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Evaluation of stability in rock-fill dams by numerical analysis methods: a case study (Gümüşhane-Midi Dam, Türkiye)

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Abstract. Serious stability issues could arise both during and after construction if the dams' body designs are not realistically accurate. Engineering studies are therefore crucial for identifying the body's instability properties in designing the dam body. In this study, horizontal and vertical displacement and stress-deformation analyses were carried out on the body of the Midi Waste Dam located in Karamustafa Village of Gümüşhane Province. In these analyses, the elasticity modulus and Poisson's ratio of the soil were determined using the seismic method, which is one of the commonly used geophysical methods. The cohesion and internal friction angle of the rock fill were determined by taking into account Leps' charts. The state of the dam body under the influence of the siltation load and seismic load at the end of operation was shown by applying the finite element method. It was found that there was no instability issue with the researched dam because the safety numbers obtained from the stability study of the dam body were greater than the 1.2 safety number accepted for the stability of the dams (SRF: 2.03, SRF: 1.37). The maximum vertical displacement of the dam body at the foundation base was found as 3.78 cm, the horizontal displacement as 5.80 cm, and the total displacement amount as 6.75 cm when the dam body was examined in terms of displacements. In terms of the statics of the dam body, the vertical, horizontal, and total displacements estimated with the numerical analysis methods did not present a problem, and it was demonstrated that this scenario was also supported by the stability of the body in the applied analyses.

Keywords: *waste dam; stability; rockfill; finite element method*

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INTRODUCTION

Dams are large-sized retaining structures built from different materials and in different types. These structures can be used for many different purposes, such as irrigation, drinking water, industrial water use, and the production of electrical energy. In recent years, they have been widely used to collect solid waste and mining waste. Dam bodies are designed for a variety of uses, taking into account a number of engineering factors such as the geotechnical properties of the material to be used in the body, the bearing capacity of the bedrock on which the body will rest, permeability, deformation properties, and the stability of the body. Numerical analysis for a successful dam design can be made by using parameters gathered from geological and geophysical approaches. Shallow subterranean structures, elastic-dynamic parameters, thicknesses, depths, conductivity, seismic velocities, resistivity, fracture-fracture systems, positions of tectonic formations and covered faults, groundwater level, geological foundation, and solid ground depth can all be determined using geophysical and geological methods (Sari *et al*. 2020; Alemdağ *et al*. 2022; Junaid *et al*. 2022). Geophysical approaches should be taken into consideration while planning the numerical analyses of the dam body to avoid elements like severe instability issues and financial losses.

In this study, the end-of-operation siltation load of the dam body and the seismic load effect were assessed. This was done by using the finite element based (FEM) RS2 (Rocscience 2021) computer programme to analyze the horizontal and vertical displacement and perform stress-strain analyses of the Midi Waste Dam body located in Karamustafa Village, Gümüşhane Province. Using the finite element method, stress-strain analyses and analyses of the body's stability were performed while determining the engineering parameters (Poisson's ratio and elastic modulus) and the strength parameters of the fill material (cohesion friction angle) that were obtained from geophysical applications on the dam body.

These stability analysis methods have been widely used by many researchers (Bishop 1955; Bishop, Morgenstern 1960; Morgenstern, Price 1965; Strang, Fix 1973; Sarma 1973; Hughes 1987; Duncan 1996; Yu *et al*. 1998; Kim *et al*. 1999; Griffiths, Lane 1999; Abramson *et al*. 2001; Kim *et al*. 2002; Duncan, Wright 2005; Hammah *et al*. 2006; Li 2007; Gürocak *et al*. 2008; Akgün 2011; Alemdağ *et al*. 2013, 2014, 2015, 2016; Alemdağ 2015; Kaya *et al*. 2016a; Yi *et al*. 2015; Kaya *et al*. 2016b; Alemdağ *et al*. 2019; Hegde, Das 2019; Gupta *et al*. 2020; Dağ *et al*. 2020) in the design of large engineering structures until today.

GEOLOGY AND SEISMICITY OF THE STUDY AREA

Gümüşhane is located in the east of the Pontide-orogenic belt in the northeast Turkey and in the southern zone of the Eastern Pontide tectonic unit, where generally sedimentary rocks outcrop (Taş *et al*. 2003). The study area is located in the southern zone dominated by sedimentary rocks. Units are distinguished from these rocks of distinct age groups, facies, and lithologies in the research region, where Palaeozoic, Mesozoic, and Cenozoic rocks outcrop, on the basis of the lithostratigraphic unit (Fig. 1).

