An Alternative Way to Stop Water Incomes in Tunnels

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1. SUBJECT

This paper is essentially related to repairing of road tunnels. Compared to train tunnels (train, subway, streetcar) or river-crossing tunnels, their specificity lies in the following aspects:

- a number of impacts, especially scraping of the vehicle clearance profile corner due to unguided heavy goods vehicle traffic,
- risks due to the presence of black ice on the road or to the fall of stalactites,
- risk of accidents and aggravated accidents due to a reaction of surprise or fear of a driver (HGV or light vehicle) in case of an even minor event (fall of light debris, drops of water, etc.),

2. SCOPE OF THE PROBLEM

Water inflows are a recurrent cause of damage in numerous tunnels, especially the older ones (built without waterproofing geomembrane till the beginning of the 80s in France). A quantitative idea of what this problem represents can be obtained through the methods of maintenance and supervision of tunnels [1], thanks to the IQOA evaluation ('Image qualité Ouvrages d’Art') which is applied to the State tunnels since 1997.

Each tunnel is given two grades: one for the Civil engineering (CE) and one for the Action of water. There are several grade levels, from the best (1) to the worst (3 for the CE and 2 for the water) and mentions indicating evolving problems (E), safety implications (S) or points to be dealt with urgently (U).

On the basis of the water IQOA grading at the end of the year 2005 (before the transfer of numerous tunnels to the territorial authorities), nearly 44% of the road tunnels which then belonged to the national network had a grade of 2, which means that the water inflows could represent a specific drawback or result, in the long term, in a worsening of the distresses affecting the structures. In 3% of the cases, the grade of 2 was followed by the mention S... and yet numerous improvement works had already been performed to reduce these waterproofing issues.
Thus the water inflows had always been and still remain an important source of damages and operating difficulties in road tunnels.

3. THE STAKES OF TREATING WATER INFLOWS IN ROAD TUNNELS

3.1 Users safety

During long cold spells, the risks are related to the presence of black ice on or above the roadway. Access to the emergency telephone and extinguishers can even become impossible, as the photo nb 1 below shows.

Even in summer, during stormy periods, it is still possible to encounter very strong water inflows of the “geyser” type in some tunnels. These could result in reactions of fear in some users, leading them to swerve unduly and risk colliding with other vehicles.

3.2 Difficulties of operation

The difficulties of operation due to water inflows are mainly faced in winter related to the risk of black ice and ice stalactites (photo nb 2). This requires operators to make regular supervisory rounds for keep the tunnels safe.

3.3 Equipment preservation

In all seasons, the presence of water is harmful to the resistance of the equipment and its anchoring (accelerators, cable trays, lamps, video cameras, sensors, etc.).

In the following example (photo nb 3), the risks related to maintenance of the equipment were becoming so high that the subcontracting company did not wish to work on them any longer …

3.4 The structures durability

Water is a major cause of structural damages (see photo nb 4). Depending on its physical and chemical composition, it can produce carbonaceous or sulfate concretions and deteriorate the lining by leaching. Depending on the nature of the materials it flows through, it can cause blooming on mortar, concrete or coating, resulting in portions coming loose and debris falling on the roadway.

During freezing periods and particularly in the presence of freezing-melting cycles, it greatly aggravates the deterioration of the materials: joints in the masonry, stones, chipping of the concrete lining, coating coming loose, etc.
4. THE VARIOUS TYPES OF TREATMENT OF THE WATER INFLOWS

Two major types of treatment can be distinguished: the first aims at obtaining integral sealing while the second offers either local solutions or “improvement” (that is, a “permissible leak rate”) [2].

Since 1. the water inflows are a real danger to the users, the structure and the equipment and, in case of accident, can involve the responsibility of the operators, 2. any repair in a in-service tunnel results in inconvenience to the users (closing or regulation of the traffic) and high costs which are, partially, impossible to reduce (worksite installation, signalling, traffic management, additional cost for work by night, etc.), 3. any repair resulting in the slightest protrusion within the vehicle clearance profile will end up by being torn off by a heavy goods vehicle (HGV), 4. the “improvements” do not fully eliminate the operating constraints and the risks for the users; in the long term they have a negative impact on the economic level (higher final cost), CETU recommends trying for integral sealing and favoring techniques which are efficient, long lasting and resistant to shocks and tearing. Obviously this general recommendation does not replace a detailed study of each particular case.

