Water Inrushes onto the Face of the Karavanke Tunnel

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ABSTRACT

This paper presents two water inrushes, safety measures preventing further ones and geological and hydrogeological researches and interpretation that brought the choice of assantion works and the decision of restarting the crown excavation. The assantion measures showed up satisfactory for the tunnel's long term stability.

Finaly, a brief review of other water incomes is given, together with the commentig notes and explanations describing why the second inrush was not a suprise for the contractor.

INTRODUCTION

The 7864 m long Karavanke Motorway Tunnel (of which 3437m on the Yugoslav side) challenged the constructors with a series of technical difficulties. The major problem was the construction of the tunnel through a rock mass of extreme plasticity made of Permian Carboniferous clay schist in which the measured convergences reached values that had not yet been measured in any of the motorway tunnels in Europe. Unfortunately this was not the only difficulty faced during the construction of the tunnel. Far more dangerous was the threat of water inrushes to the tunnel face while advancing through the water bearing strata of Low and Middle Triassic dolomite in a total length of 798 m. On the Yugoslav side of the tunnel the works had to be discontinued twice for inrush of high pressure water that threatened the stability of the tunnel. Luckily the two inrushes took no human lives. In both occasions the caving-in was a consequence of a water bearing fault zone in dolomite but whose exact location could not, because of the great depth of the tunnel, be defined at the stage of geological investigations.

This article discuses the locations of the two water inrushes, the safety measures that were implemented, the geological and hydrological investigations carried out to define remedial measures and to decide upon the continuation of driving works, the geological interpretation of the occurrence of the in-rushes and the measures that made possible a stabilization of the tunnel in those two locations.

FIRST WATER INRUSH

Geological background

The first of the two major water inrushes into the tunnel occurred at the beginning of May 1987, at chainage 740 m, when the driving penetrated a water bearing fault zone in Werfen dolomite (fig.1). Previous to that, water was not a major trouble: there were only weaker sources, with a flow of up to 3 l per sec. A larger source appeared on the passage of the face from gravel into rock mass only (at chainage 315 m - 15 l per sec). Its outflow now varies depending of the volume of precipitations from 5 to 10 l per sec. Yet in the largest part of the tunnel nothing but drippings of water were recorded, which was far below the expected incomes.

The last 80 m thick section prior to the inrush location is made of impermeable rock: red clay schist containing thin seams of sandstone and lenses of dolomite. The contact with dolomite creates a cca 70 m wide fault zone that strongly folded the clay schist and crushed and mylonitized the dolomite. Within the dolomite this zone continues for another 20 m. This section in the immediate vicinity of the fault zone in dolomite (in which the rock was pronouncly collapsed and already partially mylonitized) was almost fatal for the tunnel.

Description of the inrush

The first major water appearances were registered on the face at chainage 728 m. Water poured from open fractures on the bottom of the top heading. At chainage 734 m water already poured from the total surface of the tunnel face. The advance drilling showed that in the ensuing 10 m section more water had to be expected, which was proven to be correct when the face driving progressed. The water that poured into the tunnel was bearing fine dolomite and red-brown clay stone debris. The volume of the water inrush and of material kept increasing. Because of the numerous and increasingly copious water inflows from the rock mass the supporting measures implementation at the driving face became difficult: the adhesion of shotcrete to the rock decreased considerably and the cement grout was washed out from the rock bolt holes. On the right side of the tunnel minor collapses of limestone and dolomite occured. The water pouring from behind the lining washed out unhardened cement. But notwithstanding these difficulties the face advanced to chainage 742 m.

Water inflow and collapsing of crushed material (20 to 25 m^3) became most important between chainages 734 and 742 m (8 m behind the face where the rock was, due to continuous washing out, increasingly permeable). The highest inflows of water into the tunnel were measured - 120 l per sec. Water pressure was estimated to 12 to 15 bars.

On Saturday, May 16, 87 at 1 a.m. at chainage 742 m occurred a partial collapse of the right side of the tunnel. The rock compressed the roof and the right flank of the heading for 0.4 to 0.5 m. Simultaneously the convergence measurements at chainage 734 m showed an increase for 114 mm, while the pin for measurements of roof settlements fell out from the shotcret lining. The driving of the face was immediately stopped at chainage 746 m and was discontinued for three weeks.

Measurements and remedial measures

The first task after the occurrence of the caving-in was to insure the safety of the remedial works. The roof and the right flank of the heading was thus supported by wooden supports propped both in the bottom and into the rock core retained on the driving face to maintain its stability (see picture 2).

Safety measures and measurements were carried out in the tunnel well before the principal caving-in. These were advance drilling, measurements of water inflows and an attempt to measure the water pressure by piezometers.

During the advancement of driving works a number of discharge drainage boreholes, 6 m long, was made. Daily measurements of convergence and of roof settlement were carried out.

