Pre-stressed tunnel lining – pushing traditional concepts to new frontiers

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Objective

Ontario Power Generation (OPG) is increasing the capacity of the existing Sir Adam Beck (SAB) power plant by implementing the third stage of the construction programme. As of the year 2013, an additional 500 m³/s of water will be drawn from the Niagara River from above the Horseshoe Falls and diverted through a new tunnel (NTFP) to the existing powerhouse, boosting the annual energy output to some 1.6 billion kilowatt hours. The tunnel is 10km long with an internal diameter of 12.8m. The largest hard rock TBM at the time is used. The initial lining includes bolting, shotcrete; the final lining comprises cast-in-place concrete and has a regular thickness of 600mm. Waterproofing membrane is applied to prevent seepage and contact of aggressive groundwater with the lining.

The lining is non-reinforced. Pre-stressing prevents cracking under internal pressures during operation over the entire design life.

Concept

The concept of pre-stressed non-reinforced concrete tunnel lining was first addressed by Kieser [2] in the 1940s and then further developed by Seeber [3]. It was applied for a number of hydropower projects, mostly in the European Alps. Pre-stressing is achieved by grouting the interface between inner lining and rock mass.

The development of radial stress equilibrium in the tunnel lining and the rock mass is illustrated in Fig. 3. The level of pre-stress is chosen according to the internal water pressure pi and to cover all losses to be anticipated due to temperature changes during operation and time-dependent effects (losses) such as creep of both concrete and rock mass.

It is hence ensured that the tunnel lining is in a permanent, crack-free state of compression and that it is kept in constant contact with the rock mass.

Stretching the limits

While the concept has been widely used for pressure tunnels with ratios between radius and lining thickness up to 5, the slenderness of the NTFP exceeds this boundary by some 100% up to a ratio of 10 and higher.

The NTFP is constructed in highly anisotropic and heterogeneous geologic conditions with horizontal stresses exceeding vertical stresses many times over. Rock squeezing and a high swelling potential pose further challenges both during construction and for the design of the final structure.

Although the original concept of pre-stressing postulates axial symmetry and homogenous, isotropic conditions, the NTFP demonstrates that the concept can be adopted successfully under boundary conditions deviating from perfectly axial symmetry.

Design and Construction Aspects

A major focus of the design is placed on anisotropic loading conditions originating not only from the grouting procedure but also from lateral rock squeezing and swelling. Extensive analyses are therefore required to thoroughly assess the structural performance under all loading conditions to be anticipated over the design life of the NTFP.

Since, in the course of pre-stressing, the lining concrete is potentially stressed to its limits, its performance needs to be monitored closely during grouting works. The measured deformations are checked constantly against defined permissible ovalisations.

