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French national report on tunnelling in soft ground

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SYNOPSIS: The following general report on french practice about tunnelling in soft ground describes the recent and present french experience about these kinds of works. It mainly focuses about the various construction methods used in french projects (conventional techniques with or without soil treatment, semi-mechanized methods and shields), the types of lining, the evaluation of pressures due to ground and water, and the evaluation and monitoring of ground movements. The existing codes of practice and manuals are also described.

1. PRESENTATION OF THE PAPER

The aim of this general report is to present the french practice about tunnelling in soft ground. It is based on the recent experience (about 10 years) of these kinds of projects in France or for abroad projects in which french contractors are involved.

It will describes the main techniques used in recent projects (for roads, railways, undergrounds and sewers), which include conventional techniques, sometimes associated with ground treatment (grouting, dewatering), semi-mechanized techniques, and shields.

Afterwards some specific topics will be discussed: kinds of primary lining used, evaluation of the soil and water pressure for the lining design, ground movements associated with tunneling: evaluation and monitoring.

Finally a quick review of the main french codes of practice and manuals will be given.

2. CONSTUCTION METHODS

In the past ten years, many underground projects have been done in soft ground, due to the environmental conditions in towns, preventing in many cases the "cut and cover" method for the construction of underground projects:

-this is the case of course for metro projects (in Paris: EOLE and METEOR, in Lyon, Lille, Toulouse, Strasbourg, Bordeaux,...), but also for urban highways (in Paris and in Lyon);

-furthermore the new high speed railways (T.G.V.) included various tunnels, both for the South-West line (Villejust, Sceaux, Fontenay and Vouvray tunnels), and for the Lyon-Valence prolongation of the South-East line (Dombes, Costières, Meyssiez and La Galaure tunnels);

-the channel project (Transmanche Link) is of course also a "magnificent" project of tunneling in "soft rock" which provided very interesting data about tunneling for very long projects;

-finally underground methods are more and more oftenly used for sewers construction (2 to 4 m in diameter) in towns.

2.1. Conventional methods

Conventional methods, with generally machine excavation and support either by steel ribs or by bolts, associated often with shotcrete (NATM method), are yet widely used in France. Their range of application as regards the size of the tunnel covers generally relatively small length (some hundredth of meters), but of very variable sections (from sewers size up to about 150 m^2 for the two-tracks TGV tunnels).

Of course, in the case of large size tunnels in soft grounds, the excavation is not done in one single step, but generally in several stages, in order to reduce the face stability problems.

2.2. Ground treatments

When the ground is too poor with respect to the dimensions of the tunnels to allow the use of conventional methods alone, and if the project conditions do not permit the use of shields, different techniques of ground treatment have to be used.

This is the case of several projects, which are presently done in very poor conditions in Paris for new metro lines: large sections up to 20 m wide for connection of several lines, to be excavated at shallow depth (less than one diameter) in sandy gravels without any cohesion, below the water table, and in a very sensitive environment.

Dewatering is used in some cases, but very scarcely from the ground level. The most common use of dewatering is with subhorizontal drains driven for the tunnel face, or from a pilot-gallery. In some cases of very large tunnels, the dewatering of the lower excavation section is done from pilot-gallery or upper half-section, by using well-points or by pumping in bore-holes (cf fig. 1).

Grouting is of course also widely used in many tunnels excavated by using traditionnal methods in soft ground, either for consolidation or for water-proofing. The following general trends in soil grouting may be pointed out:

-the more and more frequent use of "new grouts"

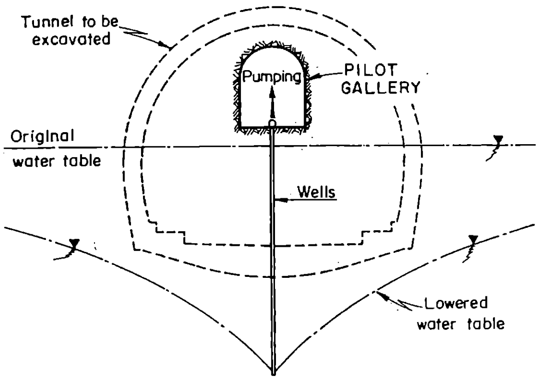

Fig 1. *DEWATERING OF LOWER HALF-SECTION*
(T.G.V La Galaure tunnel)

such as "over-grinded" cements, which allow the grout penetration in finer soils than the classical grouts, or "hydrated calcium silicates", with the same properties than the classical silicia gels, but without their usual drawbacks;

-the jet-grouting in tunnels is much less used: it was done sometimes in underground projects, for instance in order to improve a karstic clay zone, or as pre-treatement of the lower half-section, for the MEYSSIEZ tunnel (Lyon-Valence TGV) in "molasses": poorly cemented sandstones and sandy marls (see fig. 2).

