Analysis of Cave System in Weak Sandstone Using RS2

Simon Ferley[1] (✉) and Ian Williams[2]

[1] Dentonside Geotechnical Consultants, Carlisle, UK
simon.ferley@dentonside.co.uk
[2] Rocscience UK Representative, Swansea, UK

Abstract. The Rocscience finite element program RS2 [1] has been used for a preliminary study to examine the stability of shallow caves in weak sandstone rock beneath a proposed development site in the UK. Focusing on the influence of in-situ horizontal earth pressures, this paper presents one of several models that were analyzed to gauge the potential impact of construction plant loads on cave stability. The results helped inform the specification of a detailed ground investigation to obtain additional information for more rigorous modelling and consideration of mitigation options.

Keywords: RS2 · finite element · cave · stability · sandstone

1 Introduction

A new multi-storey building is to be constructed above an existing man-made cave system in weak sandstone rock. The caves are distributed on two levels at shallow depth (circa 3 to 9 m below ground level) and a piled foundation is proposed to carry structural loads beneath the lower level of the caves. During development, loading from the construction plant will be imposed on the upper level of caves with the consequent risk of failure. To examine the potential for cave instability, geotechnical analysis were carried out using the Rocscience finite element program RS2 [1].

Several sections through the cave system were modelled and a parametric study was undertaken to examine the influence of several material characteristics on model performance. The work presented here concentrates on one section and on the influence of the initial ratio of horizontal to vertical effective stress, K_o, in the sandstone rock.

The analyses were necessarily preliminary in nature. They were based on very limited ground investigation data and highly idealized 2D representations of the 3D cave system, the geometry of which is irregular and complex. The primary objectives of the analyses were to:

- estimate the prevailing stability of the caves;
- gauge the likely impact of construction plant loads on the prevailing stability; and
- inform the specification of a detailed site investigation to provide additional information for more rigorous analysis and consideration of mitigation options.

R. E. Hammah et al. (Eds.): RIC 2023, AHE 19, pp. 23–30, 2023.
https://doi.org/10.2991/978-94-6463-258-3_4

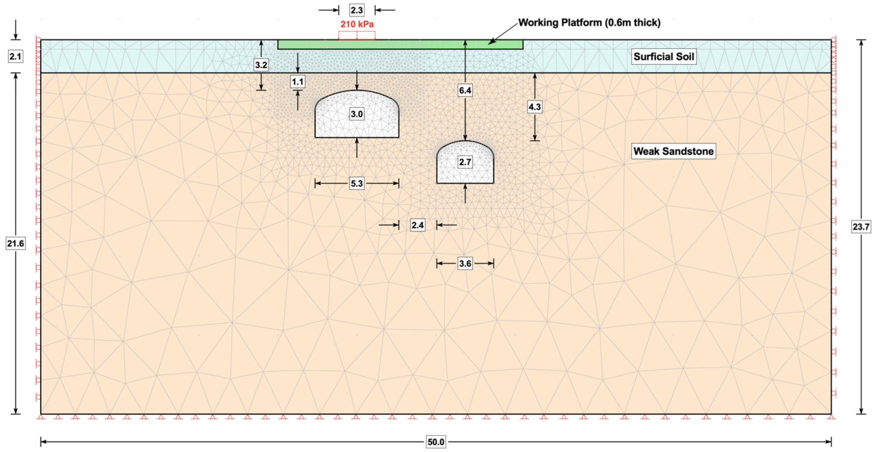

Fig. 1. The RS2 finite element model

2 Finite Element Modelling

2.1 Model Geometry

The RS2 plane strain finite element model of the 2D section considered in this paper is shown on Fig. 1.

The model represents a geological succession comprising 2.1 m of cohesionless surficial soil overlying a substantial thickness of weak sandstone rock within which the cave system is constructed.