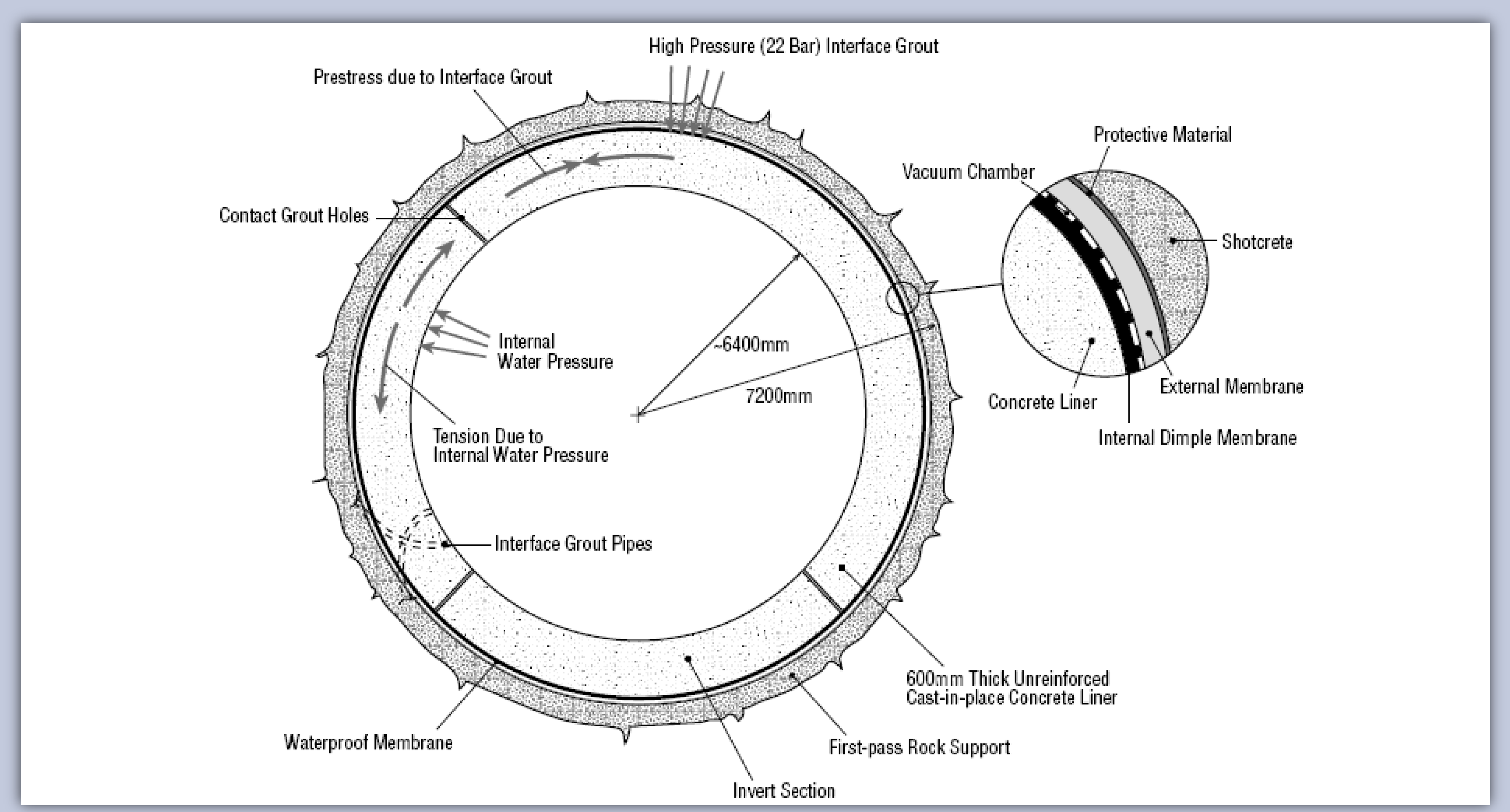

FIG. 1. Typical cross section (not to scale) [1]