Ground freezing is of course a technique sometimes used for very difficult situations, when grouting is not applicable. Nevertheless, due to its cost, problems related to bore-holes deviations, and soil heaves, this technique is often considered as an "ultimate solution".

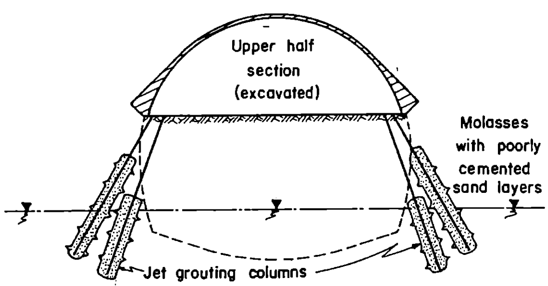

Fig 2. *SOIL TREATMENT WITH JET-GROUTING*
(T.G.V Meyssiez tunnel)

2.3. Semi-mechanized methods

Among the semi-mechanized methods, a particular attention must be paid to the "pre-vault method", which was developped in the late 1970's, and which had much applications in the recent years. It allows the realization of a pre-support of the soil (see fig. 3), by:

-sawing a small slit along the outer line of the section to be excavated, 15 to 25 cm thick, and 3 to 4 m long,

-shotcreting of the slit,

-excavating under the protection of this vault.

This method, initially applied mainly for the upper half-section of tunnels, was progressively used in full-section, even for very large tunnels, as for the construction of LA GALAURE tunnel (about 150 m^2 excavation section), on the Lyon-Valence TGV, associated with fiber-glass nailing for stability of the 11 m vertical face.

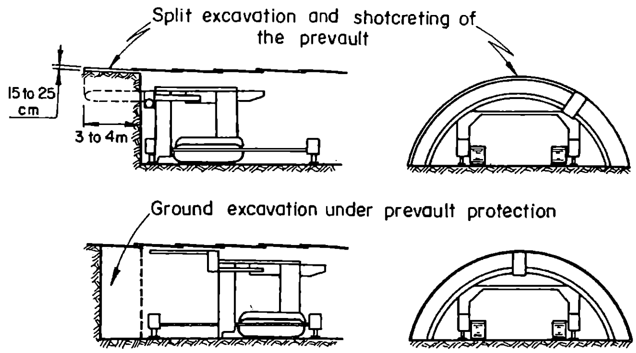

Fig 3. *PREVAULT TECHNIQUE*

2.4. Shields methods

Since the first application in France of a slurry shield, which began for the LYON metro in 1984, pressurized shields have been more and more widely use, and now many kilometers of tunnels in soft ground are done each year. About 40 tunnels have be done or at least begun from 1984 to 1992, in France or abroad by french contractors (Caracas, Singapour, Storebelt, Shangai, and soon Athens and Le Caire).

As this report is dedicated to soft ground, we mention only pressurized shields. The different kinds of pressurized shields have appeared progressively in the french projects:

-in the first years, most of the projects, whatever their size, were done with slurry shields; nowadays, such shields have done tunnels in almost all the different kinds of soft ground (sands, gravels, silts, clays, marls, chalk, even random demolition fills); presently the largest slurry shield was for the TGV Villejust tunnel, with 9.25 m diameter.

