MONITORING AND MAINTENANCE OF SOIL ENGINEERING STRUCTURES ON THE A43 MOTORWAY

A. Bergère
Terrasol -, France
a.bergere@terrasol.com
P.L. Veyron
Setec, France
veyron@tpi.setec.fr

ABSTRACT

The A43 motorway was designed to fit into the Arc en Maurienne valley. The layout was adapted to steep and very deeply-cut mountainous relief with complex geology in a site of rock, scree and alluvium. It crosses previously constructed traffic lanes and water engineering structures. The engineers faced major difficulties in ensuring the stability of structures located on delicately-balanced sites and improving the valley's environmental aspect.

Through two examples of sensitive structures located on evolving sites, this article presents the monitoring operations and the maintenance work carried out to keep the motorway in service. Each of these two structures corresponds to a very different environment. The first, consisting of bridges and access embankments on compressible layers in the Rieu Sec region, was designed to support a very high amplitude of settlement. The second, consisting of a tunnel and retaining walls in the Les Sorderettes area, concerns a very steep slope exposed to instability where the hydrogeological conditions still cause problems.

These structures were adapted both during their execution and some years after being opened to traffic. The systems for monitoring and maintenance were designed and applied in line with the development of the respective sites, which are still classified as sensitive.

PRESENTATION OF THE A43 MOTORWAY

The A43 motorway is one of the major European routes linking Lyon, in France, to Turin, in Italy. This mountain motorway leads to the Fréjus international road tunnel that passes through the Alps. The contract for the French part of the 65 km long motorway was given to Société Française du Tunnel Routier du Fréjus (SFTRF), which financed the design and construction of the project and now operates the motorway (see Figure 1~~Figure 1~~).

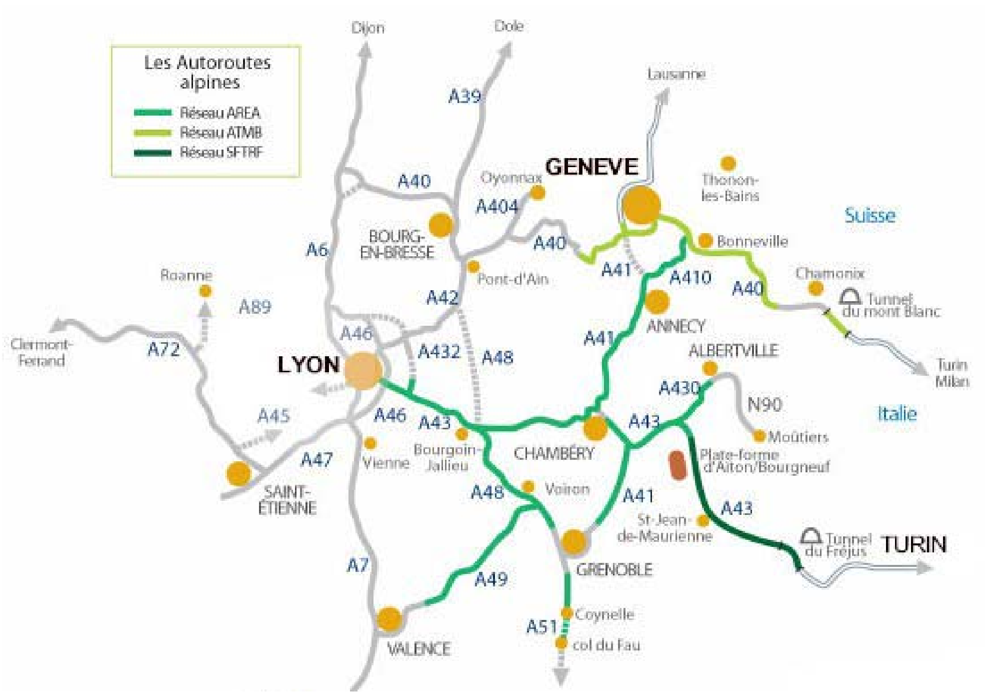

Figure 1 *– Geographical location of the La Maurienne A43 motorway*

The main technical and financial features of the A43 motorway are shown in Table 1~~Table 1~~:

Sections	Pont d'Aiton Ste Marie de Cuines	Ste Marie de Cuines St Michel de Maurienne	St Michel de Maurienne Le Freney
Project Manager	Scetauroute DDE 73	Setec	Setec
Length (km) Difference in altitude (m)	30.7 165	19.6 252	13.5 332
Earthworks Cuttings/excavation debris (million m^3) Fill and embankments, including rock fall protection barriers (million m^3)[1] Subgrade (m^3) Rock riprap (m^3)	2.250 3.876 600,000 446,000	2.940 4.370 473,000 423,000	1.100 1.000 200,000 220,000
Non-standard engineering structures Viaducts Tunnels / Covered trenches Non-standard engineering structures / Canal bridge	1 3 3	5 - 8	7 2 3
Standard engineering structures Upper Passages / Lower Passages Walls	37 3,300 m	20 8,600 m	12 8,100 m
Cost per km in €M (at 1998 prices)	13.9	21.6	41.9

Table 1 *- Main quantities of motorway sections.*

1. TECHNICAL CONSTRAINTS AND REQUIREMENTS

The A43 motorway is in the valley of La Maurienne, a restricted space where, apart from the built-up urban areas, there were many obstacles that interfered with the project, these were dealt with as well as possible as part of an exemplary landscape integration scheme:

- the River Arc and its tributaries whose floods conveyed "torrential lava", causing major scouring action.,
- the RN6 main trunk road and the Lyon – Turin railway, which carry heavy traffic,
- water engineering structures (dams, canals and underground water conduits) of the Arc – Isère hydroelectric complex,
- electricity power lines (150 kv to 400 kV),
- industrial sites:
  - five factories in production, to be preserved,
  - seven old industrial sites, to be integrated into the environment (industrial wasteland, depots and dumps, requiring the neutralisation of major pollutants),
  - two undermined sites (sites with an underground coal-mine and abandoned underground water conduits underneath them).

The motorway project is in a relatively complex geological environment. The sides of the Arc valley are often unstable, and the crest lines towering over 1,000 m above the valley create unstable blocks and masses whose potential trajectories were a threat to the motorway.

- screes of shale and torrential deposits, rich in fine particles, where major circulation of water has been found,
- rock cliffs which are extensively cracked, and which are changing under the action of rain and frost.

Major work was carried out to provide protection (purges, rockfall nets, and construction of rock fall confinement barriers). The foundations of civil engineering structures were then designed according to non-standard criteria in order to address soil engineering risks as well as possible:

- scouring action causing undermining in the bed of the River Arc,
- instability of slopes,
- compressibility of lake bottom deposits upstream of the former ice barriers,
- difficulties in construction work related to the specific local features (elevated shore cliffs, hard blocks, cavities, soft horizons or intercalary loose layers) and very heavy loads on drilling tools (deviation, abrasion, horizontal thrusts, etc.).

Due to the topographical and morphological environment, structures with exceptionally large heights, spans and able to withstand large imposed loads are required.
The seismic consideration (the area is in 1a and 1b zones) also requires the earthquake-proof design of structures in accordance with currently applicable regulations.
Lastly, the winter conditions also require specific protection of the structures against the following:

- avalanches,
- ground frost and freezing of ground drains at nailed and anchored walls,
- the action of de-icing salts on concrete.

2. CONSTRUCTIONS, OPERATION AND TECHNICAL INSPECTION/MONITORING

2.1. Completion times

Studies and design of the project in 1993 and continued in stages until 1997. The construction work, which was also done in stages, met the deadlines mentioned in Table 2~~Table 2~~:

Section	Pont d'Aiton Ste Marie de Cuines	Ste Marie de Cuines St Michel de Maurienne	St Michel de Maurienne Le Freney
Start of construction work	1994	1995	1995 (1)
Opening to traffic	1997	1998	2000

(1) Orelle Tunnel

***Table 2** – Duration of construction work on the A43 motorway.*

2.2. Monitoring of sensitive sites

Within the project management and design teams, Terrasol participated in the design of the structures and subsequently in supervision of the construction work for the soil engineering part. From the opening to traffic of the Ste Marie / St Michel / Le Freney sections, Terrasol has conducted technical monitoring of twenty sensitive, potentially unstable sites for SFTRF.

