculated based on a predetermined calculation method, which is established according to the actual nature and state of the installed pressure ducts. Therefore, fan(s) placed at the beginning of the line must not only be able to generate the required final flow rate, but also have the total pressure characteristics necessary to overcome the resistances of the circuit in which it must operate (including diameter, friction, type and maintenance status of the selected ducts).

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Table 6.4 Scenario 1 air demand

Phase	*Equipment*	*Quantity*	*Nominal power*			*Air demand BS 6164*				
			Unitary		*Total*	*Unitary*	*Total*		*Correction factor*	*Total*
		No.	*HP*	*kW*	*kW*	*m³/min/kW*	*m³/min*	*m³/sec*		*m³/sec*
Excavation	MSV 85	2	283	385	770	3	2,310	38.50	0.30	11.55
	PSV 20	1	40	55	55	3	165	2.75	0.30	0.83
	J250K	1	168	228	228	3	684	11.40	0.30	3.42
	MSV 35	2	129	175	350	3	1,050	17.50	0.30	5.25
	MSV 120	1	283	385	385	3	1,155	19.25	0.30	5.78
	Workers	48	-	-	-	3	144	2.40	1.00	2.40
Total					1,788		5,508	92	3.14	29.2

Table 6.5 Scenario 2 air demand

Phase	*Equipment*	*Quantity*	*Nominal power*			*Air demand BS 6164*				
			Unitary		*Total*	*Unitary*	*Total*		*Correction factor*	*Total*
		No.	*HP*	*kW*	*kW*	*m^3/min/kW*	*m^3/min*	*m^3/sec*		*m^3/sec*
Excavation	MSV 85	3	283	385	1,155	3	3,465	57.75	0.30	17.33
	PSV 20	2	40	55	110	3	330	5.50	0.30	1.65
	J250K	1	168	228	228	3	684	11.40	0.30	3.42
	MSV 35	2	129	175	350	3	1,050	17.50	0.30	5.25
	MSV 120	1	283	385	385	3	1,155	19.25	0.30	5.78
	Workers	48	-	-	-	3	144	2.40	1.00	2.40
Total					2,228		6,828	114	3.18	35.8

6.7.2.5 Design pressures calculation

In conclusion, the ideal fan design must be able to produce a minimum flow rate in order to generate the required stream at the duct end, and it must reach the necessary pressure so as to overcome the resistances of the circuit in which it will work. The formula used for the calculation of the pressure losses along a duct is the following:

$$dp = \sum\nolimits_{x} \left(\lambda \rho dx u^{2}\right) / (2D) \tag{6.4}$$

where

- dp is the static loss for unit length dx of the duct;
- λ represents the loss coefficient due to the roughness of the inner surface of the duct, section variations and duct joints;
- D equals to the nominal diameter of the duct;
- u stands for the average speed of the airflow inside element dx;
- ρ is the air density (at reference temperature).

The sum of all the unitary losses along the total duct length provides the total pressure required for the main fan outlet installed at the beginning of the line. The total pressure values of the fan must be added to the remaining pressure p_0 needed for the final airflow so as to allow the air to come back to the tunnel's exit. In general, p_0 assumes values under 50 Pa, and only for very long tunnels and high return velocity (w), it can reach up to 100 Pa.

Along ducts, transporting air to the excavation face, losses within the flow are inevitable. Air leakages are induced by tears along the ducts, tissue degradation and in-line junctions that not always are airtight. Flow losses are calculated using the formula:

$$Q_p = c_{\text{eff}} f \ A_d P^{1/2} \tag{6.5}$$

where

- Q_p is the flow loss for each section of unitary length dx (m) of the duct;
- c_{eff} equals to the discharge coefficient plotted inside standard;
- f stands for the loss factor of duct surface, expressed in mm^2/m^2;
- P represents the inside pressure (Pa) of each unitary portion of the duct;
- A_d is the duct's total surface (m^2) exposed to leaks.

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By varying the pressure along the duct, the unitary air leakage varies; in fact, reducing the pressure *(P)* in formula (6.5) induces Q_p to decrease. With a decrease in Q_p, also velocity and unitary pressure losses dp calculated in equation (6.4) decrease. Therefore, the formulation above can only be solved starting from the duct end up to the beginning of the network (fan outlet). This implies that along the tunnel length, the flow rate and air velocity inside duct will decrease continuously when reducing unitary pressure losses; as shown in Figure 6.50, the pressure gradient P decreases with a quadratic trend along the duct, starting from the outlet fan pressure to the design value p_0.