The section is intersected by two parallel caves located at different levels within the sandstone. The upper cave is 5.3 m wide and has a maximum height of 3.0 m. Its crown is just 1.1 m below the rock surface (3.2 m below ground level). The lower cave is smaller, with a width of 3.6 m and a maximum height of 2.7 m. Its crown is 4.3 m below the rock surface (6.4 m below ground level). The horizontal spacing of the two caves is 2.4 m.

The model also incorporates a 0.6 m thick working platform to provide the surficial soils with adequate bearing capacity to safely support the construction plant loading.

The finite element discretization comprises 4,754 six-node triangles with increased mesh density in proximity to the caves and the imposed construction plant load.

The in-situ stress field was initialized based on the material weight densities and K_o values before removing the elements within the cave voids to simulate the impact of the historical excavation work on the in-situ stress field.

2.2 Material Models

The surficial soils and sandstone rock were modelled as elastic-perfectly-plastic material with a Mohr Coulomb yield surface. Preliminary estimates of material parameters were derived from a combination of available ground investigation data (which, as mentioned above, was very limited), authoritative literature values [2–8] and engineering judgement. Due to the significant uncertainties regarding the selection of representative material parameters, parametric studies were conducted with lower bound, upper bound and best estimate values being considered. Only the best estimate values have been used for the analyses presented here.

The working platform was modelled as an elastic material on the basis that it will be designed to provide adequate bearing resistance for the imposed design loads.

2.3 Groundwater

Groundwater is not present within the depth of interest and has therefore not been included in the model.

2.4 Loading

The anticipated worst case plant loading comprises an unfactored bearing pressure of 210 kPa applied via a pair of parallel caterpillar tracks with effective plan dimensions 2.30 m long $\times$ 0.75 m wide and a horizontal separation of 3.65 m (centerline to centerline).

In the RS2 model, the track loads have been applied as a 2.3 m wide 210 kPa uniformly distributed load (UDL) located centrally over the crown of the upper cave. This represents an infinitely long load in the out-of-plane direction (along the cave axis) and is expected to produce results that are conservative in respect of cave stability. The degree of conservatism associated with this idealization has not been examined in detail at this preliminary stage. However, based on a simple 2V:1H load spread, the average vertical pressures induced at the top surface of the rock in the idealized plane-strain model may be up to around 2.85 times actual field values.

3 Analyses and Results

3.1 In-situ Conditions and Prevailing Stability

The prevailing stability of the caves has been estimated for in-situ stress fields within the sandstone rock corresponding to K_o values of 0.5, 1.0, 2.0 and 4.0. This was achieved by performing shear strength reduction, SSR, analyses without any external loading.

The critical shear strength reduction factors, SRFs, derived from these analyses are plotted against K_o on Fig. 2. All critical SRFs are well above unity and are consistent with the currently stable condition of the caves. The peak in the plot of critical SRF against K_o reflects a transition in the mode of failure from roof collapse at low K_o values (0.5–2.0) to side wall squeezing at higher K_o values (4.0).

Some results for the case of $K_o = 1$ are summarized on Fig. 3 which shows contours of vertical displacement together with element yield indicators. The results show that roof collapse is the critical failure mechanism with tensile failure zones propagating up from the cave crown and down from rockhead above the cave shoulders.

