275 m high Yusufeli arch dam – Geotechnical modelling during construction

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ABSTRACT: The World's highest double curved arch dam outside of China was recently completed near the town of Yusufeli in NE Turkey. The project was ordered, supervised and managed by the State Ministry of Hydraulic Works (DSI), and constructed by contractor LIMAK of Ankara. The implementation of the 275 m high dam necessitated the construction of almost 480 m high very steep cut-slopes in extreme terrain. The contractor decided early during his contract to perform a multi-staged site investigation and consequent 3D geotechnical modelling. Data from a large variety of SI methods, including detailed geological documentation of ~20km of tunnels and ~200,000m² excavated slopes were continuously integrated into this 3D geo model. Together with a co-operative approach between acting parties, an active project management and highly professional service providers, the flexible 3D model helped to effectively deal with the important geotechnical issues and complete this ultra-high dam project without significant delays.

Keywords: 3D modelling, digital data base, steering tool, design and construction management.

1 THE PROJECT

Yusufeli HEPP is part of the Coruh River hydro scheme in the Artvin Province in NE Turkey. In 2012, DSI – the project Owner – awarded the contract for design and construction. iC consulenten ZT GmbH was appointed by the contractor LIMAK and his general designer Su-Yapi to accompany executive design works with geological, geotechnical consultancy.

With a height of 275 m, Yusufeli dam is the World's highest double curved arch dam outside of China. The reservoir storage capacity is 2.2 billion m³ and the total installed power 540 MW. The arch dam necessitated the construction of almost 480 m high very steep cut-slopes in extreme terrain and large underground caverns, where Coruh River had formed a deeply incised valley through magmatic rocks of the Ikizdere Pluton. Executive design and construction commenced in 2013. Dam foundation excavation was completed in July 2018, dam concreting and grouting in February 2022. Impounding started in November 2022 and is scheduled for completion in 2023. At the time of paper submission (February 2023) impounding had exceeded the bottom outlet (Figure 1).

Figure 1. Yusufeli dam, February 2023 (photo courtesy of LIMAK).

2 3D MODELLING – MOTIVATION AND APPROACH

Key motivations for applying a digital 3D ground model at Yusufeli dam and HEPP site were:

- Demand of continuous adjustment of detailed site investigation programs for all civil works and investigation targets.
- Development of a consistent geotechnical classification scheme, parameters, and design models for all geotechnical design applications (underground structures, dam, dam foundation, slope excavation & support.
- Development and documentation of groutability testing programs.
- Geotechnical guidance of slope excavation process.
- Monitoring, visualization, and geotechnical guidance of grouting works.
- Verification of grouting success.
- Continuous and easy flow of information between project parties.
- Pro-active design and construction management by early detection of geotechnical problems.

The geotechnical model for the executive dam design was developed between 2013 and 2018, while preparatory and dam excavation works were ongoing. The contractor decided already soon after the commencement of preparatory works to perform a multi-staged site investigation and consequent 3D geotechnical modelling. The amount of data, complex design requirements and the necessary flexibility throughout the design and construction periods demanded innovative tools and workflows, which were met by using the software “Leapfrog” (by Seequent ltd.). As works were proceeding and information was compiled, modelling strategy and the model itself were developed and constantly adjusted.

Until 2015, geotechnical information was largely provided to the designers in 2D sections that were created and interpreted from the 3D geo base model. The 2D distribution of geotechnical materials was sufficient for local design applications (transformer hall & powerhouse caverns, shafts, headrace- and tailrace tunnels or small-scale slopes in dimensions of meters).

Later in the project, 3D geotechnical volume models became increasingly important for large-scale and geometrically complex design issues (e.g., excavation support design and dam design in dimensions of many 100s of meters). For meeting the requirements and limitations of the design software, these large-scale geotechnical models needed to be reasonably simplified, without neglecting the observed rock mass heterogeneity and related uncertainties.

