Estimation of soil characteristics for design of large earth-fill dams: challenges and solutions at an early design stage: case study of the Atdorf pumped storage plant

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Introduction

Schluchseewerk AG intends to construct a new 1,400 MW pumped storage hydropower plant (PSP) close to the village of Atdorf (Federal State of Baden-Wurttemberg, Germany). This project comprises two reservoirs, an approximately 10 km long tailrace tunnel, two approximately 700 m high headrace shafts, a roller compacted concrete dam 115 m in height and three large earth-fill dams with heights between 20 m and 60 m.

The project area in the south-western Black Forest is situated at the eastern margin of the prominent Rheintal Graben, one of the most seismically active zones in Germany. Due to this special geological setting and its inherent seismic constraints, the assessment of the dam's stability and the high requirements of the dam-fill materials were already a major task at the early design stage of this PSP. Furthermore, large amounts of excavated soils and rocks are to be reused, since the Atdorf PSP represents a major project comprising a variety of surface and subsurface facilities. In contrast, the geotechnical properties of the excavation and dam-fill materials are usually only available to a limited extent during early design stages.

This paper shows how the geotechnical soil and rock characteristics for the preliminary design of the upper basin earth-fill dam of the Atdorf PSP were assessed during the permit application design stage, in order to meet the high requirements for dam-fill materials.

1. Geological setting

The geological setting and rock mass properties in the Atdorf PSP investigation area were assessed by multiyear investigation campaigns, comprising data compilations, geological, geotechnical and hydrogeological field mapping, geophysical surveys, extensive drilling campaigns (incl. in-situ borehole measurements/tests) and a variety of geotechnical laboratory analyses. Crucial data concerning the rock mass properties and behaviour have been obtained from the construction of the reservoirs, caverns and tunnels of the existing PSP groups Schluchsee and Hotzenwald (Pfisterer et al. 1969, Bellut et al. 1980).

According to these data, the investigation area is made up of several kilometres thick metamorphic and magmatic Palaeozoic bedrocks, comprising of thick paragneiss series (Wiese-Wehra diatexite, and Murgtal gneiss anatexite complexes) intruded by granite complexes (Säckingen and Albtal granites, incl. different dikes; see Figure 1). These crystalline bedrocks are discordantly overlain by Permian and Lower Triassic clastic redbeds (Oberrotliegendes and Buntsandstein) and, outside of the investigation area, by a succession of Triassic to Jurassic marine sediments (mainly carbonates, not encountered in the Atdorf PSP area). During the Quaternary, a variety of glacial, fluvio-glacial, fluvial and gravitational soils were deposited (LGRB 2004, 2006).

The structural setting is characterised by folded but moderately dipping gneisses (mainly W-dipping, i.e. towards the westerly adjacent Rheintal Graben), massive granites and gently dipping redbeds. In the Atdorf PSP area, the bedrocks are faulted along some major normal fault systems, oriented around i) N-S (Rheintal-/Wehra-Graben system, neotectonically active), ii) WNW-ESE (Vorwald and Wolfrist fault systems) and iii) NW-SE- to WNW-ESE (Eggberg fault system). Consequently, both crystalline bedrocks and sedimentary cover rocks have been segmented into different horst-graben blocks with substantial vertical displacements (some up to 100m). The fault zones are characterised by several metre thick core zones (featuring different geotechnical properties due to the occurrence of fault breccias, non-cohesive kakirites and/or cohesive fault gouges) and several decametre thick damage zones (featuring variably fractured bedrocks).

The geotechnical properties of the excavation material and its use for the large earth-fill dams are therefore predisposed by the geological setting, mainly the metamorphic and sedimentary inventory (layering, schistosity, bedding), the brittle fracture sets (faults, joints) and the resulting degree of fracturing and weathering. Besides these parent bedrock parameters, a variety of soil characteristics (grain size distribution, density, strength parameters etc.) must be considered for the dam design.