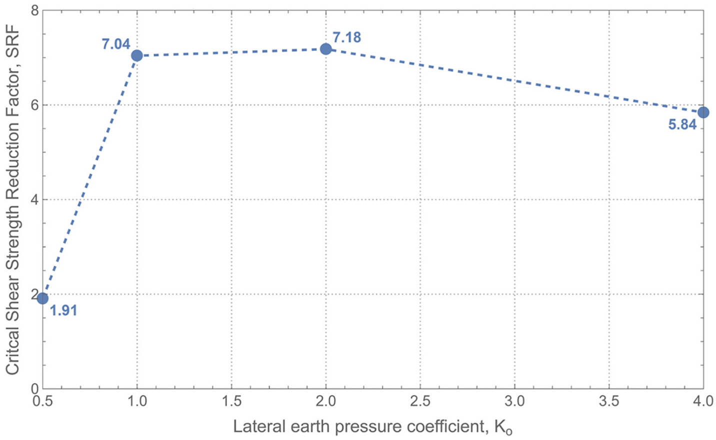

Fig. 2. Variation of critical SRF with K_o for prevailing conditions

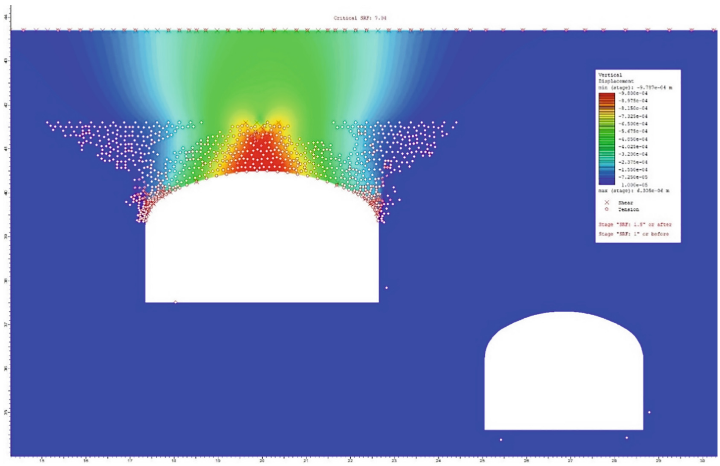

Fig. 3. Contours of vertical displacement at SSR = 7.05 for existing conditions and $K_o = 1$

3.2 Impact of Construction Plant Loading on Prevailing Stability

The stability of the caves when subjected to plant loading has been considered using two alternative approaches.

In the first approach, the unfactored 210 kPa construction plant bearing pressure was applied and shear strength reduction analyses were performed with the load held constant at 210 kPa. The critical SRF values obtained from these analyses are compared with the corresponding prevailing values on Fig. 4. This comparison shows that the plant loading has an appreciable impact on the critical SRFs, which are significantly reduced compared with the values for prevailing conditions.

With the plant load is applied, the SRF values increase consistently with K_o, from an unacceptable value of around 0.83 at $K_o = 0.5$ to a potentially tolerable value of

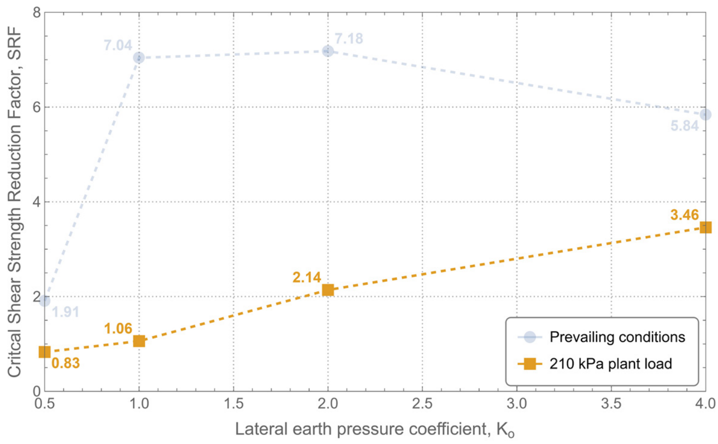

Fig. 4. Variation of critical SRF with K_o when 210 kPa construction plant load is imposed

around 3.46 at $K_o = 4$. Examination of the model displacement fields (not presented here) demonstrates that cave roof collapse represents the critical failure mechanism for all the K_o values considered.

In the second approach, the construction plant load was increased incrementally and vertical displacements at the crown of the upper cave were monitored. Plots of imposed bearing pressure against crown displacement from these analyses are presented on Fig. 5. The imposed bearing pressures plotted on Fig. 5 are expressed in terms of an applied load factor, LF, that represents the incrementally imposed bearing pressures divided by the 210 kPa plant load. The values of these load factors at failure, LF_f, are plotted against K_o on Fig. 6.

