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Geomechanical Characterization of a Weak Sedimentary Rock Mass in a Large Embankment Dam Design

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Abstract

The geomechanical characterization of a weak and tectonically undisturbed sedimentary rock mass (“molasse”), carried out for the design of a large embankment dam in the Kurdistan Region (Iraq), is presented. In view of the relevant dimensions of the dam and of its main ancillary works, the rock mass characterization has represented one of the basic focus of the geological and geotechnical investigations. However, various uncertainties have been considered to potentially affect the final estimate of the engineering properties of rock masses in the context of the present study. In particular, besides the natural variability of weak rocks characteristics and the well-known difficulties in their realistic estimation, uncertainties may also arise from the potential incompleteness of the basic data available, mainly due to time and budget limitations. In order to quantify such uncertainties and adequately incorporate their effects into the design process, a probabilistic approach based on Monte Carlo method has been adopted to determine the probability distribution functions describing the rock mass strength parameters. A practical example of application of the followed probabilistic approach to the design of large excavation rock slopes is briefly illustrated.

Keywords

Weak rocks • Geomechanical characterization • Probabilistic approach • Slope stability

148.1 Introduction

The Mandawa Dam is presently under construction for irrigation, hydropower production and drinking water supply, in the Kurdistan Region (Northern Iraq) along the main course of the Greater Zab River, a major left tributary of the Tigris River. The dam is a 65 m high embankment with gravel and sand shells and a central silty core. It extends straight for about 1,000 m from the two extreme abutments and includes, on the left side, a concrete structure composed of three blocks housing the main hydraulic structures for the temporary diversion, the bottom outlets and the inlets of the penstocks of the hydropower plant (Fig. 148.1). A very large spillway channel is located on the right side, separated from the dam. The subtended reservoir has a maximum storage capacity of about 520 million m^3.

The foundations of the left concrete part of the dam body and of the spillway channel have required the design of large excavations on both river banks, resulting in cut multi-bench rock slopes even more than 80 m high.

148.2 Site Geology and Geotechnical Investigations

The rock mass characterization was based on data gathered from an investigation geotechnical campaign carried out during the 2012, that has included a total of 1,700 m

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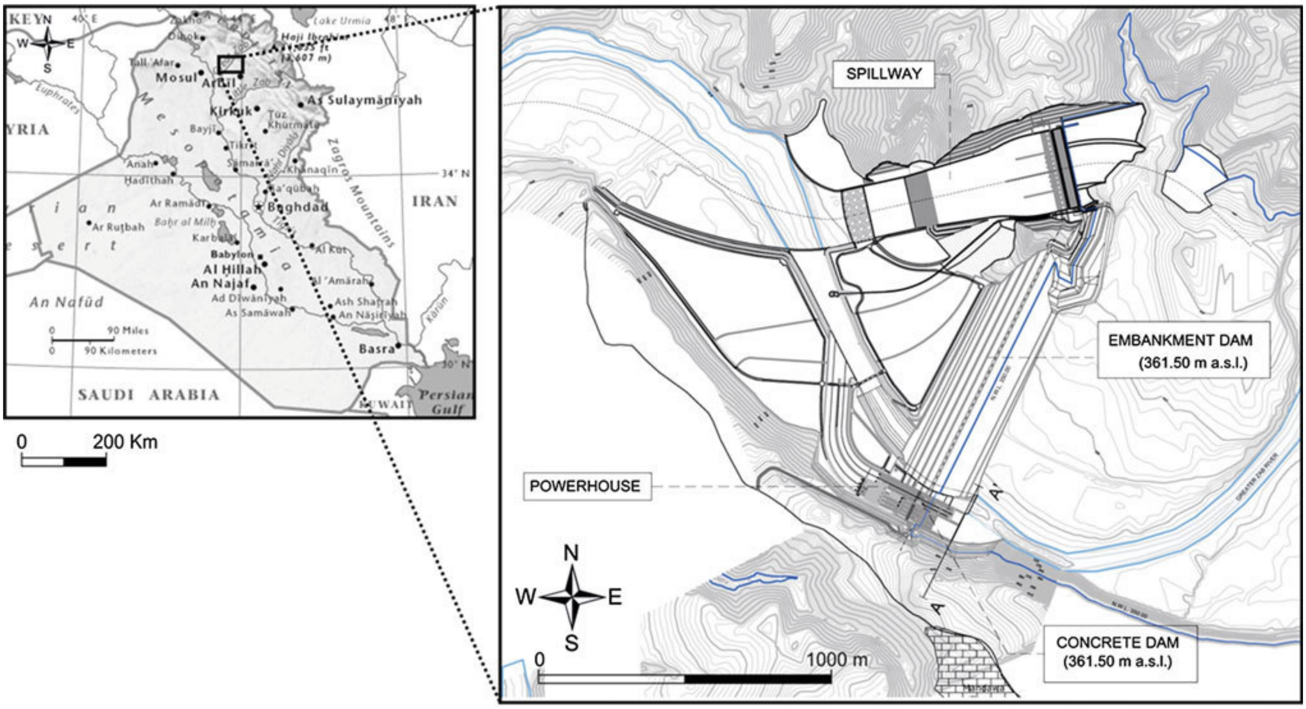