By 2017, a digital base model with factual data and interpreted geological structures was established, that facilitated deriving different geotechnical models for various design applications. The model setup (1) allowed efficient adjustment to additional data, and (2) guaranteed the model`s consistency and validity by – partly automatized – checking algorithms (Weil et al. 2019). Newly collected factual data were continuously compared with the rock mass behavior experienced during construction and with the results delivered by design calculations. By considering the obtained information for short- and long-term decisions, the digital model also served as platform for actively steering design and construction processes.

In 2018 the geotechnical dam foundation model was completed. This model – later also referred to as pre-grout model - served as basis for the final dam design calculations and for the definition of grouting measures, which were required for improving the foundation conditions. While dam concreting and grouting works were ongoing, a verification survey was performed for guiding the grouting program (Kieffer et al. 2019). In 2022, after dam construction and grouting was completed, the – then actual - foundation conditions were presented in a post-grout geotechnical model and the suitability of the dam design could be confirmed before impounding started.

3 BASE DATA

Geological and geotechnical data collected throughout the construction period were compiled into the 3D model, which served as factual data base for modelling of fault structures and rock mass volumes. Type and approximate quantities of the most relevant data are summarized in Figure 2.

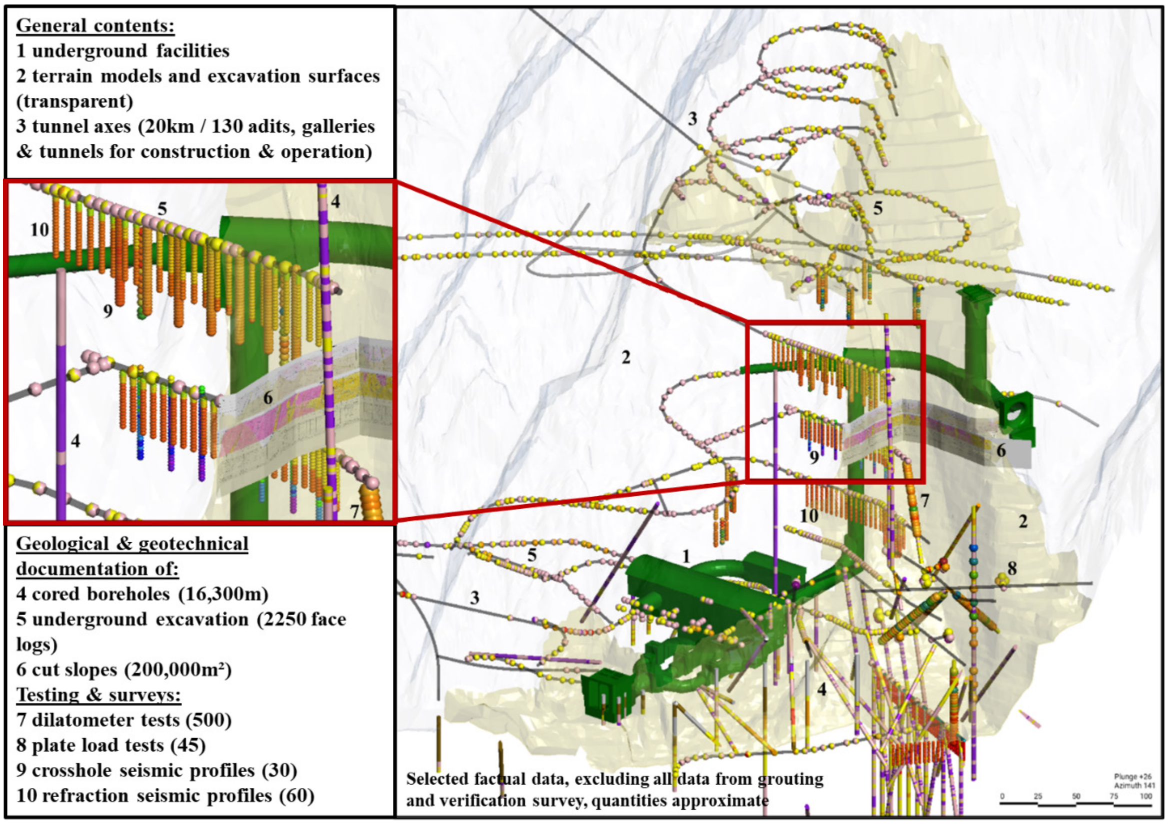

Figure 2. Factual data in 3D digital ground model.

