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Coupled hydromechanical modelling of surface subsidence in crystalline rock masses due to tunnel drainage

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ABSTRACT: Settlements above fractured crystalline rock masses are rarely observed and in the past, geotechnical engineers would not expect substantial subsidence to occur in association with a deep tunnelling project. However, recent high precision levelling measurements along the Gotthard pass road in central Switzerland, have revealed up to 12 cm of subsidence along sections that pass several hundred metres above the Gotthard highway tunnel. Large-scale consolidation resulting from tunnel drainage and pore pressure changes in the rock mass are believed to be the contributing mechanism. This paper presents results from an extensive numerical modelling study focussing on the processes responsible for this subsidence. Results derived from 2-D discontinuum (i.e. distinct-element) and continuum (i.e. finite-element) modelling show that both discrete fracture deformation (i.e. fracture closure and shear) and poro-elastic consolidation of the intact rock matrix equally contribute to the observed magnitudes and shape of the surface subsidence trough.

RÉSUMÉ: Des tassements aux dessus de massifs cristallins sont rarement observés et par le passé les géotechniciens ne prévoyait pas de subsidence significative associée avec des projets de tunnel profond. Cependant, de récentes campagnes de nivellement haute précision le long de la route du Col du Gotthard (Suisse centrale), ont mis en évidence des subsidences atteignant 12 cm sur des sections passant plusieurs centaines de mètres au-dessus du tunnel routier du Gotthard. Le mécanisme invoqué pour expliquer ce phénomène est la consolidation à grande échelle due au drainage du tunnel et aux variations de pression de pore dans le massif rocheux. Cet article présente les résultats d'une modélisation numérique intensive mettant l'accent sur les processus responsables pour la subsidence. Ces résultats obtenus grâce à des modèles 2-D discontinus (p. ex. éléments distincts) et continus (p. ex. éléments finis) montrent que la déformation sur des fractures discrètes (fermeture de fractures, cisaillement) ainsi que la consolidation poro-élastique de la roche intacte contribuent également aux magnitudes et aux géométries de subsidence observée en surface.

ZUSAMMENFASSUNG: Beachtliche Oberflächensenkungen in einem kristallinen Gebirge, deren Ursache im Vortrieb eines mehrere hundert Meter tiefgelegenen Tunnels liegt, wurden bisher nicht erwartet und beobachtet. Dennoch wurden nach dem Bau des Gotthardstrassentunnels, entlang der Gotthardpassstrasse Oberflächensenkungen mit einem Maximalbetrag von 12 cm bei der Auswertung von Präzisions-Nivellements entdeckt. Dieser Maximalbetrag wurde in einem granitischen Gneis gemessen. Die örtliche Übereinstimmung zwischen dem maximalem Senkungsbetrag und dem maximalem Wasserzufluss zum Tunnel, und die zeitliche Abfolge von Tunnelbau und auftretenden Oberflächensenkungen lassen hydromechanisch gekoppelte Prozesse als Ursache dieser Gebirgsverformungen vermuten. In dieser Arbeit werden die Ergebnisse ausgedehnter prozessorientierter numerischer Simulationen präsentiert. Resultate aus den 2-D Diskontinuum (d.h. distinct-element) und Kontinuum (d.h. finite element) Simulationen zeigen, dass beide Verformungsmechanismen, d.h. an diskreten Brüchen und der intakten Gesteinsmatrix, gleichbedeutend für die beobachteten Senkungsbeträge und der Form des Setzungstroges verantwortlich sind.

Introduction

In 1998, the Swiss Federal Office of Topography completed a routine high-precision levelling survey over the Gotthard Pass road in central Switzerland. Comparison with the results from a survey over the same route in 1970 revealed that up to 12 cm of subsidence had occurred over a 10 km section that passed several hundred metres above the Gotthard highway tunnel. Earlier surveys between 1918 and 1970 showed only a steady alpine uplift rate of approximately 1 mm/year. Temporal and spatial relationships between the measured settlements and construction of the Gotthard highway tunnel (started in 1970 and completed in 1977), pointed to causality between water drainage into the tunnel and surface deformation. Geodetic triangulation measurements supplemented with Global Positioning System data have since confirmed the existence of the settlement trough [1].

