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ORIGINAL PAPER

Leakage and abutment slope stability analysis of Arjo Didesa dam site, western Ethiopia

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Abstract

Arjo Didesa dam is located in western Ethiopia which is designed for irrigation purposes to improve the food security problem in the country. This site is characterized by a complex geological and structural setup that makes it susceptible to engineering geological problems of leakage and slope instability. This study is, therefore, aimed at evaluating the leakage and abutment slope stability of the dam site. The leakage evaluation was done based on results obtained from the Lugeon tests, while slope stability analysis was performed using the kinematic method, limit equilibrium method (LEM), and finite element method (FEM). From the Lugeon tests conducted along the dam axis, more than 57% showed a potential for excessive leakage which needs grouting to control leakage. From these percentages with more than 3 Lugeon units (Lu), about 19.04% were classified into high and very high permeability classes. This indicates that rock masses along the dam axis are mostly cut by interconnected open joints. Slope stability analysis through kinematic analysis showed that some slope sections of both abutments are unstable for a planar mode of failure. Further stability analysis using LEM for a planar mode of failure revealed the presence of potentially unstable slopes at saturated conditions. Moreover, both LEM and FEM showed that some slope sections of both abutments are unstable for a circular mode of failure at saturated conditions with the factor of safety (FOS) and stress reduction factor (SRF) as low as 0.1 and 0.132, respectively. The results from slope stability analysis indicated that the water pressure through seepage is the major causative factor of slope instability. Hence, curtain grouting to the depths of 40 m at the left abutment, 53 m at the central foundation, and 43 m at the right abutment was recommended to control the leakage problem. Moreover, removal of overhanging rocks and slope angle reduction and applying rock bolts and inserting drain holes were recommended for slope stabilization in the dam site.

Keywords Lugeon test · Kinematic method · Limit equilibrium method · Finite element method · Curtain grouting

Introduction

On a global scale, irrigation is very important for increasing food production, thereby improving food security. According to Gebul (2021), there is huge irrigation potential in most African countries that needs to be developed for enhancing agricultural production and food security. In Ethiopia, however, agricultural production through irrigation is far from pleasing (Garo and Meten 2021), and the agricultural sector largely relies on seasonal rainfall. Nevertheless, the agricultural sector contributes to 43% of the country's GDP, about 80% of employment, and approximately 75% of export commodity values. With the recent increase in population, food insecurity, and pressure on rain-fed agriculture due to

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climatic variability, the importance of irrigation in the country is becoming indispensable. Moreover, the country also has a huge irrigation potential which varies between 1.5 and 4.3 million hectares (MoWR 2001; Werfring 2004; Awulachew et al. 2005; Makombe et al. 2011). However, the total land under irrigation is currently estimated to be in the range of 160,000–200,000 ha which is less than 5% of the country's irrigable land (Awulachew et al. 2005, 2007; World Bank 2006; Makombe et al. 2007). To improve this agricultural production through irrigation, the government is currently constructing several micro-dams (Garo and Meten 2021) in which the Arjo Didesa dam is one of such schemes.

Like other micro-dam constructions elsewhere in the world, the history of micro-dam construction in Ethiopia is also associated with several geotechnical problems. For example, over 70 micro-dams were constructed in Tigray Region alone in the past two decades (Abay and Meisina 2015). However, due to inadequate geological, hydrological, and geotechnical investigations during the initial stage, more than half of these dams have suffered from problems of leakage, reservoir siltation, damages to the spillway, and dam body without giving their desired services (Abdulkadir 2009; Berhane 2010; Desta 2005; Haregeweyn et al. 2005; Nedaw and Walraevens 2009). The failures of previously constructed micro-dams have necessitated the importance of proper engineering geological investigation for similar projects which will be constructed in different parts of the country. For example, the Arjo Didesa dam project is located in a complex geological and structural set up which can cause engineering geological problems.

There are also numerous case studies of dam failures all over the world in the past years with leakage, differential settlement, abutment instability, and other foundation defects being the major causative factors (Barzegari, 2017). Leakage, in particular, is the dominant causative factor for dam failures on a global scale (Mozafari et al. 2011; Uromeihy and Farrokhi, 2011), and it occurs dominantly due to insufficient geotechnical and geological investigations (Barzegari, 2017). This problem has been studied by several researchers on a global scale (Goodman et al. 1965; Heuer 1995; Karagüzel and Kiliç 2000; Kiraly 2002; Barton 2004; Foyo et al. 2005; Coli et al. 2008; Uromeihy and Farrokhi 2011; Li et al. 2008; Kanik and Ersoy 2019). In the Ethiopian context, some researchers such as Berhane (2010), Berhane and Walraevens (2013), Abay and Meisina (2015), and Garo and Meten (2021) have also dedicated their work for evaluating leakage problems for numerous dams constructed in different parts of the country. Hence, the evaluation of the leakage is the most significant task during dam site investigation (Kanik and Ersoy 2019). The mechanisms of evaluation and controlling techniques for this problem are strongly dependent on the determination of permeability (Barzegari, 2017; Kanik and Ersoy 2019). Accurate determination of permeability of dam foundation is therefore important for evaluation of leakage quantity and determination of corresponding controlling mechanisms (Sharghi et al. 2010; Barzegari, 2017; Garo and Meten, 2021). The water pressure or the Lugeon test is the most widely applied technique in acquiring permeability of the rock mass (Quinones-Rozo 2010; Ghafoori et al. 2011). This test involves pumping of water with pressure into a borehole by setting the test section from 3 to 5 m (Barzegari, 2017). The pressure for this test is usually decided by formation pressure and is applied in increasing and then decreasing order in a total of five stages (Houlsby 1976). The application of such consecutive rising and falling pressures creates a connection between the volume of water injected into the borehole and the formation pressure from which permeability in terms of Lugeon value can be calculated (Barzegari, 2017). The rock mass permeability is strongly dependent on joint characteristics such as opening, spacing, persistence, and filling material. Hence, an accurate interpretation of permeability obtained from such a test requires a correlation of joint hydro-mechanical properties and water flow behavior of the test (Quiñones-Rozo 2010; Ghafoori et al. 2011; Barzegari, 2017). Lugeon test-water flow behavior interpretation proposed by Houlsby (1976) allows such correlation and is currently the most widely utilized technique for water pressure or Lugeon test interpretation.

Abutment and reservoir rim slope instability are also among the common engineering geological problems of a dam site (Kanik and Ersoy 2019; Garo and Meten 2021). In the dam site, such instability mostly occurs due to geological defects, adverse slope geometries, high degree of weathering and fracturing of slope materials, human activity, heavy rainfall, and earthquakes (Basahel and Mitri 2017) . Numerous researchers have attempted to analyze the stability of rock slopes with kinematic, LEM, and numerical methods (Hoek and Bray 1981; Goodman 1989; Pettifer and Fookes 1994; Hammah et al. 2004; Gurocak et al. 2008; Raghuvanshi 2019; Shaz et al. 2019). The kinematic method is only used to identify the possible mode of rock mass failures without determining the factor of safety (Gischig et al. 2011). It uses the dominant discontinuity planes within rock slopes to forecast the probability of failure (Gischig et al. 2011). It commonly predicts potential structural failure mechanisms (i.e., planar, wedge, and toppling) using a stereonet projection (ZainAlabideen and Helal 2016; Raghuvanshi 2019). This method also assumes that all discontinuities are cohesion-less, dry and fully persistent, and rigid. On the other hand, the LEM and numerical methods analyze the stability of the slope in terms of factor of safety (FOS) and strength reduction factor (SRF), respectively (Pain et al. 2014). LEM compares the magnitudes of the driving and resisting forces that act along the slope to estimate the FOS for rock and/or soil slopes where translation or rotational movements can take place (Eberhardt and Vancouver 2003; Faramarzi et al. 2017). The LEM, however, is not the preferred technique for slopes that exhibit variability in its geometry, heterogeneity in a geological formation, non-linearity in the potential failure plane, uneven distribution of the water forces in the slope with induced surcharge, and variable seismic loading conditions (Alzo'ubi 2016). To simulate such complexities, numerical methods are preferable (Eberhardt and Vancouver 2003) . Moreover, unlike LEM, the numerical methods incorporate rock mass deformation, the stress distribution of the slopes, and its effects on slopes in the determination of SRF (Jing 2003; Tang et al. 2016). They determine the stability of a slope by dividing slopes into several finite elements or zones in which forces and strains in each zone are analyzed using suitable constitutive laws (Alzo'ubi, 2016). Among the numerical modeling methods, FEM is the most utilized technique, particularly for soil and highly weathered and fractured rock slopes (Eberhardt and Vancouver 2003).

This research work deals with the evaluation of leakage and abutment stability of the Arjo Didesa dam site, which is located within the volcanic terrain of the Southwestern Ethiopian plateau. The dam site is located in a very complex geological and structural setup which makes it susceptible to engineering geological problems such as leakage and slope instabilities. For example, according to OWWDSE (2009), the dam site is constituted by rocks of extremely variable degree of weathering and fracturing which are affected by variably oriented joints and fractures. This study is, therefore, aimed at evaluating the leakage and abutment slope instability of this dam site. This dam is an Earth and rockfill dam with a wide central impervious core and crest length of 502 m, a height of 50 m, and a reservoir capacity of 330.96 million cubic meters. It is designed to irrigate a command area of 80,000 hectares of land for both sugarcane and cereal crop production. Engineering geological mapping, discontinuity surveying, sampling and laboratory testing, core drilling and Lugeon test, LEM, and FEM were applied to come up with a comprehensive result that can help to recommend proper site-specific remedial measures.

Location of the study area

The Arjo Didesa dam site is located in the East Wollega Zone of Oromia Regional State in Southwestern Ethiopia (Fig. 1). This area is part of the Southwestern Ethiopian Plateau and is 491 km far from Addis Ababa. Geographically, it is bounded between coordinates of 8°38′N to 8°41′N latitudes and 36°38′E to 36°41′E longitudes.

