Stability Assessment of the Cavern Roof: Voussoir Beam Method
Outline

• Geological structure of an underground opening
• Voussoir beam method (failure and statics)
• Stress analysis of the beam
• Factors of safety against failure modes
• Conclusion
Underground opening

- Rockmass behavior is dominated by parallel laminations and cross-cut joints.
- They reduce or eliminate the ability of the rockmass to sustain tensile stresses.

Fig. 1. An excavation in a stratified rock mass (after Brady and Brown, 2004)
Underground opening

- Underground strata separate upon deflection
- Each laminated beam transfers its own weight to the abutments rather than loading the beam beneath.

Fig. 2. Jointed rock beams in horizontal(left) and inclined(right) opening (after Diederichs and Kaiser, 1999a)
Underground opening

- Stability of an excavation depends on the stability of a single beam.
- This process of stress distribution is described as arching effect in immediate roof.
- An arch structure is formed within the beam, confined between two abutments.

Fig. 3. Stress distribution within the beam (after Diederichs and Kaiser, 1999a)
Voussoir beam

• One could assume this type of rock as a discontinuous media, which is formed of individual rock blocks.
• These blocks are called Voussoirs.

Fig. 4. Voussoir structures in ancient Rome architecture
Failure modes

Primary modes of failure:

a) Snap-through
b) Crushing at midspan and abutments
c) Shear failure at the abutments

Fig. 5. Failure modes of Voussoir beam (Diederichs and Kaiser, 1999a)
Statics of model

- Weight of the beam causes a moment at the abutment, $M_W$.
- Deflection of the beam generates a resisting moment, $M_R$, at the midspan.
- To achieve stability, the opposite moment needs to compensate the moment of weight

\[ M_W = M_R \]

- Span, thickness, unit weight, etc. are known.
- Iterative approach to get the midspan deflection and maximum lateral stress.
Stress distribution

Distribution of the compressive stress at different cross sections shows a high stress concentration at the bottom edge and top midspan.

Fig. 6. Compressive stress distribution in a typical voussoir beam using UDEC.
Stress distribution

Fig. 7. Reaction line of horizontal stress along arch axis
Sensitivity analysis

As thickness decreases and span increases, the stress concentration increases.

Fig. 8. The relationship between maximum horizontal compressive stress and beam thickness for span=3, 7 and 9m. Original data published by Hatzor (solid line), results of the iterative solution using Matlab (data points).
Fig. 9. Factor of safety against shear along abutments for friction angles of 20°, 40° and 70°. Original data published by Hatzor (solid line), results of the iterative solution using Matlab (data points).
Factor of safety

Fig. 10. The factor of safety against compression for span=5, 8 and 14m. Original data published by Hatzor (solid line), results of the iterative solution using Matlab (data points).
Conclusions

• Using voussoir beam method along with numerical simulation gives a good understanding of the roof behavior.
• Low span/thickness ratios lead to slip at the abutments, while high span/thickness ratios cause crushing and snap-through failure.
• Diagrams of the factors of safety could be used for preliminary assessment of the roof stability.
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References


