



## Numerical simulation - Optimisation of foundation and underground works

### 1) Optimisation, a philosophy

Engineers have to keep abreast of the latest technical developments, particularly by being able of taking advantage of the enormous possibilities now available in the field of applied numerical computing. For several years, the engineers of STUCKY Ltd have been working with scientists and investing to develop new computing tools. The aim of this collaboration is to produce software to improve design work, making it safe and economically sound. It is with this aim of optimising the design of the foundation and underground structures that STUCKY is proposing its experience and applied numerical simulation capabilities. It hopes to develop collaboration between partners wishing to offer owners structures at the best price and in total safety.

### 2) Numerical simulation model

The desire of continually improving and progressing is the result of over 60 years' experience in Switzerland and worldwide and a solid international reputation in the design and construction of hydroelectric structures and dams.

Nowadays, the structures are increasingly complex and are built in places where the foundation conditions are difficult. Foundation costs have become a determining factor. STUCKY proposes a method for optimising the underground structures based on its experience, a traditional approach to define the objective to be achieved and the use of the Z\_SOIL 3D™ simulation model to check and support the designers' expectations. This software, dedicated mainly to the calculation of underground structures, can be used for all types of 3-D modelling. It has been designed to constitute a genuine decision-making tool for civil engineers.

Its calculation module is based on the theory of two-phase (solid-water) continuous media, simulating elastoplastic constitutive behaviour of the solid medium and solving the equilibrium equation by the numerical finite element method.

Z\_SOIL 3D is the result of over 15 years' academic research and active collaboration between private industry and the Federal Institute of Technology in Lausanne. Some of STUCKY's collaborators have played an active role in bringing this software to maturity and making it operational. They know the theory behind it as well as its limits and are now proposing their numerical experience to you.

Displacements x 50  
Safety factor 3 (ultimate state)

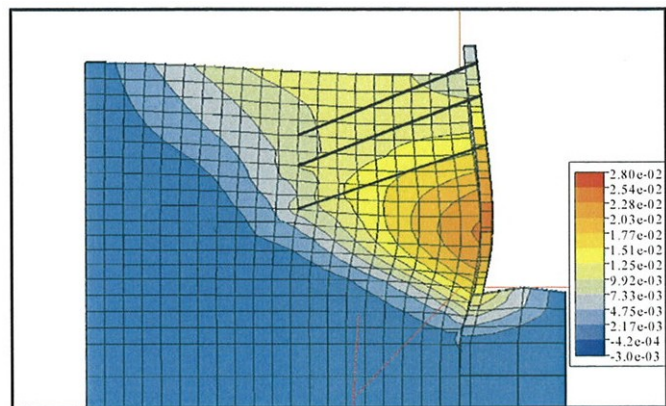


Figure 1: Horizontal isodisplacements (m) of an anchored diaphragm wall

Safety factor 2.2 (ultimate state)

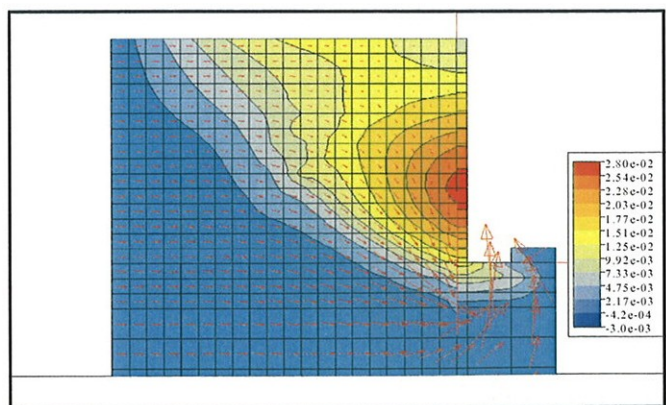


Figure 2: Drainage of groundwater in the presence of an anchored diaphragm wall - Horizontal isodisplacements (m)



With Z\_SOIL 3D and its unified solution to problems basically connected to soil, engineers benefit from an increasingly precise representation of the real behaviour of the ground and the structure with which it interacts. In figures 1 and 2, the interaction between the soil, water and structure (anchored diaphragm wall) is effective mainly because of the presence of a contact element developed to ensure free movement between wall and soil. The water flow is modelled with the mechanical effect of the water on the solid part of the ground. In the same way, the illustrations in figures 3 and 4 show how any type of coupled-stress stratification of the ground and modelling of the local or overall stability of a structure can be handled simply. Similarly, it is easy to obtain the distribution of the internal forces in the structure analysed. Input processing and data modifications are strong points of the software, allowing a rapid analysis and interpretation of the results.