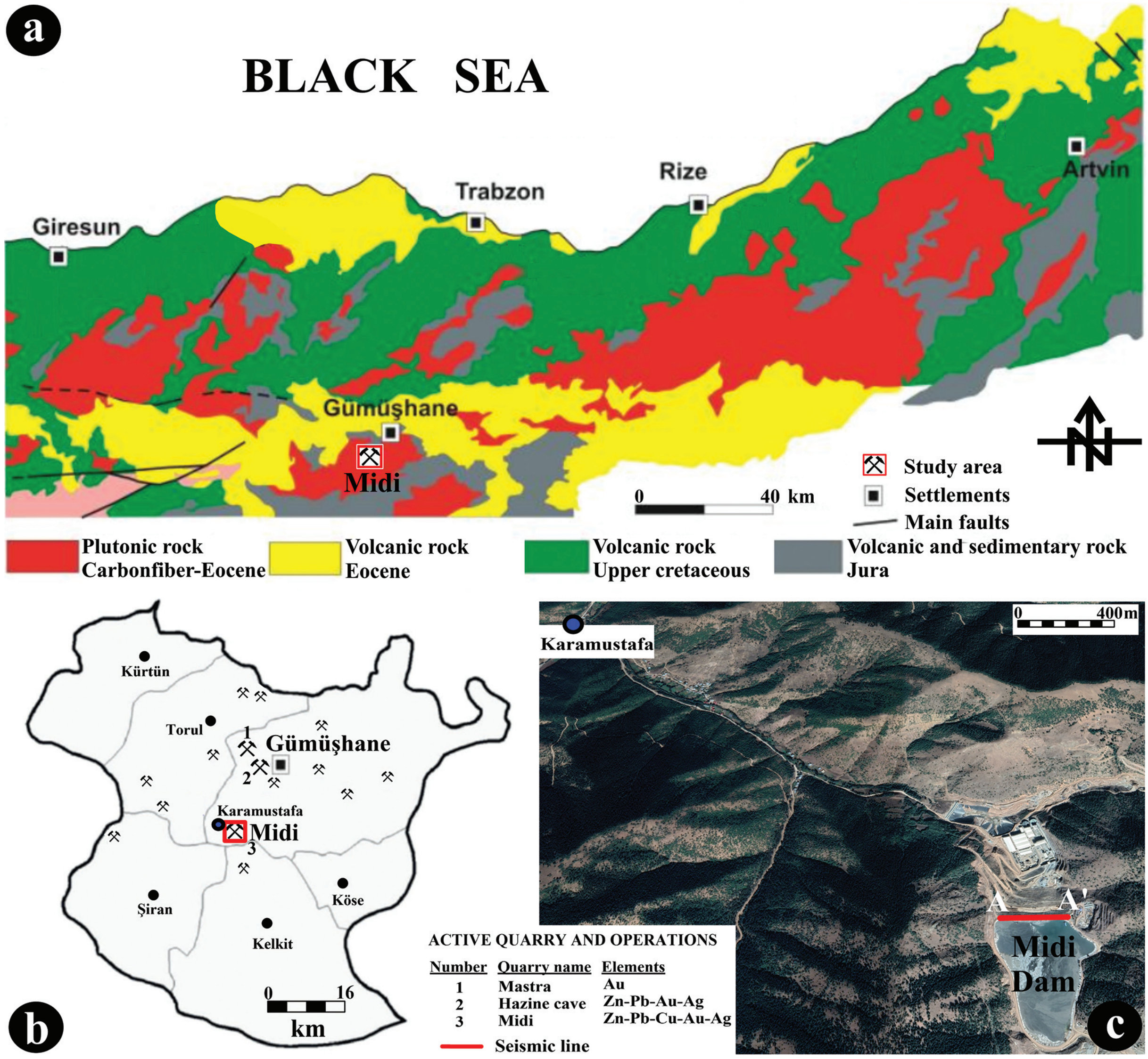

Fig. 1 (a) Simplified geology of the Eastern Pontides, modified from Akbulut (2020); (b) active quarry and operation areas, modified from Cihan *et al.* (2016); (c) A-A' geophysical line (seismic) taken on Midi Dam body

Rock units of different ages and lithologies are observed in the study area and its immediate surroundings. These are from the oldest to the youngest; Gümüşhane granite, Hamurkesen (Zimonköy) formation, Berdiga formation, Mescitli formation, dykes and alluvium (Fig. 2).

