# Analysis of the stress state of a pressure tunnel considering nonlinear deformation of the rock massif

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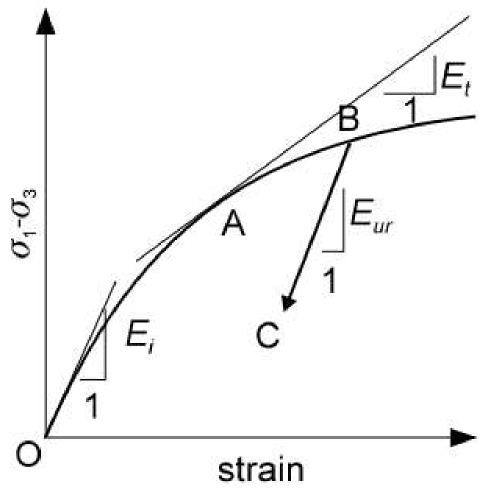
**Abstract** The presented study is based on the calculation of the "tunnel-surrounding massif", a unified system taking into account the nonlinear operation of the surrounding massif, where a hyperbolic model of rock material is used. Numerical calculations were carried out on the example of the Aspindza HPP diversion tunnel.
The Aspindza HPP hydro node (on the Mtkvari River) includes a diversion tunnel, the operation of which is envisaged in the pressure mode and, together with the equalization reservoir, partially receives a hydraulic shock, taking into account which the pressure from inside the tunnel reaches 25 m.
It was accepted that the nonlinearity of the material has a significant impact on the construction and operational stress states of the tunnel. In particular, the influence of nonlinearity reduces extreme stresses in the construction and, accordingly, reveals strength reserves, which allows for optimization of reinforced concrete construction.
The horizontal tensile stresses identified by nonlinear calculations in the tunnel bottom cross-section were significantly reduced compared to linear calculations, and when taking into account the phased nature of the tunnel construction (compared to the sudden construction scheme), the tensile stresses were completely eliminated.
The paper presents some results of the calculation of the derivation tunnel for the construction and operation periods, taking into account the nonlinear operation of the surrounding massif.

## INTRODUCTION

The nonlinear behavior of a material is represented using a hyperbolic model (Duncan and Chang, 1980). In the hyperbolic E-B constitutive model, the bulk modulus (B) is assumed to be constant, while the elastic modulus (E) changes according to a hyperbolic function under loading (Fig. 2.1 1).
The theoretical formulation is based on the analysis of the shape of the "stress-strain" curve, as well as the volumetric response of the material (O-A-B). At the time of failure of the




material (in accordance with the condition of constancy of the bulk modulus), the increase in the volume strain tends to zero, which is consistent with the concept of a critical state.
Fig. 1. Nonlinear stress-strain curve.
The E-B hyperbolic model also allows for the determination of the loading-unloading modulus.
The "stress-strain" response at any loading-unloading instant (B-C) is the deformation modulus (stiffness response) with respect to the initial state (O), which is controlled by the ratio of the specified initial elastic modulus to Poisson's ratio.
The deformation modulus at any point on the nonlinear stress-strain curve can be expressed as the tangent of the tangent. It is defined from the instantaneous elastic modulus by the

condition:

$$E_t = \left[1 - \frac{R_f\ (\sigma_1 - \sigma_3)(1-\sin\phi)}{2c\,(\cos\phi) + 2\sigma_3 \sin\phi}\right]^2 E_i$$

Where,
Ei - initial shear modulus,
Et - shear modulus,
φ - soil friction angle,
c - specific friction;
σ1 - maximum shear stress;
σ3 - minimum shear stress;.
C and ϕ are strength parameters; σ_1 and σ_3 are principal stresses; and R_f is the failure parameter, which is determined by the formula:

$$R_f = \frac{(\sigma_1 - \sigma_3)_f}{(\sigma_1 - \sigma_3)_{ult}}$$

The material strength condition is presented as follows:

$$\frac{(\sigma_1 - \sigma_3)_f}{2} - \frac{(\sigma_1 + \sigma_3)_f}{2} \sin\phi \geq R_f c \cos\phi$$

The presented conditions allow the assessment of the material's stress state and strength reserves.
The surrounding massif of the Aspindza tunnel is mainly represented by sandstones. Therefore, calculations were carried out using the CNI method (according to the generalized Hawk-Brown criterion) with the obtained stress-strain curve - obtained for limestones and sandstones.