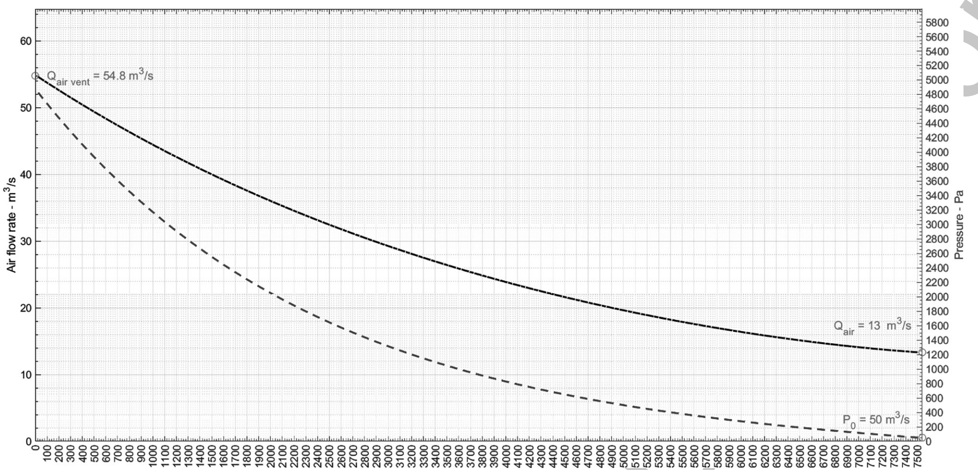

Figure 6.50 Pressure and velocity (flow rate values Q_0 vs Q_1) trends along tunnel ducts.

6.7.2.6 *Fan losses*

Due to the presence of silencers (normally installed on both fan nozzles), inlet grids, conic fittings between fan and duct, elbow and other resistances in the duct connection, the total fan pressure must be normally increased. Generally, pressure losses for "all other equipment" depend on the velocity of the fan outlet and must be carefully evaluated since globally, they can assume values of several hundreds of Pa.

6.7.2.7 *Calculation parameters*

As seen above, the main parameters that must be fixed during ventilation design and sizing are as follows:

- Hydraulic diameter or, in case of TBM use, boring diameter (m).
- Filing ratio (percentage of free space on the tunnel section). It can reach high values in case of TBM and invert work.
- Ventilation scenarios and their equipment used for excavation.
- Gradient and service temperature, if it has been considered that they can affect ventilation calculation.
- The number of people involved in underground works.

In order to correctly perform sizing and finalize ventilation design, we also have to know:

- Type and quality of ducts (design values of λ and f).
- Duct shape and its hydraulic diameter D.
- Fans' characteristics.

6.7.2.8 *Lambda and duct leakage factors*

Lambda (λ) is the coefficient of the specific resistance for the installed flexible duct in a system. It may vary from one site to another, since the quality of installations greatly influences the value. The value will also vary according to the duct diameter. The equivalent of λ is obtained by technical information, experience and type of application. SIA standards recommend three classes with respective λ for underground installation, as well as the specific leakage within ventilation systems (Table 6.6). The SIA standards also provide diagrams for the leakage area, which concern systems which are not airtight. Due to the leakage area along the ducts, as described above, the entry duct airflow will be greater than the outlet airflow at face. However, the air lost due to the leakage will be supplied as fresh air along the tunnel, increasing gases and noxious dilution and providing healthy environmental conditions for workers.

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6.7.3 Equipment and material characteristics