At any given time, there was always only one updated model valid and made available for viewing and use to the acting project parties. Output formats and model collaboration tools evolved during the project. They comprise e.g., exported map and section layouts and 3D shapes in CAD and other formats as well as encapsulated model viewer files and cloud-based collaboration platforms, including versioning control and model-based communication.

4 GEOTECHNICAL CLASSIFICATION SCHEME

The rock mass classification scheme for the executive design was based on the classification system applied during previous project phases and adjusted to EC and ISRM standards. The associated rock mass classes A1 (most favorable), A2, B, C and D (least favorable materials) related to small-scale rock mass volumes (<10m), which were defined according to standard rock mass properties and referred to as GT ground types. The spatial distribution of ground types documented in boreholes, surface and subsurface outcrops was displayed in the base model (Figure 2).

For the dam and large-scale cut slope design, the observed rock mass heterogeneity and related uncertainties were accommodated in a reasonably simplified geotechnical model, where large-scale volumes of foundation materials (most favorable FM1, FM2, FM3, least favorable FM4) represent particular mixtures of ground types. GT ground types are assigned to small-scale rock mass mainly by visual inspection, FM foundation materials are assigned to larger scale rock mass volumes in 3D model space.

While excavation works were ongoing in 2016, it became obvious, that confinement conditions affected the rock mass behavior more severely than anticipated. The main argument for considering the confinement conditions routinely in the geotechnical model was the distribution of deformation properties (e.g., elasticity modulus E), which were measured by repeated in-situ test series and often showed no or little correlation to rock mass properties used for standard classifications. The role of rock mass relaxation was introduced into the modelling scheme by establishing confinement zones (Cf1, Cf2, Cf3, Cf4). Within superficial relaxed zones (Cf3 and Cf4) the measured E moduli were atypically low and controlled by the degree of relaxation, largely independent from the type of FM. The thickness of these relaxed zones depended mainly on the local discontinuity configuration and on the surface geometry. Within high confinement zones below the thalweg and deep below the valley flanks (Cf1), E moduli were atypically high. Only within the low confinement zone CF2, E moduli fitted well to standard properties and parameter assessments for the FM foundation materials.

An approach was developed for creating a 3D parameter model (P model), which considered the spatial distribution of foundation materials FM1 to FM4 (FM model) and the influence of the confinement zones Cf1 to Cf4 (Cf model). For maintaining the classification scheme as simple as possible, a standardized and reproducible relationship between GT ground types, FM foundation materials, Cf confinement zones and P parameter sets was established. Figure 3 depicts the modelling process for an exemplary 2D section along the (curved) dam axis.

A systematic parameter assignment was achieved by blending the FM model and the Cf model in the digital modelling software. The resulting volumes with characteristic Cf/FM combinations were attributed by parameter sets according to the interrelation displayed in Figure 3-D. The associated P model comprised six rock mass parameter sets P0 to P5. Parameter sets P1 to P4 were originally assessed for foundation materials FM1 to FM4 along the valley flanks (initially assumed as low confinement zone Cf2). If a FM volume is situated in a more confined (Cf1) or less confined (Cf3&4) zone, the acting parameter set can rise or drop to the adjacent parameter class. The most favorable parameter set P0 relates only to FM1 foundation materials within the high confinement zone Cf1. The most unfavorable parameter set P5 relates only to intensely relaxed rock mass (irrespectively of FMs) along the surface.