An extensive field, laboratory and numerical modelling investigation was initiated to explore and explain the processes and mechanisms underlying the subsidence [2]. As explanations relating to localized surface processes (e.g. a deep, creeping landslide) could be excluded given the absence of local indicators and the 10 km extent over which the settlements were measured, the working hypothesis pointed to surface subsidence associated with deep drainage and consolidation of the fractured crystalline rock mass. In light of the new 57 km AlpTransit Gotthard base tunnel, which is currently under construction and whose trajectory passes close to several important surface structures (e.g. concrete arch dams), the assessment of possible surface subsidence is of great interest.

This paper presents the results from the numerical modelling component of the above mentioned study, and focuses on the combined roles that fractures, fault zones and the intact rock matrix play in promoting consolidation settlements in crystalline rock masses as induced through deep tunnel drainage.

Tunnel-Induced Consolidation Settlements

Consolidation processes resulting from tunnel excavation and groundwater drainage have a history of causing unexpected and problematic settlements, and as a consequence, damage to surface structures. Schmidt[3] notes that in general, tunnel engineers and project managers fail to consider the potentiality of such problems, but that enough cases have now been reported to build up an experience-base to better understand the underlying causes. These cases, however, almost exclusively involve shallow tunnels excavated in soft, unconsolidated soils.

In fractured rock masses, consolidation phenomenon is not recognised as being important even though large reductions in pore pressure can occur when driving a deep tunnel. Precedence does exist, however, for tunnelling-induced consolidation settlement in fractured rock, albeit significantly more limited than those experiences in soil. Karlsrud and Sander[4] report a case in Oslo, Norway. However, in this instance, the fractured bedrock through which the tunnel was driven only provided the drainage network and soft marine clays lying above the bedrock were considered as being the sole consolidating material.

More pertinent though, is the case of the Zeuzier dam in western Switzerland, where Lombardi[5] reported the occurrence of 13 cm of vertical settlement at the dam site in relation to the driving of an investigation adit 1.5 km away through a confined, fractured, marly-limestone aquifer. Although these settlements may appear to be small, especially compared to those associated with some fluid extraction schemes [6,7], they can have serious consequences since only minor differential displacements are necessary to induce damage in concrete structures. In the Zeuzier case, cracks in the dam appeared which required it to be emptied and repaired over a period of several years.

These experiences provided some initial insight into the surface settlements measured over the Gotthard highway tunnel (Figure 1). The rock mass penetrated by the tunnel primarily consists of paragneisses and granitic gneisses. The majority of fractures and fracture zones are sub-vertical and strike ENE-WSW. Semi-quantitative measurements of tunnel inflow during construction indicated a 3-km wide section where transient inflows were markedly higher, with one fracture zone producing an estimated inflow of 300 l/s. The location of this 3-km section closely corresponds to the centre of a broad trough seen in the settlement profile, and the peak-inflow coincides with the maximum displacement (Figure 1).

This spatial correlation and the temporal relationship between tunnel construction and settlement directed investigations towards the causality between deep tunnel drainage and surface deformation. Several conceptual models were subsequently developed by Zangerl *et al.*[8] to investigate consolidation settlement mechanisms in fractured crystalline rock and to explain the processes responsible for the subsidence measured over the Gotthard highway tunnel. These primarily involve: the closure of sub-horizontal joints (Figure 2a); the deformation of sub-vertical joints and brittle fault zones through changes in the localized horizontal stress state (Figures 2b,c); and the consolidation of the intact rock matrix acting as a poroelastic medium (Figure 2d). Given the dependence of these consolidation mechanisms on geological structure and rock mass behaviour, extensive mapping, laboratory and numerical modelling studies were undertaken [2].

