ACTION TO REDUCE THE HYDROGEOLOGICAL IMPACT PRODUCED BY UNDERGROUND WORKS

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SUMMARY: Environmental problems connected with the interference of tunnels with underground water tables are taken very seriously. An approach is proposed that allows water drained from tunnels be used as a resource that can be redistributed at the surface, on the basis of real environmental requirements, much more rationally than nature or man in the past could have done.

1 THE NATURE OF THE PROBLEM

For some years now the problem of interaction between major civil works and the environment has been subject to particular attention and study, much more than in the past. This is due to both a much greater general awareness of the problem and to the need to build underground structures in intensely anthropogenic areas.
When a tunnel runs into underground water it is important to assess, both at the design and the construction stage, whether it is possible to proceed in hydrodynamic conditions (drainage), in hydrostatic conditions (complete waterproofing) or whether it is preferable to resort to a combination of the two with controlled drainage. An outline of the principles on which to approach the problem is given in this paper. It is based on experience acquired on the subject of interference between tunnels and underground water tables and aims at providing an understanding of the context of this difficult problem and thereby make it possible to solve it.

2 THE INFLUENCE OF DRAINAGE ON THE ENVIRONMENT

The choice of method and the criteria adopted must be made after assessing the radius of influence produced by drainage on the surface as a result of the change in piezometric levels.

Correct long and short term assessment of the zone affected by the underground drainage that occurs as a result of the formation of a cavity is a useful guide for assessing consequences on the surface (subsidence, surface hydrology, etc.) and for performing a cost benefit analysis of the action to be taken.
Study of the radius of influence of tunnel drainage is performed differently depending on whether the ground is classified as a porous medium or, more generally, as one of various fractured mediums.

2.1 Porous mediums

In this first case, the choice of drainage or water proofing is often also tied to problems concerning the stability of the cavity and therefore surface subsidence too.
There are many closed formulas that assume a continuous, homogeneous and isotropic medium for assessing changes to underground water systems induced by drainage. They are valuable simplifications which must be carefully assessed in practice. One of the most accredited theories is that of Federico (1984), in which the tunnel is assumed to be rectilinear with a horizontal axis and the water table, initially at rest, at an initial distance b_0 and depth H, both measured from the centre of the tunnel (Fig. 1). The ground is assumed to be a homogeneous, isotropic and undeformable medium with permeability K, porosity n and capillary height zero. It is also assumed that the intensity of infiltration due to precipitations, is constant over time and that drainage starts in a given cross section at the moment when the face reaches that section.
With these assumptions, the flow rate per metre of tunnel and the radius of influence of the tunnel are a function of the following variables (Fig. 1):

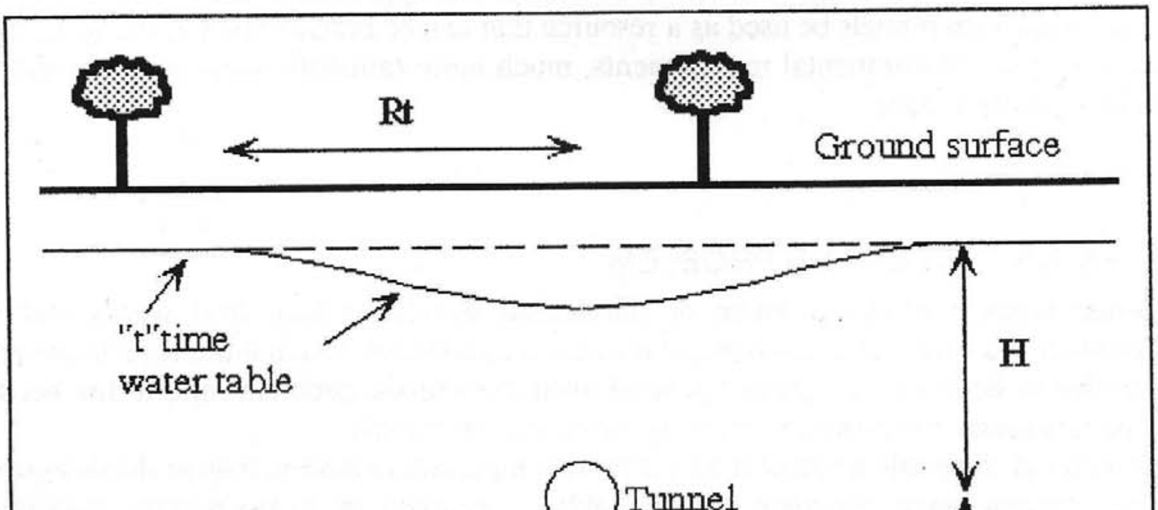

Figure 1. Radius of influence in porous mediums

$Q_t = f(\varepsilon\ ; K^2\ ; H\ ; b_0; n; t;)$,
$R_t = f(\varepsilon\ ; K^2\ ; H\ ; b_0; n; t;)$,
For a given section of tunnel, the ranges of possible variation of the variables K^2, H, b_0 and n are set on the basis of the characteristics of the ground through which the tunnel passes.