There are no fault lines with substantial activity in Gümüşhane, one of Türkiye's least seismically active and tectonically active places. However, due to its proximity to the North Anatolian Fault Zone (NAFZ), one of Turkey's most active strike-slip fault zones that passes about 80 km to the south, this zone has the potential to be affected by any significant earthquakes that may occur on this zone (Öztürk 2017). The main tectonic structure for Gümüşhane and its surroundings is modified from Şaroğlu *et al*. (1992) and Bozkurt (2001).The duration magnitude, Md, provides a measure of the earthquake's size. The star symbol indicates earthquakes with Md > 5.0 between 1970 and 2022 (Fig. 3). When historical earthquake statistics are compared to current earthquake statistics, it becomes clear that Gümüşhane's borders do not have a large earthquake potential. The NAFZ in Şiran, Kelkit, Köse, Bayburt, and Erzincan is associated with many fault segments and fault zones. The fault segments, basins, and fault zones identified in this study include the Kelkit Fault segment (KLFS), Kelkit basin (KLB), Bayburt basin (BYB), Kelkit-Çoruh Fault zone (KÇFZ), Akdağ-Çayırlı Fault zone (AÇFZ), Tercan-Aşkale Fault zone (TAFZ), and Dağyolu fault (DYF). The KÇFZ has a length of approximately 600 kilometres and is characterized by a left-lateral strike-slip fault configuration.