-while slurry shields continued to be used, appeared shields with use of compressed air (sizes from 3 to 6 m in diameter, up to 7,64 m for the ORLYVAL project). They were first limited to soils with low permeability (pervious soils causing large flows and air surge at the ground level). These shields, with only a small chamber at the face under compressed air (which limits the drawbacks of men working in hyperbar conditions), were developped, mainly by projection on the face of impervious products (bentonite, foams, ...). Indeed, as it is the only pressurized shield which allows to see what happens at the face and to intervene easily, this method found many application for small size tunnels in very difficult ground, mainly with large blocks which can be taken out with less difficulties than in others shields;

-the first earth pressure balance shields (EPBS) appeared in France only in 1987, and most of the projects done with this EPBS were performed in rather firm ground (such as chalk for the Channel tunnels or Lille metro, but also molasses for Toulouse metro, or marls and stiff clays). Indeed they worked mostly with open face, which of course allows better advance rates, but the face could be shut when facing unstable soils; as it is always very difficult to know exactly when such poor conditions will be found, these EPBS had to face some troubles. Only very recently true EPBS began to be used, but the french experience remains somewhat limited. However it must be said that the largest shield ever working in France will be an EPBS, 11 m in outer diameter, which will soon begin a tunnel for the Lyon North ring, through hard gneiss and alluvial sands and gravels.

3. TUNNEL PRIMARY LINING

In tunnels done with conventional methods, i.e. in grounds which offer a free standing span of 1 or 2 m for several hours, the primary lining is generally made of:

-either steel sections, with recent use in some projects of reticulated sections, generally associated with shotcrete, but sometimes also with timber or steel plates;

-or shotcrete associated with bolts (steel or fiberglass) according to the NATM method, which was sometimes used successfully in plastic marls; it may be noted that in many cases for large tunnels steel ribs are added to shotcrete in order to reinforce it.

It is difficult to distinguish different kinds of ground in which one or the other method is more often used. The choice is more dependant upon the size of the tunel and the environmental conditions, but also upon the past experience of the engineer or of the contractor.

For shallow tunnels under urbanized zones, where the ground settlements are often the governing factor, the choice will be generally done between NATM method, when it is possible to close quickly the shotcrete ring (which proved to be very efficient to reduce the settlements, when it is possible to excavate in full-section), or steel ribs, possibly with jacking, and shotcrete in divided sections.

With shields, almost all the tunnels were lined with reinforced concrete segments. They are more frequently bolted, and grouted afterwards (immediatly behind the shield in sensitive environment, or later); water tightness proved to be satisfactory, even under water table, by using self-swelling joints. Expanded segments were also used in order to reduce the settlements, although it may present some problems for water tightness.

The only few exceptions to concrete segments for lining of shield-built tunnels are:

-extruded concrete reinforced with steel fibers for the first one in Lyon metro; due to some difficulties related to stops of the shield, this method was no longer used;

-cast-iron bolted segment in about four tunnels, mainly for underground sewers;

-an original (for shields) primary lining of steel ribs with timber in seven small diameter tunnels, 3 to 4 m.

4. EARTH AND WATER PRESSURES ON TUNNEL LINING

Three usual kinds of earth pressure calculation methods on tunnel lining are widely used:

-the "hyperstatic reactions" methods: the loads on the lining are estimated according to the usual formula (Terzaghi, ...); the lining is modelized as bars with bending stiffness, and the ground reaction as springs with stiffness related to the ground moduli. This method is considered as efficient in order to consider varied geometries, but very limited as regards the estimation of the ground loads, and for no consideration the construction sequences.

-the "convergence-confinement" analytical method, which proved to be very efficient to investigate the interaction between the ground and the lining, and to give a basis for the interpretation of the field measurements. But its tremendous assumptions (circular tunnels, homogeneity, isotropy, no gradient of gravity) prevent its use for final design of most of the large and shallow tunnels.

-the "Finite Element Methods" (FEM), integrating the basic principles of the convergence-confinement general method, is much more interesting, as it theoretically allows the analyse of almost any soil condition (geometry of the layers, soil behaviour), any kind of structure, but above all any sequence of constuction. Moreover only the FEM allows the assesment of the state of stresses and deformations in all the modelized mass, which is of main importance for the projects which may have an influence over existing structures.

Of course the FEM has also some limitations: selection of accurate soil behaviour and parameters, time and cost consuming which limits in most cases the application to 2D models (but the face effect is taken into consideration by an apparent confining pressure varying with the face distance). But its advantages and the development of computers led to an extensive use of the FEM for most of the projects since the 1980's.

The required soil parameters are:

-the strength parameters: in most cases a Mohr-Coulomb failure criteria is considered (with cohesion c and friction angle ϕ, generally measured through laboratory shearing tests), both in short term and long term conditions;

-the elastic parameters: further to laboratory tests, the in-situ pressuremeter or dilatometer test is very widely used in France to evaluate the soils moduli. Such a modulus corresponds to "short term conditions", while long term behaviour is required for the calculation of the tunnel in service; the ratio between the short and the long term moduli (often related as a "creeping coefficient") is determined by extrapolation of deformation tests;

-another important parameter is the deconfinement ratio λ at each calculation step: rules exist for the regular cases, but much research is under progress in order to have a more realistic evaluation of λ, which has a basic influence on the ground deformations and lining behaviour.