As might be expected, the stiffness of response and the limit loads increase with increasing values of K_o in the sandstone. The plots also show that failure is quite sudden, or brittle, with very little evidence of plastic yielding at the cave crown as the failure loads are approached.

As per the results of the SSR analyses, the load factors at failure increase consistently with $K_{o,}$ from an unacceptable value of around 0.97 at $K_o = 0.5$ to a potentially tolerable value of around 2.41 at $K_o = 4$.

Some results from the incrementally loaded model with $K_o = 1$ are visualized on Figs. 7 and 8 which respectively present contours of vertical displacement and volumetric plastic strain when the model has just failed (i.e. when the applied bearing pressure was 1.12 times the unfactored 120 kPa plant load). Both figures show that collapse of the cave roof represents the critical failure mechanism. The asymmetrical influence of the lower cave is also apparent. Regions of tensile failure extending up from the crown of the cave's roof and down from rockhead above the cave shoulders can be seen on Fig. 8.

The above observations indicate that the rock material in the roof of the cave appears to behave in a manner similar to a pre-stressed beam. With further investigation, this may afford opportunity to formulate a relatively simple calculation model for rapid stability assessment and/or initial risk screening purposes.

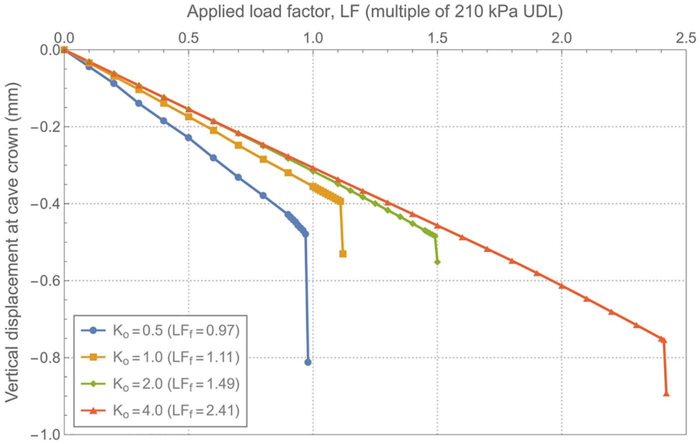

Fig. 5. Load-displacement curves and inferred factors of safety for different K_o values

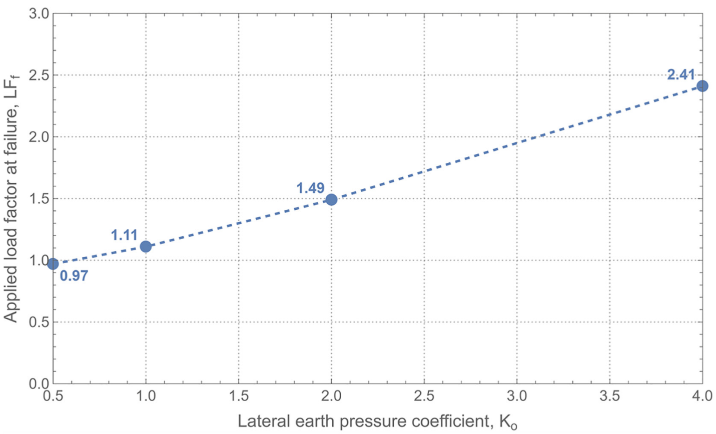

Fig. 6. Variation of applied load factor at failure, LF_f, with K_o

4 Conclusions

RS2 has been successfully used on a commercial project in the UK to undertake preliminary stability studies of a shallow cave system subjected to surface construction plant loading.

Using idealized ground models, the analyses have established that the stability of the caves critically depends on several characteristics of the sandstone that have not yet been adequately investigated. Such characteristics include the rock structure (e.g. bedding and jointing), the rock strength and the initial ratio of horizontal to vertical effective stress, K_o.