Immediately after the caving-in the number of drainage boreholes was further increased; it became clear already during the boring of these holes that the water had washed out a great amount of dolomite debris from behind the tunnel linning that had to be replaced most urgently. By injecting of a cement betonite suspension (3% of betonite) into 4 boreholes of m 85 mm at the pressure of 11 bars and 5 to 7 m deep the first step of immediate safety measures was carried out.

The project of remedial works that was made upon an investigation of the tunnel envisaged a construction of a 2 m thick supporting arch made of grout material in the zone of the principal caving-in. For this purpose a systematic grouting was carried out in a net pattern of 2 x 2 m to a depth of 3.5 m from the tunnel. The monitoring of the injecting was made by test drillings.

The rock mass was additionally protected by a systematic rock bolting with perfo-bolts 6 to 9 m long at intervals of 15 to 20 m, and by TH arches at 1 m intervals. The remedial works were continuously monitored with measurements of convergences and by 2, 4 and 6m long extensometers. They showed that remedial works were successful.

To assure a final stabilization of the rock mass 17 m long rock bolts were built in. Continuous measurements of water inflows showed that the total water flow began decreasing immediately after the caving-in: from the initial maximum flow of 120 l per sec it decreased after one week to 80 l per sec and after one moth to 24 l per sec. Then the contractor took the decision to continue with the driving works.

As there was a possibility that the inrush water be in direct connection to the Prešušnik brook 320 m above the caving-in, a colouring of the brook with uranine was carried out. After six months of chemical testing the colouring still showed no connection between the waters of the brook and the water in the tunnel.

In the caving-in zone, after the remedial measures had been implemented, 3 piezometers were built in, located at 3, 6, and 9 m distance from the shotcreting lining. During the exploitation of the tunnel these gauges are still being used for monitoring the water pressure and the functioning of the drainage system.

Geological and geotecnical evaluation of the situation

In Carbonate rock a horizon of underground water did not empty steadily but begun emptying intensively only after the breakthrough of the aforeside fault zone with a core of practicaly impermeable mylonite and edges of strongly fissured and crushed rock. During the advancement of the tunnel through these edges of the zone appeared at first smaller and later on larger water inflows that increased to a total volume of 120 l per sec at the driving face. The water inrush under great pressure (and velocity) caused the washing out of loose rock material in the tunnel neighborhood. Erosion resulted in both stronger inflows and a formation of cavities (eroded spaces) behind the constructed shotcrete lining on the right side of the tunnel, which was discovered when drillings for rock bolting were performed. Thus the prerequisite for successful safety measures to be implemented according the New Austrian Tunneling Method was not met: the interaction of a rapidly built security shotcreting lining with reinforcement and the rock was prevented. In the right flank of the tunnel, in a water saturated tectonically crushed rock was thus created a totally unsupported space. This situation led to the instability of the tunnel at its face and on the right flank behind the face.

From the evaluations we could expect from this precipitation basin of 1.0 km^2 an average of 30 l per sec of water inflows into the tunnel. Together with some other sources from this dolomite the volume of inflow at this fault zone has stabilized at 15 l per sec.

SECOND WATER INRUSH

Geological background

The second water inrush occurred at chainage 3028 m, in the last section of the Yugoslav half of the tunnel. Prior to that the driving face advanced for 1000 m through Permian Carboniferous clay schist with seams of sandstone and limestone, several 10 m thick. These strata form a hydrological barrier reaching to the surface, ca 700 m above the alignment of the tunnel. With a series of parallel faults perpendicular to the dinaridic direction this unit is in tectonic contact with Lower Triassic limestone and sandstone underlying Middle Triassic strata (Anisian dolomite and the Ugovizza breccia) and Upper Triassic Schlern dolomite. In the last 20 m of the tunnel the face advanced through carnian marly limestone of low permeability.

The water inrush occurred at the intersection of two faults, inside of light gray, mostly non-stratified Schlern dolomite, in the central zone of the greatest water bearing fault in the alignment of the tunnel.

The faults that intersect in the zone of the tunnel lie in a dinaridic direction, sub-vertical and are anticlined. The central section of the fault zone is 6 to 8 m thick. Here the dolomite is completely mylotinized with occasional clay pockets. Both faults are accompanied by a series of parallel secondary faults 1 m thick. In the whole 50 m long area the dolomite is crushed into fine gravel .

Description of the water inrush

At the beginning of December 1988 the advance boring indicated the appearance of high pressure water at the tunnel face. The advance boring was carried out within the framework of continuous research work at the tunnel face for methane and water detection and study of the geological structure of the rock 30 m before the tunnel face.

The first measurement of the water flow rate showed 64 l per sec. A second measurement, two days later, showed only half of the previous flow rate and in the ensuing days the borehole was completely clogged by dolomite debris.

Similar strong water flows were detected, before the occurrence of the principal water inrush, on two other locations (at chainage 2583 m the water pressure was over 27 bars, and at chainage 2901 m where water rushed from the bottom of the top heading in a jet 20 m long and 6 m high), yet the rock mass there was only slightly crushed and the caving-in of the tunnel face did not occur.