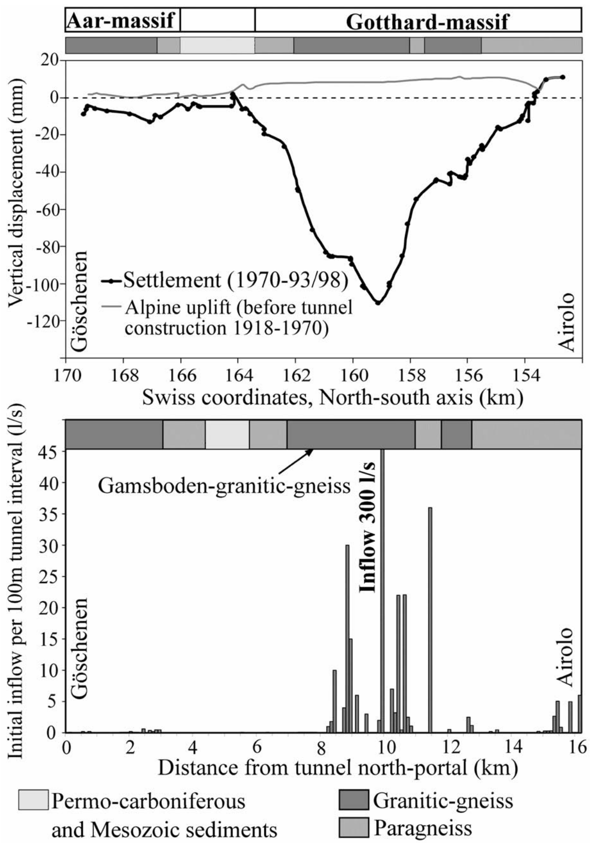

Figure 1. Surface settlements above the Gotthard highway tunnel, and water inflows into the tunnel during excavation.

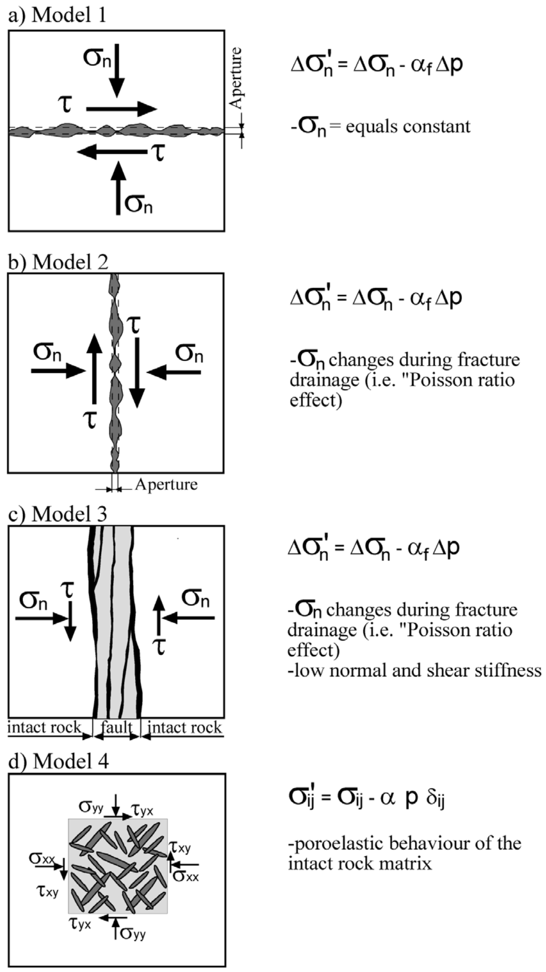

Figure 2. Conceptual consolidation mechanisms for fractured crystalline rock masses involving: (a) horizontal joints, (b) vertical joints, (c) vertical faults, and (d) intact rock. After Zangerl *et al.* [8].

The diverse mechanical and hydraulic characteristics of the problem, ranging from the response of discrete fractures to that of the intact rock matrix, required that two different modelling approaches be taken. The distinct-element code UDEC[9] was used to analyse the hydro-mechanical coupled processes associated with fractures within the rock mass. The intact rock matrix response was analysed assuming a poro-elastic continuum using the finite-element code VISAGE[10]. The geological mapping and laboratory testing components of the study were used to provide input and constraints for the numerical models.

Discontinuum Analysis

Formulation and Model Setup

The spatial conformity of measured maximum subsidence and maximum water inflow rates into the Gotthard safety tunnel (Figure 1) suggests that one steeply dipping fault zone in particular had a greater influence than the others with respect to acting as a major drainage conduit (i.e. initially producing more than 300 l/s when intersected). Inside this drainage conduit, it can be assumed that the pore pressure was significantly reduced along strike of the fault zone given the volume of water inflow into the tunnel. The model geometry used for the discontinuum analysis thus corresponds to a N-S topographic profile along the Gotthard highway tunnel, centred on this steeply inclined fault zone (Figure 3a).