This monitoring includes:

- preparing a detailed "structures report", including a summary of measurements taken during construction,
- recommending additional measurements required for monitoring the stability of structures and quantifying any movements,
- interpreting these measurements and publishing a technical report determining any variations in the structures and setting out the measurements to be followed and, if necessary, work to be planned for stabilisation and/or maintenance.

The sensitive sites subjected to specific monitoring are listed in Table 3~~Table 3~~:

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Section	Road Length Reference Point	Location of the structure	Comments
Ste Marie de Cuines - St Michel de Maurienne	159.70	Cône du Fay: retaining walls and cutting	Declassification of sensitive sites in 2002
	160.00	Peak of Le Grand Châtelard: unstable masses	Declassification of sensitive sites in 2000
	162.90	Rocher de l'Escalade left bank: nailed wall and rockfall protection barrier	Declassification of sensitive sites in 2001
	167.40	Slope facing Pechiney: nailed wall	Declassification of sensitive sites in 2002
	167.80	Pechiney wall: Freyssisol walls	Declassification of sensitive sites in 2002
	173.00 to 174.00	Rieu Sec area: settlement area - OH no. 90 - PI no. 91 - OH no. 92 - embankment	Area still active, being specifically monitored
	174.40 to 175.00	St Martin la Porte area: - stability of SNCF platform - retaining walls	Area still active, being specifically monitored
St Michel de Maurienne – Le Freney	178.800 to 178.900	Upstream bed of Le Merderel	Declassification of sensitive sites in 2003
	179.600 to 179.350	Le Merderel outlet - La Saussaz retaining structures	Area still active, being specifically monitored
	~~179.600 to 179.800~~	~~La Saussaz slope - La Saussaz viaduct~~	~~Area still active, being~~

			specifically monitored
	179.800 to 180.200	La Saussaz area 1957 wall (RN6)	Area still active, being specifically monitored
	180.200 to 181.180	Drainage of Les Sorderettes spur - Les Sorderettes Tunnel	Area still active, being specifically monitored
	181.180 to 182.050	Les Sordières slope – cuttings and large retaining structures	Area still active, being specifically monitored
	184.350	Ventilation plants for Orelle Tunnel	Declassification of sensitive sites in 2003
	186.100 to 187.020	Les Chèvres viaduct and Les Berchettes embankment	Declassification of sensitive sites in 2003
	189.040 to 189.360	Combe Noire - Les Teppes area	Area still active, being specifically monitored

Table 3 *- Sensitive sites of the A43 motorway from Ste Marie de Cuines to St Michel de Maurienne.*

2.3. Publications

"*Travaux*" magazine devoted its September 1998 issue (no. 745) to the La Maurienne motorway (A43). In addition, several articles have been published, detailing the context and the solutions determined for certain structures. This article completes the bibliography and details the monitoring surveys carried out in two sensitive sites where evolution is not entirely completed:

- The Rieu Sec area between St Jean de Maurienne and St Michel de Maurienne includes three civil engineering structures and a very high embankment on a compressible base.
- The crossing of the Les Sorderettes spur between St Michel de Maurienne and Le Freney includes a tunnel that conveys the uphill lane through the slope under thin cover, and a series of retaining structures in cuttings that free the land take required for the downhill lanes.

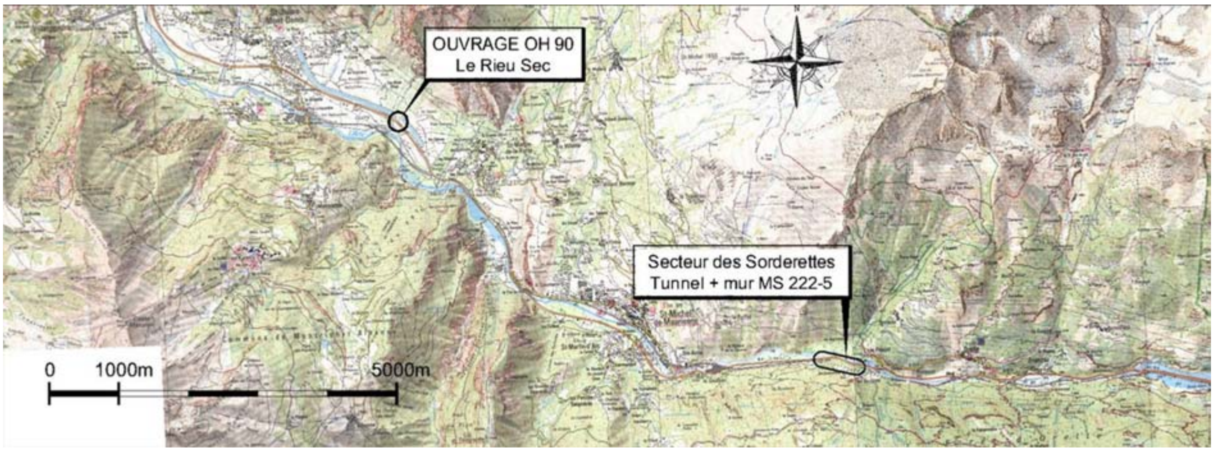

Figure 2: *Location of sensitive sites in the Rieu Sec and Les Sorderettes areas.*

B. RIEU SEC AREA (ST JULIEN - MONT DENIS)

1. HISTORY OF THE DEVELOPMENT AND OVERALL FEATURES OF THE SITE

Before 1957, the RN6 secondary road along the River Arc required major maintenance and repair work after every major flood of the torrent. The 1957 flood – with a flow-rate estimated at 650 - 700 m^3/s – submerged the RN6 road and destroyed several hundred metres of it (see Figure 3~~Figure 3~~). The 100-year record maximum flood (800 - 900 m^3/s) would have been even more destructive. In 1960, the RN6 road was rebuilt outside of floods, in its present location. The hydraulic structure on the Rieu Sec River (which had shallow foundations) and the road platform constructed with 7 to 8 metres of fill both date from that period.

Légende:
Flow-rate (m3/s)
June 1957
(hydrogram unknown)
September 1993
June 1994
September 1994

100-year record maximum flood
(design flood)

10-year record maximum flood

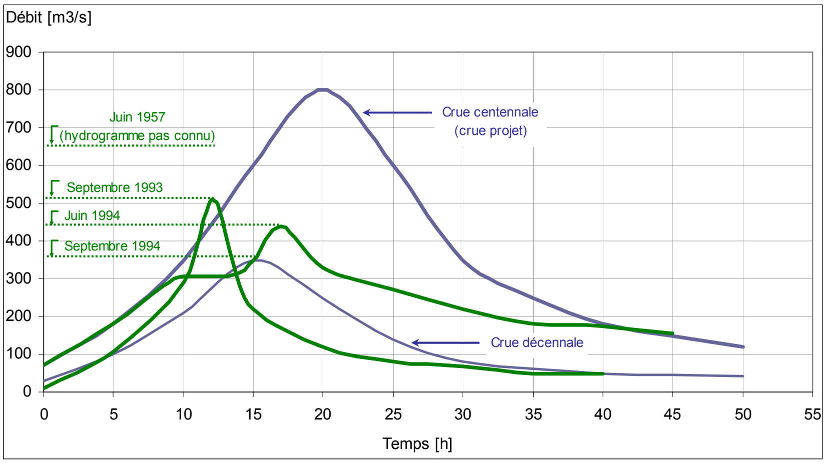

Figure 3 *- Histogram of floods of the River Arc.*

Between 1965 and 1970, Electricité de France completed the Arc - Isère hydroelectric development, including the Hermillon canal constructed by embankments a few tens of metres north of the RN6. The 12 to 18 m high parallel embankments that formed the canal underwent major deformation, with internal movement and settlement of their bases. In 1973, to impede these movements and reduce the danger of major landslide, the responsible authorities (EDF and DDE) decided to fill in the "dip" that remained between the south embankment of the Hermillon canal and the embankment of the RN6 road. Then, in 1978, this space was filled again with a few metres of fill. Considerable settlement of 0.5 cm/year was still occurring in 1995 at a depth of more than 26 m under the existing ground level:

- total settlement at the crest of the embankment from 1974 to 1995: 25 cm,
- total settlement at the crest of the embankment from 1984 to 1995: 8 cm,
- settlement of the base of the embankment from 1984 to 1995: 3 cm.