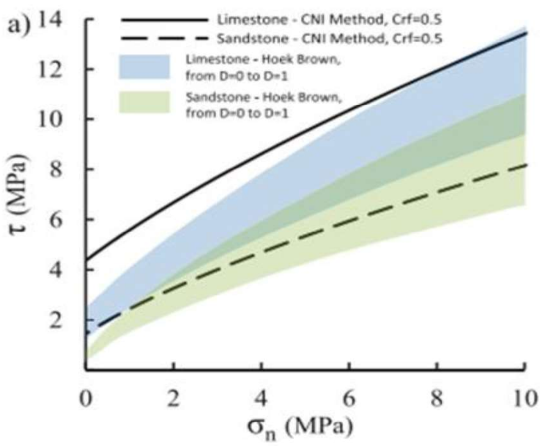



Fig. 2. Stress-strain curve for limestones and sandstones.

- **Calculation under the conditions of a sudden and construction phase construction scheme**

The calculation results provided a complete picture of the stressed state of the repair. In this regard, the contact area of the foundation slab and the walls of the repair is important, which is a stress concentration zone (Fig. 3).
- Horizontal normal stresses in the contact zone are tensile and under the conditions of the "sudden construction scheme" reached the values:
-1700 kPa, -1200 kPa, linear and nonlinear, respectively.
When taking into account the construction phase, tensile stresses in the mentioned zone were practically eliminated when taking into account the nonlinearity.
- Vertical normal stresses in the contact zone, during both linear and nonlinear deformation of the material, when taking into account the construction phase, the stress concentration is increased, although compressive stresses are maintained (Fig. 3)

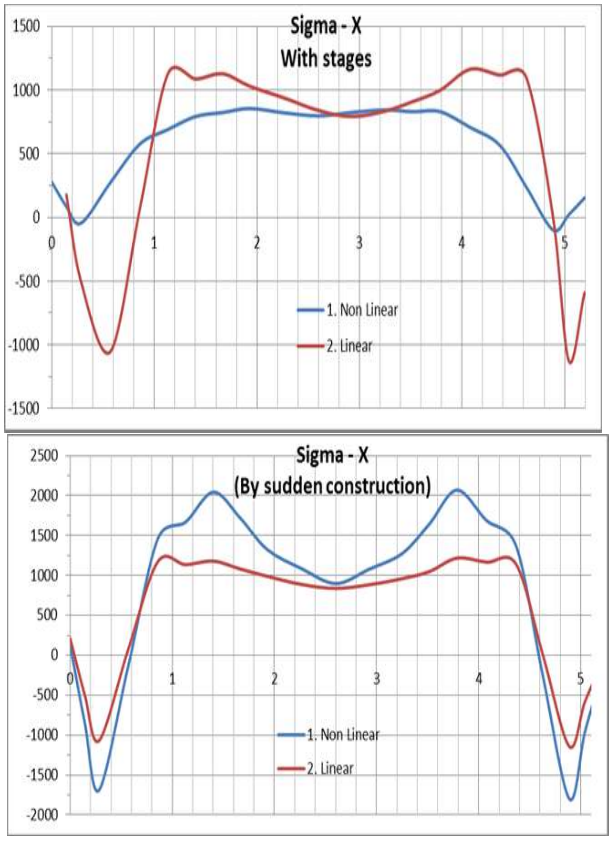



Fig. 3 Distribution of horizontal normal stresses at

the contact section of the tunnel lining base (construction status): taking into account the construction phase and sudden construction schemes.

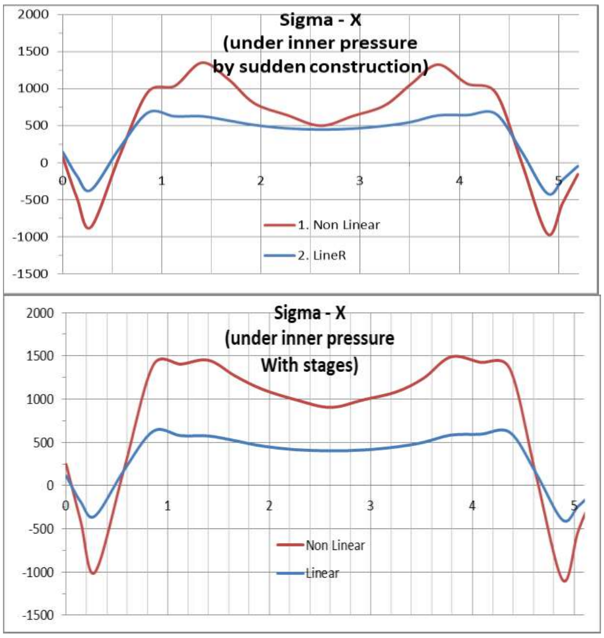
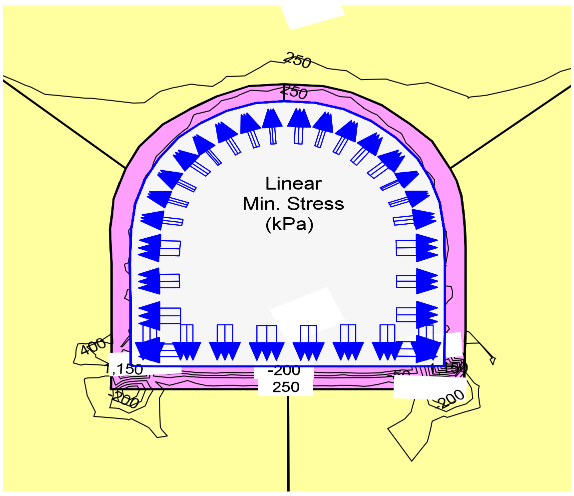