As illustrated in the discontinuity-based conceptual models in Figures 2a-c, drainage of a fracture will affect the effective stress conditions, which in turn will influence the hydraulic flow field through variations in the fracture aperture. As the fracture drains, the normal effective stress ($\Delta\sigma_n'$) along the fracture increases resulting in normal deformation/closure (Δu_n), the magnitude of which depends on the normal stiffness (k_n) through the relation:

$$\Delta u_n = \frac{\Delta\sigma_n'}{k_n} \qquad (1)$$

Discrete fractures were added to the model, primarily focussing on subvertical brittle faults mapped from within the tunnel and at surface [2]. As such, the fracture spacing and geometry for these faults were a direct representation of those mapped *in situ* (Figure 3b). Normal and shear stiffness values for the faults were assumed to be constant and equal to 1.0 and 0.1 MPa/mm, respectively. The transition from elastic shear displacement along the fault to plastic slip was dictated using a Coulomb-slip law where cohesion was set to zero (c_j = 0 MPa) and the friction angle, ϕ_j, equalled 30°.

Next, horizontal joints were added to the model to provide connectivity for fluid flow. The normal set spacing for these joints were likewise based on mapping data, with spacing values decreasing with depth. To maintain numerical efficiency, the horizontal fracture spacing implemented into the model was up-scaled by adjusting the corresponding normal stiffness. Normal stiffness values for the horizontal joints were based on a semi-logarithmic closure law, where values were varied with depth (i.e. as a function of increasing normal stress). A constant shear stiffness of 1 MPa/mm and Mohr-Coloumb strength parameters of c_j = 0 MPa and ϕ_j = 40° were applied to the horizontal fractures.

Elastic constants for the intact matrix blocks were based on laboratory values with a Young's modulus of 45.5 GPa and a Poisson ratio of 0.12. The rock density for the granitic rock mass was set to 2700 kg/m^3. Integration of the conceptual hydrogeological model into UDEC was achieved by calibrating the sub-vertical hydraulic conductivities of the representative fault zones based on their transmissivities as estimated by Lützenkirchen[11]. Hydraulic boundary conditions along the side boundaries were set as impermeable (i.e. no flow boundaries). The lower boundary was fixed to a pore pressure of 26.5 MPa, which represents a mean watertable 500 m above the tunnel elevation. To consider surface recharge a constant pore pressure condition was applied to the upper boundary (e.g. 0.001 MPa representing low surface recharge and 0.01 MPa representing high recharge).

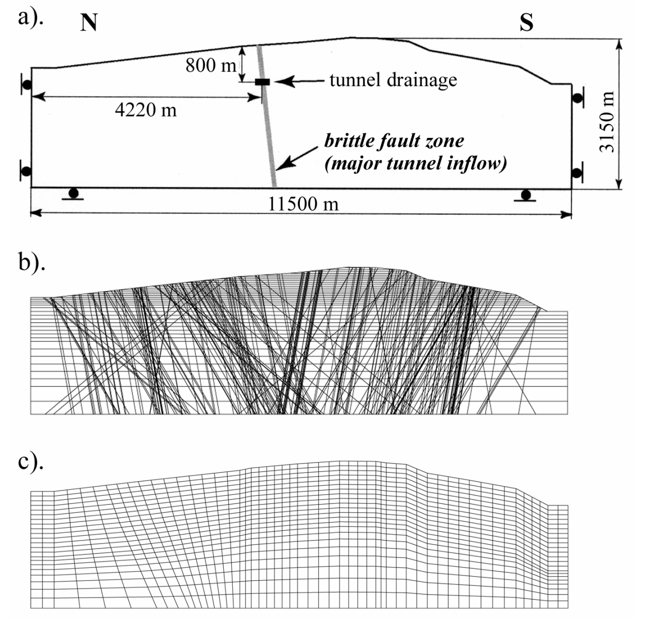

Figure 3. Gotthard highway tunnel case study of tunnelling-induced consolidation subsidence, showing: a) model geometry and boundary conditions; b) discontinuum model; and c) continuum model.