Methodology

In this study, engineering geological mapping, discontinuity surveying, sampling and laboratory testing, core drilling and Lugeon test, kinematic, limit equilibrium, and finite element methods were used. To identify the major geological units and structures, mapping was first undertaken along the northwest-southeast trending line considering the orientation of geological units and structures. Representative rocks from each geological unit were collected for laboratory testing, after which engineering geological units were classified based on the degree of weathering and intact rock strength for rocks and the type of soils and the degree of plasticity for soils.

A discontinuity survey was also carried out with the main emphasis on joints favoring slope instability and potential leakage. Hence, discontinuity parameters such as spacing, persistence, orientation, aperture, infill material, roughness, wall weathering, and associated groundwater conditions were measured and described following ISRM (1981) standard. The results of this survey were then used as input data for abutment slope stability analysis. Furthermore, the orientation data from this survey was also studied using Dips 6.0 software (Rocscience 2004a) via a Rosset diagram to analyze the influence of discontinuity orientation on the potential leakage path.

Upon completion of mapping and discontinuity surveying, borehole geotechnical data was used for analysis along the dam axis. Eleven boreholes were drilled by Oromia Water Works, Design and Supervision Enterprise (OWWDSE) to the depth between 20 and 92 m with a total core length of 476 m, and logging was carried out within each borehole based on ISRM (1981) recommendation. Then, eighty-four Lugeon or water pressure tests were conducted along the dam axis using a single packer. For this, the test section length was varied between 2.5 and 5 m depending on variation in the degree of weathering of rocks. The Lugeon values were then calculated, and water flow behaviors were determined for each test section based on Houlsby (1976). Finally, the interpretation of the Lugeon values was made based on the study by Ghafoori et al. (2011).

Regarding slope stability analysis, the selection of appropriate methods mainly depends on the geological conditions of the site, potential mode of failure, weakness, and limitations of methods (Gurocak et al. 2008; Basahel and Mitri 2017) . According to Park and West (2001) and Raghuvanshi (2019), the stability analysis of strong and slightly fractured and weathered rock slope section involves the application of kinematic analysis to determine the mode of failure, followed by LEM to analyze the slope in terms of FOS. According to Hoek and Bray (1981), the failure of such slopes mainly occurs through structural discontinuities. Hence, kinematic analysis was first applied using Dips 6.0 software to identify mode of failure for slope sections constituted by slightly fractured and weathered rocks. Then, FOS was determined for the identified mode of failure/s using LEM-based software/s.

On the contrary, when rock slopes are highly fragmented and weathered, a possible failure surface tends

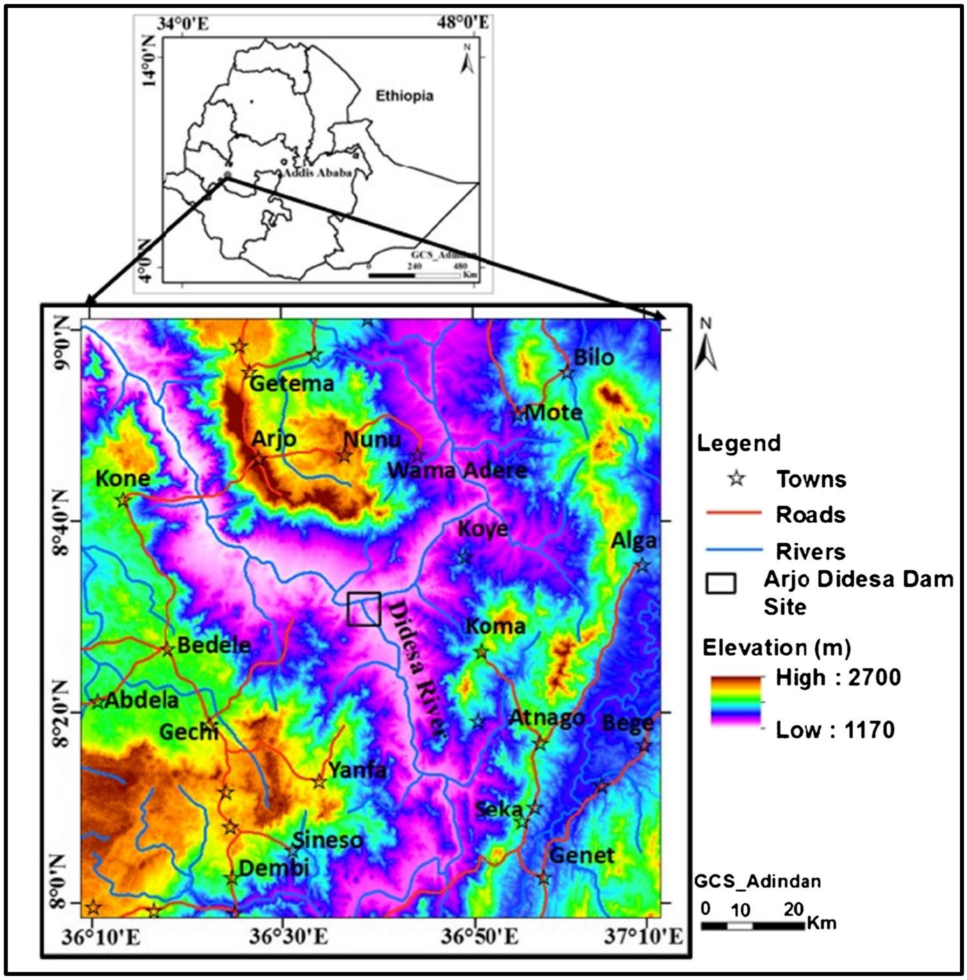


Fig. 1 Location of Arjo Didesa dam site

to follow a circular path like a failure in soil mass rather than through stronger intact material (Wyllie and Norrish 1996). In such a scenario, the classical principles of soil mechanics for slope stability analysis apply (Sarma 1979), and either LEM and/or numerical methods can be directly used to determine the stability of the slope in terms of FOS or SRF (Mahboubi et al. 2008). Based on this notion, the stability of some sections of dam abutment constituted by highly weathered and fractured rock masses was done by adopting LEM and FEM.

Results

Surface and subsurface engineering geological mapping

At the preliminary stage of an engineering geological mapping, the geology of the dam site was determined in the field using conventional field mapping methods in which the dam site is constituted by tertiary rhyolite rock and quaternary deposits such as residual, alluvial, and colluvial deposits (Fig. 2). The rhyolite rock is exposed along the right and left abutments and reservoir area and is characterized by porphyritic texture with a slight to a high degree of weathering and is affected by numerous joints. The residual deposit covers the majority of the reservoir area over gently dipping escarpment and flat farmland and is red to brown with various particle sizes. The alluvial deposit is exposed along the river channel and consists of a 3 to 5 m thick mixture of major soil types ranging from silty clay to boulders. The colluvial deposit, on the other hand, is deposited at the toe of both abutments and consists of an extremely wide range of soil types ranging from clay to boulders as well.

To analyze the subsurface geological condition of the dam site, eleven boreholes were drilled along the dam axis by OWWDSE (2009) (Fig. 3). Accordingly, two boreholes, namely AD-3 and AD-4, were drilled along the central part of the foundation to the depth of 92 m and 50 m, respectively. Logging showed that this part of the dam is underlain by a 5 m thick alluvial deposit, followed by fresh to slightly weathered and moderately jointed basalt (Fig. 3). Similarly,

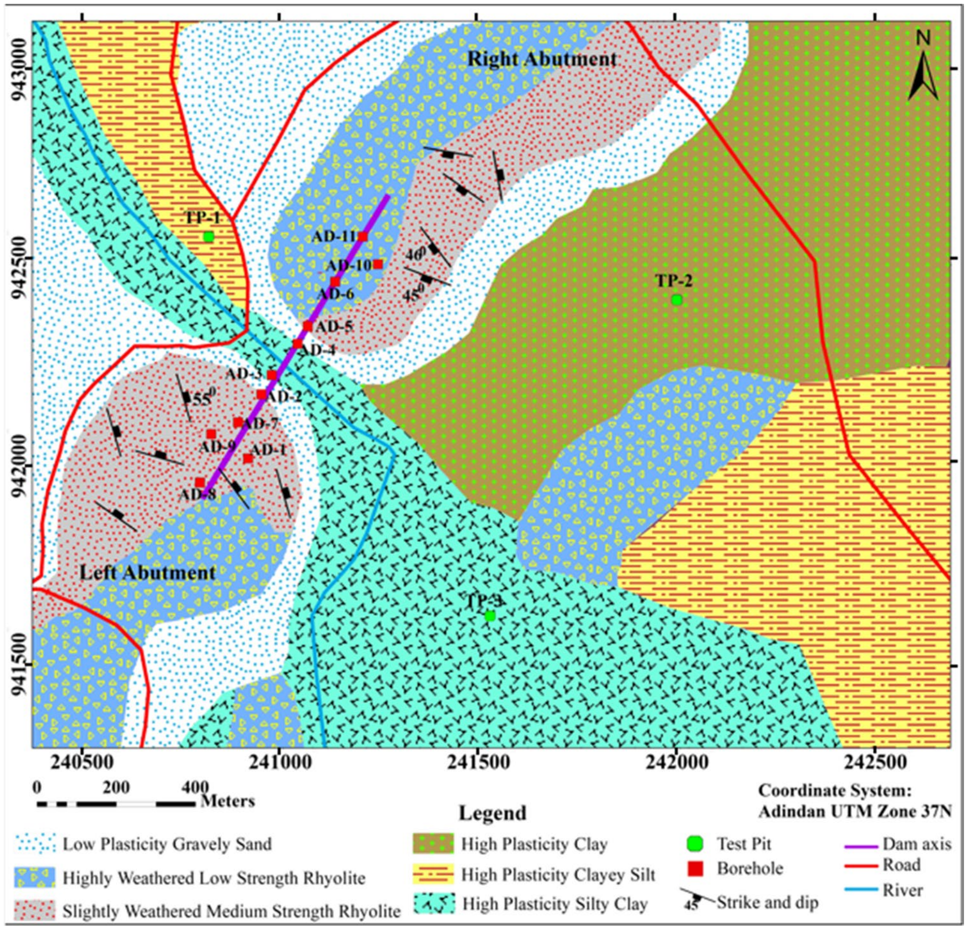


Fig. 2 Engineering geological map of the Arjo Didesa dam site (scale 1:2000)

logging along all boreholes within both the right and left abutments of the dam has shown that the site is successively underlain by slightly to highly weathered rhyolite, moderately to highly weathered basalt, and fresh to slightly weathered basalt (Fig. 3). Moreover, colluvial deposit (mainly silty sand with gravel) is also mapped in the boreholes that were drilled at the toe of the abutments (Fig. 3).

