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Lausanne's M2 subway stays on track

F Gaj and M Badoux, of Metro Lausanne – Ouchy SA, describe the construction of Lausanne's new subway line and in particular the collapse and recovery of the Saint Laurent Tunnel in 2005

With a population of about 250,000 the city of Lausanne, in Switzerland, is unusually small to have its own subway line, particularly a fully-automatic one. The goal of this ambitious project, called 'Projet M2', is to boost public transportation in a city characterised by difficult topography and an ever-growing traffic problem.

The project received broad public support in November 2002, when the local state population voted to fund the project. Construction started in spring 2004 and at present is on schedule, with commercial service planned for fall 2008.

The M2 line will climb over 300m on the slopes of Lausanne. The average gradient being 5.7%, rising to a steep 11.7% at its maximum. Driverless trains will feature rubber tyres allowing them to climb slopes that would usually require cable-car or 'crémaillère' railway technology.

The 6km long infrastructure project includes fourteen stations, 2.9km of new roadheader excavated tunnels, 2km of new cut and cover tunnels, 0.6km of renovated 19th Century tunnels and 0.5km of bridges and open cuts (figure 1). The total US$607M project cost, is split approximately 50% for the civil works and 42% for the rolling stock and the E&M installations.

The owner - a public transportation company owned by the city of Lausanne – awarded the civil works contracts based on bill of quantities and fixed prices. About 10 contractor teams were selected on the basis of a public tender procedure.

Above: Excavating the Langallerie tunnel
Right: Fig 1 - M2 alignment with tunnels

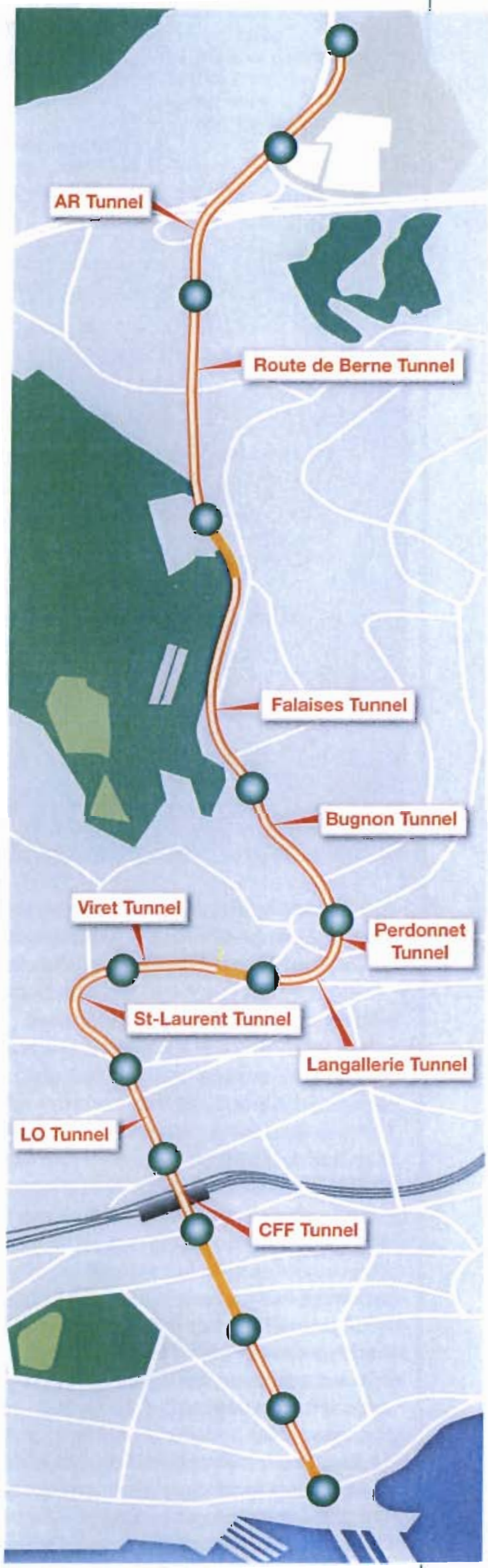
Tunnelling challenges

The M2 tunnels have been excavated by Eickhoff and Voest-Alpine roadheaders (*T&TI* November 2004) in full sections varying from 9.9m wide x 6.7m high to 11.7m wide x 7.6m high, except for the Langallerie tunnel which was excavated sequentially, starting with side drifts, top heading, bench and invert.