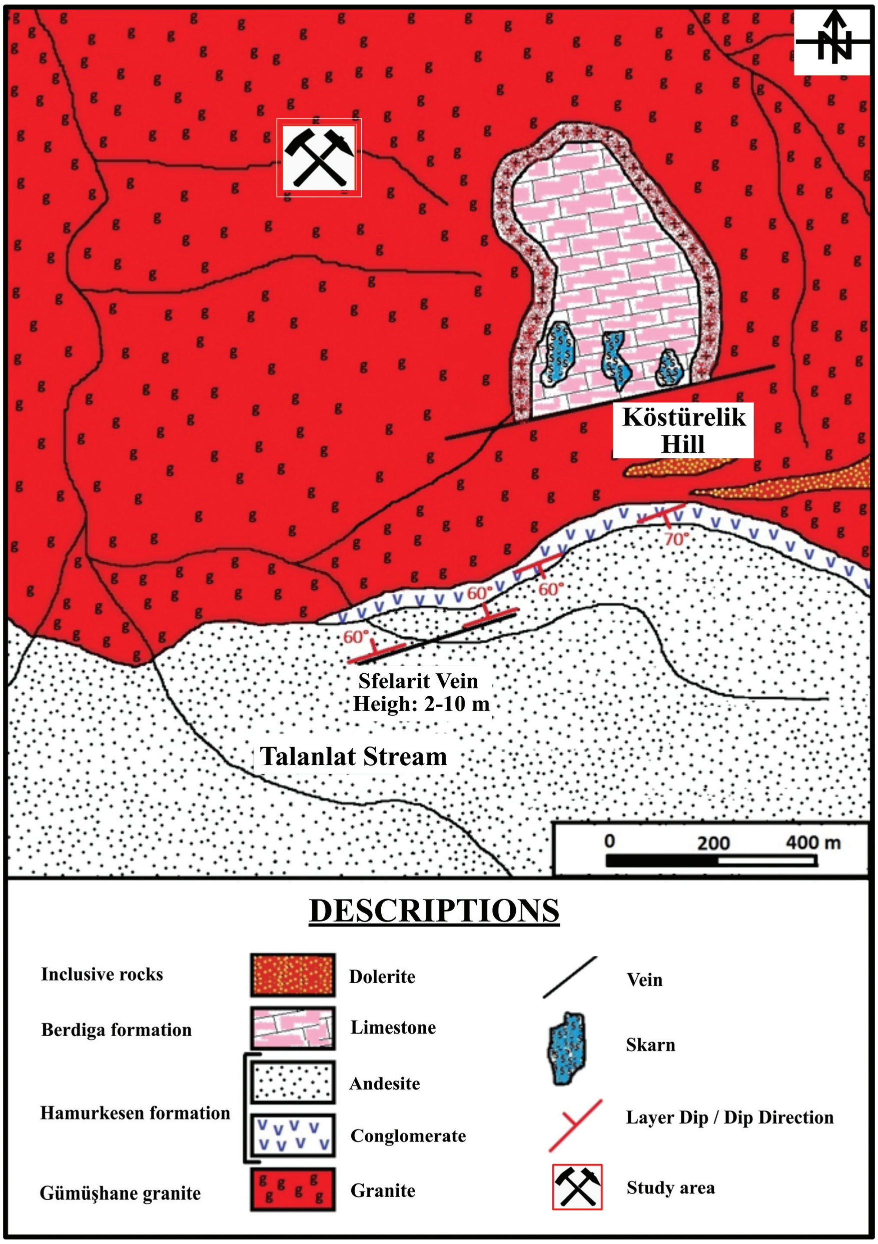

Fig. 2 Study area geological map, modified from Lermi (2003)

GEOPHYSICAL INVESTIGATION

Seismic Refraction Tomography (SRT) and Multi-Channel Surface Wave (MASW) measurements were taken in 3 profiles, coinciding with the dam body of the Midi Dam (Fig. 4). In the measurements taken by scrolling consecutively, V_p and V_s velocity information was obtained from a total distance of 226 m and a depth of 30 m. A 24-channel seismograph of the Geometrics brand, vertical component receivers operating at 4.5 Hz, an 8 kg sledgehammer, and an iron plate with a 25 cm radius were utilized to collect the data. In order to increase the signal/noise ratio of the seismic signal at each firing point, 4 vertical stacks were made.

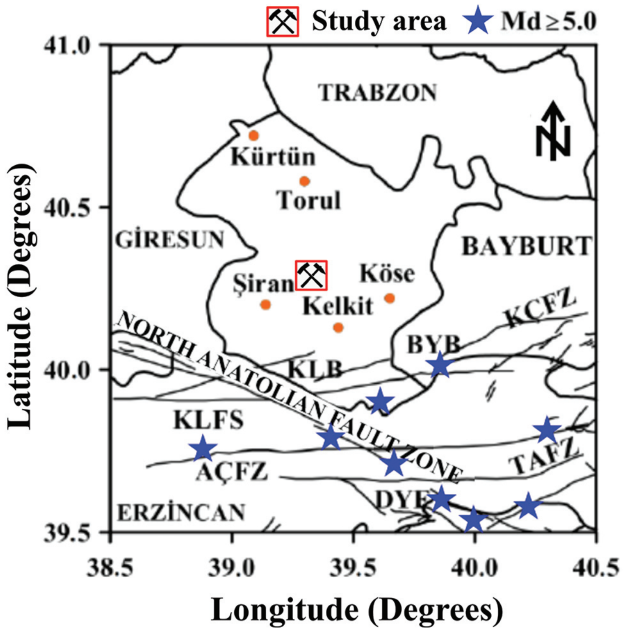

Fig. 3 The main tectonic structure for Gümüşhane and its surroundings, modified from Şaroğlu *et al*. (1992), Bozkurt (2001) and Öztürk (2017)

The sampling interval (0.250 ms, 0.5 ms), recording time (0.5s, 1s) and offset interval (3 m, 9 m) were taken for SRT and MASW data, respectively. In order to evaluate the SRT data with the first arrival tomography, a total of 15 shots were taken from the beginning, end, middle and intermediate shots of the profile. No filters were used during data collection.

SRT and MASW data were evaluated with the Seisimager programme. The two-dimensional seismic velocity depth section of the shallow underground structure was created by an inversion technique in the computer environment for the SRT analysis after the first arrival times were accurately peaked. The A-A' profile was obtained by combining the inversion values obtained from three profiles using the Surfer programme (Fig. 5). In the MASW analysis, the one-dimensional S-wave velocity values that varied with the depth of the subsurface were acquired. The phase velocity and dispersion curve were established by frequency-wave number analysis.