5. THE DIFFICULTIES RELATED TO INTEGRAL SEALING BY GEOMEMBRANE

To this day, integral sealing is obtained by using a sealing device by geomembrane (DEG). This device is notably associated, at the side walls, with a draining sheet with excrescences (type Delta MS).

Whether a technique of jacketing with formwork concrete or a technique of shells made of sprayed concrete is used, this requires the building of a structure ensuring the protection of the DEG from: 1. fire, since no geomembrane has the reaction to fire required in tunnels by the new regulations [3], 2. tearing by the traffic.
The most demanding dimensioning constraint is often the shock of HGVs, since the DEG, covering the whole surface of the tunnel, creates a complete mechanical break and leaves the possibility of a centimetric shift between the structure to be dimensioned and the existing tunnel. We thus obtain a large thickness of concrete (about twenty centimetres, or even thirty for traditional jacketing with non-reinforced concrete) which often implies boring and/or excavation in order to keep the same clearance. It is also possible to make shells which are much thinner (about ten centimetres or even less) but highly reinforced and/or anchored in the existing structure.

This type of work has heavy consequences for the operation of the tunnel and results in costs and lead times which are often prohibitive for mountain tunnels with a low traffic rate.

6. DESCRIPTION OF THE TREATMENT BY SPRAYED WATERPROOFING

An alternate solution to geomembranes coupled to jacketing or to shells could be a sprayed sealing by Masterseal 345®. Before discussing the advantages and the difficulties of this method, here is a description of the way we think of using it for treating the water inflows.

A very important preliminary phase is the implementation of a frost-free system for recovery of water at the base of the side walls. We could propose the laying of a frost-free drain as for the more conventional repairs but a “simple” gutter filled with gravel, developed at CETU by G. Chatenoud can be a very effective solution for an optimal cost.

Then begins the substrate treatment. Phase 1 is a water cleaning which must be done under very high pressure, then (phase 2) the main active water inflows are drained with, for example, draining sheets with excrescences cut in strips about 30 cm wide. These strips are also necessary to prevent the rise in pressure of the water behind the lining or later rising of water through the roadway. The large water inflows can be collected by draining pipes which are injected later.

After this preparation, if the support is regular and dry, the waterproof membrane could be sprayed directly. But this is rarely the case. Mortar is then sprayed (phase 3) to make the surface regular (and thus prevent extra thickness of the waterproofing product, costly and harmful for its polymerization).

The water inflows are often too diffuse to be all collected. The mortar must thus also act as a buffer so that the infiltrations of water do not wash out the waterproof membrane before the end of its polymerization. This point is particularly critical.

*Photo 5: Spraying of the membrane*

As soon as the mortar has set, and after watering the surface, the spraying of the membrane can begin (phase 4). It can be done either by the dry or wet method, by a fully automated robot (recognition of the substrate by scanner) or manually.

The spraying of the final lining with fibre reinforced concrete (phase 5) takes place after polymerization of the membrane. The fibres are meant to reinforce the lining, particularly in line with the draining strips behind which the water could freeze and produce high bending stresses.
In some cases, a reinforcement by welded mesh, pinned in the arch, could be preferred (in particular for structural considerations). The pinning operation can then be done before spraying the waterproof membrane since this will prevent its later perforation. The membrane bonds to metal as it does to concrete or rock.

7. THE ADVANTAGES EXPECTED FROM A TREATMENT BY SPRAYED WATERPROOFING

7.1 Integral waterproofing

This type of treatment is classified theoretically in the category of integral waterproofing since the solution is global and not restricted to points (that remains a possibility but is not what is searched for here).

7.2 Low thickness

The major advantage of a sprayed waterproofing is its adherence: 1. to the support, 2. to the sprayed concrete necessary for its protection.

This adherence has two advantages over geomembranes (fixed to the arch or supported by a shell): 1. The water is stopped; it does not flow behind a waterproof sheet to end up in the longitudinal drains; this eliminates the deterioration related to leaching, for example, for the masonry joints. Besides, a localized fault would not be an issue unless it were to coincide with a water inflow. 2. the constraints of the resistance to shocks are no longer dimensioning since the adherence between all the layers theoretically eliminates the risk of chain collapse in case of shock.