Fig. 148.1 Dam location map and general layout of works

borehole drillings, 60 geotechnical laboratory tests on selected rock cores (mainly uniaxial compression tests on specimens at natural water content and physical property determinations) and field geological mapping. In the dam area, the local bedrock consists of the Upper Miocene sedimentary Mukdadiyah Formation, composed of a clastic sequence of pluri-metric alternations of reddish siltstone and grayish silty sandstone members. It was formed in a mostly fluvial depositional environment in front of the Zagros Mountains belt and appears not significantly interested by orogenic deformations. Both sandstone and siltstone members are stratified and show grain size and induration degree rather variable among layers. Three discontinuity sets intersecting at right angles, one of which coincident with the sub-horizontal bedding and the others consisting of sub-vertical tensile joints striking sub-parallel and sub-orthogonal to the river course, were observed in the bedrock. Spacing and persistence of vertical joints result well correlated with the thickness of layers and usually varies in the range 0.5–3 m. Discontinuities in sandstone are mostly undulated, rough and free of infilling materials; those in siltstone (mainly the bedding surfaces) are frequently planar and moderately rough, sometimes with skinny silty coatings on the surfaces. Weathering effects are limited to the few superficial meters of the bedrock and disappear rapidly with depth.

148.3 Rock Mass Characterization

The rock mass has been characterized with reference to an equivalent-continuum model and the GSI classification system, combined with the strength properties of the intact rock, has been used to derive the Hoek-Brown strength parameters (Hoek et al. 2002). The uniaxial compressive strength (UCS) of the rock matrix has been evaluated through compressive tests on core specimens at varying natural water contents. The UCS values resulted sensitive to saturation degree (Sr, %) and correlated to the dry density (ρ_{dry}, Mg/m^3) of specimens. The average saturation degree of tested samples was about 30 %. Relationships linking UCS and the main index properties of intact rocks have been established by multiple linear regression analyses of the available laboratory test results, in the form

$$UCS_{sandstone}(MPa) = -66.61 - 0.107Sr(\%) + 41.282\rho_{dry}(Mg/m^3)\left[\mathrm{R}^2 = 0.69\right] \tag{148.1}$$

$$UCS_{siltstone}(MPa) = -45.27 - 0.116Sr(\%) + 28.876\rho_{dry}(Mg/m^3)\left[\mathrm{R}^2 = 0.64\right] \tag{148.2}$$

For studied rocks, established relationships allow to predict the UCS for specified values of dry density and degree of saturation expected in situ (e.g. saturated under reservoir water level and naturally wet above) and imply, for tested samples, an average reduction of the UCS between dry (Sr = 0 %) and fully saturated (Sr = 100 %) in the order of about 50 % for sandstone and 60 % for siltstone, rather in line with previous literature findings (e.g. Palmström 1995; Romana and Vásárhely 2007). Proposed relationships have, evidently, not general validity and should then be applied with extreme care for other rock types and in different geological contexts. The GSI index of the rock mass at the depths of the planned excavations has been assessed on the base of data collected from core logging and field mapping. The method reported by Hoek et al. (1995), based on traditional Q-System descriptor codes (Barton et al. 1974), has been used to quantitatively estimate the GSI through the relationship

$$GSI = 9\ln(RQD/Jn \times Jr/Ja) + 44 \qquad (148.3)$$

where RQD = Rock Quality Designation (%); Jn = rating for number of joint sets; Jr = rating for joint roughness and Ja = rating for joint alteration and filling. The GSI obtained for the unweathered bedrock with the described quantitative approach resulted in general accordance with the indicative range suggested by Hoek et al. (2005) for "blocky" molasses.

