Power Cavern Design & Back Analysis Using Phase\textsuperscript{2}

A Look at the Ingula Power Cavern Project

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The construction of the Ingula hydro power caverns in South Africa began in 2004 and is scheduled to end in 2015. Monitoring was in place throughout the construction process. Numerical models were then updated based on the collected field data and the calibrated models were used to investigate the effects of potential construction defects.
**Project Description**

The Ingula power complex is located approximately 400 m below ground level, under a mountain ridge off the Drakensberg escarpment between the Free State and KwaZulu Natal provinces, South Africa.

The complex, which is up to 50 m deep, consists of a 184 m long and 26 m wide hall, with a span:height ratio of 2.5. The transformer hall, which is up to 21 m in height, is 176 m long and 19 m wide. A pipe gallery runs alongside the transformer hall 6 m below floor level.

Other installations include 11 m diameter appurtenant busbar tunnels, 5 m diameter high pressure penstocks, a 9 m diameter main access tunnel, and other minor shafts.
**Geological Setting**

The cavern complex was constructed in horizontally bedded siltstones, and is located approximately 25 m below a 40 m thick dolerite sill. The intact rock strength and stiffness decreases with depth below the sill, and there were also a number of faults intersecting the caverns and tunnels.

**Cavern Support Design**

While the initial design was based primarily on experience, the final support design was based on geological evaluations and numerical modeling in UDEC, *Phase*², and FLAC3D.

Numerical models were used to estimate cavern convergence on the crown and sidewalls, and the time of support installation was also investigated.

![Intact Rock Properties vs Depth](image-url)

Legend:
- Overburden
- Sandstone
- Mudstone
- Granite
- Other Shale
- Phyllite/Diabase
- Sandstone
- Mudstone
- ETIE Support Jkt (100 m intervals, 1 m)

Figure 3
Rock material properties
Comparison of Phase² Results to Cavern Measurements

Instrumentation was placed in areas of concern, based on the initial modeling results. Compared to the numerical results, the following observations were made with regard to displacements:

- Measured displacements were generally lower than expected
- Sidewall displacements were generally larger than crown displacements
- The rate of displacement slowed more quickly than anticipated as the excavation progressed

Back-Analysis and Remodeling in Phase²

Phase² models were constructed in the design phase of the Ingula project. These models were fine-tuned towards the end of the excavation of the main caverns for three primary reasons. Firstly, Phase² models were updated to reflect the actual geology.

In particular, the dyke with sheared contacts was incorporated into the model. Secondly, the staging was revised to reflect the actual sequence of excavation and support installation.

Finally, the Phase² models were recalibrated using the available monitoring data from the excavation. The models were calibrated using the Phase² model for a geotechnical cross-section through Units 1&2 in the Machine Hall and the calibrated parameters were then used in the models for Machine Hall Units 3&4 as well.

Figure 4
Section of Units 1&2 Geology
One particularly interesting revision to the Phase² model was the assumption that there was the same percentage of rock bridges in the strike direction of bedding planes and joints as in the dip direction. This adjustment to the bedding and joint strength balanced the effect of infinitely long bedding planes and joints in the strike direction in Phase². Prior to the adjustment, large rock wedges were formed in the crown and sidewalls of the model. After revision, rock wedge were more typical sizes.

The results obtained from the calibrated Phase² models are compared to the actual crown and sidewall displacements up to the end of construction of the caverns. The numerical results were generally within 5-10% of field measurements.
Modeling of Construction Defects

While differences exist between the Phase\(^2\) models and the cavern measurements, the results were good enough to merit the influence of construction defects to be modeled and analyzed in Phase\(^2\).

The first defect investigated was the corrosion of invert floor dowels. This was investigated by removing all floor dowels in certain locations in the calibrated Phase\(^2\) models. The second deviation modeled was cable anchor hole deviation, which was actually noted during construction. To model this defect in Phase\(^2\), staged cable anchor removal was implemented. In the calibrated Phase\(^2\) models for Units 1&amp;2 it was found that staged anchor removal resulted in steady convergence increases, most significantly in the transformer sidewalls. In Units 3&amp;4 models, removal of an anchor resulted in rock wedge mobilization and subsequent failure of the anchors retaining the wedge. Convergence of the Phase\(^2\) model was not obtained for the final stage.

Observations and Conclusions

From the model calibration, it was observed that the presence of local rock wedges have a large effect on both the modeling results and the field measurements. In general, if a rock wedge exists in the field, there needs to be one in the model in order for comparable results to be obtained.

With regard to the modeling of construction defects in Phase\(^2\), the numerical results showed that the long term yield failure of some damaged cable anchors may have little effect on cavern excavation stability. However, the models also showed that the long term yield failure of damaged anchors at critical locations may result in rock wedge mobilization and progressive failure. Based on these Phase\(^2\) results, it was recommended that cavern instrumentation be maintained and stability monitoring continued long term.

To read the original article by M. Kellaway, D. Taylor and G.J. Keyter, please [click here](#).