The water pressure effect is very often considered in a simplified way: for the "hyperstatic reactions methods", the active ground load is calculated as an effective stress, and the hydrostatic water pressure is added (when the lining can be considered as impervious with respect to the soil). In the FEM, and for the rather simple cases, the following assuptions are considered:

-during the calculation steps which modelize the different excavation sequences, the soil

behaviour is considered in total stresses, corresponding to short term behaviour of soils, and including the water pressure;
-for the final calculation long term step, the water pressure is added as a load on the lining.
Of course, in very particular cases, when the water pressure cannot be assimilated to the hydrostatic pressure, more sophisticated computer program do exist, with coupled hydro-mechanical soil behaviour; but their use to actual projects is not very common in France.

5. GROUND MOVEMENTS ASSESMENT

The numerous projects to be built in urbanized areas, at shallow depth and in poor soils, have urged the tunnelling engineers to pay a great attention to the ground movements problem.
The empirical methods, such as Peck's for instance, are obviously yet used at preliminary stages of the studies, in order to investigate if the anticipated ground movements magnitude may cause troubles to the environment. By performing a exhausitive synthesis of the data obtained on shield-excavated tunnels during, new empirical methods for shields and for the regional ground, are presently under preparation.
But for the numerous conventional methods projects (often with divided sections), or with semi-mechanized methods, or even for the shield projects but in particular geotechnical or environmental conditions, the widely used FEM give a better evaluation of the ground deformations.

6. MONITORING OF PERFORMANCES

The performances of tunnels are monitored, mainly when they are of uncommon dimensions (such as the two-tracks TGV tunnels), or when they are done in sensitive zones (below existing buildings, or very close to existing tunnels).
The first data monitored for almost all the tunnels are the ground and tunnel deformations, because they are easier to measure than others parameters (by mean of topographic methods, convergence lines inside the tunnel, and extensometers). They offer an efficient way for the engineers to analyse daily the behaviour of the works, and to modify some of the methods in case of difficulties (excavation sequence, primary lining, drainage, ground treatement).
Furthermore, in order to check that the structural elements of a tunnel have been safely designed, monitoring of the efforts acting on the lining and existing in the structures are also monitored at least for the larger tunnels. Figure 4 shows a typical monitoring program for a section of railways tunnel, with:
-total stress cells behind the lining; due to the stress state disturbancies, their results are often difficult to interpretate, and their use is becoming less frequent;
-devices for measurement of the actual structures behaviour, i.e. micro-deformations measurements, by strain-gages or vibrating cords placed on the ribs or inside the concrete.

7. CODES OF PRACTICE

If there are very few official reglementations regarding the tunnel construction, we must point

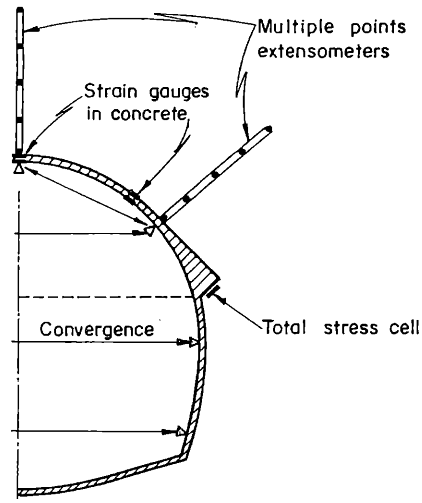

Fig 4 . *TYPICAL MONITORED SECTION*

out the very important work done in France by the AFTES (French association for underground works, affiliated to the ITA), which published since 1982 about 20 recommandations covering every aspect of the design and construction:
-sizes and geometrical definitions;
-classifications of soils and rocks;
-selection of construction methods as regards the ground and environmental conditions;
-calculation and design methods;
-construction procedures for ribs, shotcrete, bolts, ground treatement (grouting);
-safety considerations;
These documentations are prepared a wide panel of tunnelling professionals, and are considered as the actual code of practive for tunnelling.

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