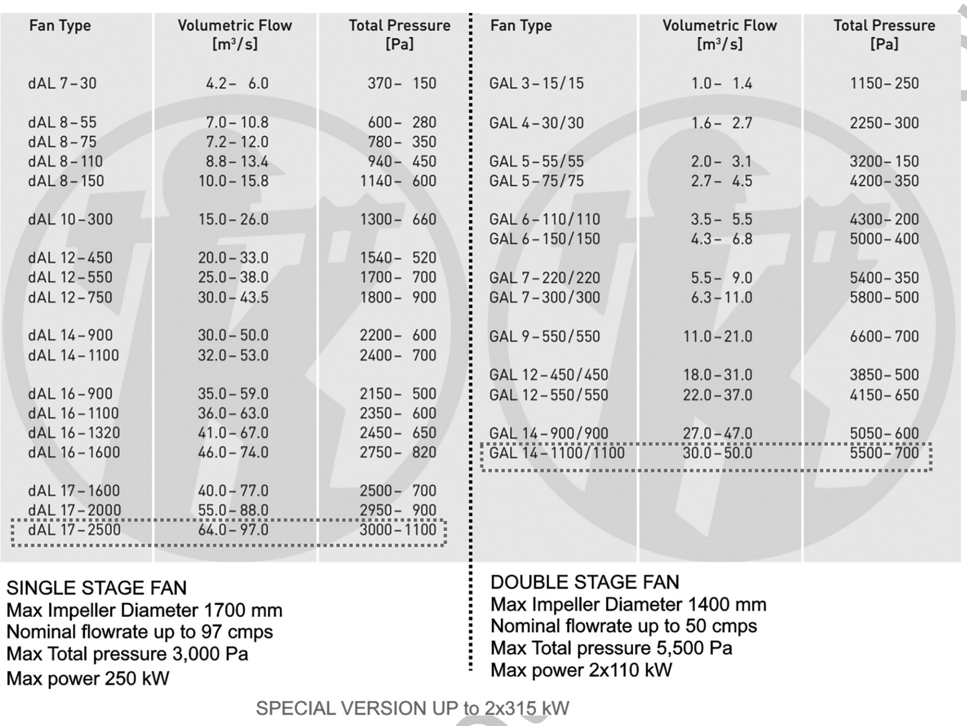
6.7.3.1 *Fan characteristics*

In general, in order to fulfil high flow rate and pressure requirements, axial fans with large diameter are used. Normally, single- or multi-stage axial fans with impeller diameters that range up to 1,800 mm are installed (Figure 6.51). Electric power can be various, and they can assume values from <100 kW up to 300–400 kW. Axial fan casings are normally made of S235JR sheet steel with motors placed on an S235JR frame, welded inside the casing. Such fans are equipped with 50 or 60 Hz motors, according to European standards, with external terminal boxes granting electric supply connection 400 V 3P. Fans may have a single stage or multiple stages, with impellers equipped with blades generally made of aluminium alloy, properly balanced [in Italy according to ISO 1940 (G 2.5)]. The fans are always equipped with up- and downstream silencers. A protection grid is attached on the fan's aspiration silencer. Each fan motor is normally equipped with an electrical starting cabinet with variable speed drive, used for motor speed variation. It includes electric boxes, each containing:

- One three-pole fused circuit breaker.
- Heating resistor and thermostat (according to the country of use).
- One variable speed drive for the control of each asynchronous motor.

Table 6.6 Duct classes provided by SIA 196

Class	*L*	*Leakage area (mm^2/m^2)*	*Application*
S (super)	0.015	5	New, with outstanding wiring and alignment installation. Ventilation ducts L > 100 m, and minor resistance in couplings and lining
A	0.018	10	New, with proper wiring and alignment and with minor losses in couplings and lining
B	0.024	20	Installation for longer duty periods, with frequent service and average losses in couplings and lining



Fan Type	Volumetric Flow [m³/s]	Total Pressure [Pa]
dAL 7–30	4.2– 6.0	370– 150
dAL 8–55	7.0–10.8	600– 280
dAL 8–75	7.2–12.0	780– 350
dAL 8–110	8.8–13.4	940– 450
dAL 8–150	10.0–15.8	1140– 600
dAL 10–300	15.0–26.0	1300– 660
dAL 12–450	20.0–33.0	1540– 520
dAL 12–550	25.0–38.0	1700– 700
dAL 12–750	30.0–43.5	1800– 900
dAL 14–900	30.0–50.0	2200– 600
dAL 14–1100	32.0–53.0	2400– 700
dAL 16–900	35.0–59.0	2150– 500
dAL 16–1100	36.0–63.0	2350– 600
dAL 16–1320	41.0–67.0	2450– 650
dAL 16–1600	46.0–74.0	2750– 820
dAL 17–1600	40.0–77.0	2500– 700
dAL 17–2000	55.0–88.0	2950– 900
dAL 17–2500	64.0–97.0	3000–1100

SINGLE STAGE FAN
Max Impeller Diameter 1700 mm
Nominal flowrate up to 97 cmps
Max Total pressure 3,000 Pa
Max power 250 kW

Fan Type	Volumetric Flow [m³/s]	Total Pressure [Pa]
GAL 3–15/15	1.0– 1.4	1150–250
GAL 4–30/30	1.6– 2.7	2250–300
GAL 5–55/55	2.0– 3.1	3200–150
GAL 5–75/75	2.7– 4.5	4200–350
GAL 6–110/110	3.5– 5.5	4300–200
GAL 6–150/150	4.3– 6.8	5000–400
GAL 7–220/220	5.5– 9.0	5400–350
GAL 7–300/300	6.3–11.0	5800–500
GAL 9–550/550	11.0–21.0	6600–700
GAL 12–450/450	18.0–31.0	3850–500
GAL 12–550/550	22.0–37.0	4150–650
GAL 14–900/900	27.0–47.0	5050–600
GAL 14–1100/1100	30.0–50.0	5500–700