In 1993, strong floods (with flow-rate of the River Arc reaching 500 m^3/h) caused infill of the Rieu Sec's bed and the hydraulic structure, reduced the cross-section of the River Arc's bed and eroded the base of the railway on the south bank of the river. The 1993 photograph in Figure 4~~Figure 4~~ shows the site after the flood.

Construction of the A43 motorway in this area started in 1995.

***Figure 4** – Photograph of the A43 motorway after the 1993 flood.*

2. SOIL ENGINEERING CHARACTERISTICS OF THE SITE

On the north bank of the River Arc, the cone of deposits from the Rieu Sec River forms a pediment whose overall slope varies from 10% to 20%.. A survey conducted by EDF in 1973 (with continuous coring, extended as destructive drilling) found the following:

- around 60 m of compact granular materials with varying silt content, in blocks (torrential colluviums),
- more than 30 m of blackish silt (lacustrine deposit).

Despite the lack of in situ measurement and sampling, EDF attributed the settlement of the Hermillon canal embankments' bases to the lacustrine sediment. The surveys conducted for design and inspection of the A43 motorway gave the following results:

Design stage		Preliminary design	Design scheme	Construction inspections	
Surveys		Pressure meter	Pressure meter	Coring	Pressure meter
Thickness (m) of torrential deposits		> 20	> 21	> 45	> 30
Identification of compressible lacustrine silt		Not performed	Not performed	Not performed	Not performed
Behaviour of torrential deposits	Maximum pressiometric pressure Pl* (MPa)	0.7 to > 2.5 (1) (> 2.0)	1.3 to 3.5 (1) (2.5)	-	1.0 to 3.6 (1) (2.5)
	Pressiometric modulus E_M (MPa)	6.0 to 34.0 (1) (19.0)	13.0 to 35.0(1) (21.0)	-	9.0 to 50.0 (1) (26.0)

(1) maximum value obtained by eliminating measurements concerning boulders

***Table 4** - Pressiometric characteristics of design and construction.*

Two piezometric levels were found during investigations for the inspection of construction works:

- Suspended flows of water in the torrential dejections at a depth of 4 - 5 m below the topographic surface.
- A slope layer 12 - 15 m below the topographic surface connected to the alluvial blanket of the River Arc.

3. DESIGN AND CONSTRUCTION OF THE STRUCTURES

The torrential deposit is strong enough to bear the structures with shallow foundations. Without precise data for calculating representative settlement, an estimate of around 30 cm appeared plausible. The presumed location of the compressible horizon excludes any use of pile foundations due to the following:

- the load-bearing level is out of the depth range and is not recognized,
- Spurious loading on the piles (negative friction and horizontal thrusts) that is not acceptable if the base moves.

The structures were therefore built on shallow strip foundations protected against any risk of scouring by large masses of rockfill in the bed of the Rieu Sec (see Figure 5~~Figure 5~~).

Figure 5: *Structure OH90 in the Rieu Sec area (PI91 on the right).*

In order to be able to adapt to settlement of several decimetres and to the corresponding horizontal movements induced by the motorway embankment (18 m maximum height), the two structures located on a sensitive site were designed to be strong and deformable (isostatic structures). The crossing over the Rieu Sec (OH90) includes two separate adjoined structures constructed by Quillery. These isostatic structures with three spans have a concrete deck with prestressed beams and a link slab with structural joints on bearings. The local minor road under the embankment is re-established by an arch bridge of prefabricated elements (PI91 – using the "*Matiere*" technique) erected on a reinforced concrete raft cast in situ (arch with three links: a keystone and the bases of the abutments).

The construction work was phased according to the soil engineering constraints and requirements, applying the so-called "observational" monitoring method which, after a period allotted for monitoring any changes in the structures, allows the following to be adapted as required:

- the law governing the behaviour of the terrain,
- the geometry and strength of the structures.

Very quickly, during construction work, greater settlement than estimated was observed in the embankment and the structures. Abutment C3 of OH90 was being slightly tilted in the downhill direction, even though the 7 m of fill remained to be applied.
Faced with this situation, it was decided, during construction work, to anticipate some of the settlement at this abutment by applying an additional load of fill before constructing the deck, in order to reduce any residual settlement that could affect the structure after its construction. In addition, to anticipate deformation of the structure during operation of the motorway and thus improve user comfort, the south deck was constructed 2 cm above its

theoretical altitude, and the "red line" of the motorway was raised to 8 cm in the area of the greatest settlement.

Phasing of construction of the OH90 structure included, on the basis of the 662 mNG reference altitude level under abutment C3 (see Table 5~~Table 5~~):

- Fine grading and compaction of old deposits present on the site, and backfilling up to the 665 mNG altitude level.
- Construction of PI91 (a “*Matière*” structure located a few tens of metres away) and, at the same time, construction of the base of abutment C3 (backfill and block of coarse aggregate concrete compacted optimally).
- Construction of abutment C3 and pier P2, then additional backfill between P2 and C3.
- Monitoring movements of the abutment for one month, beginning measurements after the adjustment of the concrete support of the bearings (Oct. to Nov. 1996). Since the settlement observed (5 cm on the River Arc side and 1.5 cm on the RN6 road side, without final stabilisation) was much higher than forecast, it was decided to pre-load the bases of P2, C3 and the access embankment.
- Construction of the embankments up to level 672 mNG in the whole area, including for PI91, and up to level 679 mNG at abutment C3 and 30 m behind it (creating an additional load of 2.0 m of fill in relation to the structure’s final altitude level).
- Construction of a temporary stabilising platform, 10 m wide by 4 m high, in the bed of the Rieu Sec.
- Monitoring movements for 4 months. On 15 March 1997, when settlement of the bases of the embankments had reached around 20 cm, it was decided to stop pre-loading, to adjust the load-bearing systems and to install the beams on OH90.
- Finishing work on civil engineering structures of embankments and construction of carriageways for opening to traffic in January 1998. During this period, the civil engineering structures and carriageway were subjected to stringent topographical monitoring.

Table 5~~Table 5~~ shows the settlement measured during the different stages of the work:

Dates	Settlement	Work stages
Oct. 1996	*< 5 cm*	*Indicative settlement – backfill to 666 mNG.*
Dec. 1996	11.5 cm	Backfilling to 672 mNG
Feb. 1997	17.2 cm	Pre-loading of the abutment to 679 mNG
March 1997	17.8 cm	Unloading of the abutment
April 1997	17.9 cm	Construction of the deck
End of April 1997	18.0 cm	Reloading to 676.0 mNG

Table 5 *- Settlement measured in the embankment at abutment C3 during construction stages.*

4. ORGANISATION OF MONITORING AFTER OPENING OF THE A43 TO TRAFFIC

Once the settlement problem was identified, instrumentation was put in place during construction work to monitor the whole Rieu Sec area in order to be able to react to any changes that could possibly be detrimental to the long-term durability of the structures and the safety of users (see
Figure ***6***
~~Figure~~ ~~***6***~~). At structure OH90, this instrumentation included the following:

- two inclinometers (at a depth of 40 m) and three piezometers (at depths of 9, 10 and 20 m) between the A43 motorway and the RN6 minor road in the area around the PI91,

- two inclinometers (at depths of 40 and 50 m) and two piezometers (at a depth of 14.5 m) at the bottom of the downhill embankment slope between the Rieu Sec river and PI91,
- two settlement gauges in drill-holes at a depth of 60 m, placed at the edge of the uphill section of the motorway's half-platform,
- several topographical benchmarks.