In the period preceeding the New Year's Eve festivities, between December 23 and 28, 1988, when the advancement of the tunnel face was discontinued, 7 drainage holes were bored into the face to decrease the water pressure in the water bearing fault. The outcoming water washed from the holes also the dolomite debris, in total about 100 m^3 . In these holes the water flow rate decreased rapidly and the holes were clogged within a few days. The introduction of drainage pipes into the boreholes was impossible due to the high water pressure that during the boring of the last hole damaged the drilling rods of the drilling machine.

When the tunnel face came at a distance of 1 to 2 m from the fault zone the first water inrush occurred to be followed in the next 6 hours by two more. The first inrush caused a caving-in of 150 m^3 of dolomite, while the last caused a hydraulic collapse of the tunnel face and completely filled the heading with loose dolomite for 16 m. Another 44 m of the heading was partially filled with the loose dolomite pouring into the tunnel. It is estimated that during these cavings-in from 0.5 to 1 million cubic meters of water run through the tunnel in the first day alone. We estimate the water pressure in the rock mass during this period to have been between 6 and 7.5 MPa.

Because of the frequent water appearances in Schlern dolomite, a 120 m long piezometer was built in December 1988 at chainage 2683m in the left flank of the tunnel, for an overall monitoring of water pressure in the aquifer outside the immediate zone of the caving-in.

Remedy works and measurements

The making good of the ensued situation comprised the following operations:

1. Protection of the tunnel face and flanks from further cavings-in.
2. Additional drainage of rock mass and definition of the shape of the open space in the immediate neighborhood of the caving-in.
3. Construction of a by-pass tunnel through the water bearing fault.
4. Injection and additional rock-bolting in the collapsed area.
5. Hydrological measurements and monitoring.
6. Gradual advancement of the tunnel face through the stabilized area.
7. Creation of a permanent control post for hydrological survey (monitoring) of the area during the tunnel exploitation.

First was constructed, 30 m behind the tunnel face, a bolted crib block retaining wall 4 to 6 m thick, with pipes for outflow of water. Thus was assured the safety of work teams that immediately after the security measures had been implemented, drilled, at chainage 3000 m, 9 test boreholes in the heading, oriented towards the spot of the caving-in. These boreholes were meant to accelerate the drainage of the rock mass and to ascertain the nature of the cavities in the area of the caving-in. The boreholes showed that the area around the tunnel was unevenly collapsed and also the water inflow from the holes was quite uninoform. Because of the extremely high water pressure in the aquifer that filled the boreholes with loose rock immediately upon the drilling, we had to adapt the drilling system with simultaneous insertion of pipes. This drilling was performed one week after the principal inrush of water, yet the water pressure in some parts of the aquifer around the caving-in remained over 18 bars which made the circulation of flushing water difficult.

The limit of the washed out space was determined on the basis of loss of flush circulation. Boreholes that reached this limit cold not be drilled further as all flush was lost in the process of drilling. The boreholes were 25 to 42 m long (see figures 3 and 4).

A similar series of boreholes was drilled in the following week at chainage 3003 m. They were primarily intended for additional drainage of the water bearing fault. To avoid collapsing of the boreholes we used the adapted OD drilling system with full pipes with perforated heads. All boreholes had a concreted water column and the outlet was furnished with a bolt and a manometer. A measurement of the pressure in the boreholes over 5 days yielded multiform results, ranging from 0.5 bars in the most collapsed part (the central part of the caving-in) to 15 bars in the the borehole that extended the farthest from the water outflow spot.

In some of the boreholes the measurements of the water inflow and of the pressure were carried out throughout the period of consolidation grouting of the collapsed rock mass, as it was feared that these works might cause an incerase of these parameters in the by-pass tunnel.

On January 23 the total water flow was 237 l per sec. From the tunnel face boreholes, the water inflow was on January 28 95.3 l per sec., on January 29, 77.1 l per second and on January 30, 66 l per sec. Indicative was also the decrease of the pressure measued by the piezometer at chainage 2683 m, from 12.5 bars (December 15) to 7.2 bars (January 31). In 1991 the pressure continues to decrease and was in July 91 3.8 bars.

A rapid decrease of water in the aquifer after the caving-in is proven also by the exhaustion of water sources on the surface and later in the tunnel itself: first the source at chainage 2900 was exhausted to be followed by the source at chainage 3016 m. After one month of flow the water temperature fell from 10.5 to 7.9° C.

Simultaneously with the dirilling of additional boreholes in the tunnel face the contractor began to excavate a by-pass tunnel through the undamaged water bearing fault, cca 10 m west of the existing tunnel. The by-pass tunnel was excavated at the level of the top heading, and after the bench was excavated its cross-section was 22 m^2 . The construction of this by-pass tunnel was carried out gradually, after a prior intensive advance drilling and grouting of 75 boreholes 18 m long and 26 boreholes 9 m long. This was a multi-purpose tunnel, serving in turn as a drainage tunnel, as a temporary main tunnel for the bridging of the water bearing fault and as a support faciltiy for injection of the collapsed rock mass in the main tunnel. After passing through the water bearing fault this by-pass tunnel was reconducted to the alignment of the main tunnel, at chainage 3066 m (see figure 5). From there on the driving was carrid out in two directions: one face advanced towards the austrian part of the tunnel and the other back towards the collapsed area, after prior drainage and grouting. In this last stage the driving of a pilot tunnel was also resumed through the collapsed and now consolidated zone.