DOUBLE STAGE FAN
Max Impeller Diameter 1400 mm
Nominal flowrate up to 50 cmps
Max Total pressure 5,500 Pa
Max power 2x110 kW

SPECIAL VERSION UP to 2x315 kW

Figure 6.51 Axial fans catalogue (extracted by Korfmann): single and double stages.

The cabinet includes a door-mounted control with:

- Remote display unit.
- One “RUN” button, one “STOP” button and one emergency stop button.
- One potentiometer or one +/− knob (or m/s) for manual speed control.

When ventilation systems are installed inside tunnels and must operate in the presence of gas (gas emissions cannot be excluded; there may be operational phases concerning gas search), in order to minimize risks, it is usually explicitly required to dispose of suitable equipment for underground and surface work in mines, always taking the risk of firedamp or explosive powders into consideration. In such cases, fans and their equipment must be classified (at least in Europe) as M1 category, when they must remain operative during gas emission, or M2 category, whenever it is possible to cut off the energy supply when gas concentration exceeds limits imposed by LEL values.

6.7.3.2 Tunnel ducts

6.7.3.2.1 PVC LOOSE DUCTS

Loose ducts represent the most common solution applied to underground ventilation for ease of assembly, availability on the market, weight and low cost. Because of its characteristics, the flexible PVC duct (Figure 6.52) may only be used in blower/pressure,

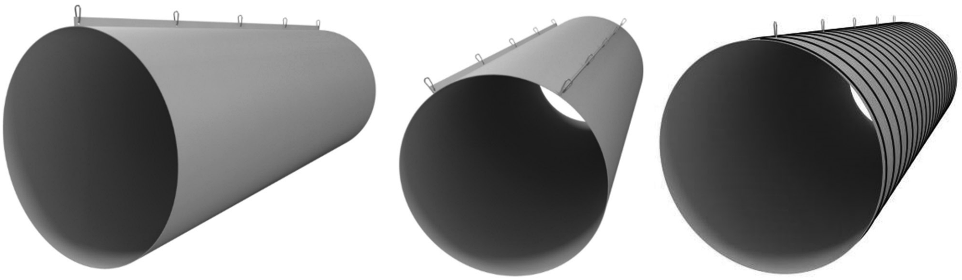


Figure 6.52 Loose PVC duct (single and dual suspension) and spiral duct.

and not in suction, and it is generally suitable for air velocities up to 20 m/s and maximum pressures of a few thousand pascals. Loose ducts are usually made up of a warp and weft fabric, PVC-coated with the following average characteristics:

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- tensile strength (N/100 mm) min. warp/weft 4,000/4,000 N (according to DIN EN ISO 1421:1998);
- tear strength min. warp/weft 600/600 N (in Europe according to EN 12310-2 N);
- min. weight 600/650 g/m^2 (up to 800–1,000 g/m^2 for heavy-duty service);
- suitable for operating temperatures between −10°C and 50°C (cold crack −30°C; heat resistance +70°C);
- anti-static and flame/fire resistance according to EN 13501-1 (class B-s1, d0, if required);
- ducts are normally produced and available on the market with nominal diameters from 300 mm to over 3,000 mm and unit lengths of 100 mm. They are normally marketed in lengths of 25, 50 and 100 m. Ducts can be equipped with single or dual suspension, pitch of 500–750 mm, and steel suspension hooks mounting over the steel cable;
- ducts can include either zip or Velcro joints; they are usually made with internal male-female coupling at the two ends, and an upper external protection band. Otherwise, it is possible to have connection with hermetic PVC joint and steel cores.

According to SIA standard requirements, PVC loose ducts should be implemented with a minimum safety factor equal to 10, in relation to the nominal operating pressure (with respect to burst pressure). Therefore, when increasing the duct diameter, the maximum pressure allowed decreases, due to max. tensile strength.

When negative pressures are foreseen due to the use of suction ducts, PVC spiral ducting installation is provided. PVC ducts are reinforced and supported by spiral helix steel wires, since it is suitable for use with both positive and negative pressures. The size of the helix determines the level of negative pressure the duct can withstand.