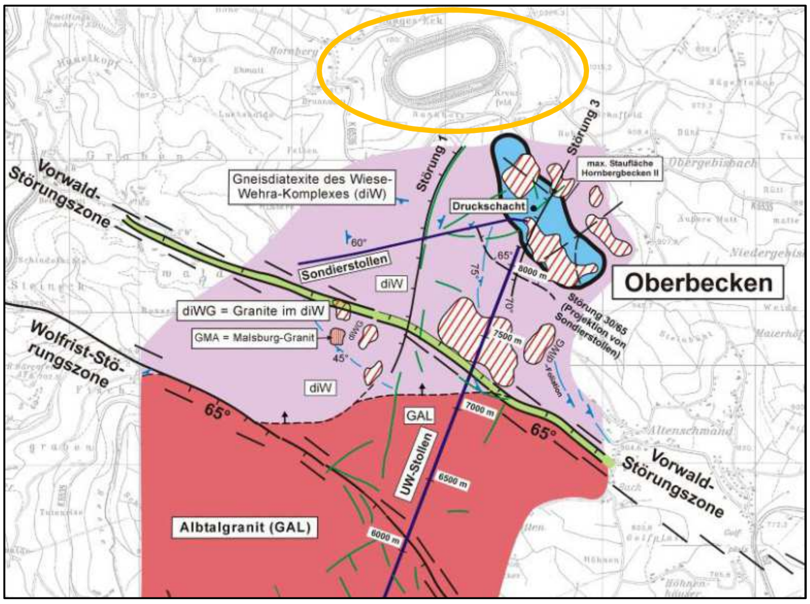

Figure 1: Structural setting of the existing reservoir (Hornbergbecken, highlighted in yellow), the investigation tunnel (Sondierstollen), and the planned facilities of the upper reservoir (Oberbecken) and tailrace tunnel (UW-Stollen). Extract from Franzke (2012). Violet: Wiese-Wehra paragneiss complex (diW). Red: Granites (Albtal granite GAL). Black and green lines: major fault zones. Extract from Schluchseewerk (2014; and Franzke 2012 resp.).

1.1 Upper reservoir

The region of the upper reservoir is composed of metamorphic and magmatic bedrocks (Wiese-Wehra paragneiss complex, LGRB 2006; see Figure 1), which are widely covered by layers of weathering debris and talus deposits of various thicknesses. Detailed geotechnical investigations have revealed that in the area of the planned reservoir the soils comprise a 0.1 to 0.5m thick layer of topsoil with an average thickness of 0.2m. This layer is underlain by fine grained, soft to stiff weathering loam. According to grain size analysis, this can be classified as sandy-gravelly silt. The thickness of this in-situ weathering soil varies between 0.5 and 2.0m, with a local maximum of 3.3m.

Beneath this fine layer, granular in-situ weathering debris of the bedrocks is encountered, here referred to as “Berglesand”. The upper sections of the Berglesand comprise poorly to well graded sands with silts and gravels. Geotechnical investigations show that within the Berglesand, the grain size and the density increase with depth, i.e.

mainly non-cohesive coarse soils are encountered. Concerning the geotechnical properties at the upper reservoir site, the boundary between soil and bedrock is not a distinct, sharp surface but rather a several meter thick transition zone. As a result, at this location it is difficult to clearly define the thicknesses of the soil in general and in particular the Berglesand. Additionally, the investigations and construction works for the nearby Hornbergbecken reservoir (Bellut et al. 1980) showed that the weathering zone (the soil-rock transition) is spatially inhomogeneous and that the weathered bedrocks can locally reach depths of up to 40m. In general, here the degree of bedrock weathering decreases with depth. Sedimentary bedrocks are not encountered within the perimeter of the planned reservoir.

Geotechnical analyses show that the Berglesand soils excavated in trial pits at the planned upper reservoir site are characterized by well to medium graded (poorly sorted) grain size distributions, are dominated by silty sands, and feature varying amounts of gravels and fines (Figure 2).