In the main and in the by-pass tunnel were drilled, additional 14 drainage boreholes between January 30 and February 5. Thus the water inflow into the tunnel was rised from 150 to 273 l per sec., causing the water pressure in the vicinity of the collapse zone to decrease from 15 bars (one week after the inrush) to 1.3 bars. When this pressure was reached the project managers decided to go on with the next stage of remedial works in the main tunnel tube: grouting of the main tube from the by-pass tunnel, and advance grouting of the main tube by boreholes in a fan-like configuration, in direction of the advancement at an angle of 10 to 20 degrees. Behind them and through the safety wall the collapsed material and the immediate vicinity of the tunnel were consolidated to the chainage 3028 m. Only then the driving of the tunnel face was advanced to chainage 3023 m.

In the next stage we advanced in 10 segments through the water bearing fault, taking care that in any moment before the tunnel face and around it there were at least 5 m of grouted rock mass. For grouting at the pressure of 5 to 30 bars 345 tons of suspension were used in the first stage and 238 tons in the second stage. The excavation of a reduced cross-section of 17 m^2 along the right side of the tunnel was done in Class VI by the New Austrian Tunneling Method. The same rock category was encountered when enlarging the pilot tunnel that was driven through the aquifer and when the grouting works of the neighbourhood rock had been terminated. The driving was carried out in steps: first were excavated the side parts of the face and each part was immediately shotcreted. Additional rock bolting was performed by using swellex and perfo-bolts.

The water inrush and the ensuing remedial works caused a delay of 3.5 moths but still the breakthrough of the tunnel at the yugoslav-austrian border was done one moth before schedule.

For measurements of water flows that were done by a hydrometric wing, four observing stations were set up. The measurement basins were installed at the entrance of the by-pass tube (chainage 2987 m) in the top heading of the main tube at chainage 2945 m, in its bench and in the invert at chainage 2500 m.

For measurements of pressure five piezometric boreholes were performed, two at chainage 3003 m and one at chainage 3025 m in the main tunnel, one in the by-pass tunnel at chainage 3011 m and another one in the main tunnel at chainage 2683 m. The water temperature was also monitored continuosly and samples were taken for chemical analysis.

The chemical analysis of the water measured 14 standard parameters: K^+ , Ca^{2+} , Mg^{2+}, NH^{4+}, Fe, Cl^-, HCO^{3-}, SO_4^{2-}, $KMnO_4$, dry residue at 105° C, carbonate hardness, hardness and pH. Results: water from the zone of the first inrush at 740 m is different from the water from the second inrush at 3028 m. The first is a Ca Mg hydrocarboniferous water from the aquifer containing gypsum and Anhydrite , while the second is Ca Mg hydrocarboniferous water that is ideal for potable water supply.

The monitoring of the time development of the water inflows into the tunnel show clearly the direct link between the by-pass tube and the main tunnel, as every increase of water inflow into the by-pass tube after the fall of pressure to 1 bar is followed closely by a decrease of water flow in the main tunnel. The figure 6 illustrates the impact of individual phases of remedial works (construction of by-pass, grouting, additional drainage, etc.) on the volume of water inflow into the tunnel. Diagrams are presented for each measuring station separately.

The decrease of water temperature from 10.5 to 7.9° C is most probably due to the increasing circulation of water through the rock mass. The temperatures on the surface were significantly lower than those inside the rock mass.

Chemical and bacteriological analyisis show that this water is indicated for water supply needs. In the last stage a water pumping station was installed in the by-pass tunnel. For this purpose another 5 boreholes had to be drilled.

The pumping station now serves to a double purpose:
- its constant water flow of 80 l/s increments the water supply of the neighbouring town of Jesenice,
- enables a constant monitoring of the operation of the drainage system in this part of the tunnel.

The measurements of pressures and water inflows on discrete points in the tunnel furnished data that helped to formulate decisions on the phases of the remedy works and on the recommencement of the tunnel face driving through the water bearing zone. This was also the basis for a prognosis of the conditions to be encountered between the caving-in and the austrian border that in the following months of the tunnel face advancement proved to be the correct one.

Hydrogeological interpretation

The experience in the Karavanke tunnel showed that the central parts of water bearing fault zones in dolomite are strong hydrogeological barriers clogged with mylonite and tectonic clay. On the contrary their external parts are extremely permeable with a permeability 100 times exceeding the basic rock mass one.

