Sentvid's merging mega caverns

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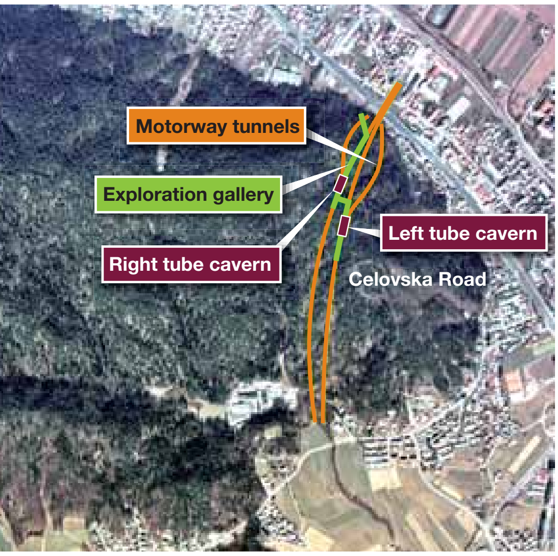
Table 1: Definition of rock mass types (RMTs)

Rock Mass Type	Lithology, prevailing	Basic description
RMT1	meta-sandstone	schistosity <150mm, Slightly to moderately sheared
RMT2	meta-siltstone	schistosity <30mm, moderately to highly sheared
RMT3	slate	schistosity <10mm, highly to intensely sheared
RMT4	fault materials	Soil-like, chaotic, intensely sheared



Left: Fig 1 - Project layout

The Sentvid Tunnel Project, as part of Slovenia's Ljubljana motorway bypass, foresees the construction of two merging caverns with a maximum cross section of ~ 360m^2 in a highly faulted rock mass. The decisions on the feasibility, layout and support design of the caverns demanded a geological-geotechnical model that could predict the rock mass behaviour to an unusually high accuracy. To achieve this target, deformation monitoring data were considered for the development of the geotechnical model. These deformation data were collected during the excavation of an exploration gallery and during the excavation of the main motorway tunnels. The interpretation of deformation data in relation to a detailed geological documentation permitted an understanding of, and the prediction of particular deformation patterns that could be critical during cavern construction.

The Project

The Sentvid Tunnel Project is situated in a highly tectonised sequence of meta-sediments at the South-Alpine Thrust Front. Two ramp tunnels are foreseen to connect the Celovska Road to the main twin-tube tunnel via two underground caverns with a maximum cross-section area of ~360m^2. In 2004 an exploration gallery (excavation cross section ~ 12.5m^2) was excavated along selected alignment sections of the main tunnel tubes to investigate the potential cavern locations in necessary detail (figure 1). Based on the information provided from gallery excavation, the general feasibility of cavern construction was confirmed and the most favourable cavern locations were selected. Excavation of the main tunnel structures commenced in January 2005 and had reached the cavern locations, including a first drift through the caverns, in March 2006.