Numerical simulations were run in a steady state calculation mode. The horizontal to vertical stress ratio (i.e. σ_h / σ_v) was set to unity. After cycling the models in an undrained state to obtain an initial hydraulic and mechanical equilibrium, a hydraulic sink (i.e. pore pressure = 0 MPa) representing the opening of the tunnel excavation was placed at its intersection with the major fault zone.

Analysis Results

Initial model results indicated that the frequency and normal stiffness of sub-horizontal fractures would have the largest impact on the magnitude of vertical displacements. However, given that the key geological structures in the Gotthard tunnel region are predominantly sub-vertical, subsequent modelling was performed to provide insight into settlement producing mechanisms with respect to consolidation of sub-vertical fault zones. Results from these model runs showed that vertical displacements could also be generated through shear deformation and slip along the sub-vertical faults upon drainage. Furthermore, a Poisson ratio effect was seen where horizontal expansion of the intact blocks in response to pore pressure decreases along the vertical fractures, produced vertical contraction strains and thus vertical displacements.

However, these models were only able to reproduce 3-4 cm of peak settlement depending on the pore pressure boundary conditions (i.e. low or high surface recharge as previously defined), or 8 cm if very low normal stiffness values were used for the faults and fractures (Figure 4). In general, the distinct-element models were able to reproduce most of the asymmetry and small-scale inflections with respect to the shape of the subsidence profile (Figure 4), but demonstrated that fracture consolidation alone could not explain the total surface settlement magnitudes measured above the Gotthard highway tunnel.

Continuum Analysis

Formulation and Model Setup

Upon drainage of an interconnected fracture network during tunnel excavation, the reduction in pore pressure will also diffuse out into the rock mass. Saturated, low-permeability intact rock blocks bounded by the fractures would likewise be obliged to adjust their internal pore pressure to maintain equilibrium at their boundaries. As a result, these pore pressure changes within the intact rock would induce consolidation strains in accordance with the theory of linear elasticity [12].

Consolidation of the intact rock matrix, however, was not considered in the discontinuum analysis due to limitations in the UDEC code where intact blocks are treated as being impermeable. Thus to investigate the contributing role of intact rock consolidation to the settlements measured above the Gotthard tunnel, continuum modelling techniques were applied focussing solely on the drained response of the intact rock using material properties derived from laboratory testing of intact rock samples (i.e. the contributing effects of fractures were not considered). This analysis was performed using a finite-element poro-elastic solution based on Biot's[12] 3-D consolidation theory, which describes the coupled hydraulic and mechanical transient response of a linear elastic, isotropic, homogeneous porous medium. One aspect of his theory is the effective stress law for elastic deformation:

$$\sigma'_{ij} = \sigma_{ij} - \alpha p \delta_{ij} \qquad (2)$$

where σ'_{ij} and σ_{ij} are the effective and total stress matrices respectively, p is the fluid pore pressure, α is Biot's coefficient, and δ_{ij} is the Kroenecker's delta. Biot's constant describes the fraction of pore pressure change that is felt by the solid skeleton as a deforming volumetric body force, and takes values ranging from 0 to 1 [13].

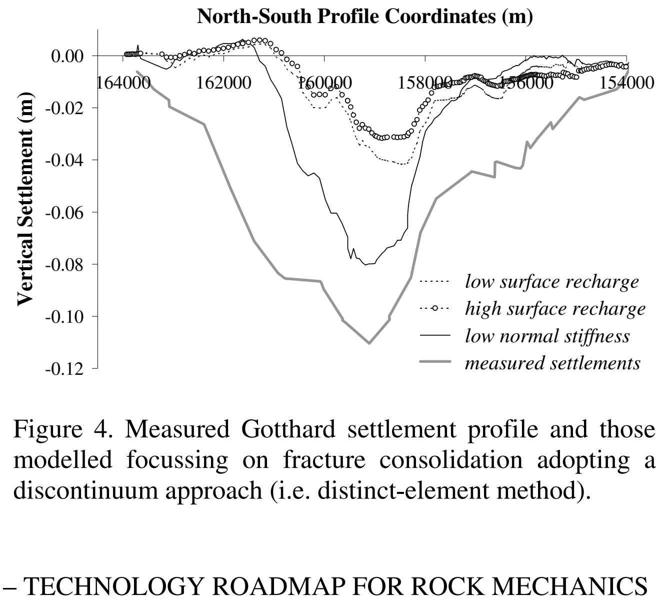

Figure 4. Measured Gotthard settlement profile and those modelled focussing on fracture consolidation adopting a discontinuum approach (i.e. distinct-element method).