In general, temporary support consisted of lattice girders or heavy steel ribs, where necessary, with a 100-250mm thick fibre reinforced shotcrete layer. Lattice girders were replaced by Swellex type anchors when the rock quality allowed it. A 200-300mm thick fibre reinforced shotcrete layer makes up the final lining.

For cost and time reasons, a traditional cast in-situ concrete final lining was not used, and most of the tunnels have not been waterproofed. The Viret tunnel is the exception, and is waterproofed with a spray-on membrane (UGC's Masterseal 345) applied directly onto the primary shotcrete lining. A full 360° waterproofing arrangement was used where necessary.

Most of the M2 tunnels are at a low depth of 15-25m, generally in relatively good rock, known as molasse, composed of alternating sandstone and marls, although some sections are very shallow and sometimes in



weak water-saturated soils of sands and gravels. These difficult soils are often situated in dense urban areas where the foundations of overlying buildings are very near to the tunnel. The most challenging tunnelling conditions on the project were found at:

- The Saint-Laurent tunnel, where excavation took place beneath an old

Lots	Engineers	Contractors
2000	**SDIA** SD Ingénierie, CETP Giacomini & Jolliet Catella, Hauenstein & Ehrensperger	**CTC 2000** Batigroup Marti et Perrin Frères Bertholet & Mathis
1900		**ATV** **Association Tunnel Vennes** Infra Tunnel, Bernasconi
2100	**EMCH & BERGER +LUSCHER**	**JPF Construction SA**
1700	SD Ingénierie, CETP Giacomini & Jolliet Catella, Hauenstein & Ehrensperger	**MABAT 1700** Marti, Batigroup
1600		**RAM** - Rusconi, Martin, ADV
1500	**GEB** Emch & Berger GEOS, DIC Architram Inst. Géotechnique	**Consortium Lot 1500 - CHUV** JPF, Induni, Evéquoz et Gétra
1400		**Groupement 1400** PraderLosinger, Losinger Construction, Frutiger Vaud, Murer, Déneriaz Sion
1300	**GEMEL** GVH Tramelan SA, Géotest, Architramm Fellrath & Bosso SA	**APB - Association Pont Bessières** Losinger Construction, Frutiger Vaud
1200	**GIT-LEB** Piguet & Associés CSD-Monod Tschumi-Merlini	**AOC** **Association Ouchy-Croisettes** Dénériaz, Zschokke Locher Grisini Zaugg, Zschokke Walo Bertschinger
1100		
1030	**SDIA** SD Ingénierie CETP Giacomini & Jolliet Catella, Hauenstein & Ehrensperger	
1020		**Consortium Lot 1020** JPF, Frutiger Vaud
1010		**Consortium RAM** Rusconi-Martin-ADV

Top: Saint-Laurent tunnel. Note the passage under the 19th Century 'Grand-Pont' masonry bridge
Above: Construction of the Pont St-Martin below the Pont Bessières

masonry bridge called the Grand-Pont

- The Langallerie tunnel, where excavation was carried out through sands, gravels and silts, just 3-4m under the foundations of the Rue Langallerie buildings
- The Viret tunnel, which was excavated less than 1m beneath the foundations of the Rue Madeleine buildings
- The Bugnon tunnel, excavated through sands, gravels and silts, less then 1m beneath an existing tunnel that connects two hospital buildings

Different consolidation techniques were used to ensure structural safety and settlement control during the construction of the tunnels which included: Umbrella forepoling for tunnel crown pre-reinforcement; fiberglass nailing of the tunnel face; jet-grouting, both vertical and horizontal; and cement grout injections by means of 'tube á manchettes' for ground improvement.

A particular feature of the M2 project is the inclusion of existing and historic masonry within the new infrastructure. This is illustrated with two examples.

A new bridge through old piles

Building the M2 required the construction of a new bridge (Pont St-Martin) through the piles and abutments of an existing 100 year-old masonry and steel bridge (Pont Bessières). Due to the changing topography of the city, it was necessary to build this bridge across a deep valley that intersected the subway line between two tunnels.

The valley is densely built up with little room for new structures, so the designers made the bold decision to build the new bridge just below an existing one. To facilitate this, mini-tunnels had to be bored through the existing masonry piers of the 100 year-old road bridge without interrupting the bridge traffic.

The technique adopted to excavate the piles of the existing bridge was a mix of structural engineering and underground technology. Firstly, the bridge's piles were reinforced using longitudinal and transversal pre-stressed cables and passive anchors to confine the remaining pile material around the mini-tunnel to be created. Umbrella forepoling was then used to reinforce and protect the crown of the void to be created.