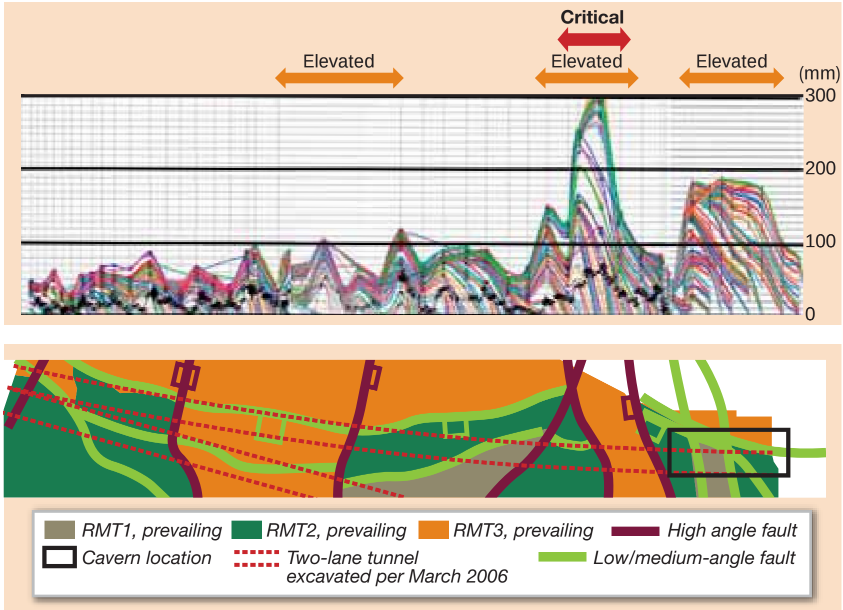
Geological documentation

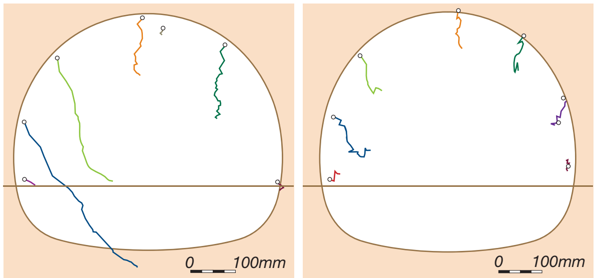
Geological face logging was/is performed routinely during the excavation of the exploration gallery and of the main tunnels. Each face log is classified and assigned to one of four rock mass types (RMT1 to RMT4, Table 1). From the documentation of the gallery excavation a geological model was interpreted and later adjusted with regard to the additional information collected during the main tunnel excavation. The geological model displays distinct geological-geotechnical domains that are characterised by the prevalence of particular rock mass types and particular fault patterns.

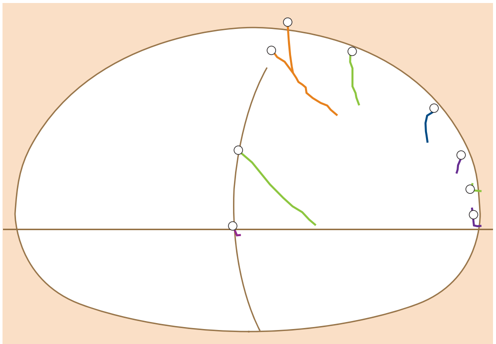
The displacements during tunnelling are monitored by optic measurements, providing absolute co-ordinates for each measurement. Monitoring targets are mounted at selected monitoring cross sections immediately after the application of primary support. Monitoring sections (MS) are placed in intervals of ~ 20m in the exploration gallery, ~ 10m in the main tunnel excavation, and ~ 5m along cavern sections. Measurements are taken daily after target implementation and weekly to four-weekly after the decline of displacements. The data are continuously processed by software for the documentation, presentation and evaluation of deformation data[5]. Standard presentations of data in weekly reports include state diagrams along the excavated tunnel section, as well as displacement history and vector diagrams for individual monitoring cross sections. For the purpose of geotechnical modelling the interpretation of displacements concentrates on geological aspects, though other influencing factors such as primary support and excavation sequence are also taken into account.

Deformations during excavation

Most deformation modes observed during gallery excavation were controlled by discontinuities that are typically sheared. Overall stress-induced failure of low-strength rock mass (RMT3, RMT4) was rarely observed but predicted to be increasingly relevant for large-span excavation of the main tunnels and the caverns. Associated radial displacements of unexpected magnitude were assessed







Above: Fig 2 - Horizontal displacements along left-tube two-lane tunnel excavation

to be the most critical risk factor for cavern excavation. Re-profiling implicated by displacements exceeding the deformation tolerance would not only affect safety issues, but would also be technically demanding, time-consuming and costly.

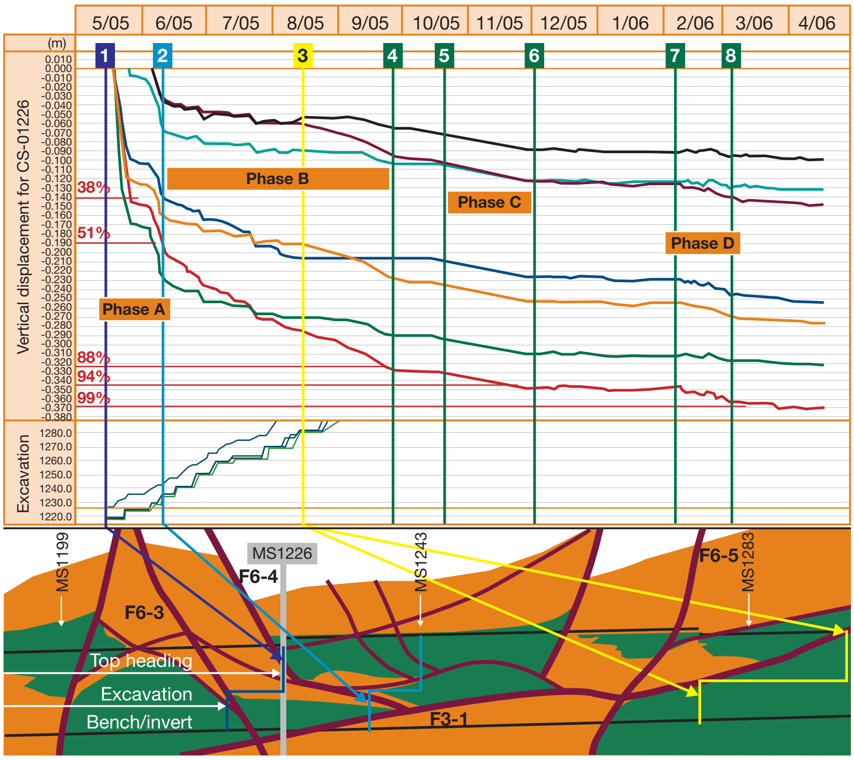
The caverns were eventually placed at alignment sections, where – in sequence of importance - 1) the lowest deformations were observed during gallery excavation, 2) the most favourable rock mass types prevail, and 3) the interference of prominent faults could be largely avoided. The overall feasibility of cavern construction was confirmed by 3D finite element calculations for both cavern locations.

