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Transient surface deformations caused by the Gotthard Base Tunnel

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ABSTRACT

The Gotthard Base Tunnel (GBT) is a 57 km long and up to 2500 m deep railway tunnel constructed between 2000 and 2011 in the Central Alps of Switzerland. As drainage of fractured rocks by deep tunnels accompanied by significant decrease in groundwater pressure causes large-scale deformations even in hard crystalline rocks, a comprehensive surface deformation and tunnel inflow monitoring system has been established and operated for more than ten years. This paper presents the results from this monitoring system and explains the observed hydro-mechanically coupled and transient rock mass behavior based on detailed assessments of geological, geomechanical and hydrogeological conditions and conceptual continuum models. The collected data show that significant tunnel-drainage induced surface deformations also develop in rock masses with moderate hydraulic conductivity (2E − 9 m/s) and small cumulative tunnel inflows (a few liters per second per kilometer). In this case deformations are caused by pore pressure reductions and rock mass deformations around the draining tunnel at depth, and not by groundwater table elevation changes. The pattern of surface settlements observed along the tunnel axis is very irregular (up to 11 cm in 2013) and strongly influenced by hectometer scale hydro-mechanical heterogeneities of steeply dipping geological units striking at large angle to the tunnel axes. At the depth of the studied tunnel section (1500–2500 m) about 50% of the surface settlements can be recorded. The surface settlements are connected to horizontal displacements and strains directed towards the tunnel axes or advancing tunnel face. The resulting horizontal displacement at the Nalps dam has reached about 65 mm in 2013. Compressive strains in the order of 20–50 microstrain are typically observed within a corridor of about 1 to 1.5 km width. Outside the reversal point of the settlement trough, extensile strains of similar magnitude develop.

1. Introduction

1.1. Study motivation

The Gotthard Base Tunnel (GBT) is a 57 km long high-speed railway tunnel constructed in the Central Alps of Switzerland (inset Fig. 1). The excavation of the two main tunnel tubes, which were constructed as freely draining underground structures, started in the year 2000 and was successfully completed in March 2011. The section of the GBT between the intermediate adits of Sedrun and Faido is situated in crystalline basement rocks of the Gotthard Massif and located close to three hydropower reservoirs dammed by concrete arch dams (Fig. 1; with Nalps, Curnera and St. Maria hydropower lakes). It has been shown in the past, that drainage of fractured rocks by deep tunnels cause surface deformations even in hard crystalline rocks [2–8]. In such rocks surface deformations induced by tunnel drainage develop laterally over several kilometers and typically amount to settlements in the order of 10 cm above the tunnel centerline. Variable settlement magnitudes lead to horizontal tensile or compressive strains which can severely damage concrete arch dams (e.g. [9]). In order to mitigate these risks for the GBT, a unique 4D surface deformation monitoring system has been put in place, together with detailed subsurface investigations such as systematic pre-drillings and tunnel inflow monitoring. These data sets have been systematically acquired over more than 10 years (until 2013) and continuously been analyzed by an expert panel in order to decide about appropriate counter measures – such as permeation grouting – in case of expected critical surface deformations.

This deformation monitoring system installed and operated before, during and after the GBT tunnel excavations in the critical section between Sedrun and Faido included (1) a high-precision

