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Innovative 3D ground models for complex hydropower projects

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ABSTRACT: Digital 3D geotechnical models have become indispensable for the design of today‘s large hydropower projects. The amount of data, complex design requirements, and the necessary flexibility throughout the design and construction periods demand innovative tools and workflows. This paper presents approaches that were developed and successfully applied for: (1) compiling, analyzing and visualising large amounts of factual data, (2) describing heterogeneous and complex rock mass properties in models suitable for large-scale 3D design software, (3) verifying and updating models during on-going investigation and excavation works, and visualizing, planning and guiding (4) grouting operations and monitoring programs.

RÉSUMÉ: Les modèles géotechniques 3D numériques sont devenus indispensables pour la conception des projets de centrales hydrauliques de grande envergure. Le nombre de données, les exigences de conception, la flexibilité, des outils et des workflows innovants sont nécessaires pendant toute la période de conception et de construction. Le présent document présente les approches qui ont été développées et mises en œuvre avec succès pour : (1) la compilation, l'analyse et la visualisation de grands volumes de données factuelles, (2) la description de masses rocheuses hétérogènes et complexes dans des modèles adaptés à des logiciels de conception 3D à grande échelle, (3) la vérification et la mise à jour des modèles pendant les travaux d'étude et d'excavation, ainsi que (4) la visualisation, la planification et le guidage des opérations d'injection de béton et des programmes de suivi.

1 INTRODUCTION

Some of the main challenges in geotechnical modelling for large hydropower projects relate to:

(1) handling large volumes of geological and geotechnical factual data (Section 2),
(2) translating detailed factual data into simplified but representative geotechnical base-line models for design works (Section 3.1),
(3) verifying and updating geotechnical models with regard to additional data collected during construction (Section 3.2).

These tasks can be efficiently supported by digital 3D modelling software. Such digital tools are widely used for mining and exploration with well-established routine methodologies. Applications for civil structures are becoming increasingly common during the last years, however they often call for early decisions and particular solutions.

iC consulenten developed streamlined, digital workflows from acquisition of geological data (Horner et al. 2016) to the development of 3D geotechnical models that are suitable for the specific requirements of individual hydropower projects. Beside the actual modelling process, such 3D models can also serve for

(4) guiding construction and visualizing geotechnical monitoring data (e.g. extensometer, inclinometer, load cells, crack metres, geodetical survey targets and InSAR surveys; Section 4).

2 GEOTECHNICAL INPUT DATA

Available software products provide a digital platform for combining and visualizing multiple datasets that can include:

(a) 0D point data (e.g. lab or in situ test results, any other information linked to a location);
(b) 1D linear data (e.g. borehole intervals, dominant rock mass classes along a tunnel axis or other information linked to chainage);
(c) 2D areal data (e.g. field maps or geological documentation of outcrops, profiles from geophysical surveys etc.);
(d) 3D data (e.g. point clouds and meshes obtained from remote sensing and photogrammetric surveys, traces of discontinuities mapped in the natural or excavated topography or slopes, 3D geophysical surveys etc.).

Figure 1 displays point-, line- and plane-type representations for subsurface factual data from various investigation and documentation methods related to one abutment and to the underground facilities of a dam project. Standardized colour coding of the displayed features visualizes the spatial distribution of e.g. rock mass classification along access galleries and boreholes or geotechnical properties like moduli from refraction and cross-hole seismic surveys and dilatometer testing. For data points comprising several parameters, one parameter is selected interactively for visualization (e.g. static E modulus from cross-hole seismic in Figure 1), while all associated parameters can be queried and displayed in related information boxes (e.g. seismic velocities etc. in Figure 1).