Consequently, the thickness of the repair is fixed by: 1. the irregularities of the substrate; they must not lead to local additional thickness of the sprayed membrane at the risk of harming its polymerization and they can thus require the spraying of a regularizing mortar layer, 2. the expected water pressure values; the sprayed concrete protection must reinforce the resistance of the membrane to the counter-pressure, 3. the risks of the water freezing behind the membrane and thus of local pressures, particularly in line with the draining strips.

A priori, even in tunnels with frost, a protective thickness of 7 cm should be enough. This leads to an additional thickness of less than 10 cm.

This low thickness can be very advantageous to avoid the costly operations of boring and/or excavation. On the other hand, a new bearing structure is not obtained as for a jacketing or a shell.

7.3 Reduced impact on the operation

Even though the implementation must be done very carefully, the principles and methods are simple and in part compatible with a partial maintaining of the traffic through the tunnel: the implementation of the water recovery systems at the base of the side walls (gravel filled gutters), the water jet cleaning, the laying of draining strips and draining pipes, the pinning and the laying of the welded mesh can be considered with alternating lane closers.

Only the operations of spraying – mortar, membrane, concrete – require complete closing of the tunnel, at least for a few hours. Shorter interruptions, managed by traffic lights, are possible according to the traffic volume or if the deviations are too penalizing. We however note that no operation can be done outside the tunnel, contrary to the case of independent shells [4].
7.4 Cost reduction perspectives

This method should allow decreasing the overall cost of the work even if the membrane itself is more costly than the conventional waterproofing membranes.

When compared with a jacketing, the difference should be clear when the tunnel is short (formwork being difficult to amortize).

When compared with independent shells, savings can be hoped for due to the decrease in the added structure thickness and especially its reinforcement.

In both cases, the decrease in thickness has a considerable effect on the cost of the work if it avoids the operations of boring or excavation.

In case of variable cross profiles, the simplifications are particularly appreciable.

The time savings which are potentially large should also work out in substantial cost savings (see the example of the rehabilitation of the Chekka road tunnel in Lebanon [5]).

8. THE STUDIES UNDERTAKEN BY CETU

Given the difficulties and the stakes related to the search for solutions for integral sealing of the tunnels, CETU decided to carry out a research action on this method. It was concretely worked out by the treatment of a twenty meters long section in the Col de Rousset tunnel, in collaboration with the District Assembly (Conseil Général) of the Drôme, the sprayed membrane supplier, BASF Construction Chemicals and the company Colas Rails, specialized in tunnel repairs. A video, available on the CETU Website, recaps the main lessons drawn from this experiment.

9. THE DIFFICULTIES ENCOUNTERED AND THE STUDIES TO BE CONTINUED

The running of the experiment can be reviewed to draw attention to the delicate points which must be specified in the contracts and carefully checked on the worksites or which, according to us, require additional tests.

The preliminary phase (implementation of a frost-free system for collecting water at the base of the side walls) is decisive to prevent the presence of water and thus of black ice on the pavements.

The water jet cleaning (phase 1) is often preferred to sand blasting because of its simplicity but its power must be sufficient to eliminate all the fragile or polluted elements and guarantee the adherence between the existing structure and the repair. We used a pressure of nearly 500 bars and we think that it was not sufficient. BASF CC recommends 1400 bars, which is more like hydro-demolition. In the end, sand blasting could prove to be more appropriate.

Phase 2 (laying of strips or draining pipes) is particularly delicate. Too many draining sheets (or geotextiles) must not be used to prevent losing all the benefits of the adherence, but all the active water inflows must be treated by suitable methods. Every drop of water passing through the membrane during its drying will be a leak. We prefer to limit the solution of “pipes & injection” as far as possible since we lack the necessary distance to evaluate the efficiency of injections in the long run, even with polyurethane resins. This solution however remains interesting in case of localized leaks after polymerization of the membrane.

The difficulty of preparing the substrate thus lies in the large areas where oozing occurs which spread beyond the draining strips.
Photo 6: example of extended damp areas which are difficult to drain

The solution thus lies in the choice of the phase 3 mortar. It must be particularly studied to meet four requirements: 1. strong hold on a damp or oozing substrate; 2. regularize the substrate (low grain size); 3. block, for the membrane polymerizing time, all the diffuse water which could not be drained; 4. offer a high tensile strength. A study has been launched on the formulation of a mortar for regularization and temporary stopping of water. Its success is decisive for the method validation.