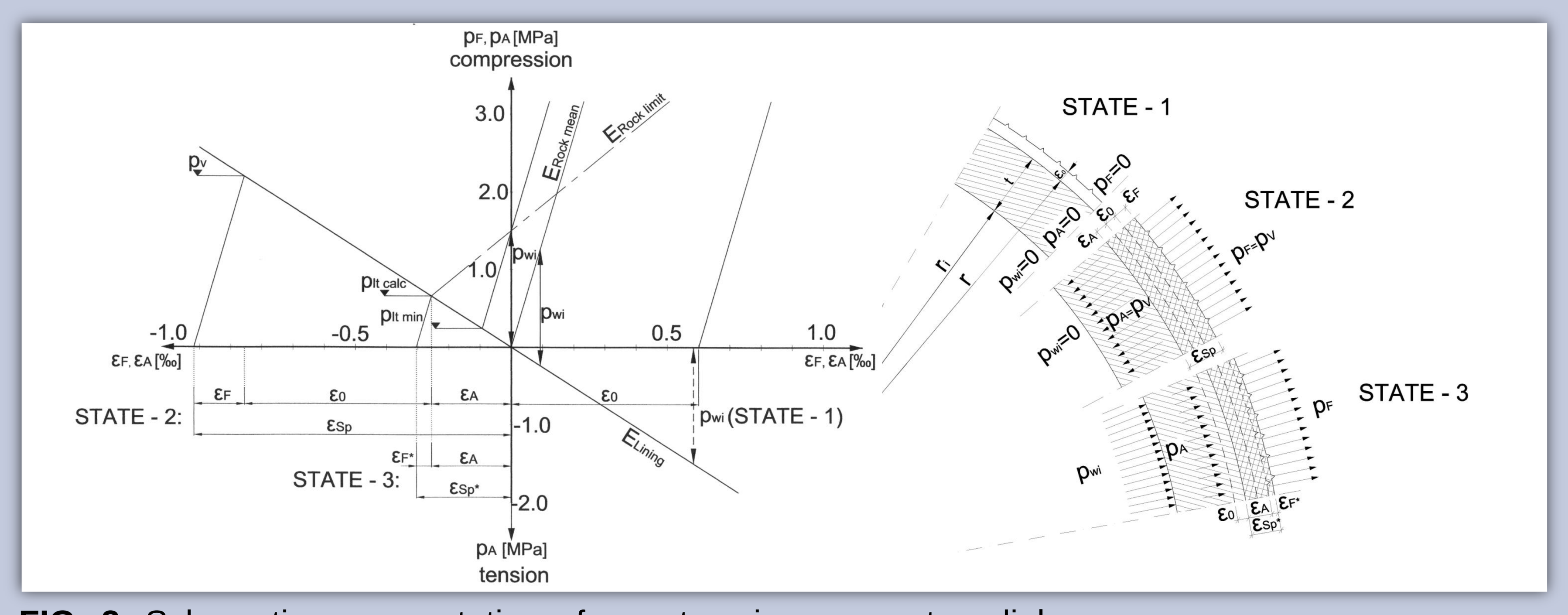

FIG. 2. Schematic representation of pre-stressing concept: radial pressure vs. radial strain for rock mass and tunnel lining