1. A time t is set and the values for K^2, H, b_0 are varied randomly to furnish a series of values for q_t.
2. The corresponding value for R_t is calculated for each series of values for ε, K^2, H, b_0 and n that generates a value for q_l within the range $q_{t\,Max} > q_t > q_{t\,Min}$. The series of values for ε, K^2, H, b_0 and n that generate q_l values outside the range $q_{t\,Max} > q_t > q_{t\,Min}$ are discarded.
3. An analysis of the distribution of values for R_t obtained from the calculation will give values for R_{tAv}, R_{tMax}, R_{tMin}. The area of land within a distance of $< R_{tMin}$ from the tunnel is considered a "high danger impact zone" while, the area between R_{tMin} and R_{tMed} from the tunnel is considered a "medium danger impact zone" and the area at a distance greater than R_{tMax} is considered a "low danger impact zone".

2.2 *Fractured mediums*

Often structurally complex formations are found in nature in which the more permeable strata and the open fracture apertures constitute ducts through which water from the surface percolates and flows. In these cases an isotropic and continuous model would be inappropriate. Probability criteria linked to the structural geology will give an assessment of the risk of water entering a tunnel and consequently of the most probably size of the radius of influence of the tunnel in the long and short term. The methodology employed defines the risk of impact for each single point of surface water as the product of impact danger and the vulnerability of water points at the surface (e.g. springs).
The dangerousness of impact consists of the probability that a surface facility is hydraulically connected to a water collection point in the tunnel through the network of fractures in the ground. It summarises the variable characteristics in the fracture spacing which is surveyed by means of measurements at the surface and below ground, statistical processing of the data and classification of zones in the ground according to fracture index validated against previous experience.
Vulnerability is given by a mechanism that relates the water point mechanism at the surface to water flow as a function of the sensitivity of the water point mechanism to a potential lowering of piezometric levels and the position of the facility relative to the tunnel according to the paths indicated by the physical model of local circulation that has been constructed.
It is worth considering that the difficulty involved in predicting the structure of the fracture system at depth makes predictions of the type, size and development over time of possible interference between underground excavation and water levels also very uncertain and difficult. In fact the high degree of structural anisotropy in nature makes it possible to identify piezometric levels in individual portions of the ground considered homogeneous with a certain accuracy and therefore to ascertain only probabilities of the extent and depth of connections with surface water tables that supply springs and water courses.
Accurate and reliable construction of physical models for each uniform portion of the ground, that can be used to assess water regimes when tunnel construction is complete can only be achieved by studies of the geological structure, the hydrogeology and the chemical composition of the materials involved based on a comparison of surface and underground observations after tunnel excavation.

3 METHODOLOGICAL PROPOSAL

In order to design the tunnel in such a way as to restore original conditions as much as possible, a model must be constructed that matches the reality as accurately as possible for each hydrogeologically uniform portion of ground within the radius of influence of the tunnel. During the transitional phase, while the tunnel is being constructed, it is indispensable to guarantee the availability of alternative water resources to compensate for the drainage effects of excavation. Careful monitoring will make it possible to decide which sources of alternative supply can be abandoned and which must be maintained.

3.1 *Action in the tunnel*

Once appropriate models have been used to understand the type, size and development over time of the effect that the drainage produced by the tunnel has on the surrounding environment, the tunnel design engineers will be able to decide which of the following options to follow:

- Hydrostatic conditions. These occur when the tunnel is perfectly impermeable. Experience in underground construction tells us that it is difficult to guarantee water proofing with a pressure of more than 5 to 6 bar on the extrados with current water proofing techniques. Higher pressures require techniques that do not fall within the sphere of normal construction practices and would therefore be particularly costly. Water proofing is performed by PVC and similar sheeting which is appropriately jointed to create a water proof tube to protect tunnel linings (Fig. 2).