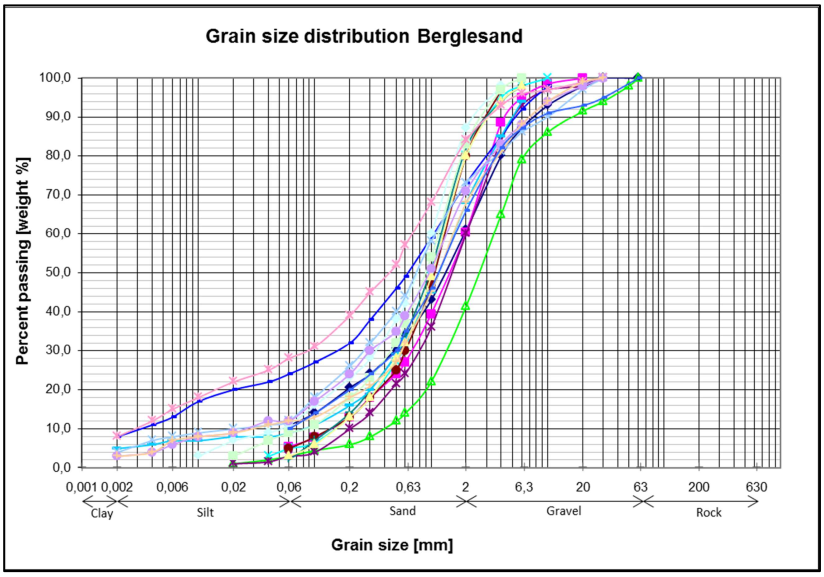

Figure 2: Grain size distributions of the "Berglesand", excavated in trial pits at the planned upper reservoir site.

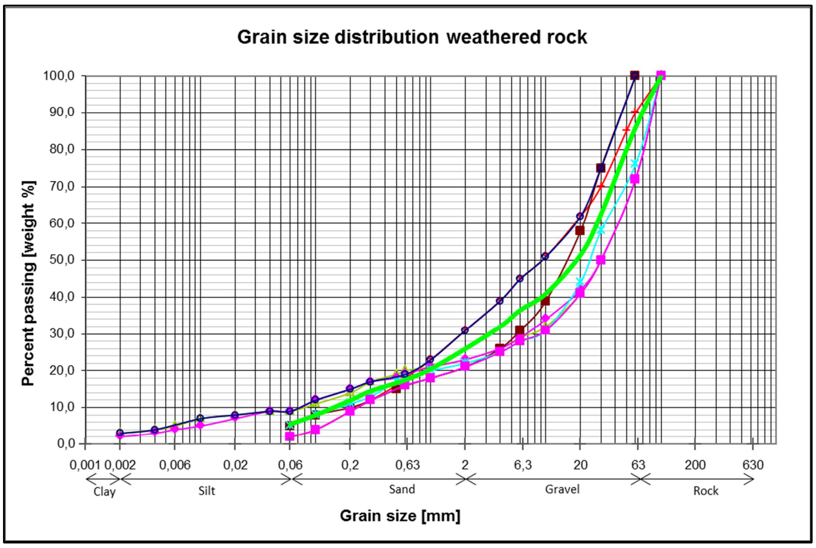

Figure 3: Grain size distributions of weathered rocks, excavated in trial pits at the planned upper reservoir.

The weathered rocks excavated in trial pits at the planned upper reservoir site are characterized by medium to poorly graded grain size distributions, dominated by gravels, and feature varying amounts of sands and fines (Figure 3). However, based on findings obtained from field surveys and drillings (core loggings), and in view of the fact that the coarse fractions of soils can hardly be sampled/sieved, for the excavation works of the weathered in-situ bedrocks substantial amounts of cobbles and boulders (coarser than 100 mm) are to be expected.

1.2 Underground facilities

Next to the existing PSP facilities (reservoir Hornbergbecken, caverns, and several tunnels; Pfisterer et al. 1969; Bellut et al. 1980), an investigation adit was driven in the gneiss series of the planned caverns of the Atdorf PSP (2009-2011; unpubl. data archive Schluchseewerk AG). In this adit, several geotechnical in-situ measurements and tests were performed as along with core drilling, with samples taken for laboratory analyses. According to results thus obtained, the planned Atdorf underground facilities will be driven conventionally in fractured and locally faulted bedrocks which comprise gneissic series (vertical shafts, caverns, up-/downstream sections of the otherwise TBM-driven tailrace tunnel) and granites (2/3 of the tailrace tunnel; see Figure 1).