Légende:
KEY FOR INSTRUMENTATION
Topographical benchmark
Inclinometer
Settlement gauge
Piezometer

***Figure 6** – Location of surveys and topographical benchmarks in the Rieu Sec area.*

The alarm threshold for deformation of the OH90 deck corresponds to a differential settlement (permissible loads in serviceability limit state) of 30 mm between spans. For embankments, the differential settlement threshold between two measurement points 20 m apart is 5 mm longitudinally and 5 mm per metre transversally. With the exception of the topographical benchmarks on the carriageway, which are positioned as part of the monitoring assignment, the site instrumentation was positioned during construction of the motorway between February and May 1997.

Monitoring before the motorway was opened to traffic in February 1998 showed the following:

- There was major settlement of the carriageway, of around 10 cm, but differential settlement remained acceptable (see Figure 7~~Figure 7~~).
- OH no. 90 underwent major settlement, which slowed down over time (10+20 = 30 cm for CO, and 18+55 = 73 cm for C3). The deformations measured were not uniform, since abutment C3 was settling more than abutment C0 and, in addition, settlement was greater on the South side than on the North side of the structure. This differential settlement caused gradual deformation of the structure's deck, which tended to twist (see Table 5~~Table 5~~).
- PI91 underwent major settlement of 30 to 50 cm during construction and 150 cm before the motorway was opened. This settlement tended to slow down in an asymptotic manner, but had caused abutting of several arch elements and cracking of several prefabricated elements (see Figure ~~Figure~~ 9).

Légende: Settlement (cm)

Raising of deck

Carriageway in the Rieu Sec area.
Deviation in relation to the original longitudinal section.

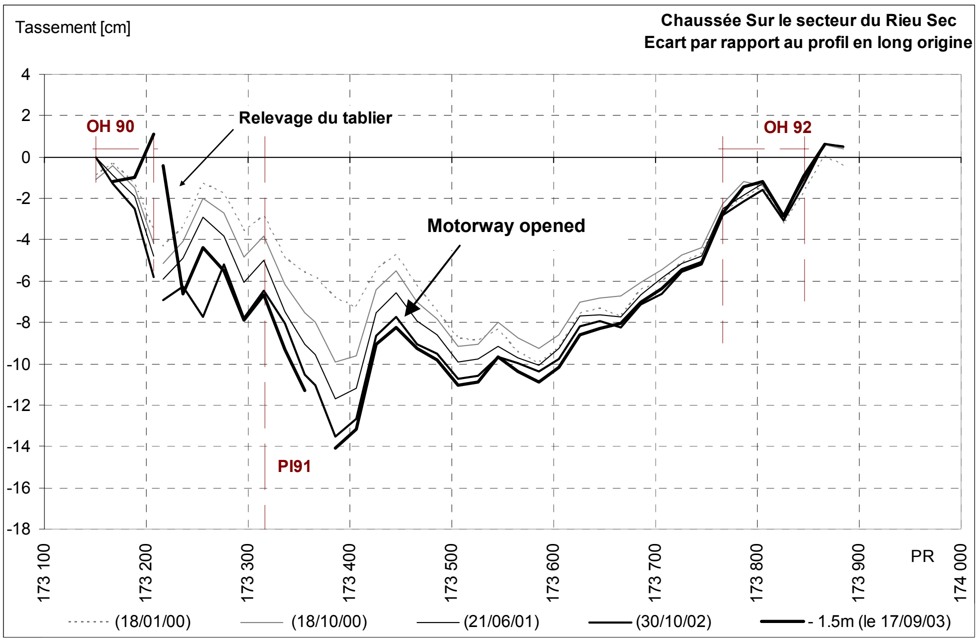

Figure 7 *- Settlement measured on the carriageway in the Rieu Sec area until Sept. 2003.*

After this first monitoring stage , the structure was subjected to 15 to 30 mm movement towards the River Arc parallel to the bearing lines, and relatively large settlement of all bearings except the P1 piles. This resulted in major distortion of the load-bearing systems. Therefore the bearings had to be readjusted (the first readjustment of the abutment level was in 2001 – see Figure 8~~Figure 8~~).

<u>During operational service of the motorway</u>, extrapolation of the currently available data indicates that this movement is continuing, while gradually slowing down. Settlement follows a law of the type s = A + B.log (T / T_o), where A and B have specific values for each pile and each abutment of the structure. In an uphill abutment, settlement follows the law s = 24 + 52 log (T / 100), with, in September 2001 (T = 1630 days), an amplitude of s = 24 + 52.log (1630 / 100) = 88 mm.
Extrapolation from September 2001 (when the level of the deck was readjusted) to September 2011 gives settlement of s = 24 + 52.log (5280 / 100) = 114 mm, i.e. residual settlement of 27 mm affecting the deck.

Since foreseeable settlement 10 years after readjusting the level of the uphill abutment should not be more than Δs ~ 27 mm, no additional readjustment has been planned for at least 10 years. Nevertheless, detailed monitoring of the structure is still necessary.

Légende: Opening to traffic

Raising of deck

downhill abutment
pier P1
pier P2
uphill abutment

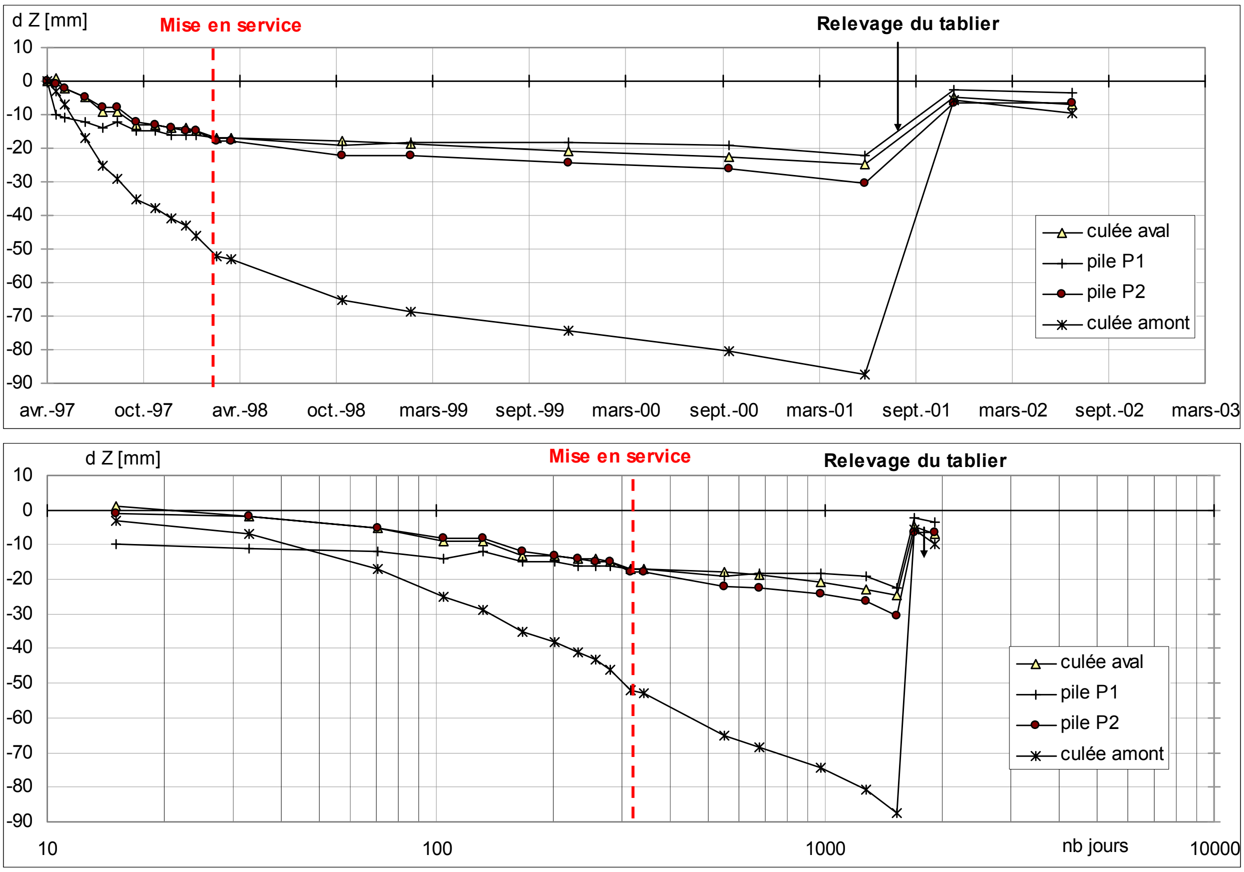

Figure 8 *- OH 90 Change in altitude – Deck in uphill direction – Normal and logarithmic time scales. Zero was redefined in April 1997, and it does not take into account settlement during the construction stage.*