Fig. 4 Location of seismic profiles and images from the study area

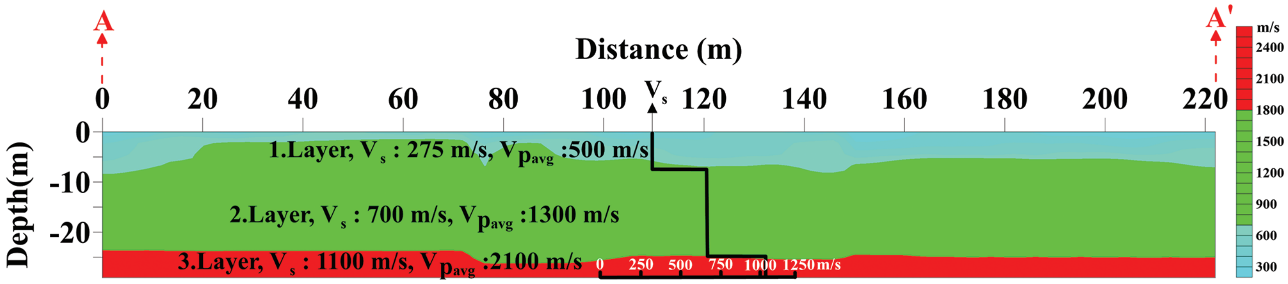

Fig.5 Two-dimensional SRT velocity-depth section

Table 1 V_p and V_s wave velocities and dynamic elastic parameters of rock fill material in the dam body

Line	Layer number	Depth (m)	V_p (m/s)	V_s (m/s)	E (kg/cm²)	Poisson's Ratio (υ)
A-A¹	1	8	500	275	2840.6	0.28
	2	16	1300	700	23602.5	0.30
	3	5	2100	1100	66473.5	0.31

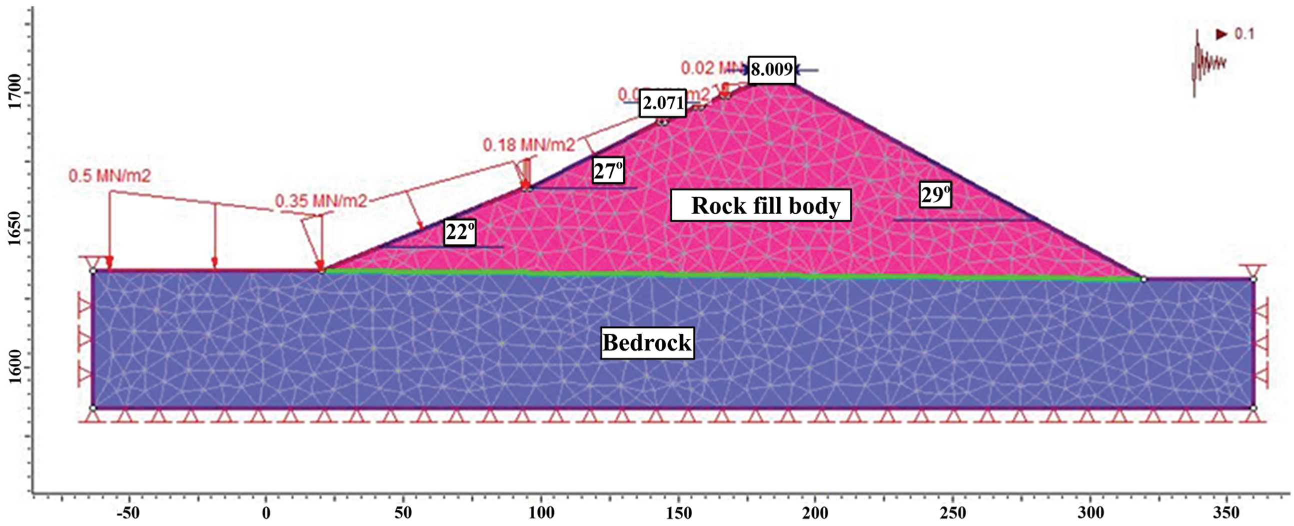

Fig. 6 Finite element triangle mesh model of dam body

Table 2 Technical information of Midi Waste Dam

Dam elevation		
Upstream slope	1635–1665 m	1D/2.5Y (22°)
	1665–1705 m	1D/2Y (27°)
Downstream slope	1635–1705 m	1D/1.8Y (29°)
Dam height (from foundation)	70 m	
Dam crest elevation	1705 m	