The rocks (paragneisses and granites) encountered in the investigation adit (conventional drive, drill & blast method) are characterized by poorly to well graded grain size distributions, dominated by coarse gravels and stones, and feature low amounts of sands and fines (Figure 4). In general, it is expected that excavating (drill & blast) the massive and fresh granites will yield coarser materials than the altered, faulted and/or weathered bedrocks, esp. paragneisses.

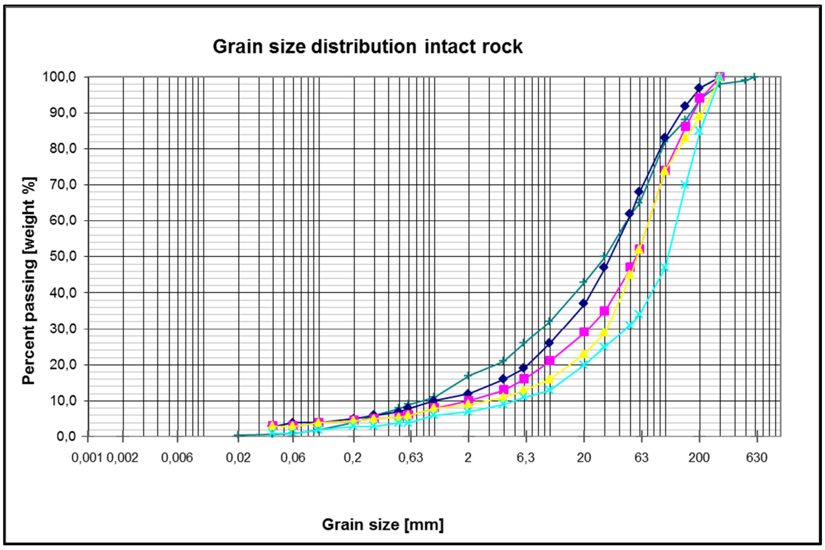

Figure 4: Grain size distributions of excavation material from intact rocks (paragneisses, granites), encountered in the investigation adit for the Atdorf cavern.

2. Challenges and solutions at the upper basin ring dam

Estimating the soil characteristics of the dam fill material for the upper basin ring dam was challenging during preliminary design phase. This is because the dam fill will be produced by processing and mixing the excavation material, and high requirements were placed on the dam design. In the following paragraphs, the constraints and requirements of the design and the solution to these challenges are described.

The layout of the ring dam is shown in plan view in Figure 5. The slope angles for the upstream and downstream side of the dam vary between 1:1.6 and 1:2.0. This variation is due to geometrical constraints like protected areas (i.e. biotopes, springs etc.), location of intake towers and the required volume of the basin.