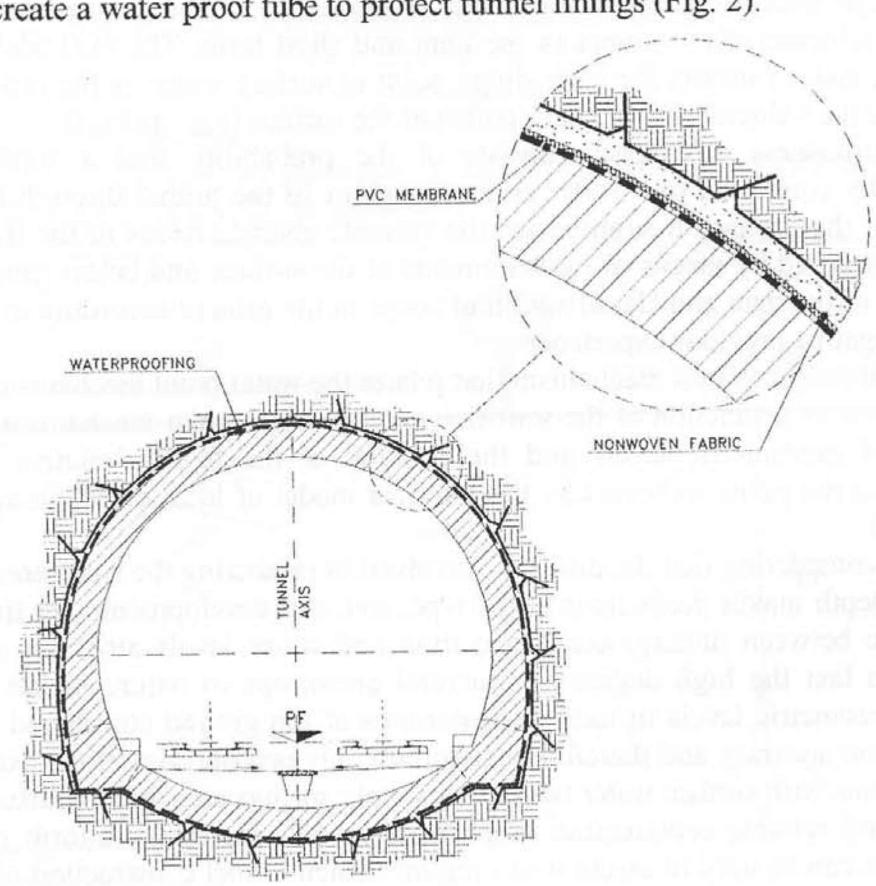

Figure 2. Hydrostatic conditions: water proofing section

The lining must be of a size and strength to withstand not only the lithostatic load but also the natural hydrostatic pressure. If hydrostatic conditions are also required during construction (e.g. in loose soils in urban areas), this can be achieved by treating the ground, in advance, ahead of the tunnel at the face and around tunnel. These operations are nevertheless very costly and need to be justified. In a few very special cases such as undersea tunnels or tunnels under large water courses where the pressure of the head of water is very high, action is taken to reduce the drainage effect by injecting water proofing substances into the rock around the cavity. In this case injection costs are compensated for by the lower costs of pumping water that filters in through the walls of the tunnel. In these cases hydrostatic pressure is considered as being applied to the extrados of the arch of improved ground while lithostatic pressure only is considered as a acting on the extrados of the tunnel lining since a drainage system around this is nevertheless always provided (Fig. 3).

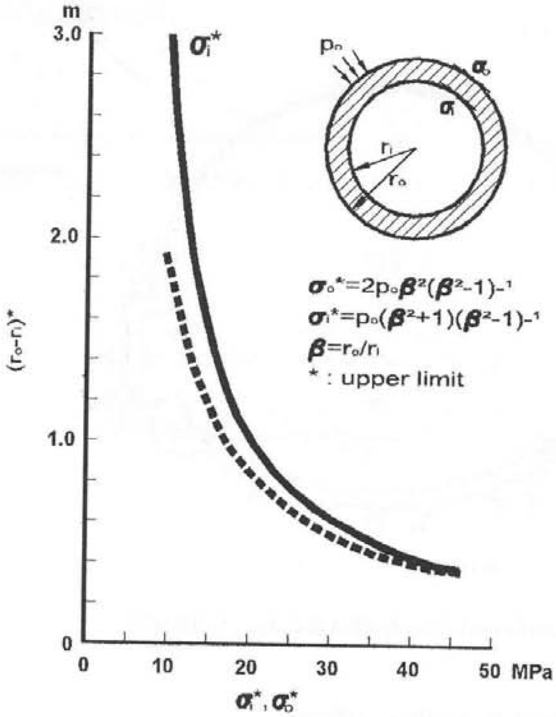

Figure 3. Relation between allowable compressive strength and necessary thickress of concrete lining

- Hydrodynamic conditions. If the natural head of water pressure is too high, then water pressure around the cavity must be reduced by allowing drainage. Although this system has been widely used in the past, today "controlled drainage" techniques are employed to prevent excessive drainage and at the same time to ensure that water pressure around the tunnel is kept within admissible limits for tunnel linings (Fig. 4). In these cases the main function of tunnel waterproofing systems is to protect linings, allowing water to be intercepted and conveyed along drain pipes outside the tunnel with flow rates sufficient maintain water pressure on the lining below set limits. This system allows:
  - water pressure on tunnel linings to be kept low even when the head of water pressure is high;
  - to experiment with the amount of drainage so as not to reduce piezometric levels completely and consequently to stabilise the radius of influence over time;
  - to convey drainage water from the tunnel into pipes to be redistributed on exiting the tunnel to meet aqueduct, irrigation or environmental requirements depending on the needs of the local community.