These zones can serve as intensive discharge points for the aquifer when the tunnel face penetrates it. The drainage of such zones becomes problamatic due to the crushed rock mass and the high water pressure. This pressure blocks the circulation of the drilling flush. On the other hand it increases greatly the speed of the outflowing water and the washing out of the loose dolomite, which results in a major mechanical unstability of the structure.

The washed out and crushed rock mass is fortified by consolidation grouting, but this decreases its permeability with the risk of increasing again the water pressure in the rock mass.

The observations and the measurements at the inrush point at chainage 3028 lead us to the following conclusions:

The construction of the tunnel through dolomite dit not, unfortunately, trigger a sufficient constant drainage of the aquifer. The water bearing fault at chainage 3028 was a narrow hydrogeologic barrier inside the aquifer thus the water pressure behind it did not decrease with the approach of the tunnel face. The barrier collapsed only when the tunnel face burst. Only then could begin the the intensive discharge of the aquifer behind the fault zone through the tunnel: 15 million of cubic meters of water poured into the tunnel. The initial water pressure of 75 bars that caused washing out of loose rock material into the tunnel fell under 1 bar in the last phase of the drainage operations.

The remedial works could not be commenced until the water pressure in the area decreased to 18 bars. This happened in one to two days. Therefore we believe that the only possible way of passing through this zone in a sensible lapse of time was to induce the water inrush.

Further outflow of water in the area of the caving-in caused an elargement of drawdown area further away from the tunnel. The process of discharge of the aquifer was further accelerated by additional drainage works and drain tubes.

Considering the infiltration area (3.4 km^2) and the coefficient of infiltration of the aquifer, the calculated dinamic water supplies in this area are between 100 and 130 l per sec. By continuous outflow of such quantity of water from the rock mass a permanent low level of underground water in this zone will be assured. The gradual decrease of the pressure measured by the piezometer at chainage 2683 m shows that the outflow of water still surpasses the inflow from the surface to the aquifer.

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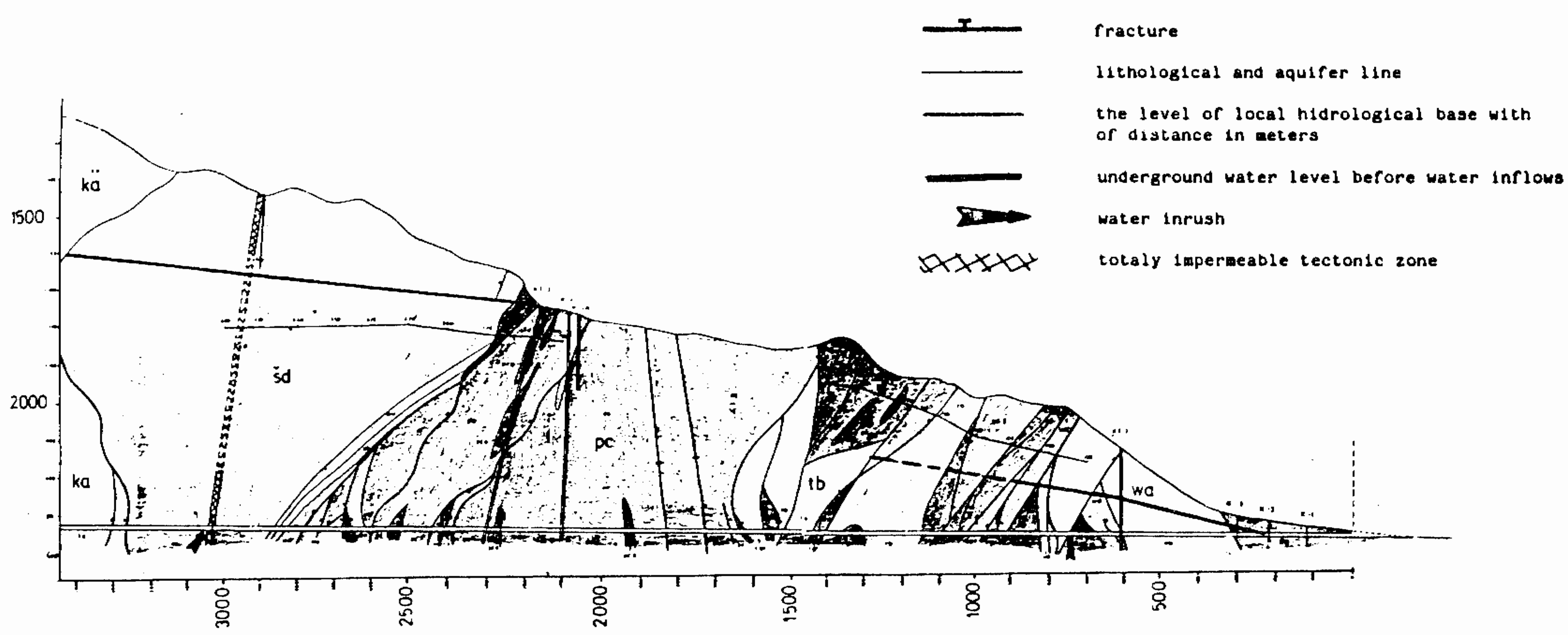