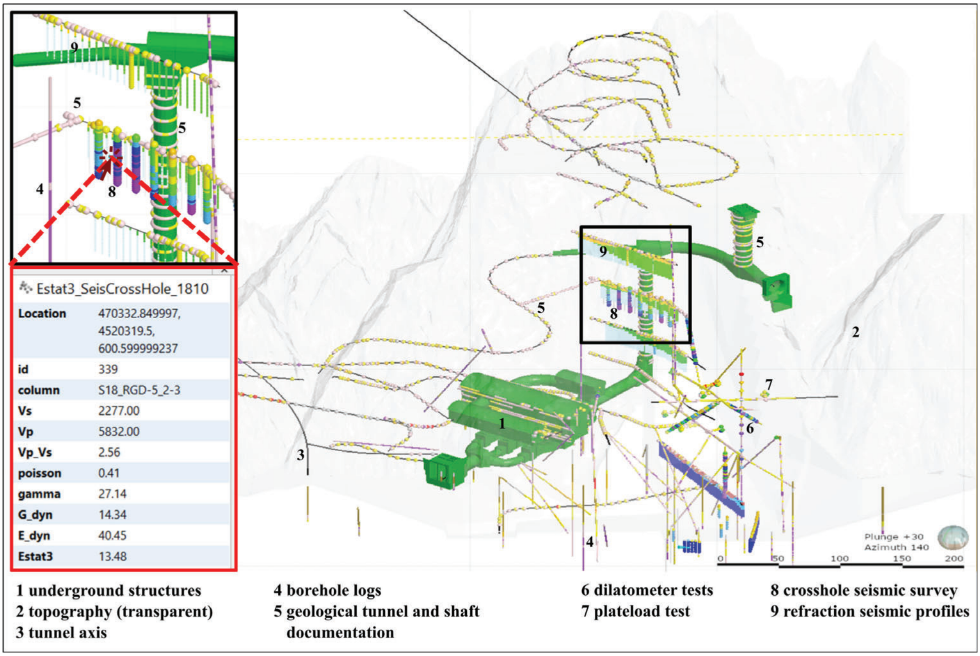

Figure 1. Visualization of factual site investigation data related to a dam abutment and underground facilities (headrace, caverns, tailrace and auxiliary tunnels).