To prepare an engineering geological map of the dam site and determine some engineering properties of rocks and soils, laboratory tests were also conducted on representative samples. The result of the unconfined compressive strength test (Table 1) showed that slightly and highly weathered rhyolite have medium and low strength as per ISRM (1981), respectively. Similarly, the analysis also showed that fresh basalt is classified as a high-strength rock while slightly weathered basalt is a medium-strength rock. The laboratory test results of soils showed that the dominant soils in the study area are low plasticity gravely sand, high plasticity clay, high plasticity silty clay, and high plasticity clay. Moreover, the average hydraulic conductivity of the study area ranges from 10^{-6} to 10^{-7} cm/s indicating that these soils are characterized as impervious. Hence, the soils of the study area are watertight and can be used as clay blankets in the areas where there are open joints in the reservoir to control leakage.

Discontinuity data

Discontinuities on both left and right abutment slopes were studied in detail based on slope face and scanline mapping. The survey was conducted in more than 200 locations, and the orientation data was processed using Dips 6.00 software (Rocscience 2004a, b) based on equal area stereographic projection. Based on this analysis, three dominant joint sets striking NW-SE (JS1), NE–SW (JS2), and WNW-ESE (JS3) on the left abutment and NEN-SES (JS1), NE–SW (JS2), and NW-SE (JS3) on the right abutment were identified (Fig. 4). In general, discontinuities of the dam site are characterized by an opening of close to wide spacing (0.1–0.7 cm) which is dominantly filled with fine materials and has slightly to highly rough discontinuity surface (Table 2).

Lugeon test/packer test results

Permeability is an important parameter for the design of dam projects. In this study, the permeability of the rock mass at the dam site was evaluated using a single packer test. A total of eighty-four Lugeon tests were conducted by OWWDSE 2009, and Table 3 shows the statistical

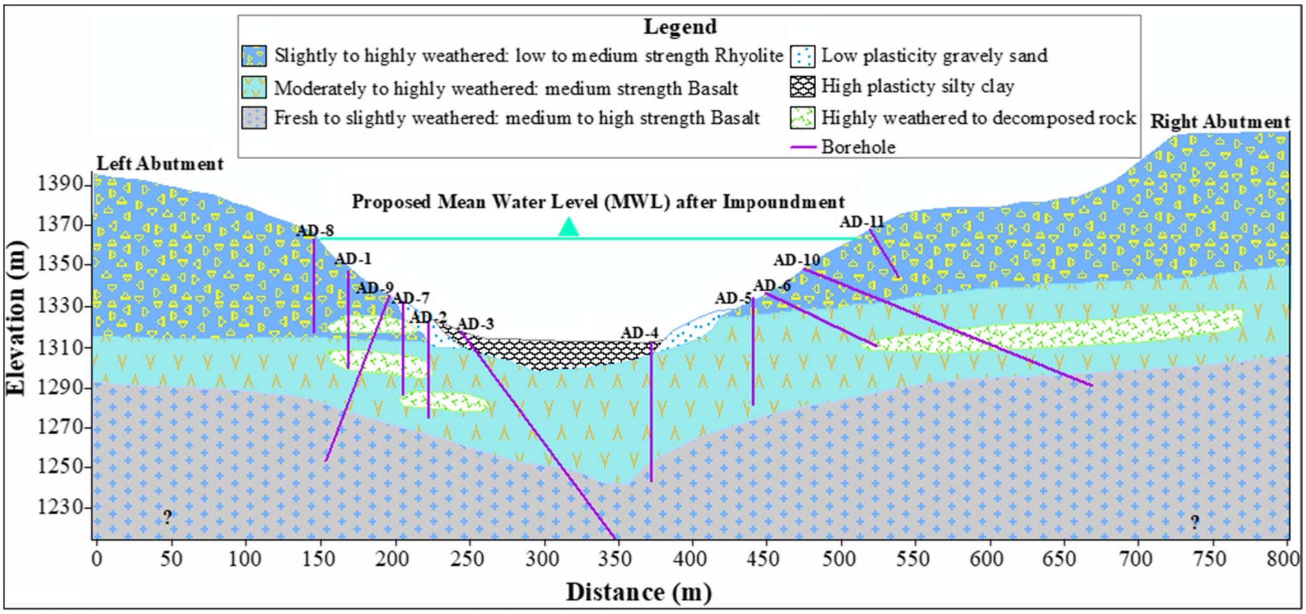


Fig. 3 Engineering geological cross-section of the Arjo Didesa dam site

Table 1 Selected unconfined compressive strength and unit weight of rocks from the Arjo Didesa dam site

Location	Depth interval (m)	Rock type	Dry unit weight (Kg/m^3)	Unconfined compressive strength (MPa)	Classification as ISRM (1981)
Left abutment (AD9)	37.45–37.75	Slightly weathered rhyolite	2854	25.456	Medium strength
	48.00–48.28		2867	48.526	Medium strength
Central foundation (AD4)	13.55–13.68	Fresh to slightly weathered basalt	2396	27.542	Medium strength
	21.80–22.13		2032	92.182	High strength
Right abutment (AD10)	13.50–13.66	Highly weathered rhyolite	2350	7.094	Low strength
	13.66–13.84		2433	8.513	Low strength
	23.48–23.89		2008	9.365	Low strength

distribution of the Lugeon values obtained along the dam axis following Ghafoori et al. (2011) classification of rock mass based on Lugeon values. Accordingly, this statistical distribution showed that about 42.86% of all determined Lugeon values at the dam site are classified into impervious class as per Ghafoori et al. (2011), while the remaining 57.14% are classified into low to very high permeability classes.

Based on the characteristics of the discontinuities at the dam site, the type of flow of water was also analyzed, and the results were plotted as shown in Fig. 5. From all tests conducted at the dam site, 24.53% showed turbulent behavior, 22.64% laminar, 20.75% dilation, 18.87% void-filling, and 13.21% washout flow behavior. As can be seen from statistical analysis, turbulent and laminar flow behavior predominates, with the former being dominant at the left abutment and the latter at the central foundation.

Analysis of lugeon values with depth and curtain grout depth

The analysis of Lugeon values with depth serves as a basis for determining curtain grout depth in the design of the dam projects (Berhane and Walraevens 2013; Garo and Meten, 2021). Several researchers have shown that the Lugeon value decreases with depth due to the overburden effect and reduction in the degree of weathering and fracturing (Lee and Farmer 1993; Nappi et al. 2005; Berhane and Walraevens 2013; Garo and Meten 2021). Nevertheless, some studies have also shown that there are some exceptions in which the Lugeon value shows no clear trend with depth (Hamm et al. 2007), and hence, the relation of the Lugeon value with depth must be evaluated with great caution for deciding curtain grout depth. Accordingly, in this study, the relation of Lugeon value with depth is evaluated by producing a permeability

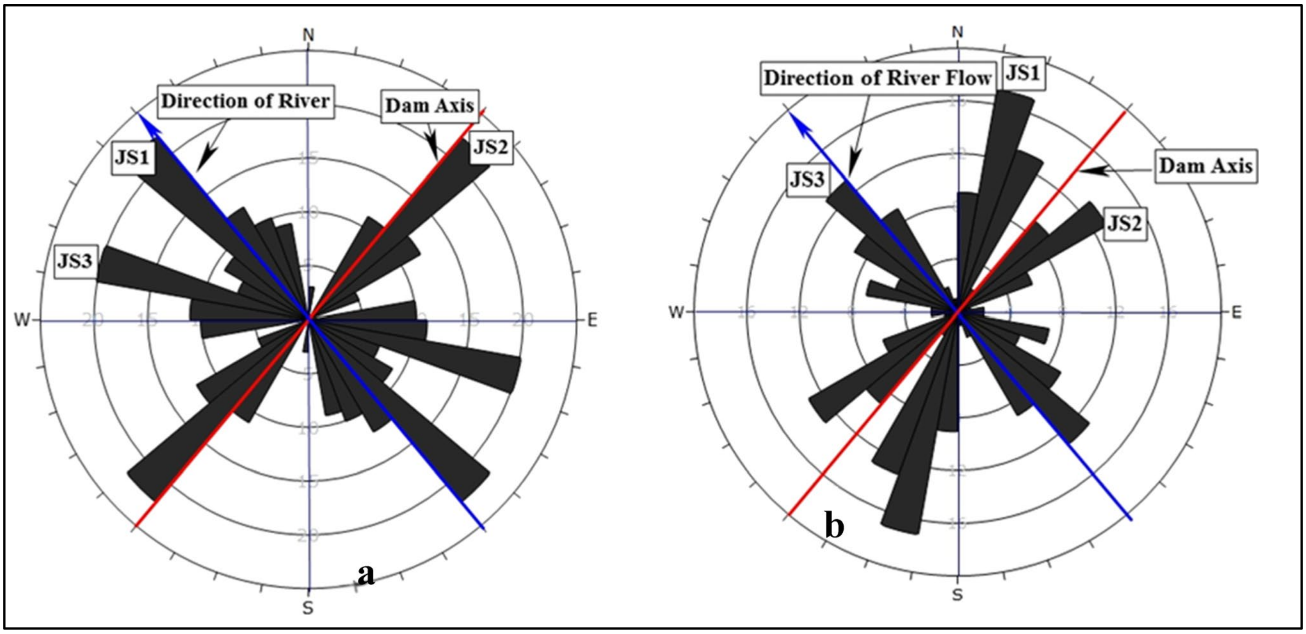


Fig. 4 Rose diagram at (**a**) left abutment and (**b**) right abutment (blue and red lines show the direction of river flow and dam axis, respectively)