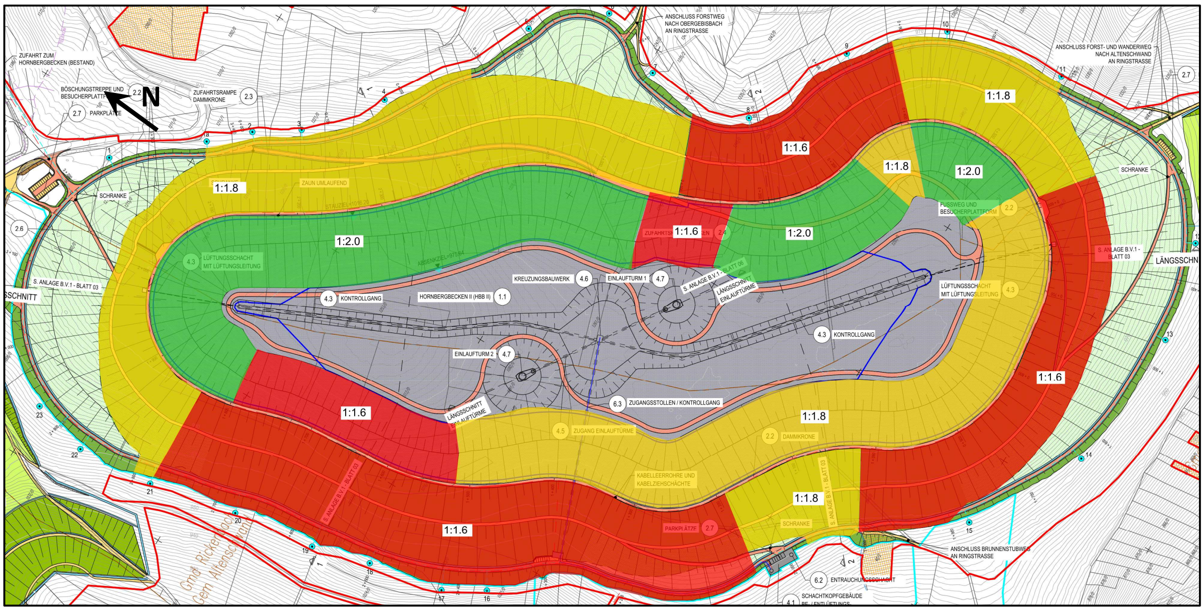

Figure 5: Layout of the upper basin ring dam with different slope inclinations coloured red (1:1.6), green (1:1.8) and yellow (1:2.0).

The soil and rock types expected during excavation in the upper basin are silty and sandy soils and gneisses/granites, with the rock consequently divided into a weathered rock layer and an intact rock layer.

The surface height of the bedrock decreases from north to south across the area of the planned basin. The north side of the dam can have foundations close or within bedrocks, whereas the south side of the dam has to have foundations on sandy soils. This implies that the excavated materials will be predominantly sand in the south of the basin and rocks in the north of the basin.

Founding the dam on sand results in higher seismic loading, due to amplification by a higher soil factor S (according to Eurocode 8, DIN EN 1998-1). Consequently, higher shear strength for the dam fill material is required in contrast to founding the dam on rock. Therefore, the highest quality dam fill material is required for areas where the expected excavation material is of lowest quality (sand).

This results in the following main challenges for the dam design:

- Design of dam cross section has to account for limited availability of high quality fill material
- The construction sequence has to allow for constructing the dam in the south of the basin with high quality material excavated in the north of the basin.
- Estimation of soil characteristics of dam fill material and developing a concept that ensures that the required shear strength of dam fill material will be reached during construction.

2.1 Excavation material to be used for dam construction

The excavation material to be used for dam construction consists of bedrock (granites, gneisses) and soils, comprising i) silty sands ("Berglesand", as shown in Figure 2), ii) weathered bedrocks (as shown in Figure 3) and iii) intact bedrocks (as shown in Figure 4). It is expected that the weathered rock will be excavated by excavators, whilst the excavation material from intact rock is expected to be broken-up by rock blasting.

The boundaries between the three rock types are gradational, i.e. with varying thicknesses of the respective transition zones.

As shown above, the expected excavation material will be highly variable and therefore geotechnically heterogeneous.

The Berglesand will be used for dam fill material only as a component to be mixed with weathered rock and/or intact rock. Experience from the construction of the existing Hornbergbecken reservoir (Bellut et al. 1980) showed that the Berglesand tended to be subject to exsolution, was difficult to compact, and that limestone had to be added in order to improve the earth-fill material.

As such, it will be necessary to mix and process (breaking, sieving) the excavated material before it can be used as dam fill.

The cross section of the planned dam is shown in Figure 6.

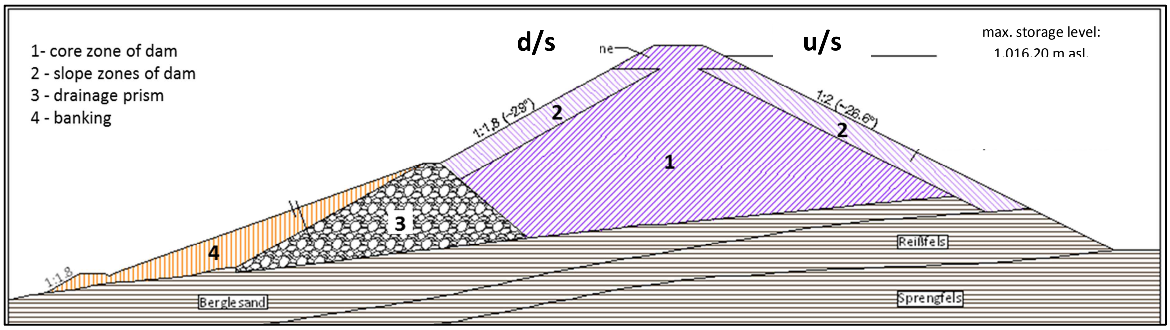

Figure 6: Cross section of the planned dam; d/s-downstream side; u/s – upstream side.