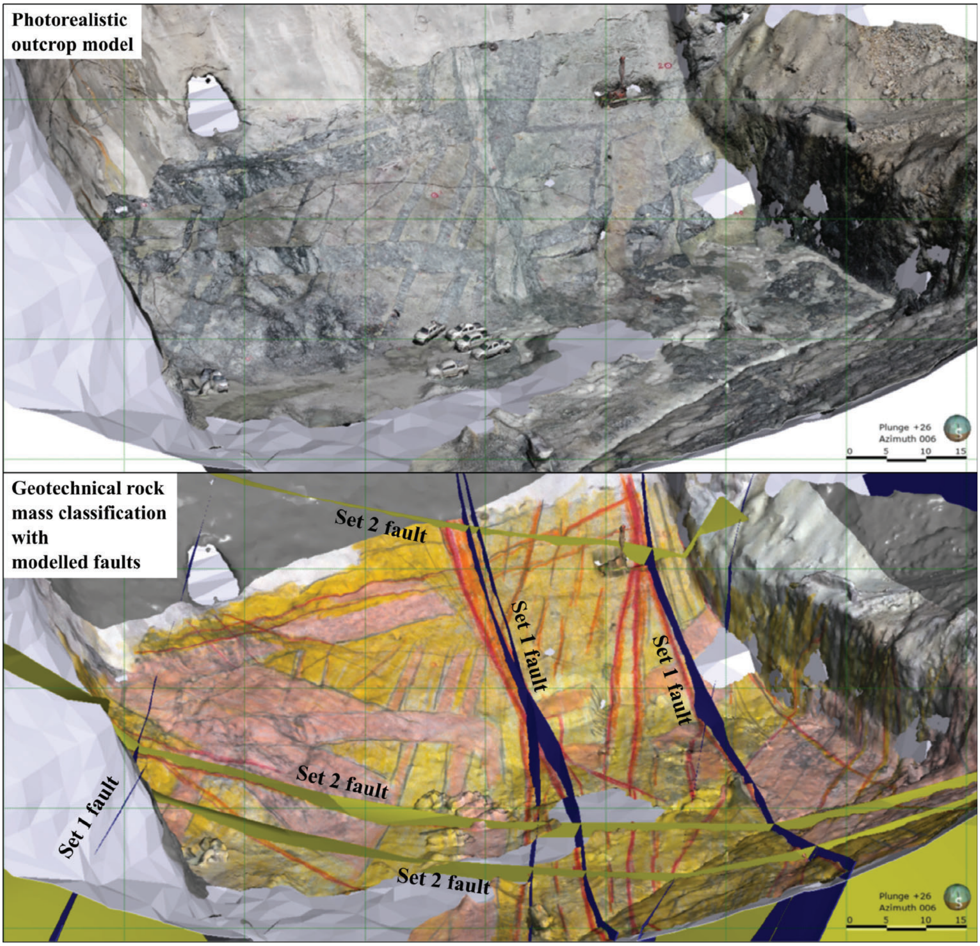

Figure 2. 3D fault meshes modeled along fault trace lines in geotechnical documentation of dam excavation draped on 3D as-built excavation surface.

In Figure 2, a 2D log of geotechnical rock mass classification is draped over the 3D as-built excavation surface of a dam foundation. Faults are modelled as 3D meshes (set 1 and set 2 faults in Figure 2) along trace lines of persistent features with fault materials across the excavation surface.

3 GEOTECHNICAL 3D MODELS

3.1 *Development of base-line design models*

Base-line models for large projects must translate complex geological conditions into simplified geotechnical models, which serve for different design topics and software. Small-scale (e.g. < 30m) applications include tunnel-, cavern- and bench-scale cut slope design. Large-scale (e.g. > 30m) applications include global excavation and dam design. Particularly in case of heterogeneous ground and complex circumstantial conditions, geotechnical design models for different applications may require substantially different contents and parameters.

For a large dam project in hard, but intensely fractured and faulted rock, slope stability and excavation design usually depend on discontinuity controlled failures, while the dam and foundation design relates mainly to deformation properties and shear strength of the rock mass. The geotechnical base-line model contains all information necessary for anisotropic and isotropic design models:

(1) Discontinuity (0D point) data collected from geological documentation and investigations (Figure 3a) are used for determining typical discontinuity orientations for probabilistic analyses of anisotropic failures (Figure 3c);
(2) High-persistence discontinuities modelled as 3D meshes provide features for deterministic analyses of failure along discrete failure planes (e.g. set 1, set 3 and set 6 faults in Figure 3b).
(3) Small-scale rock mass classification used for documentation of galleries and cut slopes (0D, 1D and 2D data shown in Figure 1) is translated into large-scale rock mass types (such as A, B and C in Figure 3b) for the dam design model.

Geotechnical rock mass parameters are assigned to these rock mass types according to standard methods, e.g. GSI/"Hoek&Brown approach" (Hoek et.al. 2002).

In complex systems, the rock mass behaviour or relevant design parameters can be influenced by circumstantial factors, which show no direct correlation to such standard rock