6.7.3.2.2 STEEL DUCTS

In sections of the air transportation network with geometric discontinuities, it is expected to encounter high air velocities and huge total pressures. In such cases, steel

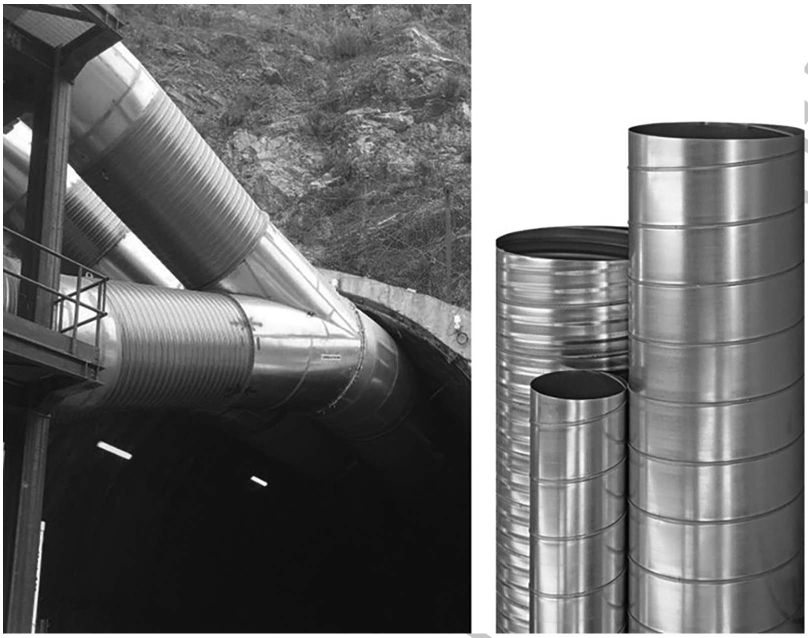

Figure 6.53 One application of rigid ducts and classical typologies.

ducts can be used instead of flexible ones. When tunnels are particularly long and/or large amounts of air is required, the total nominal pressure expected to the fan outlet is very important. In such cases, in order to perform the first part of the network, it can be useful to install steel ducts; then, when the expected pressure inside the ducts is reasonable (referred to as PVC safety limit), it is possible to connect loose ducts again.

Steel ducts are generally made through hot dip galvanized corrugated steel tubes with 3, 4.5 or 6 m lengths (Figure 6.53), suitable to work positive pressure up to 6,000–8,000 Pa and negative pressure up to 2,000 Pa, normally connected and jointed using flat bolted flanges (also frequently welded). In order to achieve self-supporting behaviour up to 20 m length (special executions), each tube element must be reinforced. Steel ducts can also be used for special elements such as elbows, curves, tees and axial reduction (fan connections).

6.7.3.3 Installation of ducts

Ducts are usually installed in the upper part of the tunnel, hanging from the tunnel vault (Figure 6.54). The sizing is generally determined considering the maximum possible diameter, so as not to hinder the course of the work as well as the regular circulation of vehicles within the tunnel. In order to optimize the ventilation efficiency and minimize pressure losses, the installation must provide the straightest line possible.

To ensure the correct distribution of the airflow produced by the final duct, it is important to maintain the correct distance between the source of air emission and

Figure 6.54 Ducts installation inside tunnel.

the excavation face. In this way, the best dilution efficiency in the working area is obtained. Generally, the opening angle of the air jet exiting the duct is equal to 10° (verified for air velocity exiting from duct within a 10–20 m/s range) and therefore the distance “L” from the duct terminal to the face is approximately equal to five times the tunnel’s hydraulic diameter.

6.7.4 Energy consumption

In order to correctly evaluate all energy requirements and consumptions, the following parameters must be taken into account:

- Average excavation speed rate per day (m/day).
- Tunnel excavation length (m).
- Number and characteristics of each ventilation scenario.

6.7.4.1 Sensitivity analysis: the importance of a correct duct sizing

The following analysis, carried out through an easy calculation, is aimed to verify the importance of duct sizing in terms of energy consumption and total costs control (Tables 6.7 and 6.8). This analysis is based on a hypothetical ventilation system applied to an 800 m long tunnel (750 m of which with duct) with a total production rate (100% of excavation) in 1 year. The maximum allowed pressure is 2,000 Pa, while the geometric and physical data are listed below. The maximum duct pressure and electric power of the fan change significantly while only changing the duct diameter of 100 mm. At the same time, the geometric variations affect the total annual consumption and direct energy costs with huge differences; up to 50% may be saved by only applying a 200 mm larger duct.