Table 2 Summary of the characteristics of discontinuities

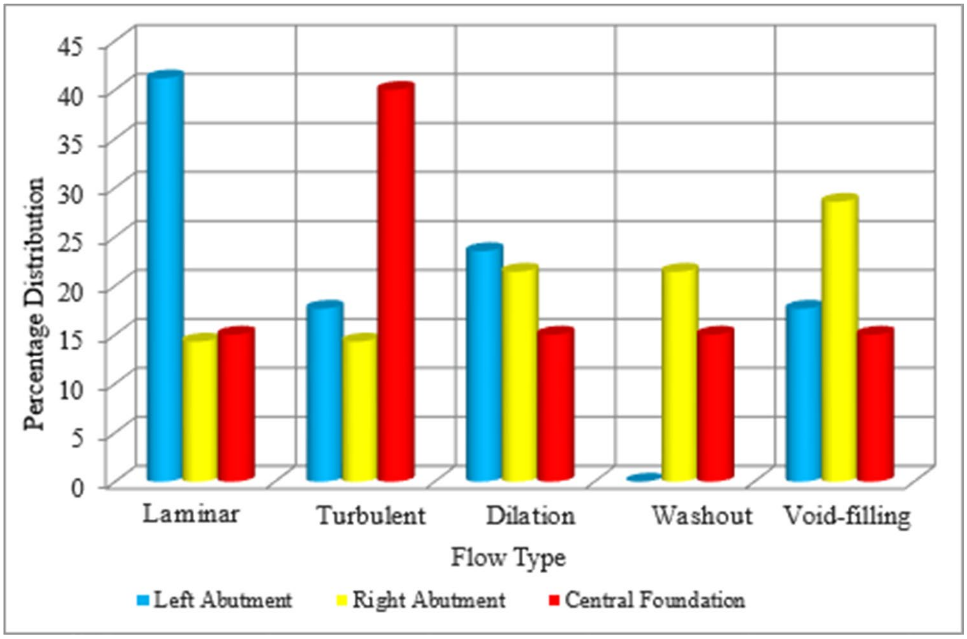
Location	Joint set	Spacing (cm)	Aperture (cm)	Persistence (m)	Roughness	Weathering degree	Infilling material
Left abutment	J1	40–90	0.10–0.50	0.5–2.0	Slightly rough	Highly weathered	Soft gouge
	J2	1–55	0.10–0.70	1.0–3.0	Rough	Highly weathered	Fine soil
	J3	9–120	0.14–0.32	1.5–3.0	Slightly rough	Moderately weathered	Fine soil
Right abutment	J1	32–50	0.15–0.60	1.5–4.0	Slightly rough	Highly weathered	Fine material
	J2	1–40	0.20–0.50	2.5–5.0	Slightly rough	Slightly weathered	clean
	J3	27–115	0.10–0.70	0.4–1.0	Slightly rough	Highly weathered	Fine material

Table 3 Statistical distribution of the number of Lugeon values in the different permeability classes

Location	Borehole	Classification based on Ghafoori et al. (2011)				
		Lugeon value range				
		0–3	3–10	10–30	30–60	> 60
		Impervious	Low permeability	Medium permeability	High permeability	Very high permeability
Right abutment	AD-1, AD-2, AD-7, AD-8, AD-9	19	3	4	3	5
Central foundation	AD-3. AD-4	8	7	4	4	0
Left abutment	AD-5, AD-6, AD-10, AD-11	9	7	7	1	3
Number of tests		36	17	15	8	8
Statistical distribution (%)		42.86	20.24	17.86	9.52	9.52

cross-section (Fig. 6) and plotting a graph of Lugeon value versus depth for selected boreholes (Fig. 7) for each section of the dam. The results obtained from both mechanisms are in close agreement and the majority of determined Lugeon values of rocks along the dam axis decrease with depth (Fig. 6 and Fig. 7a–f). Moreover, the analysis also showed that the

Fig. 5 Percentage distribution of water flow behaviors at the dam site



Lugeon value generally decreases to less than 3 at a depth of about 40 m for the left abutment, 53 m for the central foundation, and 43 m for the right abutment (Figs. 6 and 7).

Abutment slope stability analysis

Structural controlled stability analysis

Based on the field manifestation, there are some sections of dam abutment in which slope failure is controlled by structural discontinuities. These slope sections are outcropped in both abutments of the dam and are mainly constituted by a slightly fractured and weathered rock mass. The stability of these slopes was done first by adopting the kinematic method to identify the mode of failure. This analysis was done using Dips 6.00 software (Rocscience 2004a, b) using input parameters such as dip amount and dip directions of major joint sets and slope and friction angles of discontinuities, as shown in Table 4. The friction angles of discontinuities were determined using Rocdata software

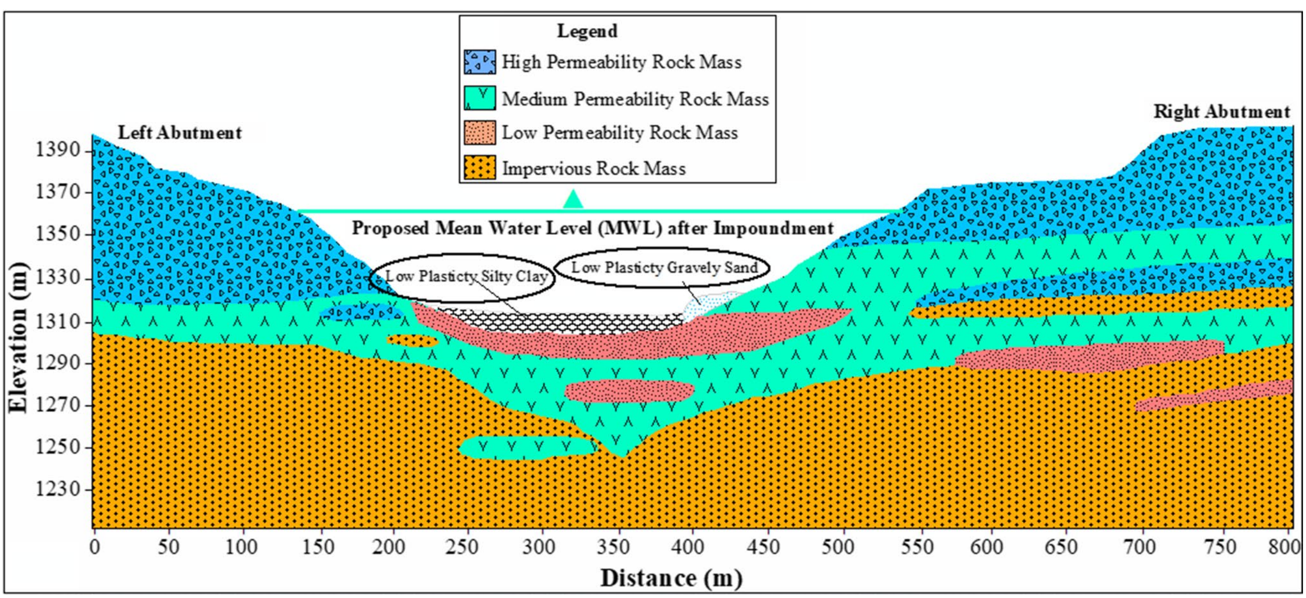


Fig. 6 Permeability cross-section of rock mass along the dam axis based on Lugeon values based on Ghafoori et al. (2011)

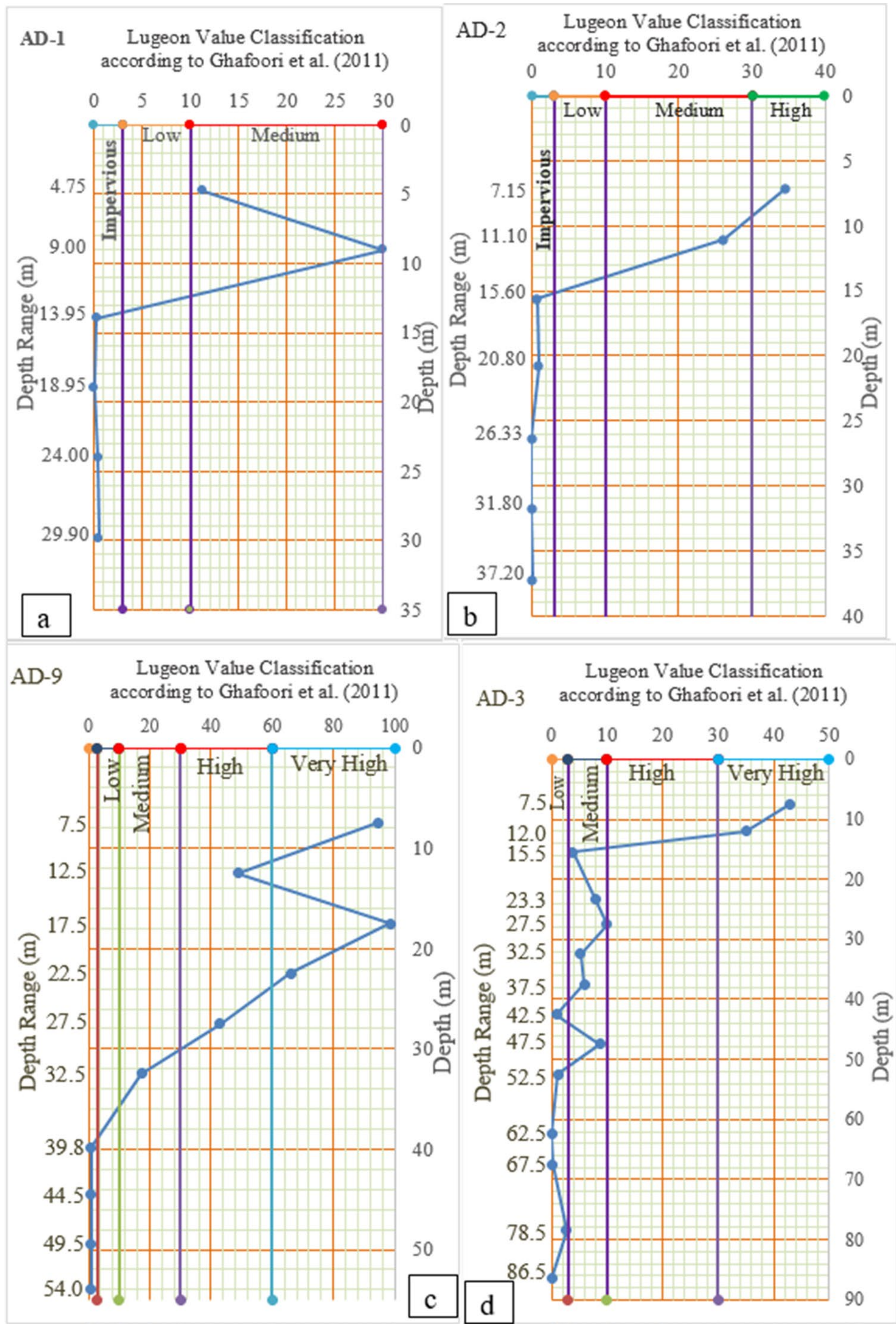


Fig. 7 Plot of Lugeon values with depth for some selected boreholes at the (**a**, **b**, and **c**) at the left abutment, (**d**) central foundation, and (**e** and **f**) right abutment