The mini-tunnels were then excavated through the bridge masonry using hydraulic hammers, and the mini-tunnels and bridge supported by the construction of a reinforced concrete frame.

19th Century tunnel refurb

The LO tunnel was built in the 1870's for Europe's first cable-car, a short water-powered train system for cargo transport. This historic traditional stone masonry

Lot n°	Tunnel	Partial length (m)	Total length (m)	Start	End	Cost (US$M '03)	Cost per m (kUS$ '03)
1200	St Laurent Sud	177	314	30/07/06	27/07/06	13.8	44
	St Laurent Nord	137		11/07/05			
	Viret	279	279	17/06/05	12/06/06	7.2	25.7
1300	Langallerie Nord side drift	136	136	04/07/05	01/02/06	12.6	95.6
	Langallerie Sud side drift	136		24/06/05	06/02/06		
	Langallerie top heading & bench	136		19/01/06	28/07/06		
1400	Perdonnet	67	67	11/02/06	21/09/05	3.4	50.6
	Bugnon Sud	358	486	30/09/05	14/03/06	14.6	30
	Bugnon Nord	128		03/03/05			
1500	Falaises	503	503	14/09/04	13/07/05	12.9	25.8
1700	Route de Berne	662	662	08/06/04	09/11/05	15.9	24
1900	Autoroute	442	442	09/08/04	16/09/05	11.3	25.8
	Total length	2889	2889		Total cost	92	31.7

Left: View inside the collapsed Saint-Laurent tunnel

Below: View of the historical Place Saint-Laurent after the accident

construction is in good structural condition and is wide enough to be 'incorporated' into the new infrastructure.

In order to adapt this tunnel to the new metro alignment, the invert of the tunnel needed to be lowered by up to 6m. Obviously, this had to be done without damaging the tunnel structure and the buildings above.

The solution chosen was to install a triple curtain of sub-vertical jet-grouted columns on both sides of the tunnel to provide vertical underpinning of the foundations. Following this, the first 2m was excavated downwards. To improve the adjacent ground and to provide horizontal support, 45° inclined jet-grouting reinforced 'anchor-columns' were installed.

These processes were repeated until the required depth was reached. To complete the task, new foundations and walls were cast, and horizontal metallic props were installed at mid-height.

The Saint-Laurent tunnel incident

The project was unfortunately marred by a serious construction accident late in the afternoon on 22 February 2005, when the face of the Saint-Laurent tunnel collapsed after an unexpected pocket of saturated sands and gravels was encountered.

The collapse was sudden and came after water infiltration went from minor to significant within two hours. A large volume of mud flowed into the tunnel. As a result, a sinkhole formed under a main square of Lausanne's downtown historic shopping district (Place St-Laurent) and partially under the foundations of a multi-story building. In the following hours, the sinkhole volume grew to about 1500m^3.

Thankfully, there were no casualties and the accident only caused material damage. The total cost - including construction costs for recovery and rebuilding, and costs incurred by third parties - is estimated at about US$13.5M.

The response to the accident obviously required prompt and decisive action. Within two days, measures had been taken to stabilise the situation and avoid the progression of the sinkhole, which threatened to cause adjacent buildings to collapse. These measures included:

- Stabilisation of the sinkhole walls with shotcrete
- Further stabilisation of the sinkhole with sprayed liquid nitrogen, to freeze the soil and reduce the erosion induced by water
- Creation of a wall of piles bored from the surface into the tunnel. This wall acted as a 'plug' by blocking the flow of material from the sinkhole into the tunnel
- Filling of the tunnel 'upstream' of the plug wall (described above) with concrete
- Filling of the sinkhole with porous material specifically chosen to avoid settlement and to match hydrogeolgical characteristics of surrounding soils
- In parallel, one of the buildings was braced with a temporary steel structure

Ten days after the accident, the sinkhole had been filled and the crisis phase was over. Three more months were required until the surface utilities and works were entirely rebuilt and all signs of the accident erased.

Rebuilding

After the crisis phase, the project management quickly turned its attention to rebuilding the damaged tunnel and restarting excavation. The first objective was to guarantee the safety of tunnelling crews and to ensure that a second accident did not occur. The second objective was to minimise construction delays and to ensure that the overall project schedule would not be affected by the accident.

It was determined that a 35m long zone of soft and partially disturbed soil between the collapsed tunnel face and a molasse rock formation would require special excavation techniques. For schedule and safety reasons, it was decided to open a new excavation front from the northern end of the tunnel in order to excavate this critical zone from the rear.