The importance of sizing becomes clear when considering excavation of tunnels which are several kilometres long and with much more important air requirements.

Table 6.7 Scenario data (example)

Duct length	750 m
Tunnel cross section	10.5 m²
Min. air velocity	0.5 m/s
Altitude	350 m a.s.l.
Average air temperature	15°C
Friction factor lambda	0.018
Leakage factor *f*	20 mm²/m²
Delivery pressure at duct end	50 Pa
Loss factor zeta	1.00
Fan efficiency	80%
Max. pressure allowed	2,000 Pa
Production days	365 days
Price of electric power per kWh	0.120 EUR
Required air quantity Q_o	15.0 m³/s

Table 6.8 Sensitivity analysis: different duct diameters

Duct diameter (mm)	*Air quantity Q_l (m³/s)*	*Max. duct pressure (Pa)*	*Fan power (kW)*	*Energy consumption (kWh)*	*Energy cost (EUR)*
1,100	17.0	2,350	50	223,800	26,900
1,200	16.7	1,550	30	145,600	17,500
1,300	16.5	1,050	20	98,300	11,800
1,400	16.4	700	10	68,500	8,200
1,500	16.2	500	10	49,100	5,900
1,600	16.1	350	10	35,900	4,300

6.7.5 Calculation of pollutants and Health, Safety & Environment (HSE) requirements

6.7.5.1 Pollutants

The guiding pollutants used to control the tunnel environment are essentially carbon monoxide (CO), nitrogen oxides (NO_x) and particulate matters (PM); normally, as long as the concentration levels of these pollutants remain within standard values, it is safe to consider that the minor pollutants produced by vehicle engine emissions (CO_2, SO_2, etc.) can be considered under control, too. The estimation of dust and gas emissions for vehicles and operating plants can be carried out for each working scenario considering the effective needs of machineries and equipment which are implemented within the worksite. Waste gas emissions released by heavy machines can be evaluated by means of reference values of basic emission factors given by US Environmental Protection Agency and estimated for the year 2022 (Table 6.9).

Pollutant emissions may also be verified by looking at the amounts reported in the following table, and referred to emission-based factors, listed for diesel engines according to EURO/CEE regulations. In general, given the state of the art of the vehicles in use on-site, Euro V emission unitary coefficients are assumed as main reference (Table 6.10).

Table 6.9 Emission base coefficients given by US Environmental Protection Agency

Equipment	*Emission factor (kg/h)*		
	CO	*NO$_x$*	*PM10*
Drilling machine	0.16	0.05	0.01
Excavator	0.30	0.13	0.01
Wheeled loaders	0.28	0.17	0.01
Cement mixer	0.34	0.21	0.01
Grader	0.33	0.20	0.01
Roller compactor	0.28	0.20	0.01
Concrete plant	0.03	0.06	0.01
Crushing plant	0.43	0.25	0.01
Crane	0.17	0.26	0.01
Conveyor belt	0.17	0.23	0.01

Table 6.10 Emission base coefficients from Euro/CEE engine vehicles

Stage	*Date*	*CO*	*NO$_x$*	*PM*
		(g/kWh)		
Euro IV	2005.10	4.0	3.5	0.03
Euro V	2008.10	4.0	2.0	0.03
Euro VI	2013.01	4.0	0.46	0.01

6.7.5.2 *Exposure limits*

Pollutant levels in the underground environment should be reduced to the lowest level reasonably applicable and must never be below the workplace exposure limit (WEL).

These limits are usually based on an average exposure time, measured over an 8 hour period with an additional short term, and may never be exceeded.

WELs are fixed, among the others, also by BS 6164 standards, as per Table 6.11 below.

Combining airflow values measured at excavation face and total pollutants production rate evaluated as described in the previous paragraph, maximum pollutants concentration can be analytically calculated. Then, the obtained results must be compared with emission threshold fixed by law, regulation or guidelines in order to check the maintenance of tenability criteria inside tunnel.

Analysing pollutants trend and peak concentrations, background level must be considered (outside environmental air quality).

Table 6.11 Emission threshold inside tunnel

Contaminant		*8-Hour exposure*
Gases	Nitrogen monoxide (NO)	5 ppm
	Carbon monoxide (CO)	30 ppm
Dust	$PM_{2.5}$-PM_{10}	0.192 mg/m^3

6.7.5.3 Temperature and oxygen level

The temperature inside tunnels, or in general in underground works, can be regulated by local regulations; one useful reference is given by BS 6164 standards: it is recommended that wet bulb air temperature should exceed 27°C, and, in case of temperature rising above 32°C, extra control measures must be implemented. Ventilation and fresh air to the excavation front must maintain oxygen levels above 20%. All the conditions above must be preserved by constantly controlling ventilation parameters. Environmental external controls should be installed in order to check the external conditions.