(Rocscience 2004a, b) following Barton and Bandi's (1990) nonlinear failure criteria, while the remaining parameters were determined in the field. The results of the analysis are shown in Fig. 8, and the results showed that both abutments of the dam site are unstable for the planar mode of failure. The planar mode of failure was identified in the Dips 6.0 software by determining the pole of joint sets that fall in the critical zone of planar failure, as highlighted in red color in Fig. 8. Accordingly, some sections of the left abutment of the dam are unstable for a planar mode of failure due to joint set 2 (JS2) and joint set 3 (JS3) (Fig. 8a) and the right abutment due to joint set 3 (JS3) (Fig. 8b).

Further stability analysis in terms of FOS was also carried out for already identified planar mode of failures using LEM. The analysis was carried out using RocPlane 2.0 software (Rocscience 2004a, b) from input parameters listed in

Fig.7 (continued)

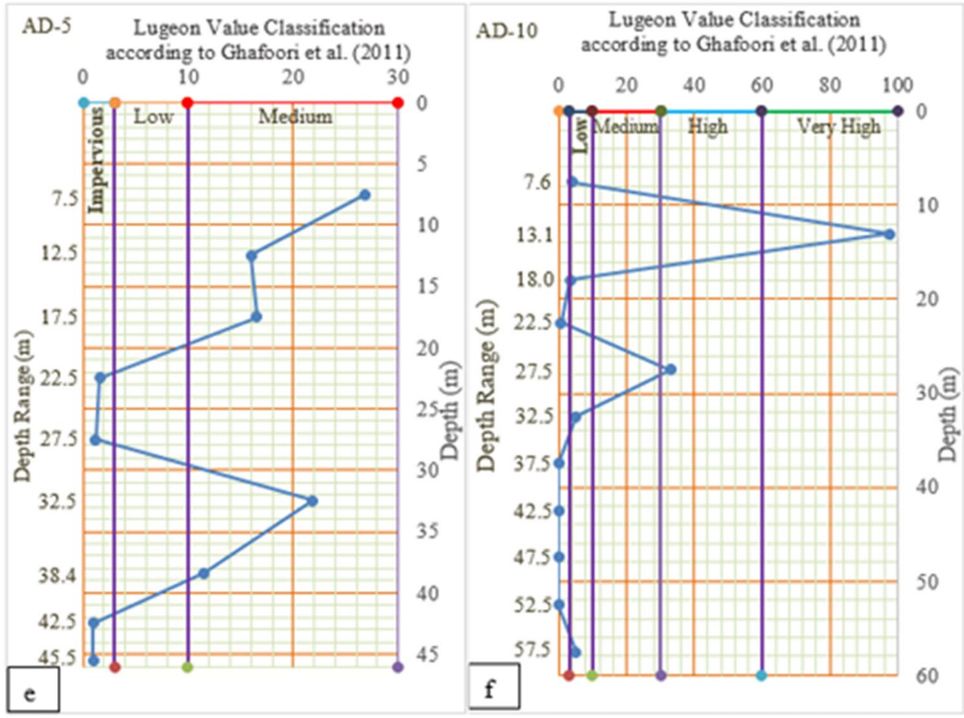


Table 4 Input parameters for kinematic analysis

Slope sections	Slope orientation (dip/dip direction(°))	Discontinuity orientation (dip/dip direction) (°)			Friction angle	Possible mode of failure
		JS1	JS2	JS3		
Left abutment	65/068SE	55/250	45/106	42/020	35	Planar failures (JS2 and JS3)
Right abutment	56/230SW	46/090	38/290	45/210	38	Planar failures (JS3)

Table 5, and the results of the analysis were presented in Table 6. Accordingly, all the slope sections at both abutments of the dam site are characterized by FOS greater than 1 during dry conditions and less than 1 during fully saturated slope conditions.

Non-structural controlled stability analysis

The stability of some sections of dam abutments that are constituted by highly weathered and fractured rock mass was conducted by considering circular or near circular mode of failure. First, the LEM stability analysis was performed by utilizing the GLE/Morgenstern-Price method using the input parameters of Table 7. The shear strength parameters used in this method were determined from Hoek–Brown failure criteria (Hammah et al. 2004) using RocLab software (Rocscience 2004a, b). Similarly, horizontal seismic acceleration (α) of the study area was acquired from the study conducted by Asfaw (1986). The analysis was conducted using Slide v6.0 software, and the results of the analysis were presented in Table 9 and Fig. 9.

According to the results, both abutments of the dam site are unstable during saturated conditions with FOS as low as 0.132 and stable during dry conditions.

Moreover, the FEM stability analysis was also conducted in terms of SRF using Pahse^2 V8.0 software to confirm and/or validate the results obtained using LEM. In the FEM, the generalized Hoek Brown failure criterion (Hammah et al. 2004) option in Phase^2 software was used to compute a critical stress reduction factor (SRF). This software utilizes input parameters such as slope height, uniaxial compressive strength of intact rock (σci), unit weight of rock (γ), geological strength index (GSI), Hoek–Brown constant parameters (a, mb, and s), intact rock constant (mi), disturbance factor (D), Young's modulus (Erm), Poisson's ratio (v), seismic load, and groundwater condition (Table 8). GSI values were determined from the chart provided by Marinos and Hoek (2000). The Hoek–Brown constant parameters and intact rock mass constant were determined based on Hoek et al. (2002) in the RocLab Software (Rocscience 2004a, b). The value of the disturbance factor (D) in this study was determined by Hoek et al. (2002), and the value of 0.7 was used.

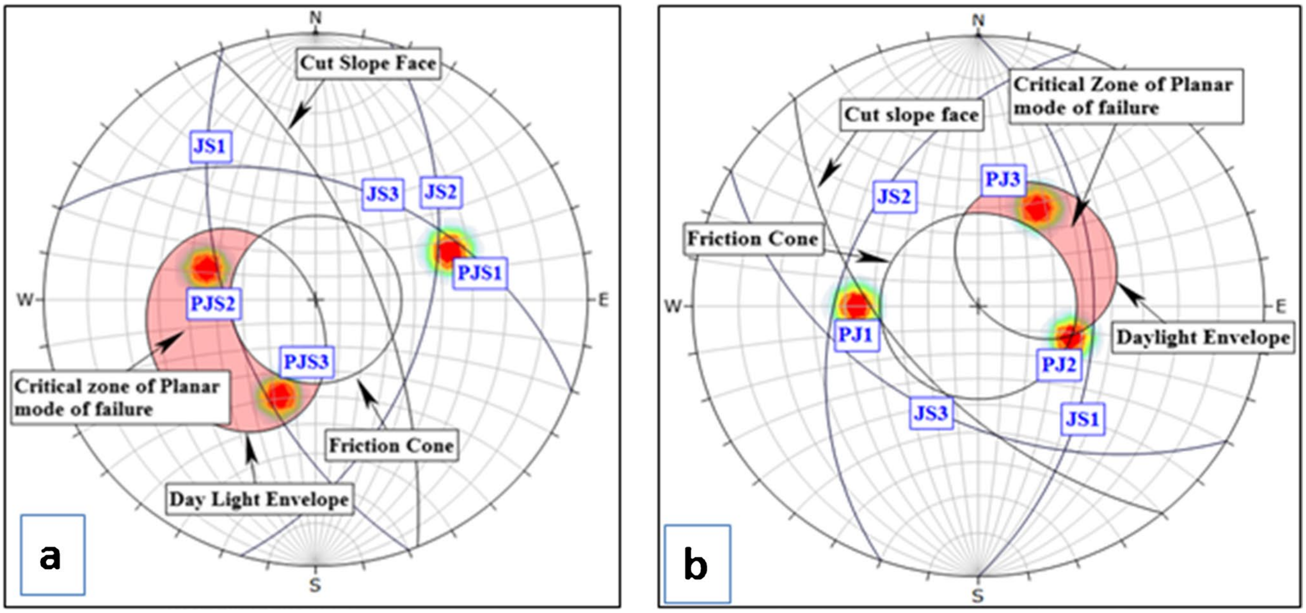


Fig. 8 Kinematic analyses for the planar mode of failure: (**a**) left abutment and (**b**) right abutment

Table 5 Input parameters used in RocPlane software for deterministic method analysis

Slope sections	Joint set	Geometry						shear strength		Forces	
		Slope angle (°)	Upper slope angle (°)	Failure plane angle (°)	Slope Height (m)	γ (t/m^3)	W	ϕ (°)	C (t/m^2)	u_w (t/m^3)	α (g)
Left	J2	65	15	45	30	2.337	8	35.40	2.0	1	0.01
	J3	65	12	42	35	2.337	4	35.52	1.8	1	0.01
Right	J3	56	12	40	26	2.337	5	37.87	1.9	1	0.01

where γ is the unit weight of the rock, w is waviness, ϕ is friction angle, c is cohesion, u_w is water pressure, and α is the seismic coefficient

Table 6 Factor of safety determined for the planar mode of failure under different anticipated conditions

Slope sections	Joint set	Factor of safety					
		Static condition			Dynamic condition		
		Dry	Moderately	Fully saturated	Dry	Moderately	Fully saturated
Left	J2	1.07	0.86	0.25	1.05	0.84	0.24
	J3	1.02	0.85	0.34	1.0	0.83	0.33
Right	J3	1.32	1.08	0.33	1.30	1.05	0.32

The Young's modulus (Erm) was determined based on Hoek and Diederichs (2006), and a Poisson's ratio value of 0.3 was used based on the study by Gercek (2007). Upon the determination of all input parameters, the analysis was executed, and the results were presented in Table 9 and Fig. 10. Likewise, for LEM, the analysis results of this method also showed that both abutments of the dam site are unstable during saturated conditions (i.e., SRF < 1) and stable during dry conditions (i.e., SRF > 1).