Légende:
P191 – Changes in levels inside the structure

Opening to traffic Feb 1998
Feb 1997 May 1997 Dec 1999 July 2002

South downhill
South centre-line
South uphill
B (RN EDF)
North downhill
North centre-line
North uphill

Number of days

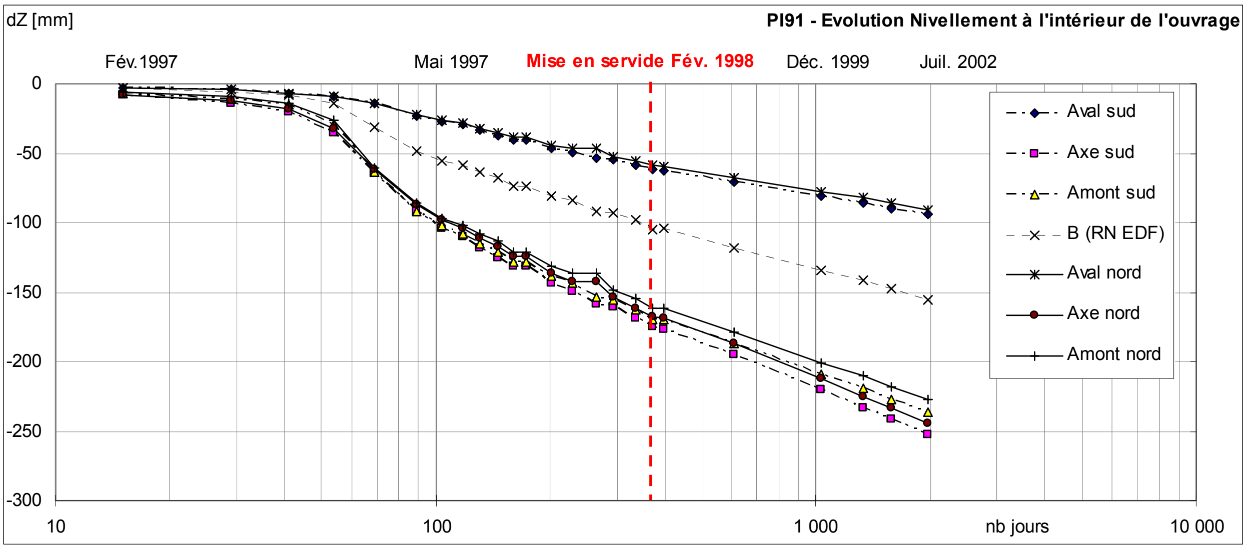

Figure 9 - *PI91 Assessment of settlement inside the structure. Zero was redefined in February 1997, and it does not take into account settlement during the construction stage.*

As a result of the assessment of settlement inside the structures and the carriageway, annual monitoring was continued until 2004. No anomalies were found in the variations in settlement. The phenomenon is developing towards stabilisation in the long term, as forecast on opening to traffic in 2000. Monitoring is now reduced, but it still necessary.

C. LES SORDERETTES AREA

1. HISTORY OF THE DEVELOPMENT AND OVERALL FEATURES OF THE SITE

The RN6 main trunk road, which is on the bank of the River Arc, at the bottom of the South slope, was considerably damaged by the floods of the River Arc. The floods in 1957 (with a flow-rate of 650 m^3/s) and 1968 (450 to 500 m^3/s) had, in particular eroded several hundred metres of the subgrade of the RN6, and it was decided to raise the road and railway permanently above flood water levels in the Eperon des Sorderettes area, and to widen and protect them.
Work was carried out in 1969 and 1970 with the development of the Le Poucet cone of deposit and the construction of walls on the south bank of the Arc that supports the RN6. Figure 10Figure 10 shows the complete present site in a narrow valley that is particularly constricted by the presence of the Arc, the Lyon - Turin railway line and the RN6.

***Figure 10**: Present state of Les Sorderettes.*

The 1969 work site suffered several ruptures of the slope, a rock landslide in the East part of the spur (see FigureFigure 11) and repeated landslides of loose ground during construction of a large masonry wall in the West part of the spur.

***Figure 11**– Rock landslide of Les Sorderettes spur in 1969.*

In this area, construction of the A43 motorway started in 1996 on the Les Sorderettes tunnel (for the uphill carriageway of the A43) and in 1998 on the major earthworks and retaining structures for the open air downhill carriageway.

2. SOIL ENGINEERING CHARACTERISTICS OF THE SITE

The Les Sorderettes spur consists of two rocky ridges that are visible in the bed of the River Arc, on the edge of a fossil-bearing groove full of scree. The rooted rock masses are shale and "*Houiller productif*" ["productive coal-bearing"] sandstone. They are very largely jointed and locally grinded. The scree is not uniform. They are composed of intertwining horizons, of silt, of silt with fragments of shale and sandstone, and of rubble including elements of the order of one cubic metre.

For the design of the tunnel and the large retaining structures, it was assumed that water flowed at the base of the scree (rubble) and in the very jointed rock through a depth of several metres. The information was obtained from the following sources:

- maps of springs which well up at the rock-scree interface on the slope a few metres above the RN6 road,
- data concerning the SNCF tunnel,
- surveys taken in the reconnaissance shaft and gallery constructed in 1994 - 1995 to validate the tunnel construction methods.

From the surface, several soil engineering and geophysical surveys were used to map the rock roof, to define the behaviour of the scree and to measure the piezometric levels. This data, which completes the observations mentioned above, was used to locate the rock substratum parallel to the slope at a depth of around 25 m, as well as large flows of water related to the fractured rock substratum and to the base of scree.
However, upstream of the slope, only the geophysical data was available, since it was impossible to have access to drilling equipment without major preliminary work. According to this geological scheme, the passage through the spur required specific earthwork:

- Excavation of a tunnel in the rock, 395 m long (including open-cut tunnel mouths) requiring excavation 15 m wide between abutments and 9.5 m high at the roof. This tunnel, which was made watertight on the extrados by a PVC membrane, has four 12 m long drainage ducts excavated perpendicular to the tunnel on the mountain side, to enable networks of drilled drains to be installed at the end of construction work to catch water flows at the rock / scree interface.
- Earthworks of which the extension, limited to the south, made it possible to not modify the railway tunnel's environment (earthworks in descending sections, in accordance with the phasing of construction of the retaining structures).
- Construction of retaining structures in gradual stages between levels 812 and 880 mNG with anchors of standard length (embedded nails 12 to 15 m long and prestressed rods no longer than 45 m) and subhorizontal drilled drains 15 to 30 m deep.