DESCRIPTION OF AQUIFER		LITHOLOGICAL DESCRIPTION
Middle pervious aquifer with intergranular porosity and free water table	Og	Scree or talus material with moraine material
Aquifer with low permeability and fracture porosity	ka	Dark stratified limestone marl, dolomite with flint
Middle pervious aquifer with fracture porosity and frequent impervious layers which create some suspension horizonts of groundwater	wa	Grey oolitic limestone and marly limestone
Aquifer of high permeability and fracture porosity or transmisivity, with free water table. Impermeable are only tectonic zones	šd	Dark and light, stratified and cracked grey dolomite

DESCRIPTION OF AQUIFER		LITHOLOGICAL DESCRIPTION
Aquifer of low permeability with fracture porosity	tb	Grey calcareous breccia with quartz conglomerate
Middle to low pervious aquifer confined or unconfined, with carsty-fracture and fracture porosity or transmisibility	pca	Dark grey ridge limestone
Impermeable area	pc	Sandstone, marl slate, siltstone dark slaty claystone

Fig.1: Longitudinal geological section

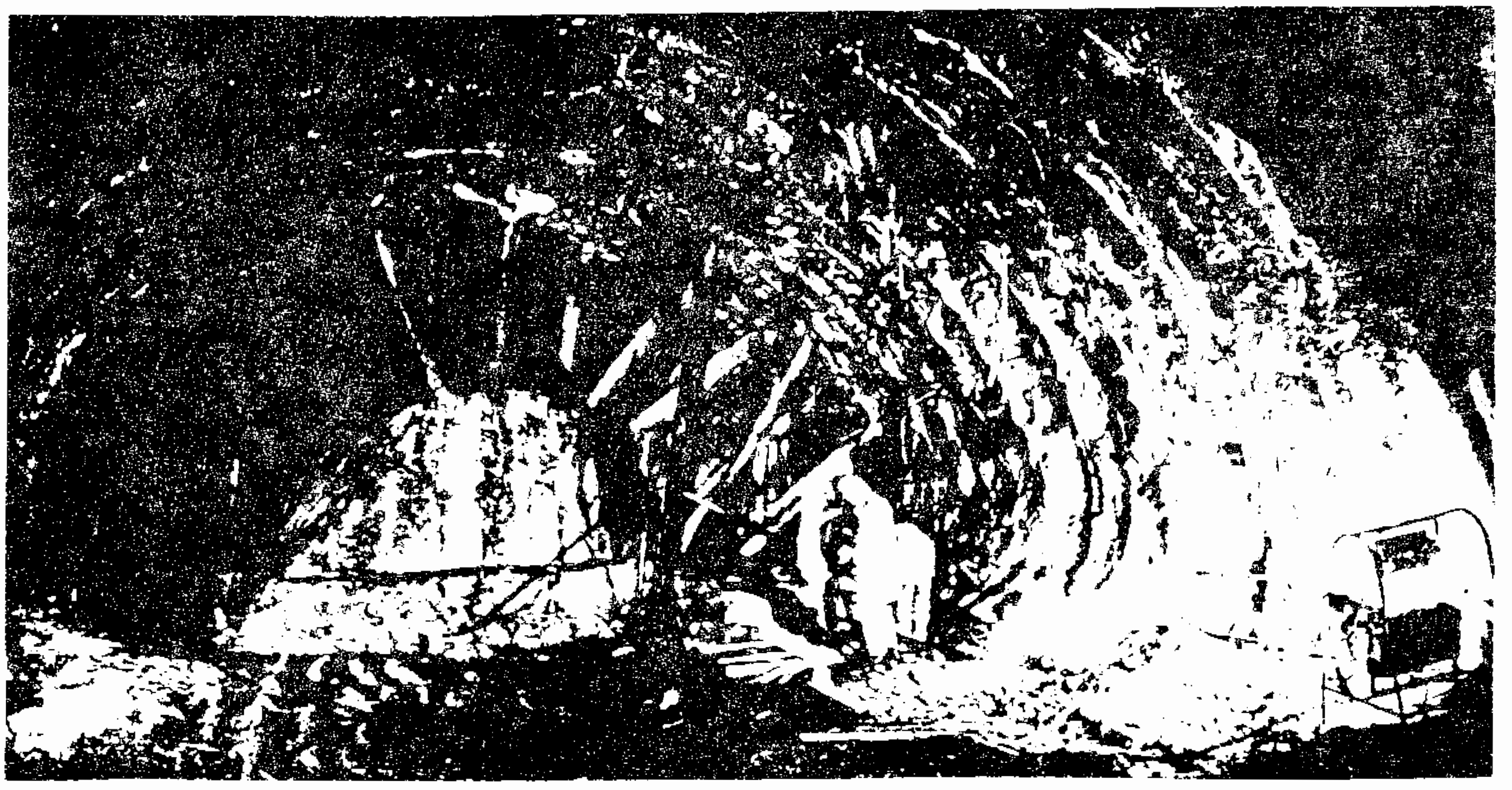

Fig.2: Temporary support measures in the tunell at the location of the first water inrush, station 732 m