Discussions

In this section, the results obtained from discontinuity surveying, the Lugeon test, and slope stability analysis will be discussed for a detailed evaluation of research objectives and recommendations for site-specific remedial measures. From the discontinuity survey, it was deduced that the study area is characterized by a complex structural system as there is a significant variation in the joint characteristics such as

Table 7 Input parameters used for limit equilibrium slope stability analysis

Material	Parameters			Slope geometry		α (g)
	C (MPa)	ϕ (°)	γ (KN/m^3)	Height (m)	Angle (°)	
Left abutment slope						
Layer 1 (HWR)	0.162	25.96	21.84	80	54	0.01
Layer 2 (MWR)	0.223	28.56	24.89	80	54	0.01
Right abutment slope						
Layer 1 (HWR)	0.235	30.41	21.84	85	47	0.01
Layer 2 (SWR)	0.339	34.66	24.89	85	47	0.01

Where C is Cohesion, ϕ is friction angle, γ is unit weight of rock, α is horizontal seismic acceleration, and HWR, MWR, and SWR represent highly weathered rhyolite, moderately weathered rhyolite, and slightly weathered rhyolite, respectively.

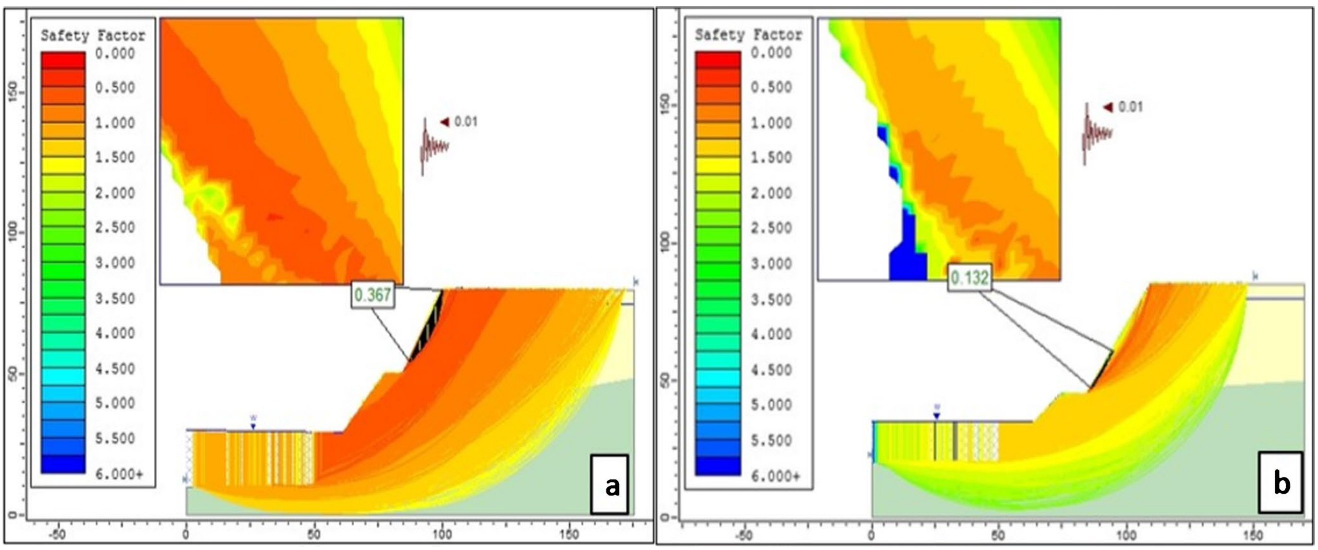


Fig. 9 Some selected slope stability analysis results using the limit equilibrium method under dynamic saturated conditions at the (**a**) left abutment and (**b**) right abutment

Table 8 Input parameters for finite element slope stability analysis

Rock unit	Parameters						Slope Geometry		α (g)
	Mb	S	a	γ (KN/m^3)	Erm (MPa)	v	Height (m)	Angle (°)	
Left abutment slope									
HWR	0.276	6.9e-6	0.276	21.84	238	0.3	80	54	0.01
MWR	0.364	1.42e-5	0.364	24.89	288.9	0.3	80	54	0.01
Right abutment slope									
HWR	0.478	2.94e-5	0.526	21.84	276.9	0.3	85	47	0.01
SWR	0.703	8.106e-5	0.516	24.89	464.1	0.3	85	47	0.01

Where mb, s, and a are rock mass material constants, γ is unit weight of rock, Erm is the modulus of elasticity, v is Poisson's ratio, α is horizontal seismic acceleration, and HWR, MWR, and SWR represent highly weathered rhyolite, moderately weathered rhyolite, and slightly weathered rhyolite, respectively

orientation, opening, spacing, and persistence. Moreover, a detailed analysis of orientation data showed that there exists a correlation between joint orientation, river flow direction, and leakage condition of the dam site. Hence, the analysis has shown that the JS1 at the left abutment and JS3 at the right abutment have a similar orientation parallel to the river flow direction (Fig. 4). Maerz and Zhou (1999) and Abay and Meisina (2015) have stated that joints that parallel river

Table 9 Comparison of the factor of safety and stress reduction factor results computed by limit equilibrium and finite element method, respectively

Slope sections	Conditions	Limit equilibrium method Factor of safety	Finite element method Stress reduction factor
Left abutment	Static dry	1.099	1.09
	Static saturated	0.377	0.1
	Dynamic dry	1.088	1.08
	Dynamic saturated	0.367	0.1
Right abutment	Static dry	1.499	1.48
	Static saturated	0.683	0.52
	Dynamic dry	1.474	1.47
	Dynamic saturated	0.132	0.51

flow direction favor leakage and infer potential seepage path in a dam site. Based on this study, the orientation of these two joint sets favors leakage in the abutment and through the foundation. Moreover, this analysis has also shown that the orientation of JS2 and JS3 at the left abutment and JS3 at the right abutment favors structural controlled failure mechanisms.

The leakage of this dam site was primarily evaluated based on the results obtained from the Lugeon tests. Accordingly, the Lugeon test results have shown that greater than 57% of all the determined Lugeon values at the dam site were above 3 (Table 3) showing that there is a need for grouting treatment (Houlsby, 1976 and 1990; Uromeihy and Farrokhi, 2011). Of these percentages of Lugeon values above 3, about 19.04% were classified into high to very high permeability classes, according to Ghafoori et al. (2011). This indicated that a considerable amount of rock masses along the dam axis are intercepted by interconnected open joints (Fell et al. 2005). As per the work of Berhane and Walraevens (2013), the incorporation of such percentages of Lugeon values into high and very high permeability classes also imply a potential for excessive leakage through the rock masses in the dam site.

Analysis of Lugeon values with depth in terms of permeability cross-section (Fig. 6) has shown variation in permeability with depth between different sections of the dam site. For example, the left abutment is relatively more pervious than the right abutment of the dam site, implying a higher degree of fracturing and weathering at the left abutment. Moreover, this analysis has also revealed that the Lugeon values rarely show a clear trend with depth (Fig. 6), and hence, curtain grout depth for this section of the dam must be determined with great caution. In general, a detailed analysis of Lugeon values has shown a general decrement to less than 3 Lugeon units at depths of 40 m, 53 m, and 43 m at the left abutment, central foundation, and right abutment, respectively. This implies that all the rock masses which are located over the above-mentioned depths at the corresponding sections of the dam site are pervious and can lead to serious leakage problems. Hence, based on Houlsby (1976 and 1990) and Uromeihy and Farrokhi (2011), curtain grouting is recommended to the depths of 40 m for the left abutment, 53 m for the central foundation, and 43 m for the right abutment to control leakage.

The slope stability analysis of the dam abutments was also primarily evaluated based on results obtained from the kinematic analysis, LEM, and FEM. The kinematic analysis was solely conducted for slope sections constituted by slightly fracture and weathered rock masses where possible failure only takes through structural planes. From this analysis, it was deduced that both abutments of the dam are unstable only for a planar mode of failure. Furthermore, further stability analysis of this mode of failure using LEM-based Rocplane 2.0 software revealed that the saturated conditions have significantly lower FOS than dry conditions. According to Hossain (2011), Ahmadi and Eslami (2011), and Raghuvanshi (2019), pore water pressure in the discontinuities reduces slope stability by lubricating and decreasing the shear strength of the discontinuities. Therefore, the lower FOS for rock failure in the study area during saturated conditions is attributable to the water force in the discontinuities.

Moreover, the stability of highly weathered and fractured sections of the dam abutments was first conducted using LEM and followed by FEM. The results obtained from both methods are in very close agreement, and both showed unstable slope conditions during saturation. Hence, this scenario illustrates that surface water and groundwater conditions are the major causative factors for slope instability in the study area. Therefore, any proposed remedial measures against slope instability in the dam site should primarily consider the saturation condition into account.