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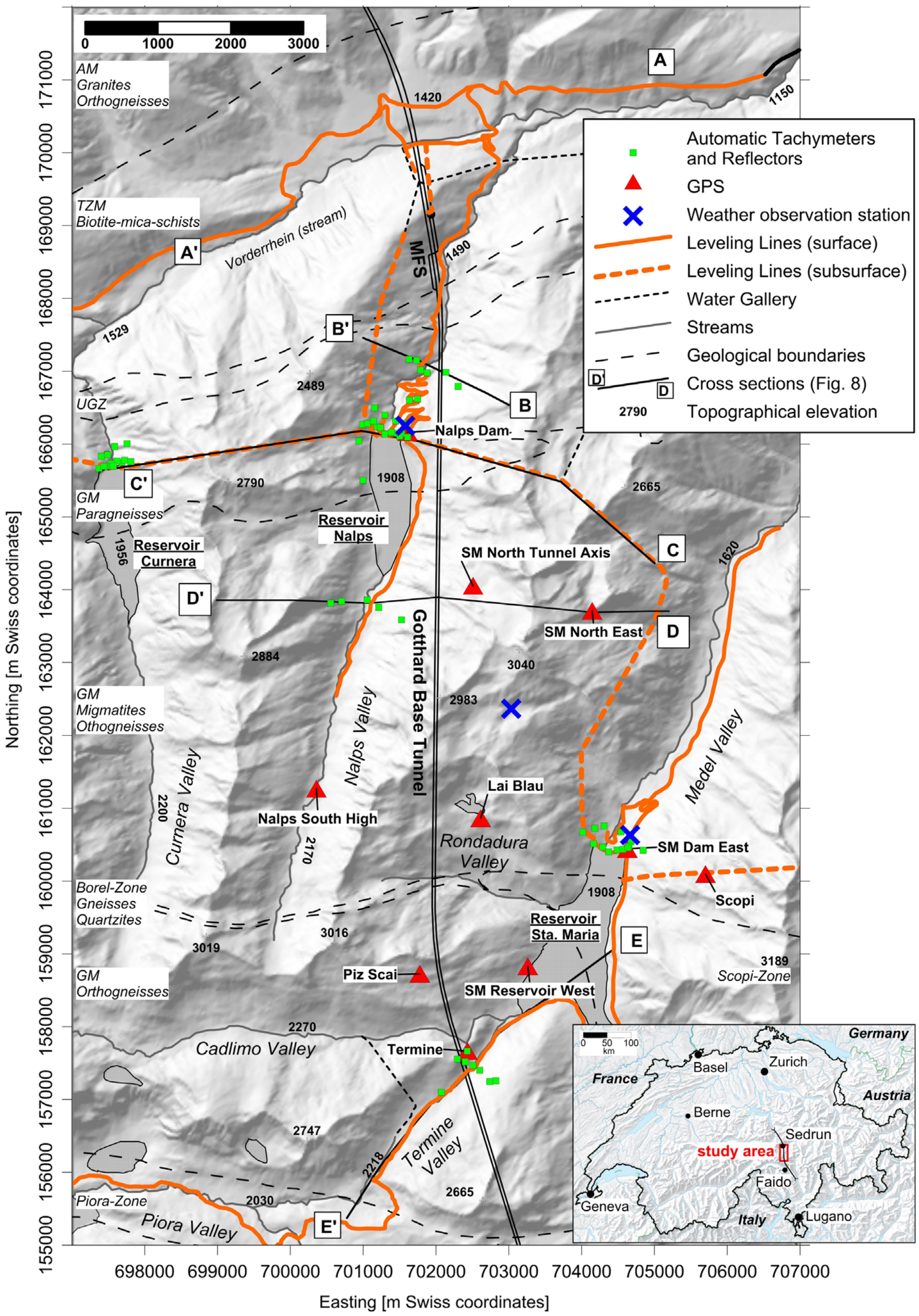

Fig. 1. Topographic and tectonic overview of the study area with tunnel alignment, Sedrun Multi-Function-Station (MFS), hydropower reservoirs and water galleries, high-precision leveling lines (orange), permanent GPS stations (red triangles), total stations and reflector networks (green), weather stations (blue crosses); inset of Switzerland shows Gotthard Base Tunnel and the study area.

leveling network of almost 100 km measured every year, (2) six continuously operating total station and reflector networks, and (3) 10 autonomous GPS stations, distributed over the whole monitoring area (Fig. 1). The resulting data allowed for the first time ever studying in great detail the temporal and spatial evolution of surface deformations caused by a progressively excavated deep tunnel in fractured hard rock. This unique data set is presented in this paper together with geological and hydrogeological conditions of the project area, and the scientific insights gained from these measurements. The lessons learnt include fundamental aspects of coupled hydro-mechanical mechanisms in fractured rock at project relevant scales, and the corresponding hydraulic and mechanical rock mass properties.

1.2. State of knowledge

In the past many cases of ground surface deformations caused by a change in fluid pressure distribution inside a fractured rock mass have been observed. Examples include fluid pressure changes as a consequence of drainage or extraction of fluids by mining [10], groundwater pumping [11], extraction of oil or gas [12], or geothermal fluid extraction [13].

Previous knowledge about tunneling induced surface deformations in fractured hard rocks was mainly based on observations made after the construction of the Rawil exploration tunnel, drilled through tectonized limestones in the Helvetic Alps [9,4], and observations made 25 years after the construction of the