6.7.5.4 Ventilation monitoring

Air velocity and airflow throughout ducts can be controlled and monitored using control systems. Such measures have the aim to check and verify the actual effort produced by ventilation systems and give feedback regulations to remote controls; in particular, the control system must:

- measure ventilation values (air velocity, flow rate, static pressure, temperature, oxygen concentration, pollution, etc.);
- make comparisons between measured values and set point references;
- drive fan motors to adjust ventilation and follow set point references.

Airflow monitoring allows to check the correspondence between required air demand and effective air supply. Measuring devices must be installed in the first (a few tens of metres away from the fan) and in the last sector of each duct, in order to verify the correspondence of measured values with target ones, and to guarantee the regulation/drive of the fans. The static pressure of the fan provides an indication of the fan's current operation and duct status (damage or restriction).

The control system is connected to a supervisor workstation with a supervisory control and data acquisition (SCADA) system and its graphical user interface (GUI), generally installed inside a control room. A telemetric monitoring (SCADA system) providing real-time information as well as air quality measures is generally monitored through the same system. Such monitoring system also allows automatic and continuous data recording. The recording of the flow rate values represents a qualifying element of a correct management of ventilation (Figure 6.55).

On the other hand, greater difficulties and uncertainties exist when evaluating reflux parameters; generally, these issues are not related to the measurement, but to the representativeness of the measured values in relation to the environment in which such measurements are made.

In fact, tunnel sections progressively change according to the excavation techniques (for example, a different degree of advancement of the final coating), in the presence of numerous movable or fixed obstacles (such as waterproofing carriage, formwork of the final casting and walls) and furniture (parked or circulating vehicles).

This variety of conditions translates into an alternation of the distributed and local value of concentrated resistances, with the consequent formation of turbulence both in the motion of air and in areas of stagnancy.

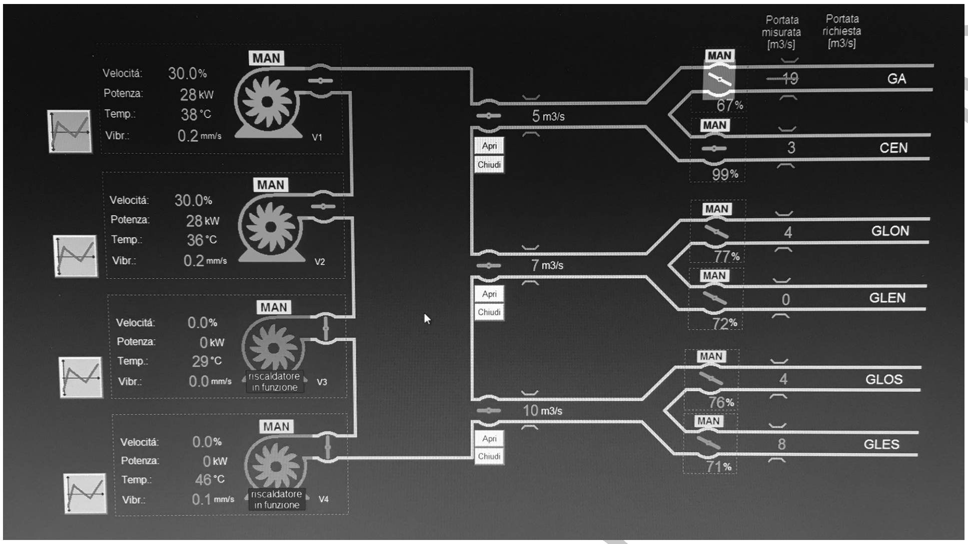

Figure 6.55 Ventilation control via SCADA.

6.7.5.5 Gas monitoring

In tunnels suspected of being at risk of CH_4 or other toxic gases spreading, the flow rate recording system allows both the management of ventilation and the concentration of ambient gas to be correlated with the airflow in case of firedamp. In fact, in such tunnels, a continuous gas monitoring system with data recording is installed in order to follow the evolution of gas emissions.

Furthermore, by recording the flow rate, it is possible to correlate the emission with the dilution action of the ventilation system and therefore determine the actual amount of emitted firedamp.