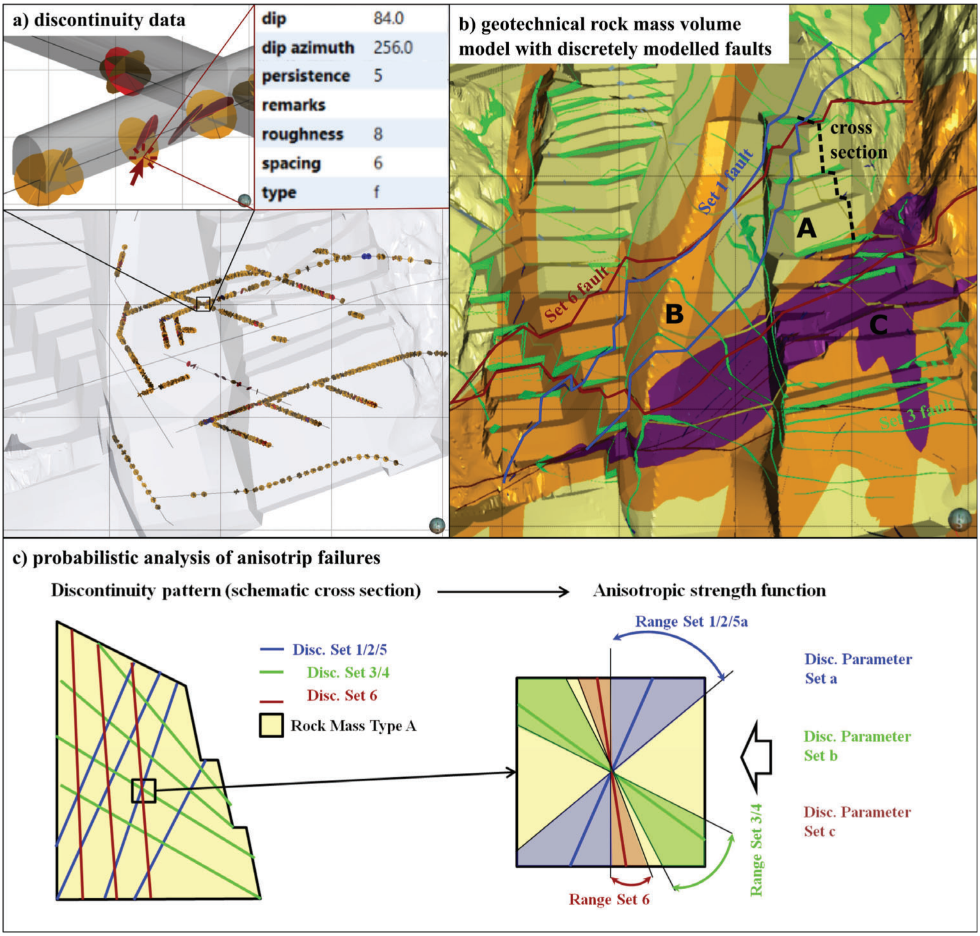

Figure 3. Discontinuity data collected along galleries (a), discrete high-persistence discontinuities in 3D geotechnical model with volumes of large scale rock mass types A, B and C (b), and design model for 2D slope stability calculations associated to relevant discontinuity sets (c).

mass classifications. These factors can be considered by further systematic modelling approaches.

For the model shown in Figure 4, site investigation data on rock mass moduli indicated that the rock mass deformation properties are unusually strongly affected by rock mass relaxation (steep natural slopes of the valley flanks, further oversteepened by excavation). This effect is described in a "relaxation model", a 3D model of distinct volumes which represent a different degree or rock mass relaxation ("relaxation zones"). Modelling theses volumes is based on the spatial distribution of moduli determined from e.g. seismic surveys and dilatometer tests. The parameter model (Figure 4c) for the dam design was created by merging this relaxation model (Figure 4b) with the rock mass model (Figure 4a). Design parameter sets were assigned to volumes of particular combinations of rock mass type and relaxation zone.

3.2 *Adjustments and verification of models*

Elaborate and well maintained digital 3D models not only facilitate deriving different geotechnical models for various applications, but also provide tools to (1) efficiently adjust these models regarding to additional data collected during subsequent project phases (e.g. geological documentation, Figure 5, or results of new geotechnical tests), and (2) guarantee the model's consistency and validity by – partly automatized - checking algorithms:

For examining e.g., the consistency of the parameter model with factual data, the geo-referenced data pool of rock mass moduli can be filtered in the 3D model and evaluated separately for the different parameter volumes. This allows for easy checks if and how much the distribution of values inside a volume changed, either because new factual data were added (e.g. insitu tests as verification surveys of geotechnical parameters) or because the model geometry was modified.