It is planned that the core of the dam (zone 1) will consist of a mixture of sand and weathered rock. The slopes of the dam (zone 2) are formed by a 5 m thick layer of a mixture of Berglesand and excavation material from weathered and intact rock (it should be noted that the Berglesand is not a mandatory part of this mixture). This zone has to meet high requirements regarding shear strength to prevent shallow slope failure.
A drainage prism (zone 3) is situated at the dam foot on the downstream side. The drainage prism consists of stones excavated from intact rock.

In four areas of the dam a banking (zone 4) will be placed along the dam foot on the downstream side. The banking does not contribute to the stability of the dam and consists of materials from excavation which are not suitable as dam fill material but shall be deposited within the construction area for environmental reasons.

2.2 Estimated grain size distributions of the expected dam fill material

In order to obtain a general understanding of the soil characteristics of the dam fill material, and especially to enable erosion and suffusion analysis for the dam, the grain size distribution of expected dam fill materials were estimated. These estimations were based on the expected grain size distributions of excavation material, expected excavation mass and mixing ratios.

The range of grain size distributions of dam fill material were estimated by using favourable and non-favourable mixing ratios for the fill of the dam core and for the fill of the slopes. A favourable mixing ratio means that the amount of Berglesand is minimized, whilst a non-favourable mixing ratio means that the amount of Berglesand is maximized.

A favourable mixing ratio for the dam core (high amount of weathered rock and minimum amount of Berglesand) consequently results in a non-favourable mixing ratio for the slopes (maximum amount of Berglesand and minimum amount of weathered rock) and vice versa due to the available quantities of excavation material.

For example, if the amount of weathered rock for the fill of the slopes is maximized in order to obtain a fill with high shear strength, little amount of weathered rock will be left over for the fill of the inner core. Hence, in this case a high proportion of Berglesand will have to be used for the fill of the inner core.

The mixing ratios used to estimate the upper and lower boundary of grain size distributions of the dam fill are shown in Table 1. The mixing ratios are derived from the estimated mass of excavation and dam fill materials.

Figure 7 shows the estimated grain size distributions for the different dam fill materials, based on the mixing ratios shown in Table 1.

		Berglesand	Weathered rock (excavated by scrapers)	Intact rock (excavated by rock blasting)
Core zone of dam	Non-favourable mixture	63%	37%	-
Slope zones of dam	favourable mixture	0%	72%	28%
Core zone of dam	favourable mixture	33%	67%	-
Slope zones of dam	Non-favourable mixture	61%	16%	23%

Table 1: Mixing ratios for dam fill materials used to estimate upper and lower boundary of grain size distribution of dam fill materials.