Excavation of the tunnel in half-sections was planned after injection of a 5 m thick ring in the roof (to consolidate and seal the ground) then draining by drilled drains rising through 5 m beyond the injection ring. The immediate retaining structure adopted was composed of bolts and concrete pumped into the rock, arch rings and shotcrete, under insufficient rock cover. Cuttings were made by explosives following sequential firing plans to comply with the vibration thresholds imposed by SNCF [the French national railway company]:

Frequency Mz	Particle speed mm/s
0 - 30	10
30 - 150	20

3. NEW DATA OBTAINED DURING INSPECTION OF CONSTRUCTION

Drill-holes for injection and drainage made it possible to define the topography of the rock roof more precisely. Through a length of 225 m, excavation of the upper half-section concerned the scree (presence of a shallow groove of glacial erosion that surface surveys had not recognized). Figure ~~Figure~~ 12 shows the position of this unique geological feature:

Légende:
Rock roof
Reconnaissance gallery
Work platform

KEY
Injection and drainage drill-holes
Loose ground

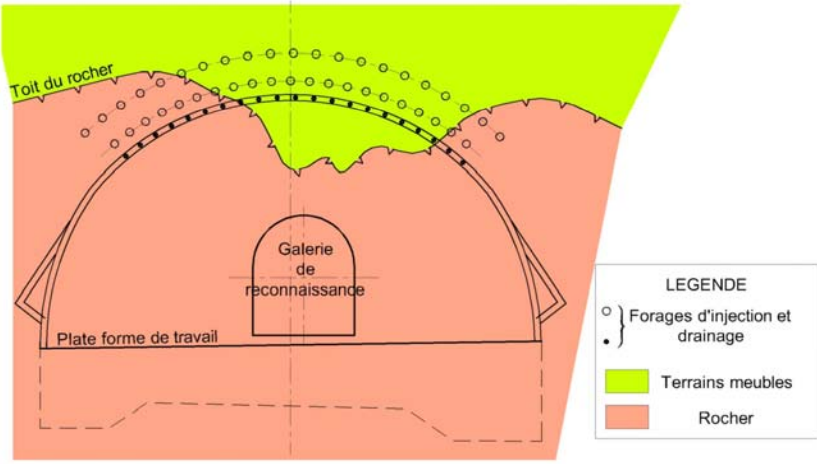

Figure 12 *– Area of penetration of loose ground in the excavated section.*

Some drains intersected strong water flows in the mass of scree whose base was often clayey. During injections, movements and cracks in the ground (observed by topographical measurements and visual inspection on the surface) were used to delimit a very large unstable area of extension that is 160 m along the axis of the project and 120 m along the gradient of the slope. The monitoring equipment including inclinometers and piezometers identified the following problems (see Figure ~~Figure~~ 13):

- unstable scree reached 30 m in thickness, such that a general landslide could cause major failure in the existing structures:
  - the RN6 during traffic flow (with 150,000 to 240,000 m^3 volume of unstable mass),
  - the access shaft to the injection site (risk of shearing between 20 and 25 m deep),
  - the tunnel during excavation (where the base of slippage is virtually tangential to the tunnel arch),
- slippage speeds up during injection phases and slows down during post-injection drainage phases (with 25 to 30 cm total overall movement),
- springs downstream from the tunnel dried up and the piezometric levels upstream from the project rose by 8 to 12 m (temporary upwelling at the top of certain piezometers).

Légende:
Former ground level

Downhill carriageway of A43
Nails

Nails
Uphill carriageway of A43
Railway tunnel
Tie rods

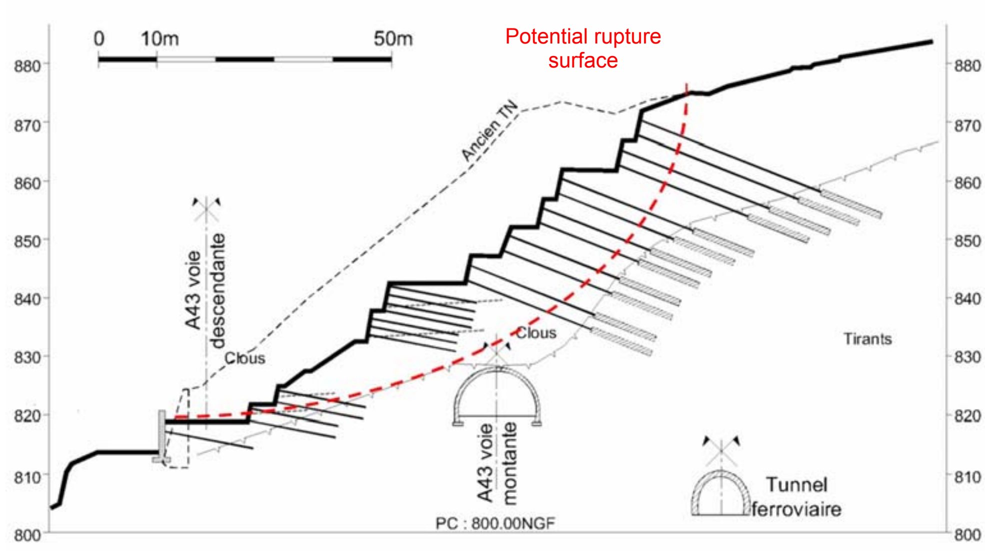

***Figure 13** – Cuttings at Les Sorderettes – Initial project design model.*

Additional investigations by coring surveys showed very high variability of the rock roof in relation to the results of geophysical measurements upstream of the slope (+3 / -10 m with successions of ridges and grooves virtually perpendicular to the River Arc). In addition, these surveys showed the presence of coal and mylonite beds in the very jointed sandy shale coal complex and masses of silt-gravel scree with large blocks, in contact with the rock, which geophysical measurements alone had not identified.

The start of slippage above the tunnel was used to calibrate a precise general stability model by converging the most realistic theories concerning the stratigraphy of the scree, the position of the rock roof, the geomechanical characteristics of the scree and the flows of underground water via localised permeable channels (since their collection by drilled drains was random).

4. ADAPTATION OF THE PRELIMINARY DESIGN FOR CONSTRUCTION

In order to continue underground work safely in the redefined soil engineering context, where surface movements exceeded 25 cm during a summer period of low groundwater level (August 1997), the following decisions were made to temporarily stabilise slippage:

- permanently stop injections,
- provide additional drainage by subhorizontal drilled drains from the bottom of the slippage (at the level of the RN6 road) by drilling upwards through 80 m, leading into the tunnel and from the shaft access track,
- consolidate the masonry retaining structures and the destabilised embankment by nailing on both sides of the access shaft.
- reinforce the tunnel's immediate retaining structure by an umbrella vault made with self-drilling bolts, 8 m long, every 0.50 m (see Figure ~~Figure~~ 12).

As regards to earthworks and external retaining structures, the two walls anchored by prestressed tie rods between levels 860 and 880 mNG were eliminated and replaced by an embankment inclined at an average gradient of 25° in relation to the horizontal. This decision resulted mainly from the lowering of the rock roof in relation to the project data, requiring the use of prestressed tie rods estimated at more than 80 m in length. The 20° to 30° angle of incidence of drilling on the rock roof through a length of 80 m also involved a major risk of deviation of the anchor zone. Stabilisation of this embankment substituted for the anchored walls required deep drainage by drilled drains, which was much more extensive than in the initial design:

Design stage	Initial design	Working design	Comments
Grid of drains (m)	5 x 20	5 x 10 5 x 5 (1)	(1) if every 10 m, the drain flow-rate is strong
Depth (m)	10 to 30	20 to 40	Requires deepening if there is any inrush of water at the bottom of drill-holes

The retaining structures below level 860 mNG were maintained, even though they required modifications of the anchorage. The nail lengths had to be increased, and the grid was decreased on the fronts that intersected low-compaction silty scree. The lengths of the active anchors were systematically modified according to the drilling parameters, in order to adapt to the real position of the rock roof and to the presence of open fractures, coal veins, mylonite veins, etc. The lengths of the drilled drains were increased and the grid decreased as for the uphill embankments (see Figure Figure 14).