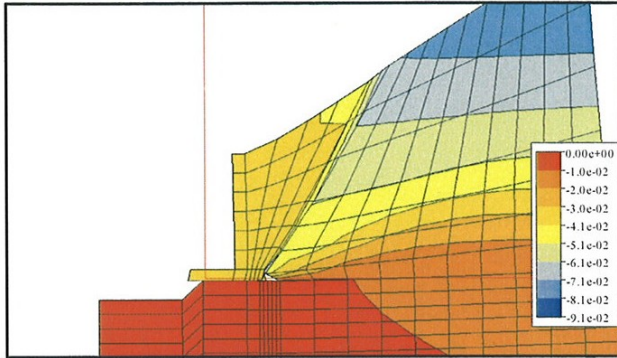


Figure 3: Horizontal isodisplacements (m) of a wall without anchorage - Sliding of the base  
Safety factor 1.6 (ultimate state)

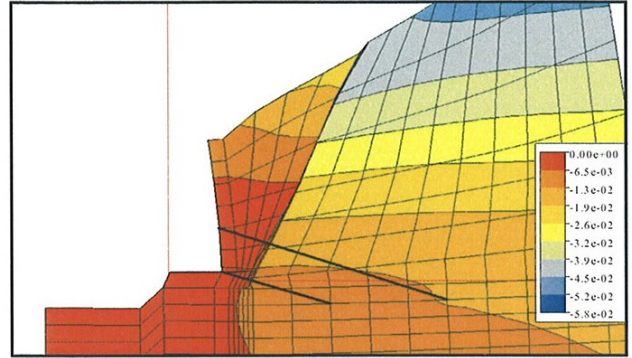


Figure 4: Horizontal isodisplacements (m) of an anchored wall  
Safety factor 2.4 (ultimate state)

### 3) Advantages of three-dimensional simulation

It has recently become possible to perform three-dimensional calculations. Z\_SOIL 3D has been developed with a tool kit to facilitate spatial representation. This means that complex non-symmetrical problems can be modelled and calculated. The advantage of three-dimensional modelling is that it avoids using simplifying hypotheses of the plane state of stresses or strains, which might be poorly adapted. The retaining wall in figures 5 and 6 is an example of this. In this highly dissymmetrical example, where the dimensions of the structure are greater than tens of meters, it was possible to perform a simulation of the staged excavation process and check the stability of each stage. In the same way, the underpinning of the anchored concrete wall was modelled and the internal forces (M, N and T) were calculated for each redistribution of the forces. This type of calculation requires close collaboration with the geotechnical specialist whose expertise is essential and complementary. STUCKY encourages and favours this sort of approach, which it considers indispensable.

Similarly, STUCKY places strong emphasis on the experience acquired by its own collaborators who carry out the modelling. As experienced project engineers, they have also acquired solid complementary knowledge of advanced numerical modelling and the application of the complex constitutive laws governing the behaviour of materials. Without this, the use of such software packages becomes risky.

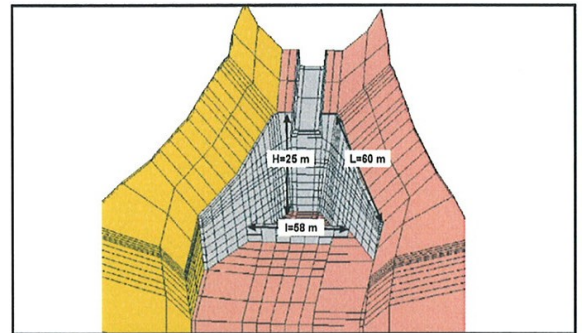


Figure 5: Anchored retaining wall  
Final stage of excavation

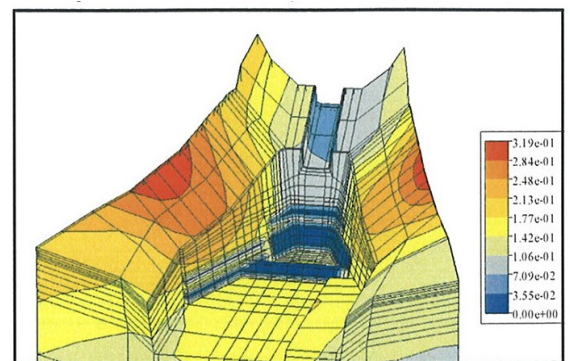


Figure 6: Retaining wall  
Isovalues of overall displacements (m)