Dynamic elasticity modulus (E_{dyn}) and dynamic Poisson's ratio (ν_{dyn}) values were determined using the V_p and V_s velocities of the layers in each profile and Bowles (1988) equations 1, 2, and 3 (Table 1). The density value was determined with the help of 4 empirical equations proposed by Keçeli (2012):

$$\upsilon_{dyn} = (V_p^2 - 2V_s^2) / 2(V_p^2 - V_s^2), \quad (1)$$

$$E_{dyn} = \mu\,(3V_p^2 - 4V_s^2) / (V_p^2 - V_s^2), \quad (2)$$

$$\mu = \rho\, V_s^2 / 100, \quad (3)$$

$$\rho = 0.44 V_s^{0.25}, \quad (4)$$

where V_p – longitudinal wave velocity (m/s), V_s – transverse wave velocity (m/s), ρ – density (gr/cm³), υ – Poisson's ratio, μ – shear modulus (kg/cm²), and E_m – the modulus of elasticity (kg/cm²).

STABILITY ANALYSIS

In this study, the finite element mesh system of the dam body obtained by using the technical information of the Midi Dam (Table 2) was created (Fig. 6). Using the finite element approach, stress-strain analyses and body stability analyses were performed while taking into consideration the parameters learned from laboratory research and the information gathered from geophysical applications (SRT and MASW) on the dam body. These analyses are calculated using the computer programme Slide v5.0 (Rocscience 2003) for both seismic and siltation loads under the influence of siltation load.

Evaluation of stress-strain and displacement by numerical analysis method

In this method, using the finite element based (FEM) RS2 computer programme, first of all, the stability of the body under the effect of seismic load and siltation load that will occur in case the reservoir area of the dam body is full was evaluated (Figs 7 and 8). Then, the vertical, horizontal and total displacements that may occur in the dam body, both the full reservoir area (siltation load) situation (Figs 9, 10 and 11) and the situation under the effect of siltation load and seismic load (operation end) were evaluated (Figs 12, 13 and 14). A four-node quadrilateral mesh system is selected as finite elements, and mesh type is entered as uniform and the number of elements as 500. The

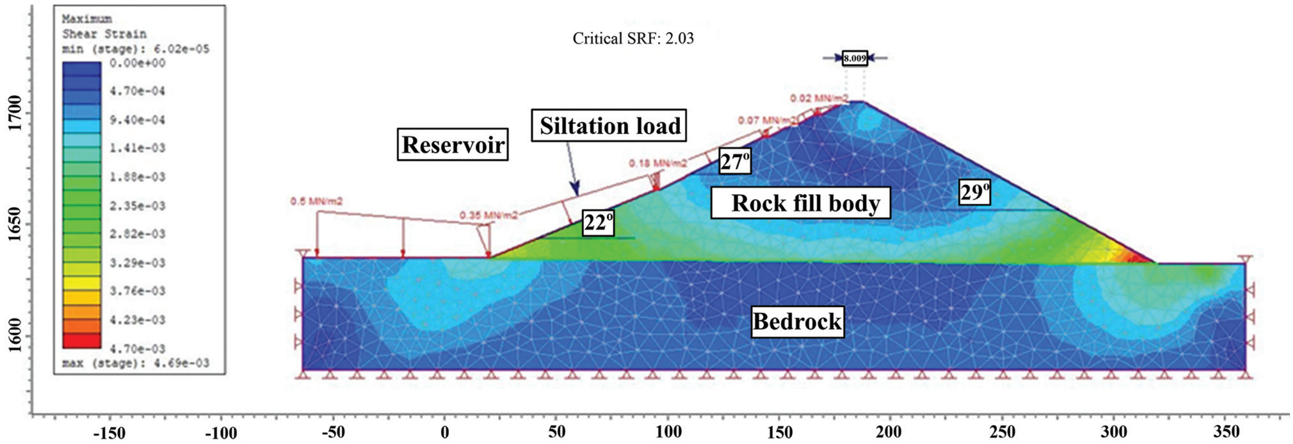

Fig. 7 Evaluation of Midi Dam body stability by FEM-SSR method (full reservoir condition)