Légende:
Former ground level

Downhill carriageway of A43

Piezometer

Location marks for monitoring survey
Piezometer
Piezometer
Inclinometer

Nails
Rock
Inclinometer
Nails
Uphill carriageway of A43

Inclinometer
Railway tunnel
Rock
Tie rods

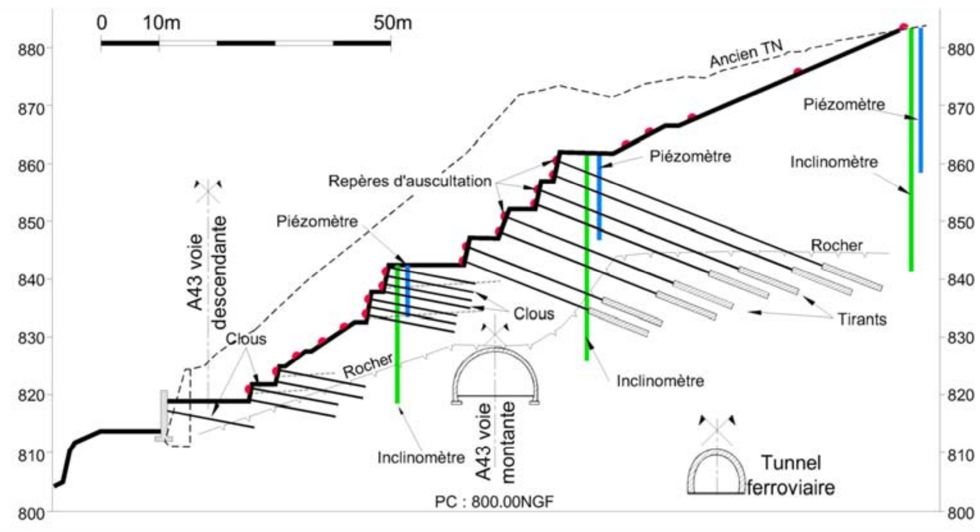

***Figure 14** – Cuttings at Les Sorderettes – Adaptation of reinforcement during construction.*

For economy, the thickness of the walls with passive anchors (nails) and active anchors (prestressed tie rods) were calculated such that the bearing ground would be frost-free. It transpired that most of the drains produced continuous flows, and the silt and silt-gravel screes were frost-prone (this classification is related to the particle size constitution, confirmed by specific laboratory frost tests). In order to assess the risks of clogging of drains by ice plugs that create high spurious pressure, due to rising groundwater and the formation of plates of ice behind the concrete facing, the Les Sorderettes structures were subjected to specific controls:

- systematic monitoring of the flow-rate of drains during the winters of 1998 / 1999 and 1999 / 2000,
- determination of the frost sensitivity of drains on the basis of the flow-rate and temperature of the underground water, the external temperature and the duration of periods of frost,
- establishment of a hydrogeological model by the Hydratec engineering firm, defining winter flow-rates on the basis of the meteorological conditions of the previous 10 months (supply of groundwater) and the potential upwelling if the drains were clogged by ice,
- definition of the reference situations and designation of the drains that required specific protection (those with flow-rates of less than 0.03 l/s in the sites considered).

Solutions using high-performance insulation were found to be very impractical, very costly and unattractive looking. As an experiment, the technique of heating water in the outfalls of the critical drains by means of thermistances (penetrating 5 m into the drains) was applied in two sites from winter 2000 / 2001. The electricity supply to the thermistances was activated according to two recorded parameters:

- external temperature (0 ≤ 0°c),
- water temperature (0 ≤ 2°c).

To date, controls by Terrasol in 2001 and then by SFTRF have not detected any indication of dysfunction of the technique, since energy consumption is very low.

5. ORGANISATION OF MONITORING AFTER OPENING THE A43 TO TRAFFIC

Major instrumentation was installed to monitor the behaviour of the walls during the different construction work phases. Movements found during the earthworks and the retaining-structure construction phase exceeded 5 cm, and exceeded 10 cm locally in retaining walls fixed by nails and tie rods. These movements decreased rapidly at the end of construction work, so that acceptance of the structures was pronounced after the near completion of the stabilisation of the site.
Work was completed in May 2000 without leaving any remaining critical areas apart from a 20 to 30 m wide strip where movements of a few millimetres towards the River Arc and settlement on two elevations continued to develop. Two particular problems were dealt with after the A43 was opened to traffic:

- frost protection of drains (an experimental heating system installed for winter 2000-2001).
- monitoring of abnormal piezometric levels in one of the retaining walls (piezometers damaged by injections of nails for anchoring ineffective retaining walls or sub-horizontal drains).

The following measurement equipment was installed for monitoring the structures during construction work:

- 67 dynamometric cells (for measuring the tension in the tie rods),
- 224 topographical targets,
- 17 piezometers,
- 12 inclinometers,
- 110 drains,

- visual observation.

The alarm thresholds were defined as follows:

Topography	Flatness: ± 20 mm of total movement. Altitude: 20 mm of total negative movement
Dynamometric cells	±10% variation in relation to the theoretical tension
Piezometric measurement	Any groundwater rise greater than or equal to the design piezometric surface (taken as the ground water level after drainage, increased by 4m).
Flow-rate of drains	The aim of drainage is to stabilise the groundwater level in flood condition. Therefore it is the flow-rate which is variable and which can increase during periods of "high water". This means that there are no fixed thresholds. However, any drying up of a drain which has always produced a flow will be considered as an indicator of an abnormal situation, which must be examined in detail.

Monitoring of the site was continued after construction work was completed. The monitoring systems were reduced, taking into consideration the stabilisation of the reference parameters. The data is presented below as an example, at the level of the tie beam in elevation H and the forest track (see Figure 15).

***Figure 15**– Locations of the measurement points on the retaining wall.*

The topographical measurements are given in *Figure ~~Figure~~ 16*. Since the original operation in January 1999, the beam has settled by -11 to -153 mm and has moved towards the River Arc by -9 to +67 mm. These high values correspond to the construction work phase. Since the motorway has been open to traffic, these movements have remained below the set thresholds: -8 to -12 mm settlement (with a threshold at -20 mm) and -1 to +5 mm crosswise movement (threshold at +-20 mm). For all points, the mean deviations are within the range of precision of the measurements, i.e., ±10 mm.

Légende:

Opening to traffic Variations in altitude due to movements of targets - Beam B10-H

J1 = 20/01/99 Zero measurement
J2 = 21/01/99 50% tensioning
J8 = 27/01/99 Lower earthworks

Target H1
Target H2
Target H3

July 98 Feb 99 Aug 99 Oct 00 April 01 Nov 01 May 02 Dec 02 June 03 Jan 04

Modane side

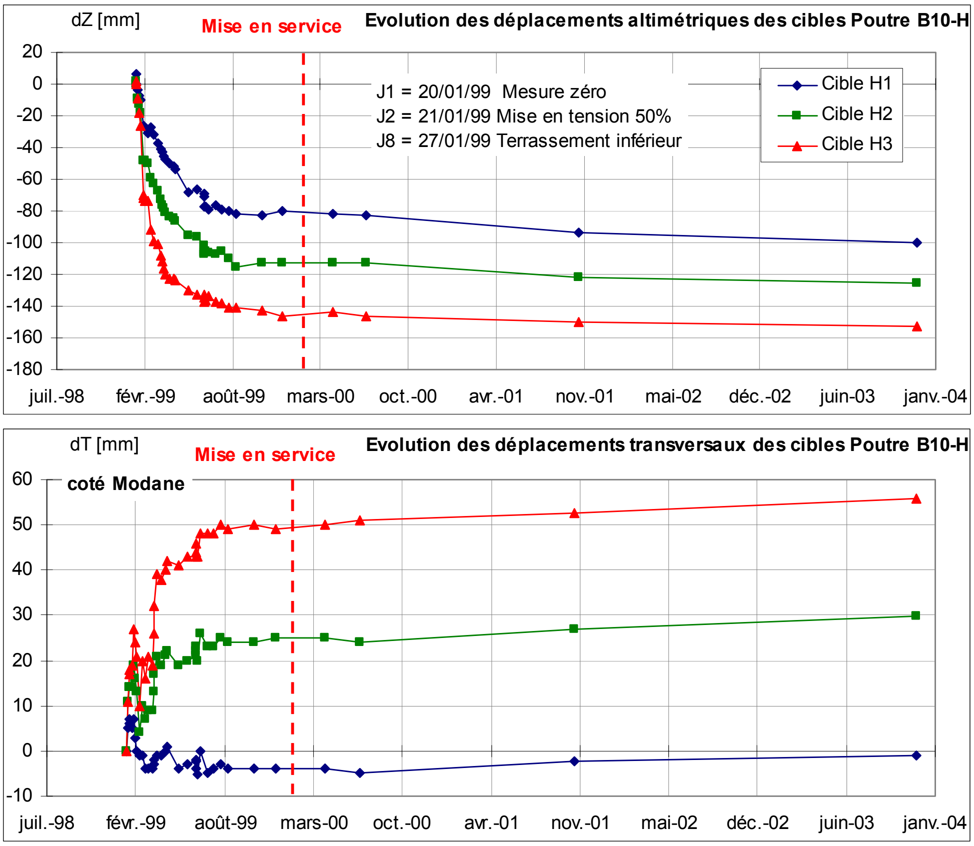

***Figure 16** - Retaining wall MS 222-5 of Les Sorderettes – Topographical measurements of 3 points on elevation H, from completion of construction until 2003 monitoring.*