Conclusion and recommendations

This study evaluated the leakage and abutment slope stability conditions of the Arjo Didesa dam site. The dam site is mainly constituted by slightly to highly weathered, low to

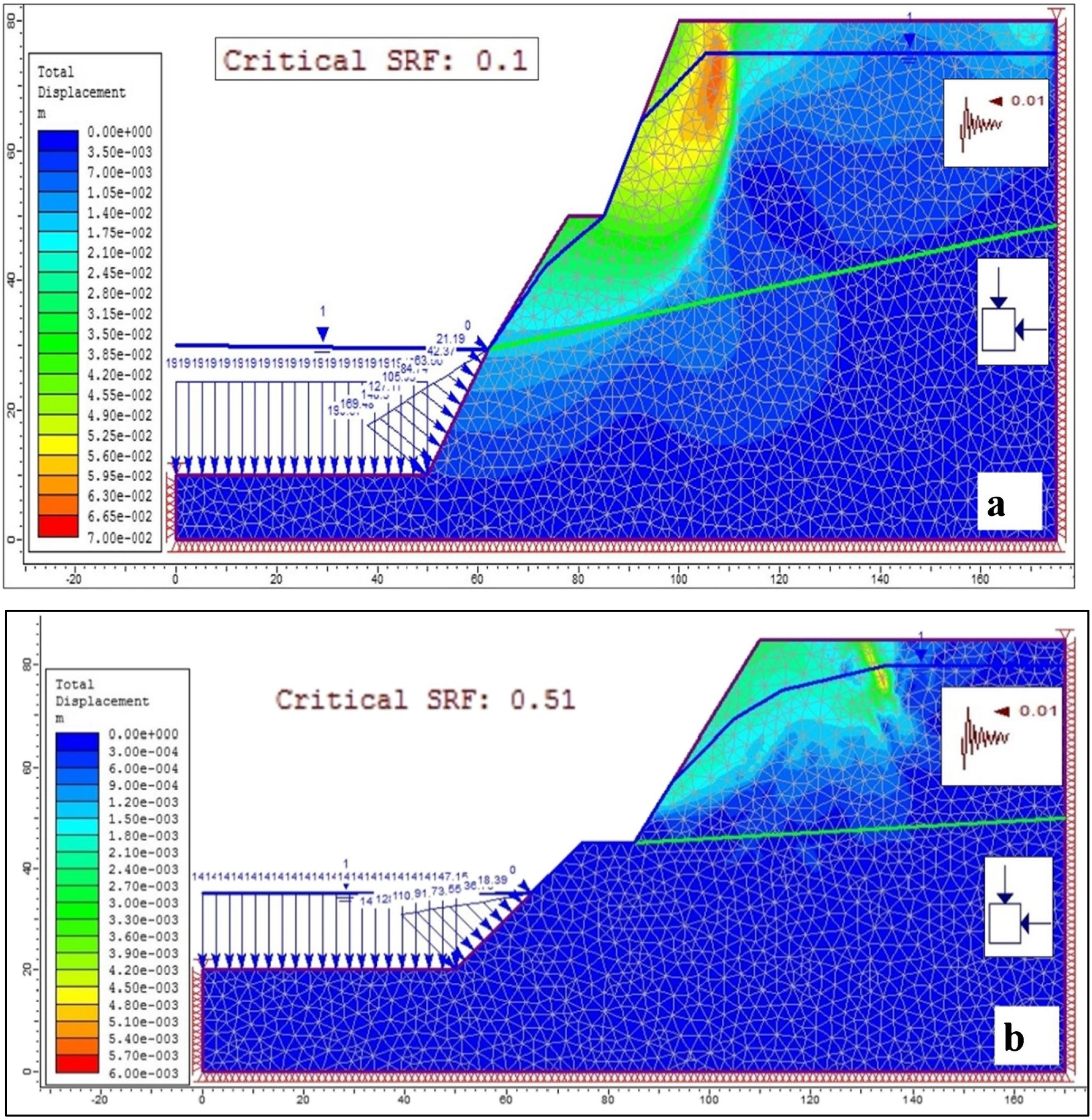


Fig. 10 Some selected slope stability analysis results using FEM under dynamic saturated conditions at the (**a**) left abutment and (**b**) right abutment

medium strength rhyolite, fresh to highly weathered, and medium to high strength basalt. These rocks are cut by three dominant joint sets in which the NW–SE (JS1) on the left abutment and the NW–SE (JS3) on the right abutment are parallel to the river flow direction, thereby favoring potential leakage. From all the Lugeon tests conducted along the dam axis, more than 57% have Lugeon values greater than 3 Lugeon units implying the potential for excessive leakage and the need for grouting to control this leakage. Moreover, from the percentage of Lugeon values above 3 Lu, about 19.04% of the values have more than 10 Lu, indicating that a considerable amount of rock masses along the dam axis are affected by interconnected open joints. In general, considering the analysis of Lugeon values with depth, appropriate curtain grouting was recommended to the depths of about 40 m at the left abutment, 53 m at the central part of the foundation, and 43 m at the right abutment to control the potential excessive leakage.

The stability of slope sections of dam abutments constituted by slightly fractured and weathered rocks was first determined by the kinematic method and followed by LEM. From this analysis, it was concluded that both abutments of the dam are unstable only for a planar mode of failure. Stability analysis of this planar mode of failure using LEM also revealed that abutments of the dam are unstable conditions (i.e., FOS/SRF < 1) during saturation. This showed that pore water pressure significantly contributes to the destabilization of these slopes. Moreover, stability analysis conducted using both LEM and FEM methods for highly weathered abutment slope sections also showed instability for a circular mode of failure during saturated conditions with factor of safety (FOS) and stress reduction factor (SRF) as low as 0.1 and 0.132, respectively. Rock bolting and removal of overhanging rock mass were recommended for planar mode failures, while providing proper drainage holes and reducing slope angle were recommended for slope sections with circular mode failures for those potentially unstable slopes at the Arjo Didesa dam site.

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Declarations

Conflict of interest The authors declare that they have no competing interests.

References

Abay A, Meisina C (2015) Engineering-geological properties of carbonates and shale their implications for dam construction in Mekelle Northern Ethiopia. Momona Ethiopian J Sci 7(1):64. https://doi.org/10.4314/mejs.v7i1.117238

Abdulkadir M (2009) Assessment of micro-dam irrigation projects and runoff predictions for ungauged catchments in northern Ethiopia. PhD dissertation, Muenster University, Germany. http://d-nb.info/1000437884/34

Ahmadi M, Eslami M (2011) A new approach to plane failure of rock slope stability based on water flow velocity in discontinuities for the Latian dam reservoir landslide. J Mt Sci 8:124–130. https://doi.org/10.1007/s11629-011-2088-5

Alzo'ubi A (2016) Rock slopes processes and recommended methods for analysis. International J Geomate. https://doi.org/10.21660/2016.25.34052

Asfaw LM (1986) Catalogue of Ethiopian earthquakes, earthquake parameters, strain release and seismic risk. In Proc. SAREC-ESTC Conference on Research Development and Current Research Activities in Ethiopia (252–279)

Awulachew SB, Yilma A, Loulseged D, Loiskandl W, Ayana M, Alamirew T (2007) Water resources and irrigation development in Ethiopia. International Water Management Institute, Colombo, Sri Lanka, p 78

Awulachew SB, Merrey DJ, Kamara AB, Van Koppen B, Penning de Vries F, Boelee E, Makombe G (2005) Experiences and opportunities for promoting small-scale/micro irrigation and rainwater harvesting for food security in Ethiopia. In: Working Paper 98. IWMI

Barton N (2004a) The theory behind high pressure grouting—part 1. Tunnels & Tunneling International, September, 28–30

Barton NR, Choubey V (1977) The shear strength of rock joints in theory and practice. Rock Mech 10(1–2):1–54

Barton N, Bandis S (1990) Review of predictive capabilities of JRC-JCS model in engineering practice. In: Balkema AA (ed), Proceedings of international conference on rock joints, Leon, Norway, pp. 603–610. Rotterdam

Barzegari G (2017) Geotechnical evaluation of dam foundation with special reference to in situ permeability: a case study. Geotech Geol Eng 35(3):991–1011. https://doi.org/10.1007/s10706-016-0155-y

Basahel H, Mitri H (2017) Application of rock mass classification systems to rock slope stability assessment: a case study. J Rock Mechan Geotech Eng 9(6):993–1009. https://doi.org/10.1016/j.jrmge.2017.07.007

Berhane G (2010) Geological, geophysical and engineering geological investigation of a leaky micro-dam in the Northern Ethiopia. Agricul Eng Int: the CIGR J 12(1):31–46

Berhane G, Walraevens K (2013) Geological challenges in constructing the proposed Geba dam site, northern Ethiopia. Bull Eng Geol Env 72(3–4):339–352. https://doi.org/10.1007/s10064-013-0480-9

Coli N, Pranzini G, Alfi A, Boerio V (2008) Evaluation of rock-mass permeability tensor and prediction of tunnel inflows by means of geostructural surveys and finite element seepage analysis. Eng Geol 10:174–184

Desta LT (2005) Reservoir siltation in Ethiopia causes, source areas and management options. PhD dissertation University of Bonn, Germany.