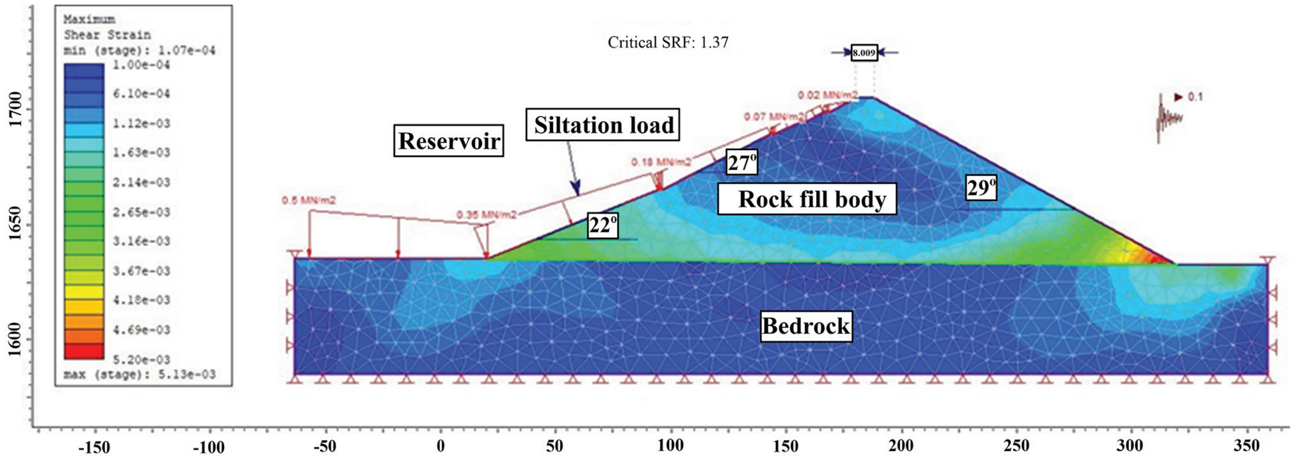

Fig. 8 Evaluation of Midi Dam body stability by FEM-SSR method (seismic load and siltation load)

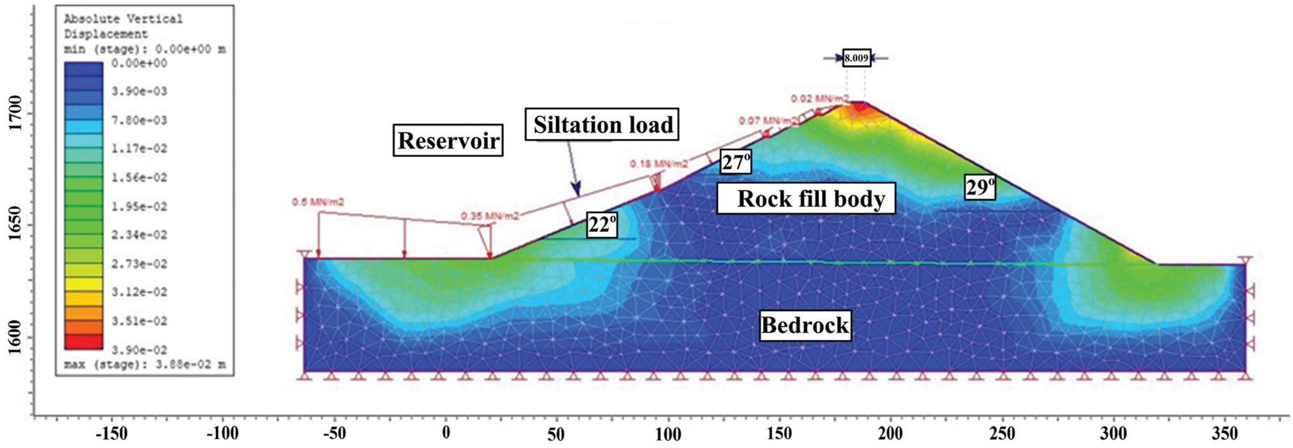

Fig. 9 Evaluation of Midi Dam body vertical displacement for full reservoir (siltation load) condition

parameters used in the analyses are summarized in Table 3, and the dynamic deformation modulus (E_m) and Poisson's ratio (ν) values were determined using the V_p and V_s velocity values obtained from geophysical methods. Leps' charts were used to determine the internal friction angle values used in the stability analysis according to the characteristics of the rock fill used in the dam body (Leps 1970).