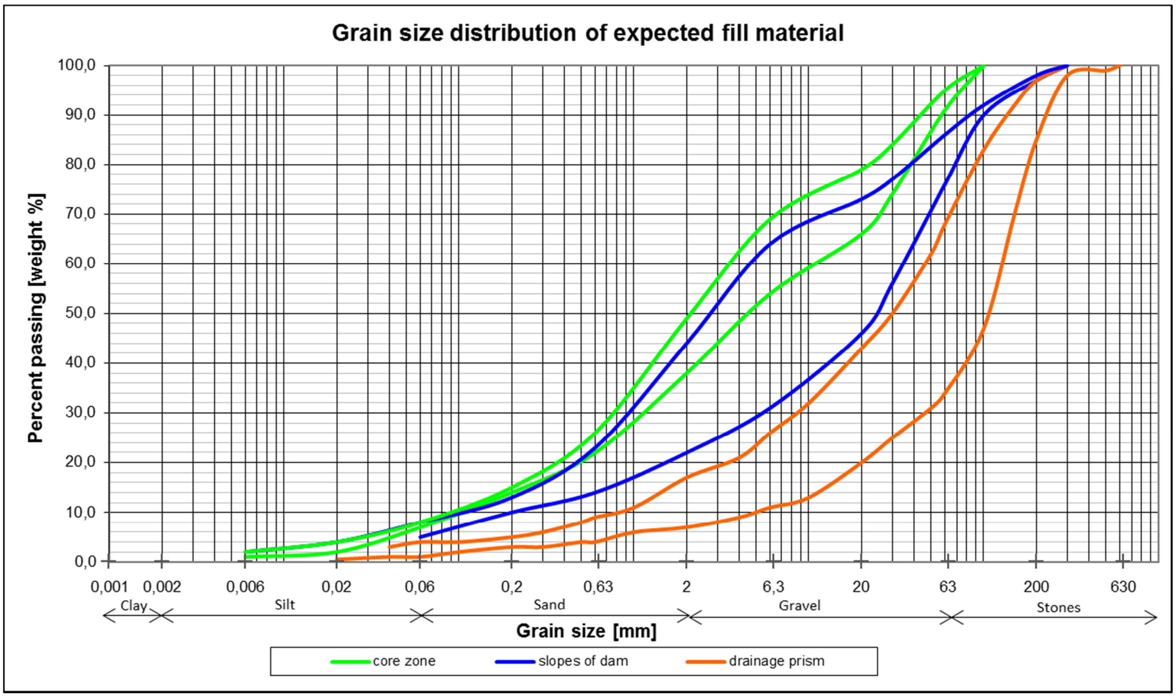

Figure 7: Estimated upper (favourable) and lower (non-favourable) boundary of grain size distribution of expected dam fill materials; green: core zone of dam, blue: slope of dams, orange: drainage prism.

The estimated grain size distributions of the different fill materials were used for soil classification according to DIN 18196 with the results given in Table 2.

	Classification DIN 18196	Description
Core zone of dam	GU	gravel, silty-sandy, well graded
Slopes of dam	GU	gravel, silty-sandy, well graded
Drainage prism	GI, GW	gravel, stony, poorly to well graded

Table 2: Soil classification of expected dam fill material (see Figure 7).

The grain size distribution, together with the soil classification, provided a basis on which the soil parameters (shear strength and permeability) for the dam fill material could be derived (i.e. from literature, engineering judgment and experience) and to obtain confidence that the required shear strength of fill material can be reached.

The high requirements for dam fill material have also been addressed in the permit application design by assuring that a quality control plan will be developed for implementation during construction. The quality control plan will contain, but not be limited to, specifications for monitoring, material processing, required limits of grain size distribution of dam fill material and field and laboratory tests on dam fill material.

In addition, a ground investigation programme containing field and laboratory testing has been scheduled in order to verify the soil parameters used during the preliminary design stage.

3. Conclusions

Estimating soil parameters for earth-fill dams at the early design stage is challenging where limited information about the material to be used as dam fill is available and high requirements are placed on the dam fill.

In this paper, the upper basin ring dam of the Atdorf PSP was used to demonstrate the solutions to the geotechnical challenges at preliminary design stage regarding the estimation of geotechnical soil characteristics of dam fill material.

The upper basin ring dam of the Atdorf PSP is planned to be constructed as a zoned dam where each zone consists of different fill material. The fill material will be produced from the excavation material, which will have to be processed and partially mixed to obtain the dam fill material.
Based on the expected mass of excavation material and the required mass of dam fill material, upper and lower boundaries of possible mixing ratios of excavation material were estimated.
These mixing ratios were used, together with grain size distribution curves of the expected excavation material, to estimate grain size distribution curves of dam fill material.

The estimated grain size distributions and the soil classification of the dam fill material provided a basis for which the soil parameters could be derived.

In addition, the requirement to develop a quality control plan during the detailed design stage and to carry out an additional ground investigation programme to verify the estimated soil parameters were stated in the permit application documents.

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