The model geometry and boundary conditions adopted for the continuum analysis were taken to be the same as those used in the discontinuum analysis (i.e. based on the local topographical, geological and hydrological conditions in the study area over a North-South section; Figure 3c). The finite-element solution of Biot's consolidation theory used in this study [10] required as input seven independent parameters: water density, rock density, drained Young's modulus, drained Poisson's ratio, Biot's constant, Skempton's constant and the rock permeability. Where applicable, material properties were kept the same as those used for the intact rock blocks in the discontinuum analysis (i.e. based on laboratory tests of intact granitic-samples by Zangerl[2]): rock density = 2700 kg/m^3; Young's modulus = 45.5 GPa; Poisson ratio = 0.12; Biot's α = 0.7; and Skempton's B = 0.92. Material properties were assumed to be isotropic and homogeneous throughout the model domain, although this condition was varied in several models to include depth dependent values for the elastic and poro-elastic coefficients, again based on laboratory test results [2]. A hydraulic conductivity of 1e-8 m/s was assumed, representative of values for medium permeability granite allowing for some small-scale drainage effects corresponding to smaller fractures.

Analysis Results

Continuum finite-element models focussing on the contributing effect of the intact rock matrix produced between 2-7 cm of settlement through poroelastic intact rock consolidation (Figure 5). Higher magnitudes of vertical settlement were obtained assuming isotropic conditions (i.e. isotropic permeability and mechanical parameters) throughout the model domain. These values significantly decreased if hydraulic anisotropy was introduced in the form of higher vertical hydraulic conductivities coincident with the orientation of the major fault zone structures in the region (i.e. K_h=1e-8 m/s and K_v=1e-6 m/s; K_h/K_v= 0.01). In effect, the higher vertical conductivities reduced the horizontal extent of pore pressure drawdown considerably, although the downward extent of pore pressure disturbance increased penetrating well below the tunnel. The net effect was to confine the volume suffering pore pressure drawdown to a narrower strip around the draining structure (i.e. the central fault zone). This geometry inhibits vertical strains with the result that settlements are more localised around the fault and thus significantly reduced (Figure 5; 'anisotropic K'). In contrast, when the horizontal and vertical hydraulic conductivities are equal, the drawdown occurs over a wider volume extending outwards from the vertical drainage structure and thus greater surface settlements can be elastically accommodated (Figure 5; 'isotropic K').

Layered models, where the elastic and poroelastic constants varied with depth, also showed a reduction in the modelled vertical settlement (Figure 5; 'depth dependent properties'). Conspicuous was a bulge at the subsidence trough maximum, which was seen to form as a result of upward bending of the individual layers manifesting itself as buckling at the surface. Through additional numerical experiments, it was determined that the anomaly was a modelling artifact arising from the contrast of elastic and poroelastic parameters between the layers, which in turn induced strain concentrations followed by vertical uplift at the hinge point. The maximum subsidence value of 6.8 cm for the layered model agrees well with estimated values derived through analytical calculations.

Conclusions

Modelling results based on the use of discontinuum and continuum numerical codes (i.e. distinct-element and finite-element methods, respectively) showed that the frequency and the normal stiffness of sub-horizontal fractures would have the largest impact on the magnitude of vertical settlements as a result of fracture drainage. However, given that the major conductive structures and brittle fault zones in the Gotthard region are sub-vertical, alternative mechanisms must also exist. Numerical models thus aided in demonstrating that vertical discontinuities upon drainage may also contribute to surface subsidence through closure and shear along the discontinuity and through intact block strains induced through a Poisson's ratio effect.