The two approaches are theoretically alternatives to each other with very different technical and economical characteristics. They must be assessed in relation to assessments of the effects of drainage on the surface and action to reduce the effect which may therefore be necessary.

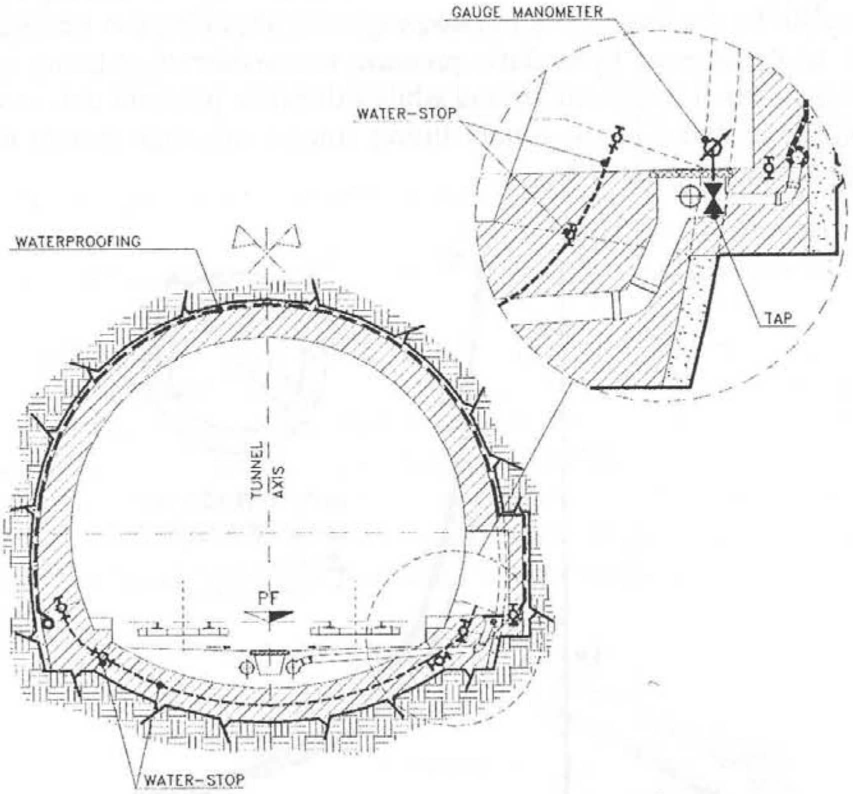

Figure 4. Hydrodinamic conditions: "controlled drenage" technique

3.2 *External action to reduce effects*

Both during tunnel construction, when the effect of drainage is greater, and in the long term, action to reduce the effects of drainage must be considered not only in relation to possible interferences but also in relation to effects that cannot be excluded with certainty. It must be possible to integrate planned operations with the final design where water draining from the tunnel is reused. This is obviously of benefit to the community especially in highly urbanised and anthropogenic environments, since it provides a rational distribution of water resources to the benefit of all and not just those communities that are located near natural sources of water.
The main types of re-utilisation can be divided into two categories:

- Aqueducts for drinking and/or irrigation requirements. Most of the aqueducts in the mountain and foothill areas are fed by springs. If these are affected by tunnel drainage, the supply they provide could remain insufficient. Long and short term plans must therefore be aimed at restoring flow rates to their original levels and at the avoidance of hardship to the community;
- Environmental with particular focus on water courses and connected ecosystems. Studies on the flow of water courses generated by emerging water that is affected by tunnel drainage should serve as a guide to the design of works to restore surface water and maintain it at minimum levels. Restoration of original equilibriums must always aim at using water flowing out of tunnels which can become a useful resource if distributed correctly.

4 CONCLUSIONS

Forecasts of the most probable effects of drainage in tunnels on surface waters can be used to identify whether it is possible to proceed under hydrodynamic conditions or if it is necessary to proceed under hydrostatic conditions. The latter is possible under heads of water pressure that are not higher than a few tens of meters, while it is very costly if the pressure is higher. If drainage of water is employed to reduce water pressure on linings it is recommended that drainage water is redistributed on the surface from tunnel portals or using deep shafts that will carry the water to where it is actually needed for irrigation, drinking or environmental requirements.

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