148.4 Probabilistic Approach in Rock Mass Characterization

To quantify the possible variability of rock mass properties and to incorporate its effects into the design process, a probabilistic approach based on the classical Monte Carlo (M-C) method has been used to derive the probability density functions (PDFs) of the Hoek-Brown (H-B) strength parameters. At this scope, probability distributions have been assessed for the input parameters used to calculate the UCS of intact rocks, i.e. ρ_{dry}, and the GSI of rock masses, i.e. the RQD and the Jr and Ja factors, by considering available field and laboratory data. On the base of such input distributions, the PDFs for UCS and GSI have been calculated by best fitting the results of M-C simulations conducted using Eqs. 148.1, 148.2 and 148.3 (Table 148.1 and Fig. 148.2). The input parameters considered for simulations have been implicitly assumed to be random and independent variables.

Table 148.1 Monte Carlo simulations inputs and outputs

	Parameters and probability distributions input into Monte Carlo simulations		Output parameters and PDFs from M-C simulations	
Intact rock	ρ_{dry}	LogNormal (Trunc: min and max values of lab tests)	UCS	Beta
	Sr	Constant = 30 % (naturally wet) and 100 % (saturated)		
Rock mass	RQD	Weibull (Trunc: min = 0 to max = 100)	GSI	Normal
	Jn	Constant = 9 (n. 3 joint sets)		
	Jr, Ja	Normal		

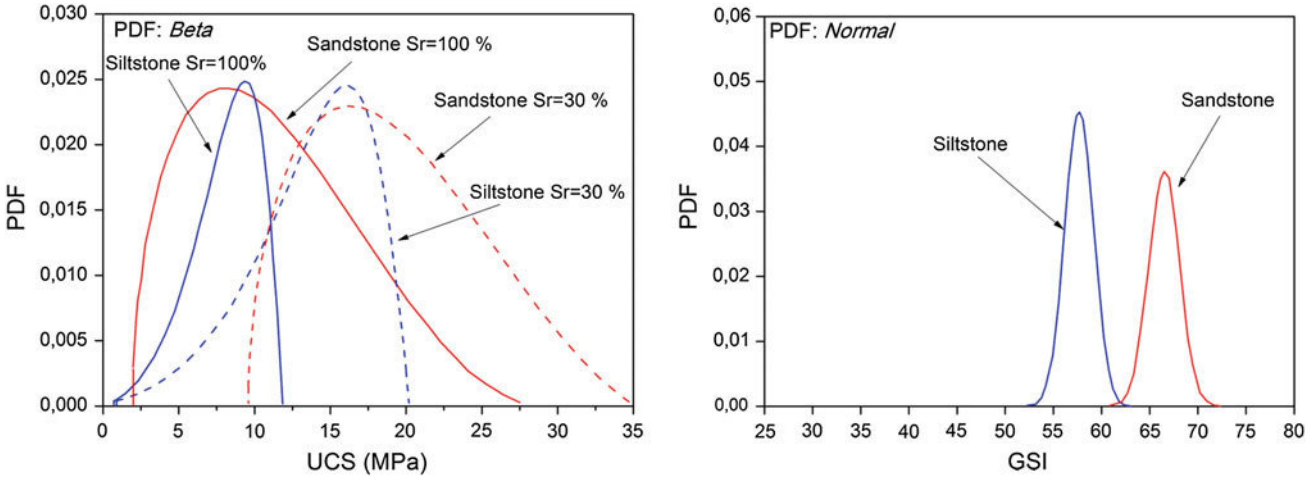

Fig. 148.2 Plots of the PDFs obtained from Monte Carlo simulations for UCS (*left*) and GSI (*right*)

The mean values of the H-B constant m_i have been derived from literature, arbitrarily assuming normal distributions with coefficient of variation (COV) of 10 %. By using the probability distributions previously defined for GSI and m_i, the PDFs of the H-B strength parameters of the rock mass, s, m_b and a, have been determined using the Monte Carlo method. The disturbance factor D has been set to zero in calculations.

148.5 Example of Application in Rock Slope Design

An example of application of the described probabilistic characterization approach in the Mandawa Dam project mainly relates to global stability analyses performed for the rock slopes to be excavated in the reservoir nearby the left side of the dam, where the HPP headrace inlets and the bottom outlets intakes have been planned (analysis section A–A' in Fig. 148.1). Since the structural setting of the rock mass does not control the stability of such slopes, global analyses were performed assuming Bishop's circular failure surfaces and using the probabilistic analysis option available in the program SLIDE (Rocscience Inc.). The possible presence of tension cracks, coincident with the joints striking nearly parallel to the river course, has also been considered. The input probability functions of main geotechnical parameters and tension crack depth derived from Monte Carlo simulations and used in the analyses, are summarized in Table 148.2.