The most critical scenarios were expected for the left tube cavern:

- Elevated radial deformations along the merging section, where the two-lane tunnel, the ramp tunnel and the associated pillar are situated in very poor rock mass (RMT3/RMT4) related to a prominent high-angle fault perpendicular to the centre line.
- Lateral displacements of the left cavern sidewall, caused by rock mass relaxation along medium-angle faults sub-parallel to the centre line.

Deformations during tunnel excavation

- As evident from deformation data of two-lane tunnel excavation, the increasing excavation span influenced the deformation patterns, magnitudes and their relation to rock mass types in ways that deviated in some aspects from the predictions:
- As expected, critical displacements were found related to the presence and orientation of specific shear planes rather than to overall rock mass properties.
- Critical asymmetric displacements with an elevated horizontal component occurred – also as expected - predominately along left sidewalls, where rock mass relaxes along medium-angle shear planes oriented (sub)parallel to the centre line. The displacements are enhanced by sliding along high-angle faults obtuse or perpendicular to the centre line. The vector diagram for monitoring section MS 1395 in Figure 2 reflects, how the rock mass confined by two prominent faults in the left sidewall moves into the tunnel excavation. Initial displacements within 1 week after zero-reading reached ~160mm, displacements before excavation of the invert accumulated to 300mm. Total displacements by April 2006 amount to 320mm.
- Contrary to the predictions, the most critical displacements, exceeding 300mm and locally 400mm, occur as roof settlements. Such displacements are observed along a 60m long tunnel section, where rapid relaxation of poor rock mass develops perpendicular to very-low-angle faults and schistosity. The displacements are initiated and enhanced by relaxation sliding along high-angle shear planes. The vector diagram for monitoring section MS 1226 in Figure 3 indicates rock mass above the tunnel excavation moving vertically into the excavation. Initial displacements within 1 week after zero-reading reached a maximum of ~170mm, maximum displacements before excavation of the invert accumulated to 230mm. Total displacements by April 2006 amount to 370mm.
- The most critical displacements develop over several deformation phases. Displacements of secondary deformation phases often take place with considerable delay and may reach elevated magnitudes that were not foreseen. The displacement history diagram for MS 1226 (figure 3) shows that initial displacements immediately after top heading excavation amounted to 38% of the total displacements by April 2006 (370mm). The displacements had reached 51% by the time the invert was installed and ring-closure achieved at MS 1226. Maximum displacements doubled throughout several secondary deformation phases. These secondary displacements were triggered as the proceeding excavation nearby (left tube, right tube and cross passage) cut through and reactivated sliding along interconnected faults nearby.
- Radial deformations caused by failure of low-strength rock mass were found to be surprisingly limited and non-critical. Vector diagram for monitoring



Left: Fig 3 - Displacement history at monitoring section MS 1226, left tube parking bay niche

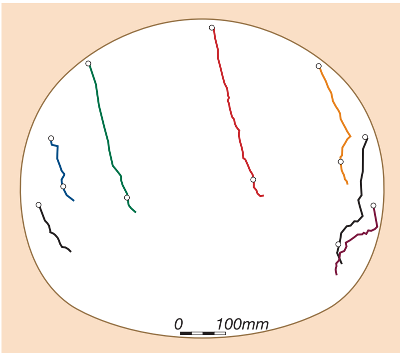
1…top heading excavation cuts high-angle fault F6-4 at MS 1226 triggering elevated and high-velocity initial displacements; 2…reduced but ongoing displacements after invert excavation passes MS 1226; 3…top heading excavation cuts F3-1, bench & invert excavation cuts intersection between F6-5 and F3-1, releasing rock mass and enhancing displacements in right side wall and roof; 4…displacements decline after excavation of invert in right tube passes fault F6-5 at MS 1250; 5…displacements re-commence indicating problems in invert; 6… displacements stop after invert opened and crack from MS 1237 to MS 1265 repaired; 7…excavation of cross passage at MS 1250 commences, reactivating displacements; 8…displacements stop after excavation of cross passage completed.

section MS 1442 in Figure 2 shows radial deformations remaining below 150mm, although the full tunnel excavation is situated in poor to very poor rock mass (RMT3 & RMT4) associated to a prominent high-angle fault.