Numerical results further showed that fracture closure alone is not the only subsidence producing mechanism, but that the intact rock matrix can considerably contribute to rock mass deformation through poroelastic strains. Although the direct summation of magnitudes of surface settlement modelled using discontinuum and continuum techniques is physically not valid, relative comparisons between the two simulation techniques can be made. Ideally, the problem requires a fully coupled hydromechanical numerical code that incorporates flow and deformation in both the explicitly-defined discrete fractures (e.g. fault zones) and the intact rock block material bounded by the fractures. Future modelling will explore this option, as well as focussing on the development of 3-D models that will explicitly incorporate key geological and hydrogeological features in the region of the Gotthard highway tunnel axis.

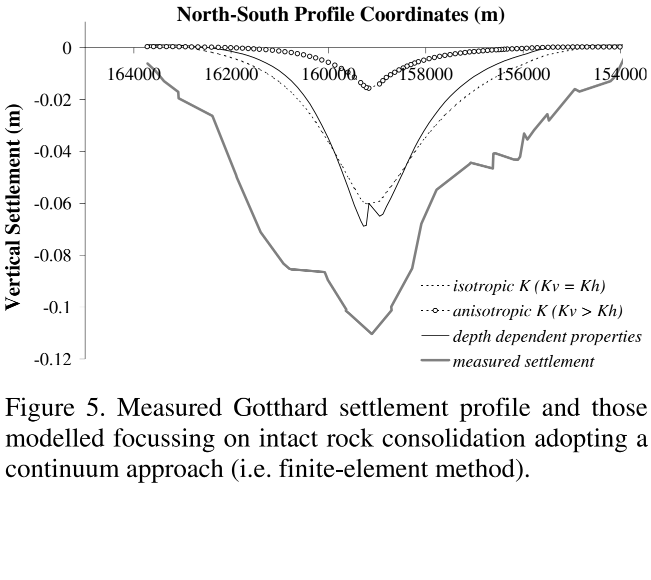

Figure 5. Measured Gotthard settlement profile and those modelled focussing on intact rock consolidation adopting a continuum approach (i.e. finite-element method).

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References

1. SALVINI D. (2002). Deformationsanalyse im Gotthardgebiet. Report by the Institute of Geodesy and Photogrammetry, Zurich: Swiss Federal Institute of Technology.
2. ZANGERL C. (2003). Analysis of Surface Subsidence in Crystalline Rocks above the Gotthard Highway Tunnel, Switzerland. D.Sc. thesis, Zurich: Swiss Federal Institute of Technology.
3. SCHMIDT B. (1989). Consolidation settlement due to soft ground tunneling. *Proc. of the Twelfth International Conference on Soil Mechanics and Foundation Engineering, Rio de Janeiro*, pp. 797-800.
4. KARLSRUD K. and SANDER L. (1979). Subsidence problem caused by rock-tunnelling in Oslo. In: *Evaluation and Prediction of Subsidence*, New York: American Society of Engineers, pp. 197-213.
5. LOMBARDI G. (1992). The FES rock mass model - Part 2: Some examples. *Dam Engineering* Vol. 3, pp. 201-221.
6. ALLIS R.G. (2000). Review of subsidence at Wairakei field, New Zealand. *Geothermics* 29(4/5), pp. 455-478.
7. POLAND J.F. (1981). Subsidence in United States due to ground-water withdrawal. *Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers* 107(IR2), pp. 115-135.
8. ZANGERL C., EBERHARDT E. and LOEW S. (2003). Ground settlements above tunnels in fractured crystalline rock: numerical analysis of coupled hydromechanical mechanisms. *Hydrogeology Journal* Vol. 11, pp. 162-173.
9. ITASCA (2001). *UDEC – Version 3.1.* Minneapolis: Itasca Consulting Group.
10. VIPS (2003). *VISAGE - Version 8.7.* Bracknell, UK: Vector International Processing Systems Limited.
11. LUETZENKIRCHEN V. (2003). Structural Geology and Hydrogeology of Brittle Fault Zones in the Central and Eastern Gotthard Massif, Switzerland. D.Sc. thesis, Zurich: Swiss Federal Institute of Technology.
12. BIOT M.A. (1941). General theory of three-dimensional consolidation. *Journal of Applied Physics* Vol. 12, pp. 155-164.
13. NUR A. and BYERLEE J.D. (1971). An exact effective stress law for elastic deformation of rock with fluids. *Journal of Geophysical Research* Vol. 76(26), pp. 6414-6419.