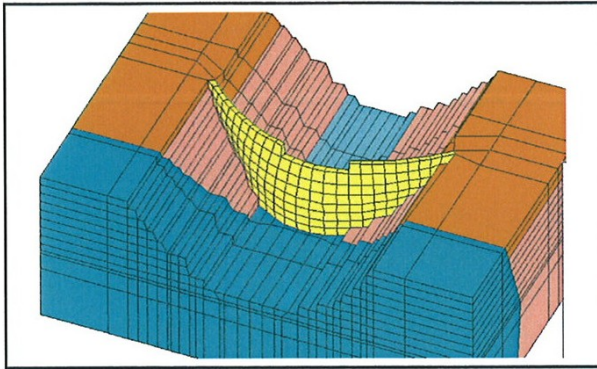


Figure 7: Arch dam (h = 130 m)  
Construction phases simulation

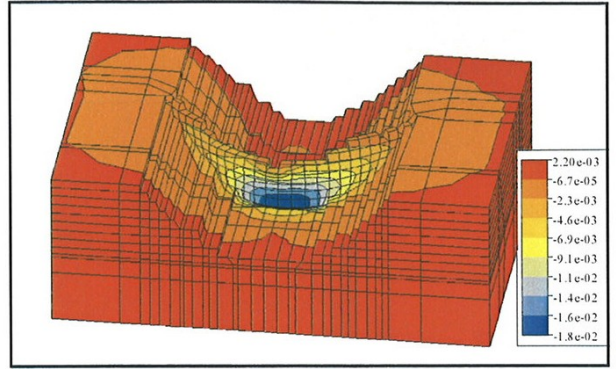


Figure 8: Vertical isodisplacements (m)  
Status after 550 days' construction

The experience acquired in the study of a large number of hydroelectric structures is carried over into numerical modelling as the illustrations opposite show. Firstly in figures 7 to 9, in the case of a concrete dam where the displacements of the foundation measured in situ had to be checked. The construction conditions were simulated before determining the evolution of the deformations of the foundation. In this case, the strong anisotropy of the rock foundation made it impossible to use traditional methods for these calculations.

In figures 10 and 11, a geological feature encountered during the excavation work of a dam required a rapid analysis of a reinforcement solution, while heightening of the dam was under way. Stability of the concrete abutment block resting on a rock wedge inclined towards downstream was analysed taking into account the hydrostatic load of the reservoir water. This study enabled constructive measures to be taken after studying their stability.

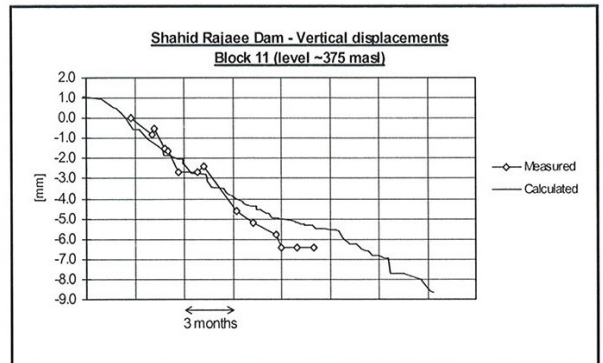


Figure 9: Comparison of measured and calculated displacements

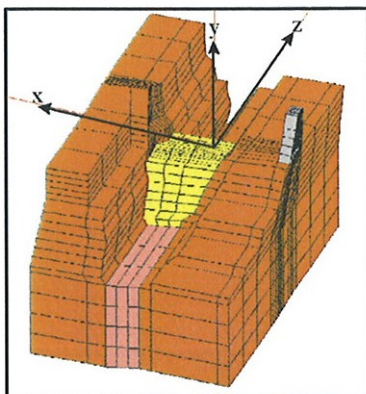


Figure 10: 2<sup>nd</sup> phase of concreting the gorge

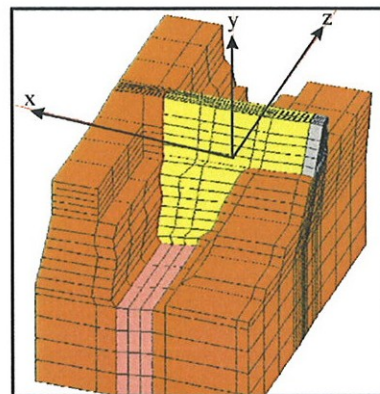


Figure 11: Study of dam abutment stability



**4) Application to underground structures at small depths**

Whether in two or three dimensions, Z\_SOIL 3D can be used to check the influence of the execution of any underground structure. The software is perfectly suited to the analysis for tunnels at great or small depths. Figures 12 to 16 illustrate the modelling possibilities. Phased realization and the effect of deferred construction of the structures (figures 13 to 16) can be represented in order to optimise the phasing of works during construction. Any local reinforcement and any grouting decisions can be simulated, enabling assessment or comparison of the effectiveness of different methods.