Adjustments of the geotechnical model

The observations permitted an improved interpretation and prediction of critical tunnelling conditions for the widening of caverns and the remaining tunnel excavation:

- Elevated horizontal displacements (> 150mm) of the sidewalls occur in all of the rock mass types (from RMT1 through to RMT4), where rock mass relaxes along medium-angle shear planes oriented (sub)parallel to the centre line. Horizontal displacements may become critical (> 300mm), where enhanced by sliding along high-angle faults oriented obtuse/perpendicular to the centre line. Such a scenario is expected at the left-tube cavern and within the merging area.
- Critical vertical roof displacements (exceeding 300mm in the two-lane tunnel) occur in poor rock mass (RMT3), where low to medium angle shear planes and schistosity occur in association with high-angle faults and shear planes. Such a scenario does not occur at the cavern locations, but may be encountered along the tunnel



alignment section that remains to be excavated.

- Critical deformations typically commence with elevated initial displacements (Phase A in Figure 3) that are triggered by sliding along shear planes. These initial displacements may reach 100mm to 200mm within 1 week after zero-reading and exceed 200mm (locally 300mm) before the excavation of the invert.
- Secondary displacements of some considerable magnitude are initiated by reactivated sliding along interconnected faults that are cut by excavation proceeding nearby. The potential for elevated secondary displacements is expected to be significant in association with cavern widening and excavation of the ramp tunnels.
- The magnitude of secondary displacements is believed to be strongly influenced by the degree of

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rock mass loosening caused by initial displacements. Therefore, the limitation of initial displacements was judged to be the most efficient measure to control total displacements.

Adjustments of the final design

To achieve a more effective control of initial displacements, intensified support at and ahead of the face was introduced for the revised tunnel and the final cavern design. The measures applied to reduce initial sliding along shear planes and rapid loosening of rock mass include increased quantities of face shotcrete, face bolts, subdivided face openings, and increased length and careful grouting of forepoling. Re-groutable IBI rock bolts are generally foreseen for cavern construction to support the self-bearing capacity of the rock mass arch around the excavation. To minimise the potential requirement for re-profiling that could arise due to displacements of unexpected magnitude the deformation tolerance for cavern excavation was increased from originally 900mm to ~ 1100mm.

Cavern excavation deformation

The data collected during cavern excavation of section A (first excavation step, ~ cross section of two-lane tunnel) so far confirm the conditions predicted in the adjusted geotechnical model.

Elevated displacements occurred mainly in the left sidewall and independently from the overall rock mass quality. Maximum sidewall displacements were observed at MS 1468 (figure 2), where favourable rock mass (RMT1/RMT2) relaxes along medium- to low-angle faults oriented sub-parallel to the centre line. Displacements are, of course, also enhanced by the unfavourable geometry of the temporary excavation. The development of elevated initial deformations could be effectively controlled. Immediate displacements within 1 week after zero-reading remained below 50mm and the accumulated displacements before excavation of invert for section A reached 150mm. Total displacements by April 2006 amount to 180mm.

Cavern excavation prognosis

The excavation of cavern section B and the ramp tunnels is expected to reactivate rock mass deformations at and nearby the cavern. Secondary displacements of the cavern walls completed by April 2006 and the total displacements along newly excavated cavern sections are expected to multiply the maximum deformations observed so far (~ 200mm) by a factor of 2 to 4 (to ~ 800mm). Accordingly, the deformation tolerance of 1100mm foreseen in the cavern design leaves a safety margin of 300mm for unexpected local deformation peaks.

Conclusions

The experiences from the Sentvid Tunnel and Cavern Project demonstrate the value of deformation data as part of geotechnical modelling. Deformation data from the exploration gallery allowed the accurate selection of the most favourable cavern location. The interpretation of deformations during ongoing excavation permitted to understand particular and potentially critical deformation mechanisms that became only evident during the excavation of the large-span main tunnel structures. The added value of the geotechnical model was used to adjust the tunnel and cavern design by employing specific design and construction measures to meet the particular support requirements in ground conditions of the given complexity.