The interaction of standard properties (GT), scale (FM), confinement (Cf) and parameters (P) of the rock mass complicated the modelling approach in such an essential way, that its justification was repeatedly scrutinized by all involved parties. The robustness of this approach, which was introduced in Dec 2016, was eventually confirmed by complementary site investigation as well as by observations and experiences during 2017 and 2018 dam excavation works.

5 GEOTECHNICAL FOUNDATION MODEL FOR DAM DESIGN (PRE-GROUT)

The final geotechnical foundation model was provided to the dam designer in Dec 2018. Figure 3 shows the 2018 FM, Cf and P models in a 2D section along the dam axis. The allocation of FM foundation materials (Figure 3-A) also considered the routine slope documentation of the dam excavation, which was completed in July 2018. The dimensions of the Cf confinement zones (Figure

3-B) reflected the distribution of E moduli determined by seismic surveys that were carried out at the dam foundation and abutments before concreting and grouting works had commenced.

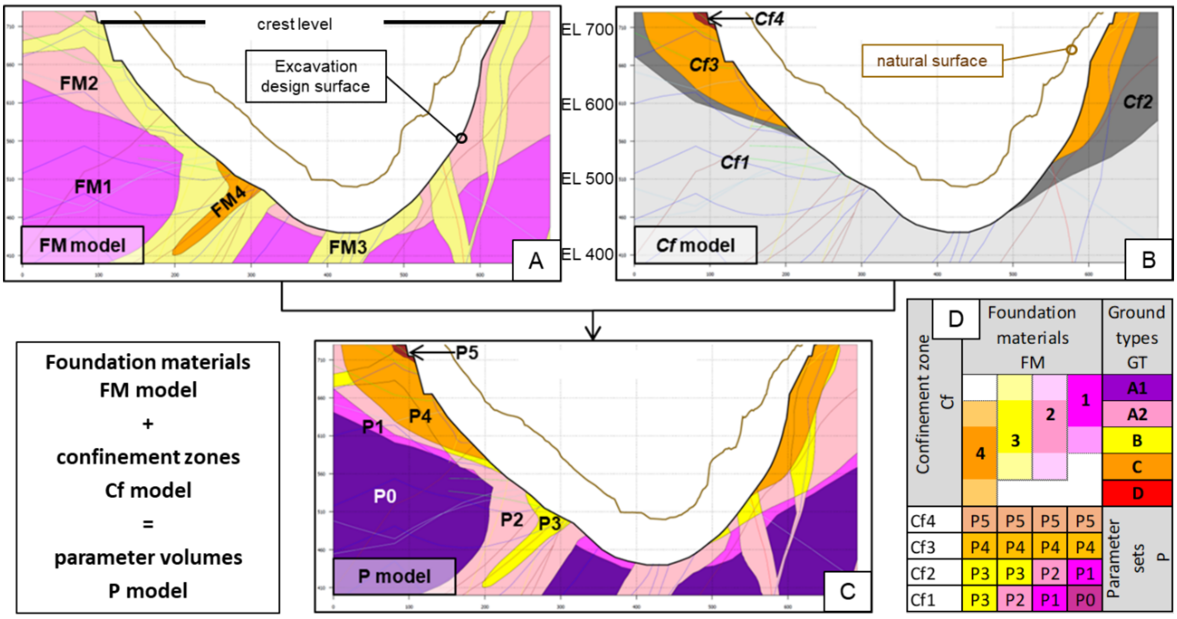

Figure 3. Pre-grout P model = FM model + Cf model in section along dam axis.

The resulting pre-grout P model (Figure 3-C) showed, that - because of the deep rock mass relaxation (Cf3 & Cf4 zones) along the steep valley flanks, - less favorable rock mass could not be completely removed by dam excavation. Particularly at the upper dam abutments, notable dimensions of P4 rock mass needed to be improved for serving as adequate foundation material.