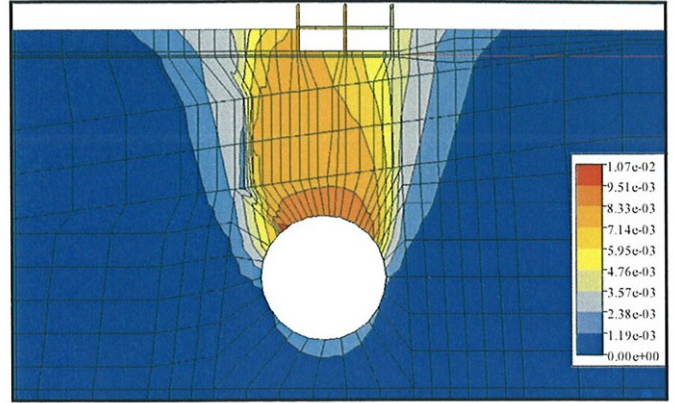


Figure 12: Checking of surface displacements before placing the lining

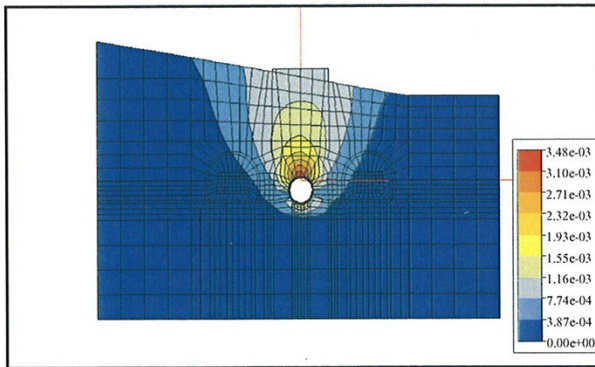


Figure 13: Execution of a pilot tunnel  
Vertical isodisplacements

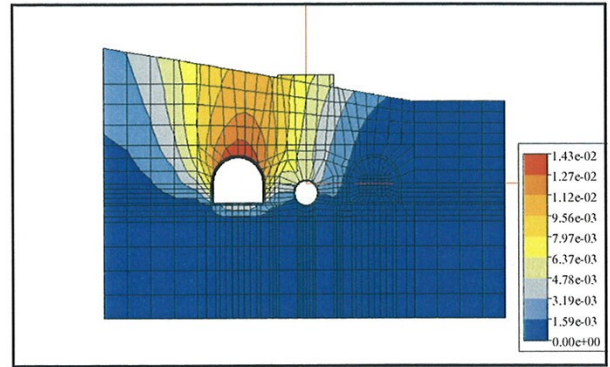


Figure 14: Execution of left-hand side tunnel  
Vertical isodisplacements

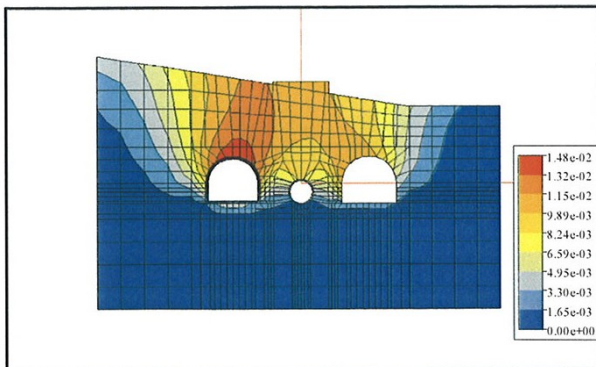


Figure 15: Execution of right-hand side tunnel  
Vertical isodisplacements

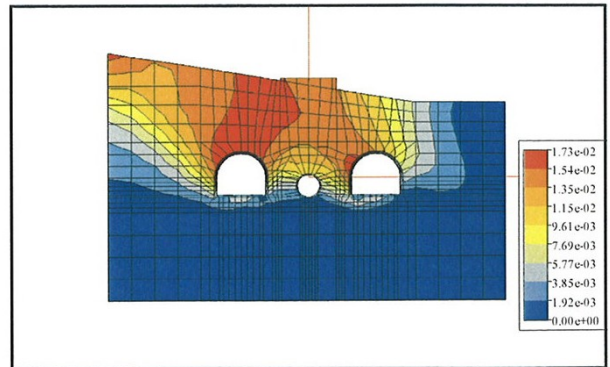


Figure 16: Evolution of isodisplacements for a safety factor of 1.9

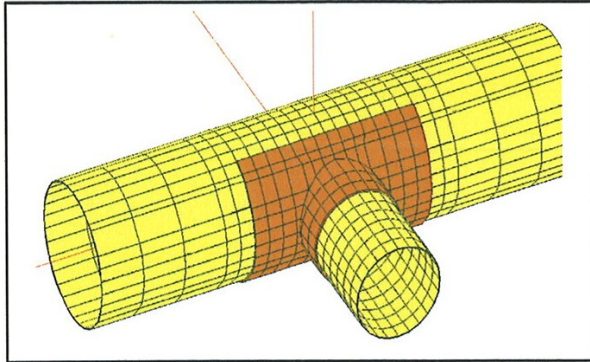


Figure 17: Junction of headrace and surge tank steel linings with local reinforcement

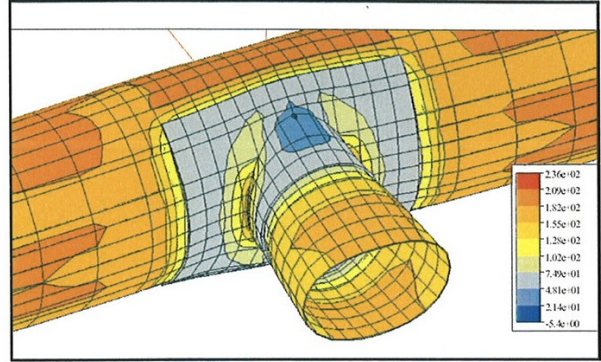


Figure 18: Tensile isostresses (MPa) for an internal pressure of 260 mCE

## 5) Multiple applications

The strength of Z\_SOIL 3D also lies in its wide range of possibilities (handling of thermal effects, concrete creep, anchors, nails, use of shell-type elements for the walls, contact between elements and a wide range of constitutive