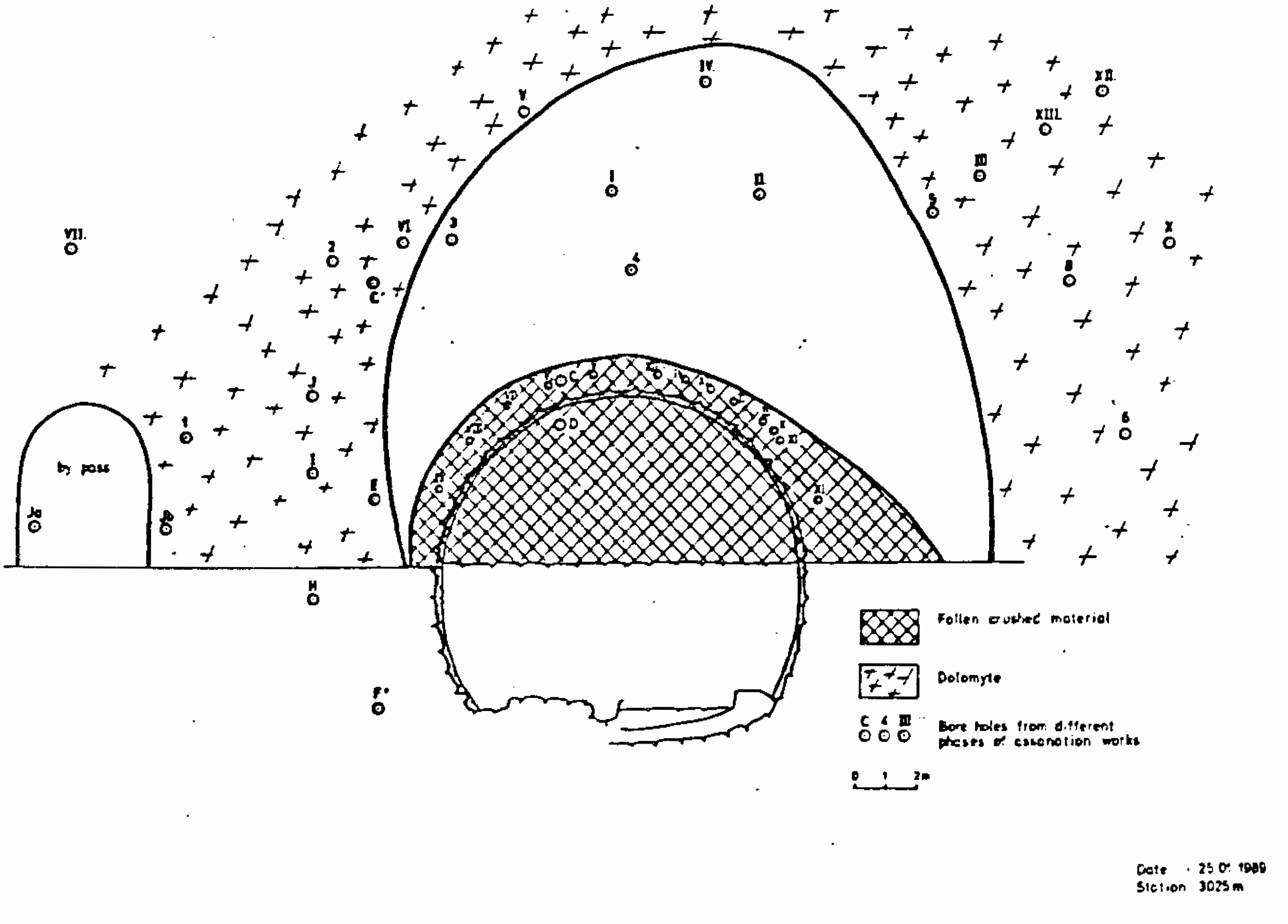

Fig.3: Cross section of highly loosened rock around the tunnel at the location of the second water inrush (chainage 3025 m)