The crown was pre-reinforced by means of double umbrella heavy forepoling, created using metallic tubes and grout injections through single 'manchettes'. Ahead of the face pre-reinforcement was carried out using fiberglass nails coupled with grout injections through single manchettes. More than 500m^3 of grout was injected into the soil, with pressures ranging from 3 and 5 bars, to improve its geotechnical characteristics.

The new excavation front was activated four months after the accident and the consolidation works and the excavation of the critical zone lasted seven months. The delay on the construction of the Saint-Laurent tunnel was less then a year and it was possible to compensate for this by reorganising and accelerating other neighbouring tunnelling and construction activities, so that there was no impact from the accident on the overall schedule of the M2 project.

Lessons learned

Clearly, incidents such this should not happen, the potential consequences are simply not acceptable. A panel of experts was set up to find the cause of the accident, and the findings confirmed that the root cause was an age old classic.

Even though it matched actual conditions along most of the tunnel length, the geological model guiding the design and excavation was locally inaccurate (water-saturated weak soft-soils were anticipated, but much higher above the tunnel).

Obviously, risk scenarios that can lead to a tunnel collapse must be thoroughly investigated through geological exploration (this can be more difficult in urban settings). In the case of a shallow tunnel with the possible presence of water, the odds of encountering dangerous, unexpected, geology must be reduced to a minimum.

But what if an accident happens nevertheless? It might be of interest to mention a few observations regarding the M2 accident - made with the benefit of hindsight. The following elements played a positive role in the crisis management and rebuilding phase that followed the accident:

A centralised crisis management structure was set-up the night following the accident. It included the project partners (owner, engineer, contractor, experts) and city services (primarily utility, emergency and communication services), as it was very important in the immediate aftermath of the accident to have access to utilities data and structural plans of neighbouring buildings. It was also important to have clear and coordinated communication with media, authorities and affected neighbours.

The owner's representatives took a leading role in the management of the crisis and in defining the course of action for the rebuilding phase. In an extraordinary situation where time is short and indecision costly, the owner's representatives must ensure that decisions are taken quickly and that they are optimised in the 'safety, schedule and cost triangle' (see box).

The political authorities (city and state authorities and the federal administration responsible for overseeing project safety) were careful not to unnecessarily block or delay the project.

They demanded additional technical reviews and new risk analysis be carried out for the tunnel in which the accident occurred and for selected other sections that were under construction. This was done within the 'pre-accident' contractual and working relationship framework, without disrupting the overall project.

In particular, the City Councilman overseeing the project, was able to help 'protect the project' from over-reactions that could have brought long and fruitless delays.

The project is set-up so all the partners are insured by a common insurance company. This reduced the potential for conflict between the partners following the accident. Together with the extremely fortunate fact that there were no casualties, having a common insurer with a stake in instigating reasonable recovery solutions, helped the partners to continue to work together independently of the investigations into who or what was responsible.

It appears that the positive management of the consequences of the accident significantly reduced the damage to the credibility and image of the Projet M2.

Despite everything, the local population still generally holds a positive view of the project, which is still on schedule to start operation on 2008. T&T

The M2 project is managed by a team assembled by the project owner and most of the engineering services are delegated, as usual, to specialised engineering firms. The Owner's team has varied tasks ranging from administrative follow-up, to the promotion of the project.

However, in the end, its primary role is to ensure that the project schedule and budget are respected without compromising the safety and quality requirements.

It is clear that on a large public construction project, the owner has to do more than record decisions and events and process payments. It has a central role in assisting and guiding the project engineers and contractors in a sustained search for better solutions. It is best positioned to arbitrate between conflicting demands.

The diagram above illustrates the 'evaluation space for technical issues' as a triangle, bringing together the three key elements of project management. Meeting technical requirements (in terms of quality, performance and durability), controlling costs and respecting schedules cannot be dissociated. It is not enough to have one or the other.

Of course, safety considerations must be treated differently because they include non-negotiable elements. But there is usually a range of solutions to a given problem which satisfy clearly identified safety requirements (if possible considered in a risk analysis framework) and optimisation in the quality-planning-costs triangle still applies.

One-dimensional problems are the exception; it is usually beneficial to explicitly try to address problems in the three-dimension evaluation space. Identifying and evaluating possible trade-offs is difficult, but it is often the key to finding a well-suited solution.

In summary, when possible - and without interfering with safety aspects of the projects for which the specialist engineers and contractors are responsible - the owner's representatives should foster a project culture in which design, problem-solving and decision making explicitly happen in the quality-planning-costs triangle.

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