Figure 5 displays how the rock mass volume model can be adjusted continuously with respect to additional data collected during project development before and during excavation

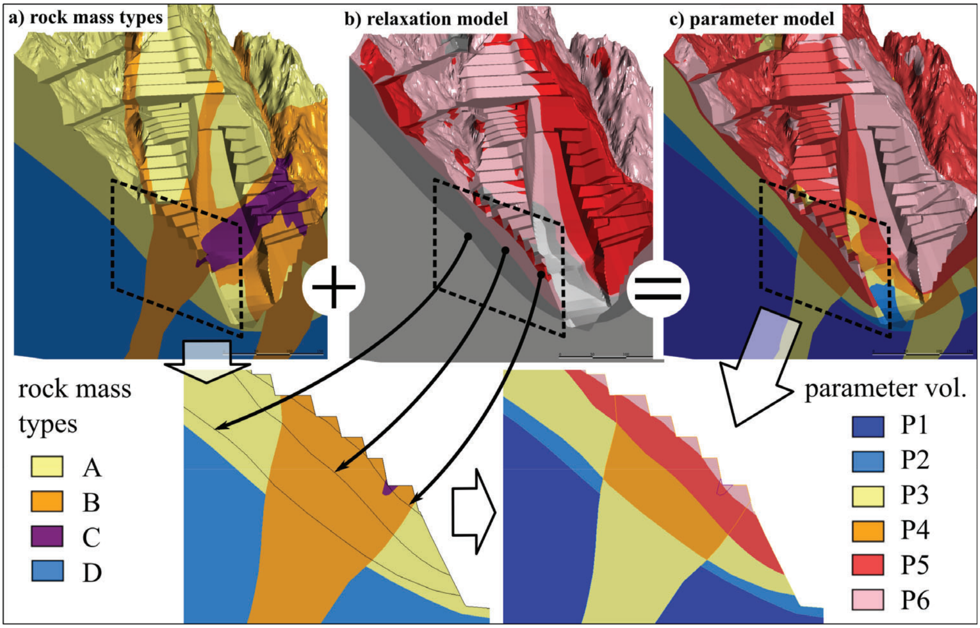

Figure 4. Parameter volume model for dam design (c), created by merging rock mass model (a) with relaxation model (b).

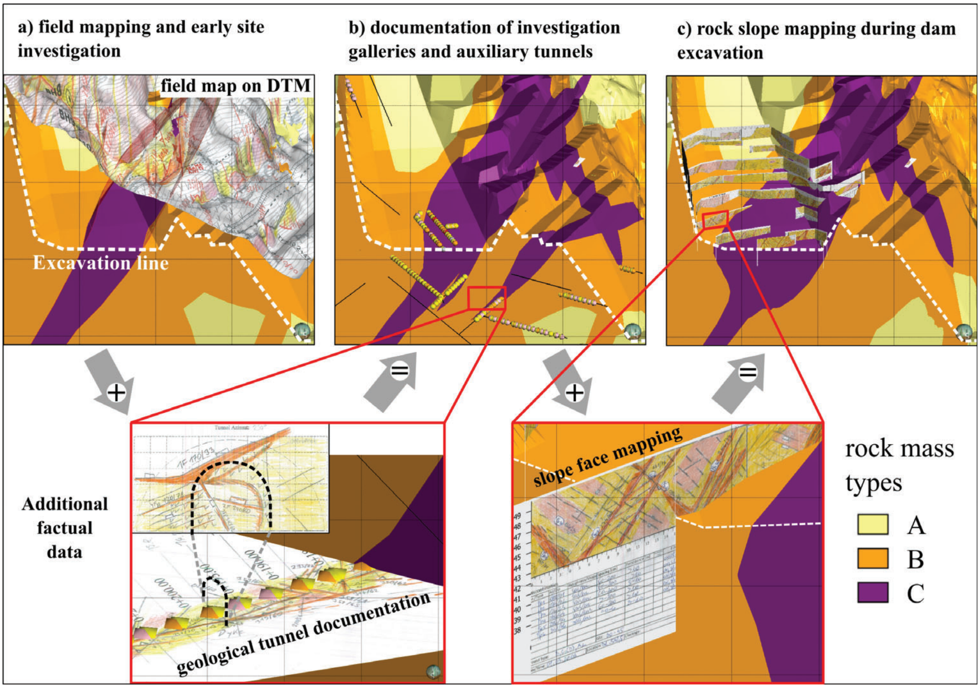

Figure 5. Adjustments of a rock mass model based on growing factual data pool (geological documentation in three exemplary project stages); cut view of a volume model.

works. Interim versions of the model can be made available on a cloud based viewer and collaboration platform to all involved parties at any time.