models to simulate various materials). This means it is also possible to carry out simulations such as those shown in figures 17 to 20. In figures 17 and 18, it was possible to check the stresses on a steel low-pressure pipe portion and, in figures 19 and 20, to compare two hydraulic diaphragm solutions for a low-pressure tunnel. All these examples are provided to show the range of application of the numerical tool used. Although the software has only recently achieved maturity in terms of three-dimensional analyses, the engineers using it for design work have considerable experience in numerical calculation and engineering work. The credibility of the proposed optimisation approach relies on the constant and critical attention that STUCKY applies to the analysis results.

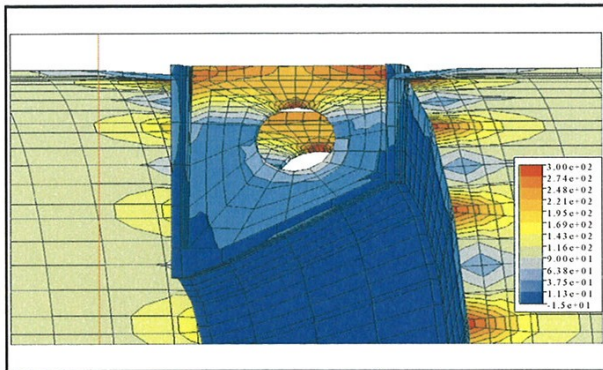


Figure 19: Tensile isostresses (MPa) on a diaphragm  
Discontinuous solution  
(appearance of strong concentrations of stresses)

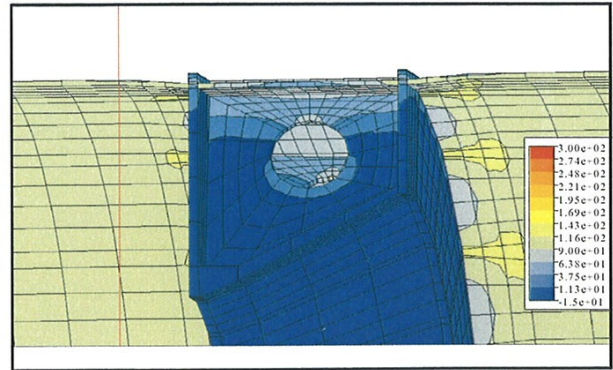


Figure 20: Tensile isostresses (MPa) on a diaphragm  
Continuous solution