Fig. 4. Distribution of horizontal normal stresses at the contact section of the tunnel lining (operational condition - under inner pressure) taking into account the onstruction phase and sudden construction schemes.

Under the action of the inner pressure of the tunnel the tensile stresses in the wall and bottom slab contact are reduced (compared to an empty tunnel) and reach up to 1000 kPa (Fig. 4).

A general picture of the distribution of the main stresses is given in the drawings (Fig. 4,5).



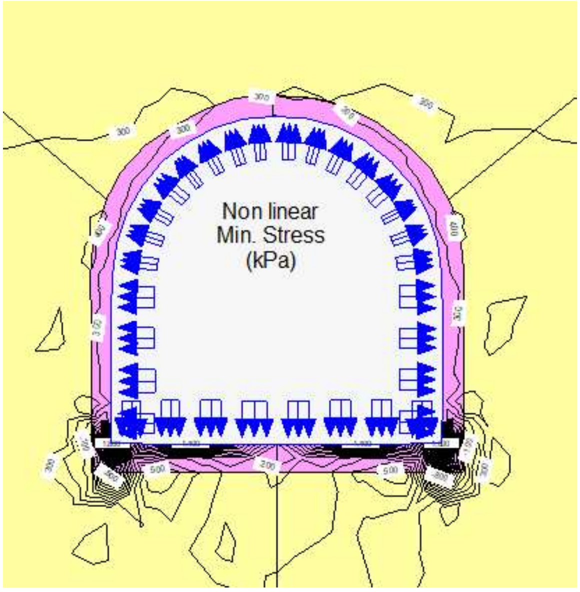




Fig. 5. Distribution of minimum principal stresses in tunnel lining taking into account nonlinear behavior of the material (by sudden construction scheme and operational condition).

Due to the nonlinearity of the surrounding massif, the value of the tensile stresses at the slab of the lining increased (from -200 kPa to -1400 kPa), however, as a result of taking into account the phased nature of the construction, these stresses decreased sharply (to -100 kPa).

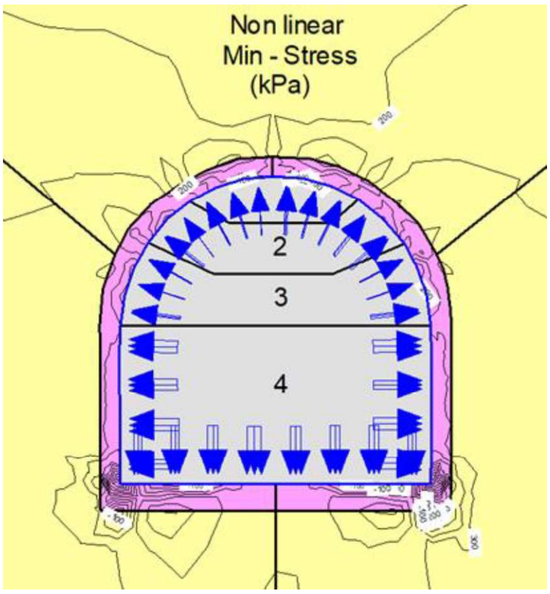



Fig. 6. Distribution of minimum principal stresses in tunnel construction taking into

account material nonlinearity and construction technology (operational condition).

## Conclusion

1. The nonlinear behavior of the surrounding massif has a significant impact on the stress states of the tunnel lining, both during construction and during operation. In particular, the nonlinearity of the massif significantly refines the joint operation of the system tunnel-massif. As a result of the distribution of loads under the influence of nonlinearity, the concentration of stresses in individual areas of the lining increases (along with tensile stresses).
2. When taking into account the construction technology and the nonlinearity of the massif, the stress state of the lining improves and, accordingly, strength reserves are revealed, which allows for the optimization of reinforced concrete lining.

The horizontal tensile stresses identified by the nonlinear calculation in the tunnel bottom slab were significantly reduced compared to the linear ones, and when taking into account the phased construction of the tunnel (compared to the sudden construction scheme), the tensile stresses were completely eliminated.

**References**

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