The results presented in this paper represent part of a larger study, but indicate that the K_o value for the sandstone is likely to be a key parameter in controlling the stability

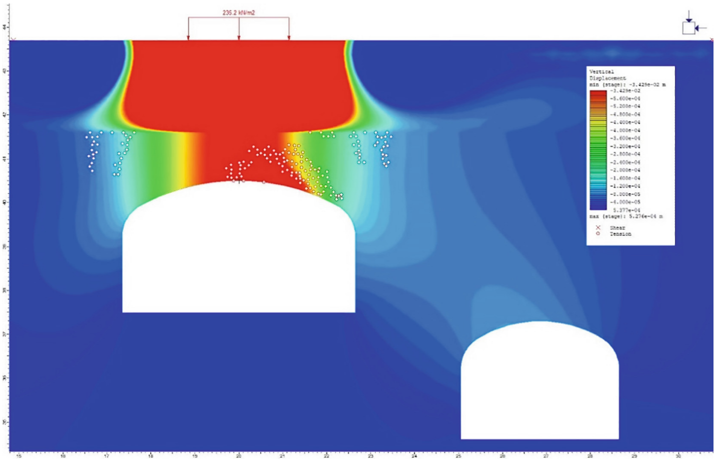

Fig. 7. Contours of vertical displacement for $K_O = 1$

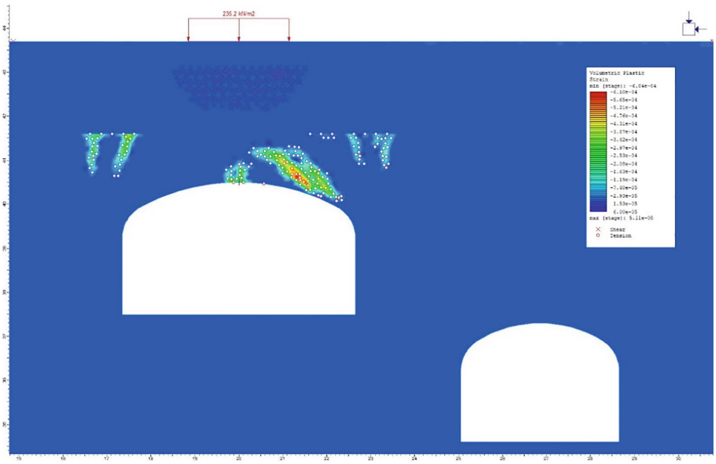

Fig. 8. Contours of volumetric plastic strain for $K_O = 1$

of the shallow caves when the plant loads are imposed. This and other findings have been used to help inform the design of a detailed ground investigation, the results of which will be utilized to refine the ground model and undertake more rigorous stability analyses. Due to the irregular geometry of the cave system and the nature of the construction plant loading, it is anticipated that 3D analyses may ultimately be warranted to provide reliable results.

References

1. Rocscience, https://www.rocscience.com/software/rs2.
2. Bell, F.G.: Engineering Properties of Soils and Rocks. 4th edn. Blackwell Science, Oxford (2000).
3. Bieniawski, Z.T.: The Point Load Test in Geotechnical Practice. Engineering Geology, Vol. 9, p. 1–11. Elsevier, Amsterdam (1975).
4. Bond, A. and Harris, A.: Decoding Eurocode 7. Taylor and Francis, Abingdon, Oxford (2008).
5. Bowles, J.E.: Foundation Analysis and Design. Third Ed. McGraw Hill (1982).
6. British Standards Institution: BS8004: Code of Practice for Foundations. BSI, London, UK (2015).
7. Hoek, E and Brown, E.T.: Underground Excavations in Rock. Institution of Mining and Metallurgy. London (1980).
8. Hoek, E and Brown, E.T.: The Hoek-Brown Failure Criterion and GSI. Journal of Rock Mechanics and Geotechnical Engineering, Vol. 11, pp. 449–463. (2019).