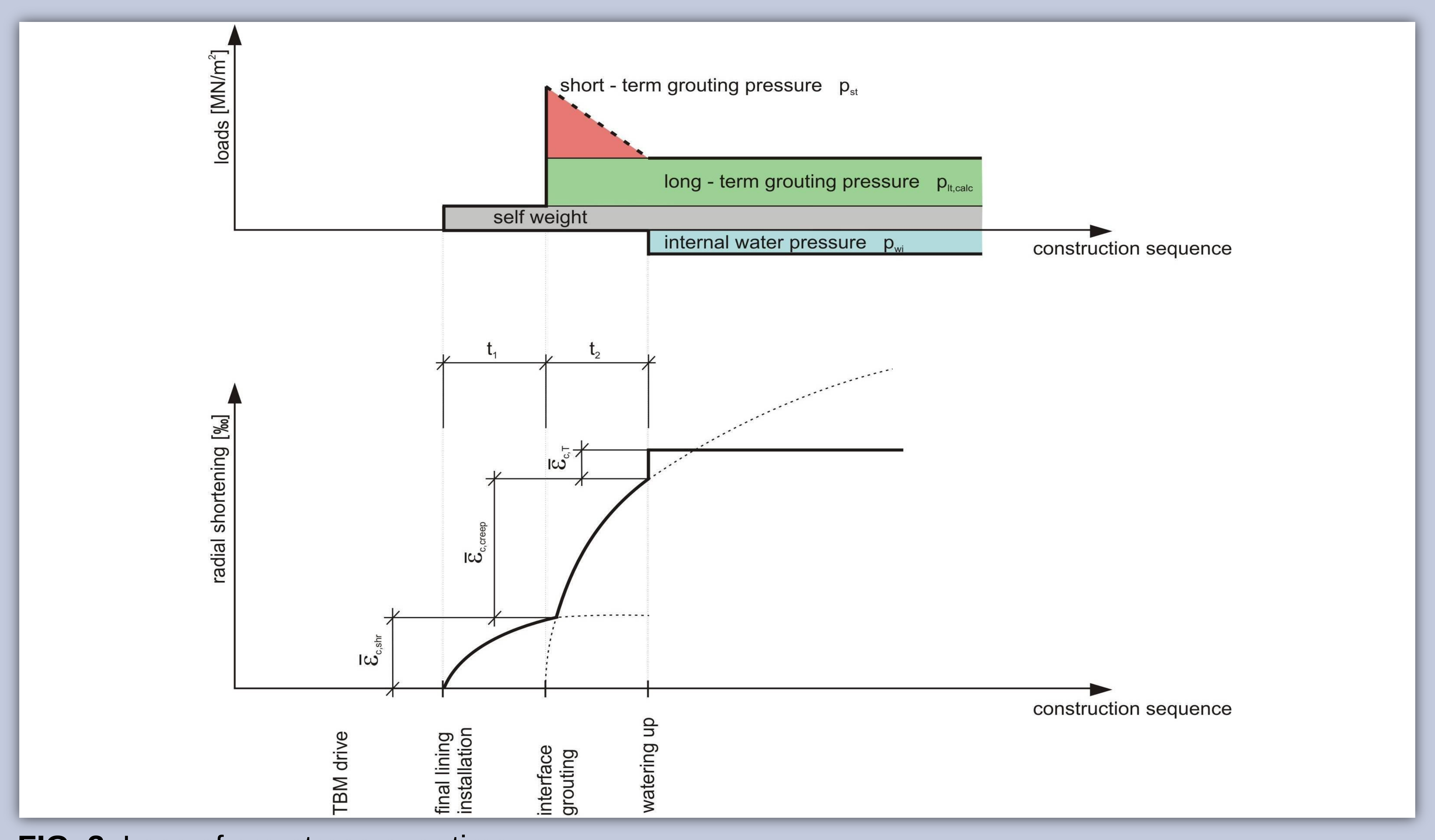

FIG. 3. Loss of pre-stress over time

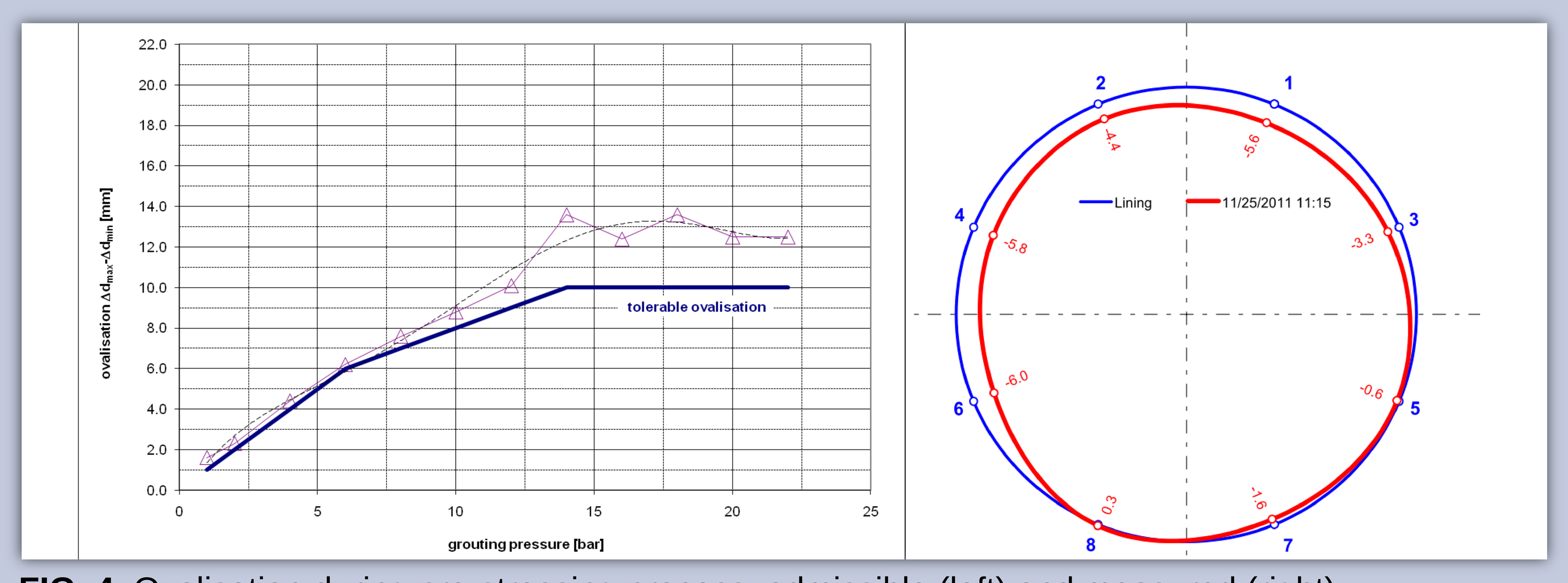

FIG. 4. Ovalisation during pre-stressing process: admissible (left) and measured (right)

Conclusions and Outlook

In a number of earlier projects the concept of pre-stressed unreinforced concrete linings was proven to be an economical approach for pressurized water tunnels within a certain range of boundary conditions. Since the concrete lining is maintained in a constant state of compression, there is no need for reinforcement, benefitting costs, construction time and durability. The Niagara Tunnel Facility Project demonstrates that the current range of application can be stretched in terms of

- **Slenderness of lining**
- **Anisotropy and heterogeneity of rock mass**
- **Rock squeezing**
- **Swelling potential**

The applicability of this concept requires a holistic and multi-disciplinary approach comprising rock mechanics, advanced constitutive models for concrete, a well prepared grouting and monitoring scheme during execution.

[1] Lauffer H. (1968): Vorspanninjektion für Druckstollen, Der Bauingenieur, 43 Jahrgang, Heft 7, 1968
[2] Kieser A. (1960): Druckstollenbau, Springer Verlag, Wien-Bregenz. 1960.
[3] Seeber, G. (1999): Druckstollen und Druckschächte: Bemessung – Konstruktion – Ausführung, ENKE im Georg Thieme Verlag. Stuttgart, New York 1999