The 2018 geotechnical foundation model was used as basis for the final dam design. As part of these design works, a custom-tailored cement grouting program was defined for achieving the required deformation properties for the dam foundation.

6 GEOTECHNICAL VERIFICATION MODEL (POST-GROUT)

While dam concreting and grouting works were ongoing, an extensive verification survey was performed for checking if the dam foundation had been improved to the necessary level. For this purpose, cross-hole seismic profiles (349 pre-grout and 2329 post-grout measurements) and dilatometer tests (251 pre-grout and 692 post-grout tests) were carried out for determining pre-grout and post-grout E moduli throughout a pattern of defined test locations. The interim evaluation of grout-takes and pre/post-grout E moduli allowed steering the grouting program. For finalizing the verification process of the dam design, the pre-grout P model was updated by integrating the post-grout E moduli derived from the verification survey.

Figure 4 compares the 2018 pre-grout P model (A) with the post-grout P model (C) and shows the improvement of the rock mass within the grout bulb. Much of the rock mass was improved to parameter classes P3, P2 and P1, and unfavorable P4 rock mass was notably reduced The close-up in Figure 4-B depicts anchor volumes and grout-takes at the downstream dam foundation, where the most unfavorable P5 rock mass was entirely eliminated and unfavorable P4 rock mass improved to P3.

Based on this post-grout foundation model, the dam designer could rerun the deformation analysis and investigate expected deformations during and after impounding.

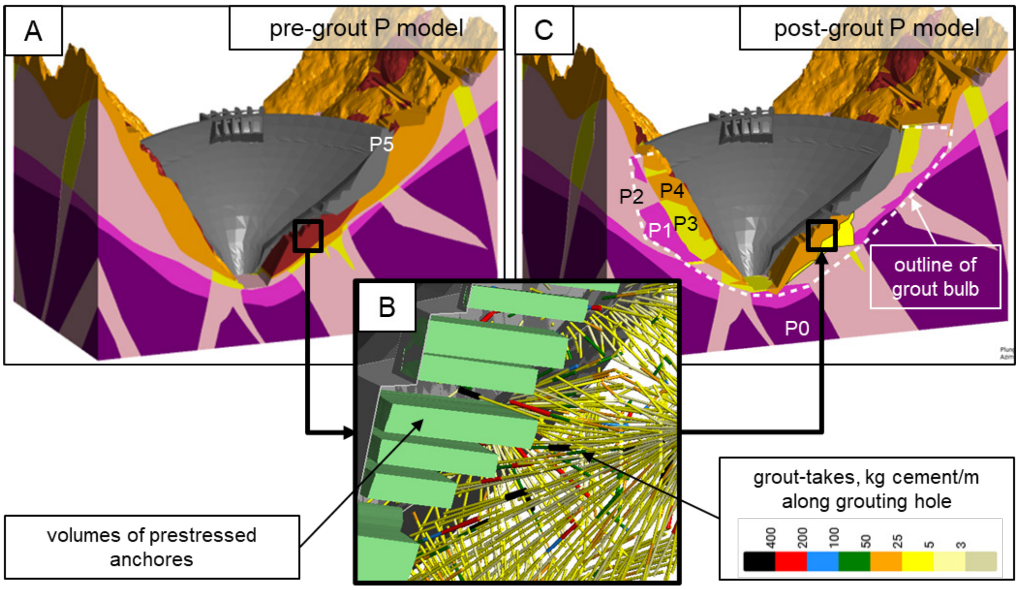

Figure 4. Comparison of pre- and post-grout parameter P models.

7 CONCLUSIONS

The experiences made during the Yusufeli dam project impressively showed the value of 3D modelling throughout the construction process. A flexible 3D model not only allows to deal with various geotechnical issues but also helps to effectively guide the design and construction process. Basic pre-conditions for a successful application are (1) a co-operative approach by all project parties, (2) a well-planned modelling strategy that allows flexible adjustments, and (3) a well-maintained digital data base enhancing easy and fast flow of information.

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