The typical slip surface considered in the analyses and the probability of failure obtained by varying the overall slope angle α, are shown in Fig. 148.3.

Analyses were performed considering the most severe condition of rapid drawdown of the reservoir, from the maximum to the minimum level without the drainage of the slope, coupled with the maximum seismic action (defined from a peak design earthquake acceleration of 0.2 g). The overall slope angle of 50° finally chosen for the design, resulting from a multi-bench shaped profile of interposed 3 m benches with vertical drops of 15 m and scarps inclined 3v:2 h (Fig. 148.3-left), allows to advantageously reduce to zero the risk of global failure of the analyzed slope (Fig. 148.3-right), ensuring, in the long term, the full operability of the dam outlets and the HPP production.

Table 148.2 Main input parameters used for the slope stability analyses

Property		PDF	Mean	Std. Dev.	Min	Max
Siltstone	UCS(sat)[Mpa]	Beta	15.79(7.89)	2.91(2.54)	0.63(0.5)	20.26(12.14)
	H-B "s"	LogNorm	0.0096	0.0019	0.0044	0.0202
	H-B "a"	LogNorm	0.503	0.0001	0.502	0.505
	H-B "m_b"	LogNorm	0.8939	0.1047	0.508	1.312
Sandstone	UCS(sat)[Mpa]	Beta	19.70(12.21)	5.77(5.77)	9.65(2.16)	35.04(27.54)
	H-B "s"	LogNorm	0.021	0.01	0.01	0.05
	H-B "a"	LogNorm	0.502	0.0001	0.501	0.503
	H-B "m_b"	LogNorm	5.149	0.624	3.166	7.762
T. Crack	Depth [m]	Uniform	20		10	30

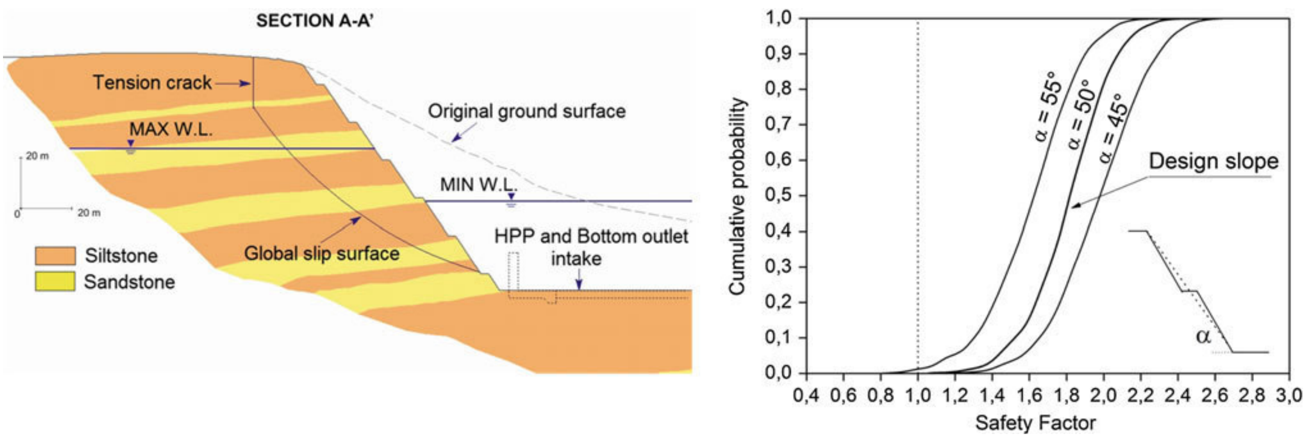

Fig. 148.3 *Left* Slope geology and typical slip surface analyzed; *Right* probability of failure obtained by varying the overall slope angles

148.6 Conclusions

A geomechanical rock mass characterization approach based on probabilistic analyses has been performed for a large embankment dam design, enabling to take into account and to quantify the possible variability of the engineering properties of the bedrock. A practical example showing how this approach has been applied to the design of cut rocky slopes has been presented. According to the wide literature available today on this subject, the adoption of a probabilistic design method proved to be suitable for managing uncertainties in rock properties assessment and can be particularly effective when, as in the presented case, the difficulties usually encountered in characterizing a weak rock mass have to be faced with time and budget limitations.

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