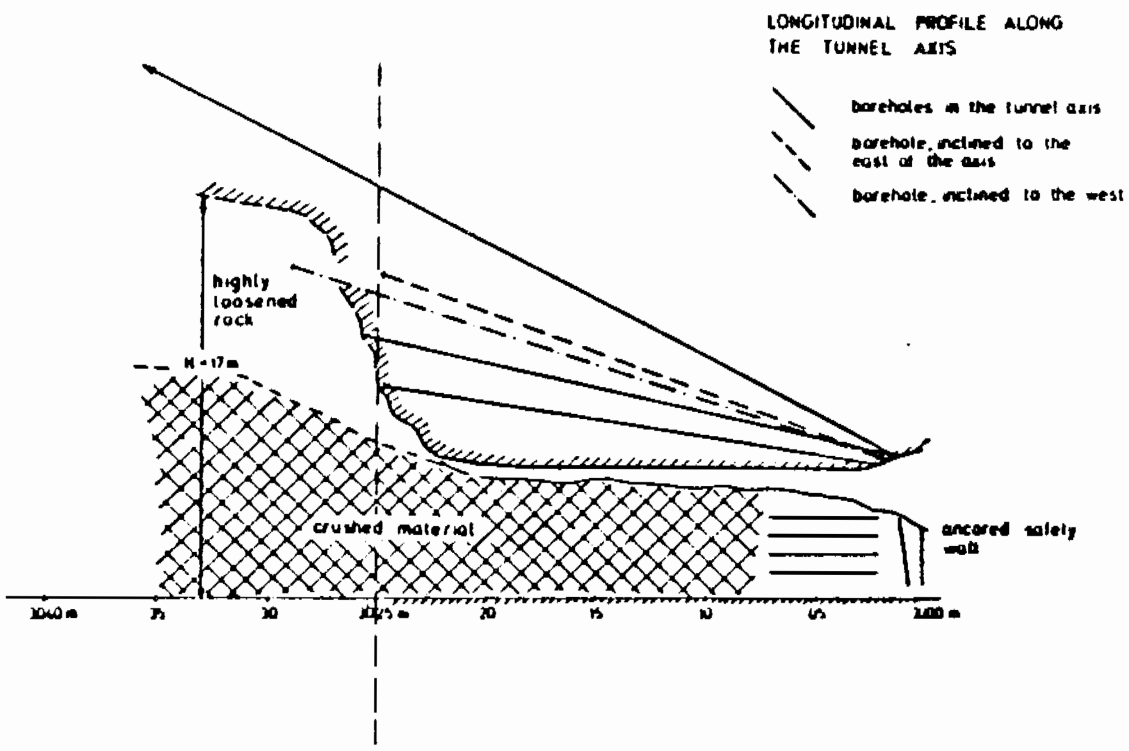

Fig.4: Longitudinal profile along the tunnel axis at the location of the second water inrush

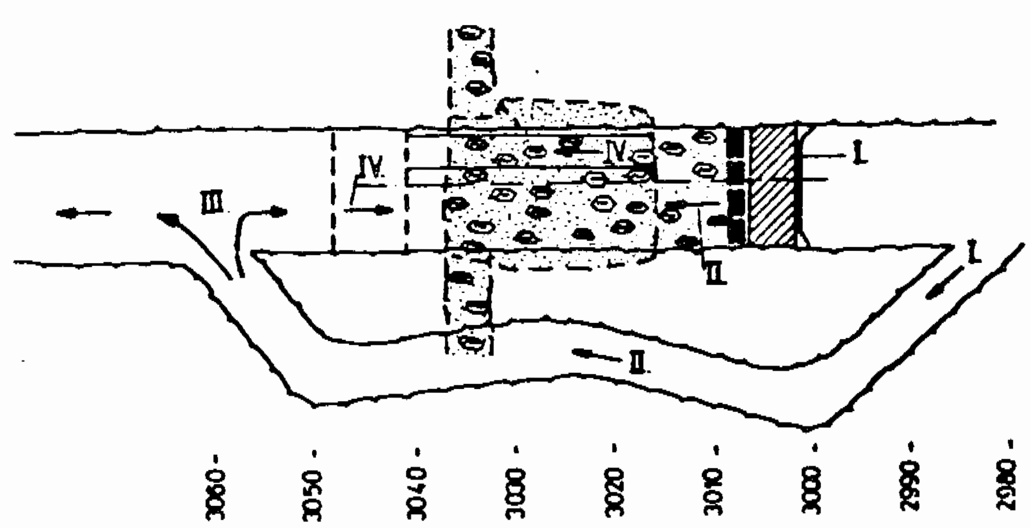

Fig.5: Ground plan of the by-pass. Flashes are indicating different phases of advance through the water bearing zone

Fig.6: Time dependent water incomes as a function of different remedial works. Measuring station are situated at 2500 m, 2790 m, 2945 m and 2960 m

1. Parallel tunnel excavation (1.17. - 3.4.89)
2. Boring of 13 dewatering boreholes at 3003m (1.19. - 1.27.89)
3. Grouting from parallel tunnel, st 3025m (1.26. - 2.3.89)
4. Boring of 6 supplementary boreholes at 3003 m (2.1.89)
5. Boring of 8 dewatering boreholes from parallel tunnel at 3009 - 3019 m (2.2. - 2.4.89)
6. Grouting ahead from the main tunnel
7. Excavation of the main tunnel to the station of 3020m (2.16. - 2.19.89)
8. Boring of 16 dewatering boreholes from the main tunnel and from the parallel tunnel (2.19. - 2.22.89)
9. Grouting from the main tunnel, at 3020m - ahead (2.27. - 3.9.89)
10. Pilote tunnel from the station 3020 - 3050 m (3.9. - 3.18.89)