6.7.6 Complex cases

6.7.6.1 Brenner Base Tunnel experience

When a very high-performance ventilation scheme is required, centrifugal fans can be used instead of axial fans. This is the case of the Brenner Basis Tunnel construction site Mules 2–3, where the ventilation system is required to cope with the renewal of the underground breathing air through a total flow of 420 m^3/s, at a pressure of 6,000 Pa, with a total installed power of ~3.2 MW (Figure 6.56). For the Mules 2–3 construction lot, the ventilation system is required to guarantee fresh air as well as the dilution of the pollutants produced by almost 10,000 kW of power (excavation vehicles and equipment) and in order to guarantee the breathiness of the air for the workers involved (~200 units).

Figure 6.56 Ventilation ducts in the Mules adit.

In such extreme cases, due to very huge pressure values, axial single- or multi-stage fans may not be enough or may not be competitive in terms of efficiency and energy consumption. Of course, centrifugal fans require lots of space, at the tunnel entrance, for equipment installation. In fact, the ventilation station in Mules 2–3 was installed in a dedicated cavern realized along the adit tunnel, where four centrifugal fans were installed. These fans would collect fresh air provided by a ventilation shaft up into the outlet chamber (Figure 6.57). Later, three flexible ventilation ducts blow air along the adit tunnel towards the excavation faces.

The ventilation system is therefore provided with four high-performance centrifugal fans with a ten-blade aerodynamic impeller able to guarantee the nominal performances required by the project overall.

Figure 6.57 Centrifugal fans during installation.

The use of centrifugal fans allows the following to maximize the operating efficiency (also reducing total installed power), always exceeding 84% of performance, minimizing energy consumptions and total direct operating costs.

6.7.6.2 *Very long adits – use of plenum*

This is the case of large infrastructure projects with underground works that must be divided into multiple sections or tasks due to the relevant length of their lines. Each task of such a structured work provides simultaneous management of several excavation faces accessible from service tunnels, which will also play an important role in terms of safety access during the operational period of the infrastructure.

One of the major railway works of this kind, currently under construction, is the high-capacity (and speed) Italian railways Milan-Genoa, which develops along the Genoa-Milan route for a total length of 53 km (36 km of which is underground). One of these service adits is about 2.5 km long from the entrance down to the chamber crossing the base tunnels. The ventilation requirements are relevant, as the correct amount of air needed for simultaneous works in four excavation fronts must be guaranteed. To achieve this goal, an air supply system consisting of two external ventilation units (both double-stage 2 × 315 kW) was first tested and then adopted with the goal of pushing the necessary airflow to the balancing unit located in the chamber (plenum), as shown in Figure 6.58.

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This plenum sorts and feeds four fans, relaunching the air through further flexible ducts for each excavation face.

The ventilation system guarantees the required performances, while ensuring full modularity of airflow rates along the nodes (different work faces) and energetic control.

The whole system is automatically regulated by a control and supervision system, thereby maximizing efficiency and optimizing energy consumption.

6.7.6.3 *Specific areas of risk*

Particular excavation scenarios, which require the treatment of particular specific risk areas, characterized by noxious pollutants (e.g. asbestos), may require the adoption of suction systems directly installed in the processing areas. In these cases, the excavation face area is confined and isolated from the rest of the tunnel.

The airflow inside the affected area is sucked in and sent, for example, to other treatment systems, such as the de-duster system (Figure 6.59), filters and blast chillers.

After being cleaned, the air is reemitted into the tunnel and pushed outwards. In general, the system is set up with the use of rigid or semi-rigid suction ducts that introduce fresh air into the closing working area; in this way, the isolation of the compartment is maintained, and contamination of the adjacent areas of the tunnel is prevented.

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This chapter has been written on the basis of the experiences of authors. Further information at the present available in the scientific literature has also been integrated in the work. All documents that have been considered are listed in the references.

Figure 6.58 Ventilation plenum installed in logistic chamber (adit end).

Figure 6.59 Mixed ventilation system with de-duster equipment and its suction spiral duct.

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The chapter was developed as follows: M. Bringiotti was involved in chapter design, coordination and integration; P. Romualdi: Sections 1.1, 1.2 and 1.3 with S. Lorenzetto: Section 4.2; P. Rufer: Section 1.4; D. Nicastro: Sections 2 and 3; ER E. Vitale: Section 4.1; P. Ferrante and E. Bertino: Sections 4.3–4.7; K. Pini, P. Cataldi and G. Faini: Section 5; and N. Faggioni: Section 6. C. Todaro contributed to reviewing and editing.

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