4 CONSTRUCTION AND MONITORING DATA

Online viewer and collaboration platforms like e.g. Central (Seequent 2018) also facilitate the management, visualization and interpretation of construction and monitoring data. All relevant data collected on site can be processed at any place (as long as online connected), and immediately incorporated in the online model. Therefore, software for cloud based ground-modelling has turned out to be an attractive tool for comprehensive workflow documentation and for guiding various site activities, such as grouting works (Kieffer et.al. 2019). Selected information recorded during water pressure tests and grouting, including flow rate, pressure, grout mix, ground heave or piezometer pressures, can be visualized and queried with a simple mouse click. Particular advantages of such models include:

1. grout takes, results of water pressure tests before/after grouting and modeled rock mass features are spatially correlated and can be readily checked against the expected behavior;
2. interpretations of instrumentation and monitoring results are improved through efficient cross correlations;
3. decisions regarding adjustments of grouting methodology such as applied pressure steps and mix ratios for subsequent stages are supported.

Figure 6 displays a model which is used for managing grouting works for a large dam. The 3D visualization of various structures and construction measures enables to rapidly assess

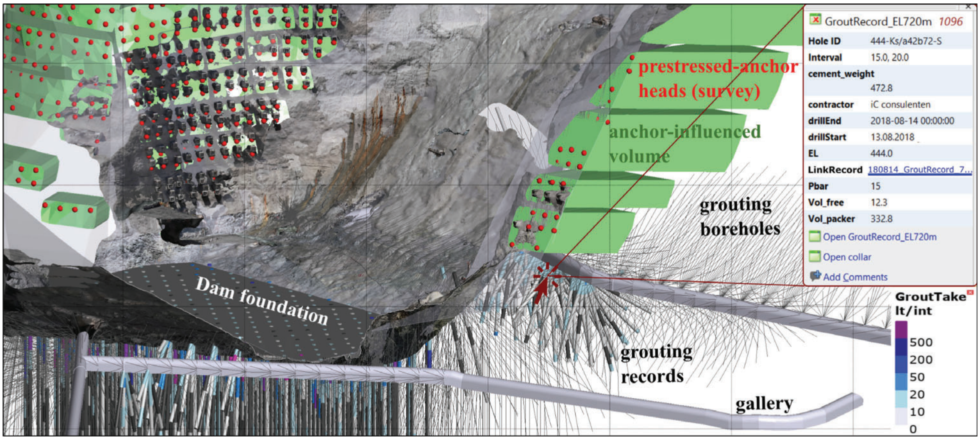

Figure 6. Visualization and query of grouting records along with geometry of various support- and design structures.

their interactions - which is particularly helpful in case of complex geometry. Possible detection of interferences between e.g. topography, slope support, subsurface structures and monitoring devices eases the development of ongoing design measures, planning of further monitoring activities and their interpretation.

5 SUMMARY

Elaborate and well maintained digital 3D geo-models not only facilitate developing different geotechnical models for various applications, but also provide tools to efficiently adjust these models when additional data are collected during subsequent project phases, and guarantee the model's consistency and validity by – partly automatized - checking algorithms.

On cloud-based collaboration and model management platforms, data from construction activities can be incorporated near-real-time in the online models, which can be shared with all stakeholders. The advantages of merging and managing geotechnical models (prediction) and geo-referenced construction data (as-built observations) in a cloud-based model are currently experienced in planning and guiding a grouting program for a complex dam structure. Extended applications are under development.

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