The tie rods were installed with a theoretical tension of 1,274 kN. The measurements taken on the control tie rods are given in Figure ~~Figure~~ 17. They show that tensions vary within the required limits, with a slight tendency to decrease. Cell B14-2 is notable for its instability since the opening of the motorway, although the topographical measurements, including those in February 2004, do not show any apparent deformation on the facing of beam H. The next measurement will provide information on the development of this tie rod (identifying either a tension fault or damage to the dynamometric cell). At this stage, the tie rod's capacity is not questioned, but replacement of the cell must be envisaged.

Légende:

Tension (kN) Tension of tie rods - Elevation H

Jan 01 Feb 02 Sept 02 Mar 03 Oct 03 April 04

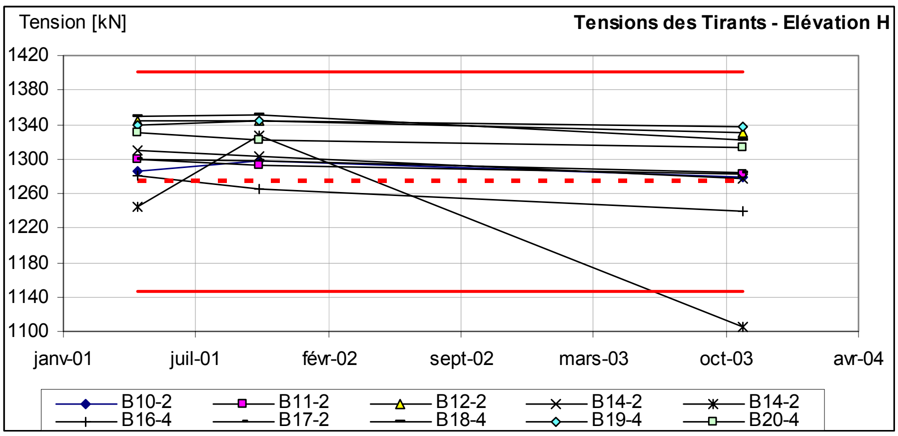

***Figure 17**- Retaining wall MS 222-5 in Les Sorderettes – Measurements of the tension of the tie rods in elevation H since the motorway opened to traffic.*

The last measurements of drains were taken in March 2001 and are given in *Figure ~~Figure~~ 18*. It is difficult to interpret the piezometric levels and to compare them to previously-defined alarm thresholds, since the measurements are not always taken in the same season. Therefore it is difficult to correlate them, because November is a period of high water levels and February is normally a period of low water levels. The level of water at beam H remains below that measured during construction work from January 2000. Piezometer No. 14 shows a sharp increase in one single value in March 2001, while the other piezometers are stable. During topographical checks between 2001 and 2004, no abnormal movement in the structures was found. Therefore this equipment must be supervised, and cleaning of the piezometers has been recommended. For the other piezometric levels, the alarm thresholds were not reached.

Légende:
Variation in the piezometric level (m) Variation in the piezometric level (MS 222-5) – Forest track
Oct 01 Oct 98 April 99 Oct 99 Mar 00 Sept 00 Mar 01 Sept 01

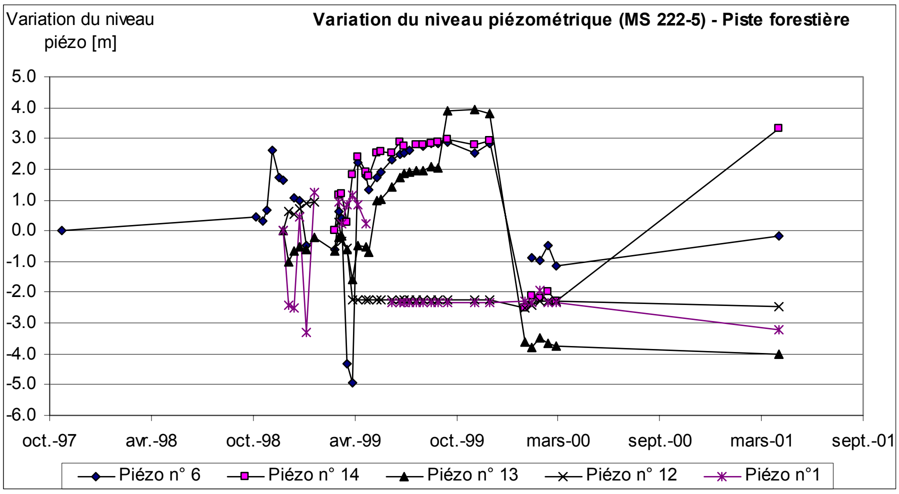

***Figure 18**- Retaining wall MS 222-5 in Les Sorderettes – Measurements of variations in piezometric level in elevation H.*

Considering the variations observed since the opening of the motorway, we must conclude that the structure is still subject to some movements. These movements go hand in hand with a slight local loss of tension in the tie rods. Following the new measurements planned for 2005, the detailed analysis of the results should enable us, if necessary, to define a maintenance programme aimed at re-tensioning certain tie rods, cleaning the drains and piezometers, and providing additional drainage.

CONCLUSIONS

The A43 mountain motorway was designed to fit into into the valley of Arc en Maurienne. The construction work required that specific adaptations be applied for each structure according to the geological and soil engineering conditions observed.
The structures in the Rieu Sec area, built on a compressible terrain of torrential colluviums and lake bottom deposits, were designed to support major settlements. The monitoring survey of this area showed that deformations exceeded the thresholds required in operational service. It was then planned to raise an abutment and the piers of the OH90 structure. Interpretation of the measurements showed that settlement is continuing to vary according to an asymptotic curve, and that all settlement in the next ten years will remain permissible. The structures must still be monitored to ensure that the deformations are varying in an acceptable manner.
The passage through the Les Sorderettes spur required two particularly difficult structures to be built: the tunnel for the uphill carriageway of the A43 and the large cuttings and

retaining structures for the downhill carriageway. The preliminary surveys provided only an incomplete account of the real soil engineering conditions, and the great heterogeneity of the site led to incidents (destabilisation of the slope in 1997, and deterioration of the drainage system). It was necessary to adapt the method for underground work; to make major modifications to the distribution of the retaining structure and reinforcements of the passive anchorage systems, with active anchorage to take into account the characteristics of certain terrains; and to improve the drainage system. These adaptations, which were made until final completion of the works, would not have been possible without the decisive participation of the following soil engineers seconded to the construction project:

- Terrasol, within the project management and design team,
- Simecsol, for the construction contractors.

The necessary monitoring surveys and the frequency of measurements were defined before the motorway was opened to traffic, and were submitted for approval to the motorways concessionary company. The instrumentation, the working procedures, the frequency of measurements and the specific alert thresholds for individual structures enabled us to anticipate any deterioration and to optimise the cost of maintaining the structures, by proposing appropriate reinforcement work to the concessionary company, in order to ensure the level of safety required by regulations.

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