Eberhardt E, Vancouver U (2003) Rock slope stability analysis–utilization of advanced numerical techniques. Earth and Ocean sciences at UBC, 41

Faramarzi L, Zare M, Azhari A, Tabaei M (2017) Assessment of rock slope stability at Cham-Shir Dam Power Plant pit using the limit equilibrium method and numerical modeling. Bull Eng Geol Env 76(2):783–794. https://doi.org/10.1007/s10064-016-0870-x

Fell R, MacGregor P, Stapledon D, Bell G, Foster M (2005). Geotechnical engineering of dams (2nd ed., 449–460). Boca Raton, Florida: CRC Press/Balkema

Foyo A, Sanchez MA, Tomillo C (2005) A proposal for a secondary permeability index obtained from water pressure tests in dam foundations. Eng Geol 77:69–82

Garo T, Meten M (2021) Engineering geological characterization for evaluation of seepage and geomechanical properties of Chalchal Dam Site, Bale Zone, Southeastern Ethiopia. Arabian J Geosci 14(23) https://doi.org/10.1007/s12517-021-08881-8

Gebul M (2021) Trend, Status, and challenges of irrigation development in Ethiopia—a review. Sustainability 13(10):5646–5657. https://doi.org/10.3390/su13105646

Gercek H (2007) Poisson's ratio values for rocks. Int J Rock Mech Min Sci 44(1):1–13. https://doi.org/10.1016/j.ijrmms.2006.04.011

Ghafoori M, Lashkaripour GR, Tarigh AS (2011) Investigation of the geological and geotechnical characteristics of Daroongar dam, Northeast Iran. Geotech Geol Eng 29:961–975. https://doi.org/10.1007/s10706-011-9429-6

Gischig V, Amann F, Moore JR, Loew S, Eisenbeiss H, Stempfhuber W (2011) Composite rock slope kinematics at the current Randa instability, Switzerland, based on remote sensing and numerical modeling. Eng Geol 118(1–2):37–53. https://doi.org/10.1016/j.enggeo.2010.11.006

Goodman RE, Moye DG, Van Schalkwyk A, Javandel I (1965) Ground water inflows during tunnel driving. Bull Int Assoc Eng Geol 2(1):39–56

Goodman R (1989) Introduction to rock mechanics (1st ed., pp. 325–356). New York: John Wiley
Gurocak Z, Alemdag S, Zaman M (2008) Rock slope stability and excavatability assessment of rocks at the Kapikaya dam site. Turkey Eng Geol 96(1–2):17–27. https://doi.org/10.1016/j.enggeo.2007.08.005
Hammah RE, Curran JH, Yacoub TE, Corkum BC (2004) Stability analysis of rock slope using the finite element method. In: Proceedings of the ISRM regional symposium EUROCK 2004 & 53rd geomechanics colloquium, Salzburg.
Hamm SY, Kim M, Cheong JY, Kim JY, Son M, Kim TW (2007) Relationship between hydraulic conductivity and fracture properties estimated from packer tests and borehole data in a granite. Eng Geol 92:73–87
Haregeweyn N, Poesen J, Nyssen J, Verstraeten G, de Vente J, Govers G, Deckers S, Moeyersons J (2005) Specific sediment yield in Tigray-northern Ethiopia: assessment and semi-quantitative modelling. Geomorphology 69:315–331
Helal M, Zainalabideen K (2016) Determination of the safe orientation and dip of a rock slope in an open pit mine in Syria Using kinematic analysis. Alnahrain J Eng Sci 19(1):33–45
Heuer R (1995) A quantitative, empirical and theoretical approach on water flow into tunnels. In Rapid Excavation and Tunneling Conference (18–21). San Francisco: CA.
Hoek E, Bray J (1981) Rock Slope Engineering (3rd ed., pp. 358–372). London: institute of mining and metallurgy
Hoek E, Diederichs MS (2006) Empirical estimation of rock mass modulus. Int J Rock Mech Min Sci 43(2):203–215. https://doi.org/10.1016/j.ijrmms.2005.06.005
Hoek E, Carranza-Torres C, Corkum B (2002) Hoek–Brown failure criterion-2002 edition. In: Proceedings of NARMSTAC 2002, mining innovation and technology, Toronto. University of Toronto, 267–273
Hossain M (2011) Stability analysis of anchored rock slopes against plane failure subjected to surcharge and seismic loads. Retrieved from http://ro.ecu.edu.au/ theses/139 on March 18' 2017
Houlsby AC (1976) Routine interpretation of the Lugeon water test. Q J Eng Geol 9:303–313
Houlsby A (1990). Construction and design of cement grouting: a guide to grouting in rock foundation (2nd ed., pp. 325–336). New York: Wiley
ISRM (1981) Suggested methods for determining hardness and abrasiveness of rocks. In: Brown ET (ed) Rock characterization, testing and monitoring: ISRM suggested Methods. Pergamon, Oxford, pp 95–96
Jing L (2003) A review of techniques, advances and outstanding issues in numerical modelling for rock mechanics and rock engineering. Int J Rock Mech Min Sci 40:283–353
Kanik M, Ersoy H (2019) Evaluation of the engineering geological investigation of the Ayvali dam site (NE Turkey). Arabian Journal of Geosciences 12(3). https://doi.org/10.1007/s12517-019-4243-1
Karagüzel R, Kiliç R (2000) The effect of the alteration degree of ophiolitic melange on permeability and grouting. Eng Geol 57(1–2):1–12
Kiraly L (2002) Karstification and groundwater flow. In: Gabrovsˇek F (ed) Evolution of karst from prekarst to cessation. Zalozba ZRC, Postojna-Ljubljana, pp 155–190
Lee CH, Farmer I (1993) Fluid fow in discontinuous rocks. Chapman & Hall, New York
Li P, Lu W, Long Y, Yang Z, Li J (2008) Seepage analysis in a fractured rock mass: the upper reservoir of Pushihe pumpedstorage power station in China. Eng Geol 97(1–2):53–62
Maerz NH, Zhou W (1999) Multivariate analysis of borehole discontinuity data. Rock Mechanics for Industry, Proceedings of the 37th US Rock Mechanics Symposium, Vail Colorado, June 6–9, 1: 43–438
Mahboubi A, Aminpour M, Noorzad A (2008) Conventional and advanced numerical methods of rock slope stability analysis:a comparison study of Gotvand Dam Right Abutment (Iran)
Makombe G, Kelemework D, Ared D (2007) A comparative analysis of rainfed and irrigated agricultural production in Ethiopia. Irrigation Drainage Syst 21:35–44
Makombe G, Namara R, Hagos F, Awulachew SB, Ayana M, Bossio D (2011) A comparative analysis of the technical efficiency of rain-fed and smallholder irrigation in Ethiopia. International Water Management Institute, Colombo, Sri Lanka, p 37
Marinos P, Hoek E (2000) GSI: a geologically friendly tool for rock mass strength estimation. In: Proceedings of the GeoEng2000 at the international conference on geotechnical and geological engineering, Melbourne. Technomic Publishers, Lancaster, 1422–1446
MoWR (2001) Ethiopian water sector strategy. Addis Ababa, Ethiopia
Mozafari M, Raeisi E, Zare M (2011) Water leakage paths in the Doosti Dam, Turkmenistan and Iran. Environ Earth Sci. https://doi.org/10.1007/s12665-011-1069-x
Nappi M, Esposito L, Piscopo V, Rega G (2005) Hydraulic characterization of some arenaceous rocks of Molise (Southern Italy) through outcropping measurements and Lugeon tests. Eng Geol 81:54–64
Nedaw D, Walraevens K (2009) The positive effect of micro-dams for groundwater enhancement: a case study around Tsinkanet and Rubafeleg area, Tigray, northern Ethiopia. Momona Ethiopian J Sci 1(1):59–73
OWWDSE (2009) Geotechnical investigation report of Arjo Didesa dam site. Unpublished Technical report, Finfine, Ethiopia
Pain A, Kanungo DP, Sarkar S (2014) Rock slope stability assessment using finite element based modelling – examples from the Indian Himalayas. Geomechan Geoeng 9(3):215–230. https://doi.org/10.1080/17486025.2014.883465
Park H, West TR (2001) Development of a probabilistic approach for rock wedge failure. Eng Geol 59(3–4):233–251. https://doi.org/10.1016/S0013-7952(00)00076-4
Pettifer GS, Fookes PG (1994) A revision of the graphical method for assessing the excavatability of rock. Q J Eng Geol Hydrogeol 27:145–164
Quinones-Rozo C (2010) Lugeon test interpretation, Revisited. In: Proceedings of the 30th Annual US society of dams (USSD) Conference Sacramento, California, April 12–16, 2010, 4.5–414
Raghuvanshi T (2019) Plane failure in rock slopes – a review on stability analysis techniques. J King Saud Univ - Sci 31(1):01–109. https://doi.org/10.1016/j.jksus.2017.06.004
Rocscience (2004a) Dips 6.0. http://www.rocscience.com/software/dips. Accessed 20 May 2020
Rocscience (2004b) Rocdata 3.0. http://www.rocscience.com/software/rocdata. Accessed 23 Aug 2020
Sarma S (1979) Stability analysis of embankments and slopes. J Geotech Eng Div 105(12):1511–1524. https://doi.org/10.1061/ajgeb6.0000903
Sharghi Y, Siahkoohi H, Alinia F, Moarefvan P (2010) Estimation of Lugeon number at the abutments of Bakhtyari Dam site using seismic tomography. Aust J Basic Appl Sci 4(2):274–285
Shaz A, Chala ET, Seshagiri Rao K (2019) Rock mass slope stability analysis under static and dynamic conditions in Mumbai. India Lecture Notes Civil Eng 15(December):189–198. https://doi.org/10.1007/978-981-13-0562-7_21
Tang H, Yong R, EzEldin M (2016) Stability analysis of stratified rock slopes with spatially variable strength parameters: the case of Qianjiangping landslide. Bull Eng Geol Environ. https://doi.org/10.1007/s10064-016-0876-4
Uromeihy A, Farrokhi R (2011) Evaluating groutability at the Kamal-Saleh Dam based on Lugeon tests. Bull Eng Geol Environ 71(2):215–219. https://doi.org/10.1007/s10064-011-0382-7

Werfring A (2004) Typology of irrigation in Ethiopia. A thesis submitted to the University of Natural Resources and Applied Life Sciences, Vienna. Institute of Hydraulics and Rural Water Management, in partial fulfillment of the degree of Diplomingeieur.

World Bank (2006) Ethiopia: managing water resources to maximize sustainable growth. A World Bank water resources assistance strategy for Ethiopia. The World Bank Agriculture and Rural Development Department. Report No. 36000-ET. Washington, DC, USA

Wyllie DC, Norrish N (1996) Landslides: investigation and mitigation (pp. 474–504). Transportation Research Board

ZainAlabideen K, Helal M (2016) Determination of the safe orientation and dip of a rock slope in an open pit mine in Syria using kinematic analysis. Al-Nahrain Univ College Eng J (NUCEJ) 91(1):33–45