The spraying of the membrane (phase 4) must of course be mastered, in particular to prevent over-thickness or insufficiencies. Eventually this is not the most difficult phase.

The spraying of the final lining made of fibre reinforced concrete (phase 5) has two types of difficulties. The first is related to the lack of experience for its dimensioning (resistance to the counter-pressure negligible in our application but resistance required to the thrust of the ice behind the draining sheets). All things considered, we have decided to test two thicknesses: 5 and 7 cm in the very cold site of the Col de Rousset tunnel (Drôme). We later learnt that a thickness of 7 cm was also selected for a repair of the same type in a Swiss rail tunnel [5].

The second difficulty of phase 5 is related to the choice of fibres for the projection of the concrete by the dry method. The metal fibres can be sprayed and produce a suitable reinforcement but, for this application, they have the drawback of not being compatible with the presence of pedestrians on the pavements (risk of scratches on the side walls); besides, their superficial corrosion, which is not a problem on the structural level, is not very aesthetic for the finishing covering. The synthetic fibres which are very light, fly about a lot during the spraying by the dry method (high air flow) and the resulting losses are unfavourable for the bending performance of the concrete.

A test campaign allowed comparing several and we finally adopted the Shogun fibre from EPC dosed at 5 kg/m³, leading, during the preliminary test campaign, to an average value of 625 J according to the energy absorption test NF EN 14 488-5. Besides, the worksite checks on the energy absorption capacity were not satisfactory (average value of 417 J ). Note that the insertion of a layer of Masterseal 345® degrades the results (average value of 339 J obtained on "sandwich" panels). These resistance levels are judged insufficient and fresh tests are necessary.

An other delicate aspect is the adherence between the layers. Conventionally in France, for structural repairs of civil engineering structures, it is considered that the original and additional concretes are monolithic if the value of adherence between layers reaches 2 MPa or 75% of the tensile strength of the concrete in place is required. Such a high value is not necessary for a repair in which the protection concrete must only withstand local pressures or shocks and not run the risk of falling on the roadway (no shearing stresses); However, the risks must be anticipated with a sufficient margin to prevent any long-term problem. Fixing a minimum value is not easy. According to the product technical data sheet, a tensile strength of about 1 MPa should be obtained.
For this experimental worksite we chose to spray concrete by the dry method with the idea of favoring adherence between the various layers. This choice should also allow a great procurement flexibility for an isolated worksite, far from the first concrete producing plant. We obtained an average value of 0.7 MPa and a minimum value of 0.4 MPa (that is, all the same 40 t/m³), which is less than the announced value while keeping a sufficient safety margin. Additional tests are foreseen to assess the influence of the substrate preparation and of the type of spraying. On the Viret tunnel worksite (Switzerland), a value of 0.85 MPa was obtained [6].

An on-site follow-up of the experimental ring will be carried out annually over a long period. To this day, we lack sufficient experience on the long-term behaviour of this product. To be considered as an integral waterproofing, it is necessary to obtain a repair which will last for decades. We have no certainty on this point.

In terms of feasibility on real worksites, we could also fear that all the necessary precautions are not taken and that the results are thus not satisfactory. We know, for example, that the evaluation of the performances of the technique applied in the Chamaduras tunnel (masonry rail tunnel in Switzerland) lead to shifting from class 4 to class 2 ("moist spots but no water drips"). It is an appreciable amelioration but we wish to obtain better results. We have noted that « moist spots coincided with irregularities of the surface as well as the discontinuous application of the waterproofing » [5].

We can also ask the question of resistance to fire. We can admit the emergence of fire induced structural damages but it is necessary to make sure that there is no risk of falling materials in areas where people may stand (equipped fire fighters can be present during short periods up to temperatures nearly reaching 150°C). The issue concerns the performances of the sealing membrane and of the fibre reinforced concrete.

10. THE FUTURE PROSPECTS

Even though the results of this experiment are not totally satisfactory, they remain encouraging and show that this method might well be up to the interest it raised.

The obtaining of a mortar (or coating) adapted to the substrate treatment requirements is necessary in order to assess that the method is truly promising. Further tests need to be carry out before the CETU can issue a pertinent opinion on its implementation.

11. BIBLIOGRAPHIE

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