The FEM was used to determine the dam behaviour by accepting the plane strain conditions of the Midi Dam body and the andesite bedrock on which the body will sit. The stability of the dam body under the effect of siltation load and end-of-operation seismic load, as well as siltation load was examined (Figs 7 and 8), and the determined safety numbers (SRF) were calculated as, respectively, SRF: 2.03

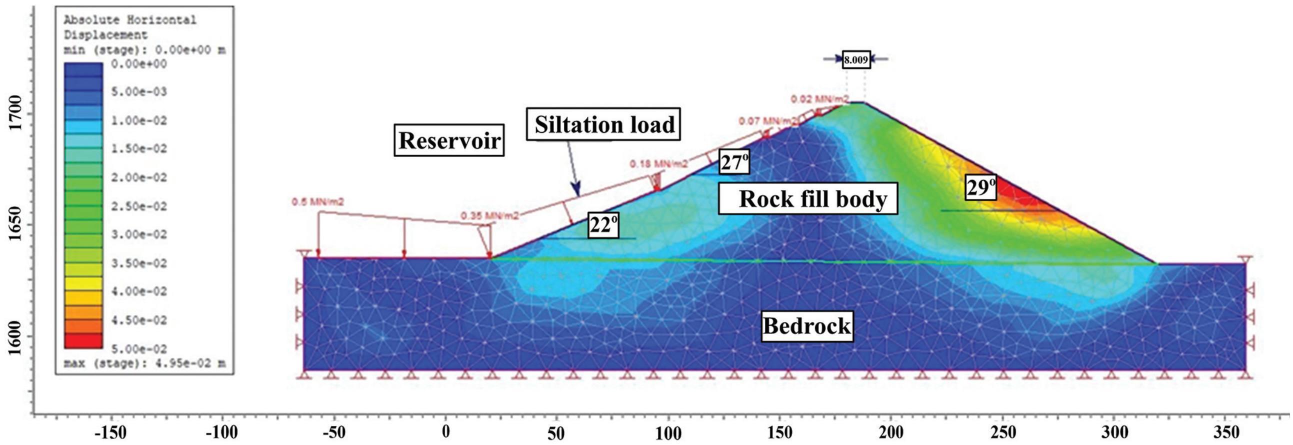

Fig. 10 Evaluation of Midi Dam body horizontal displacement for full reservoir (siltation load) condition

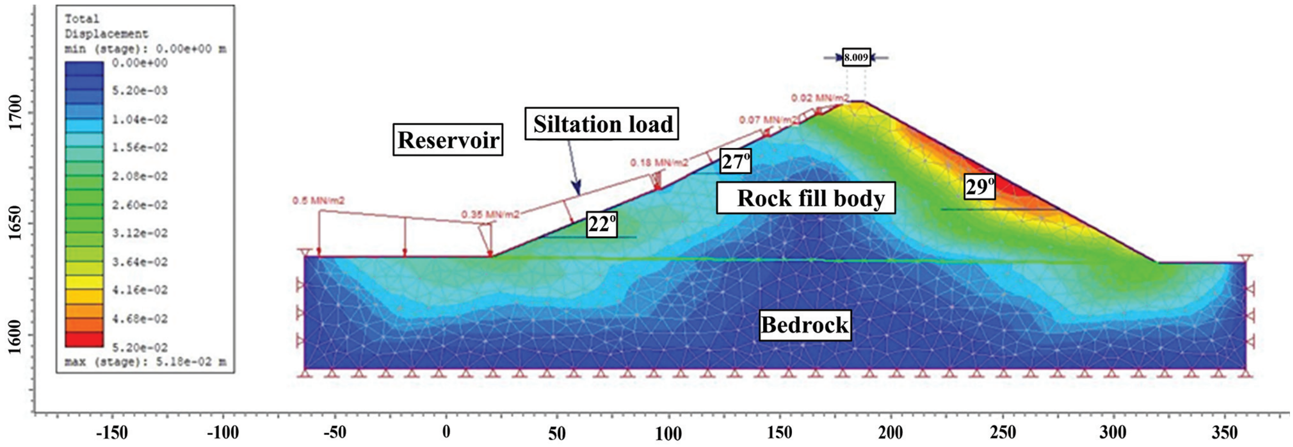

Fig. 11 Evaluation of Midi Dam body total displacement for full reservoir (siltation load) condition

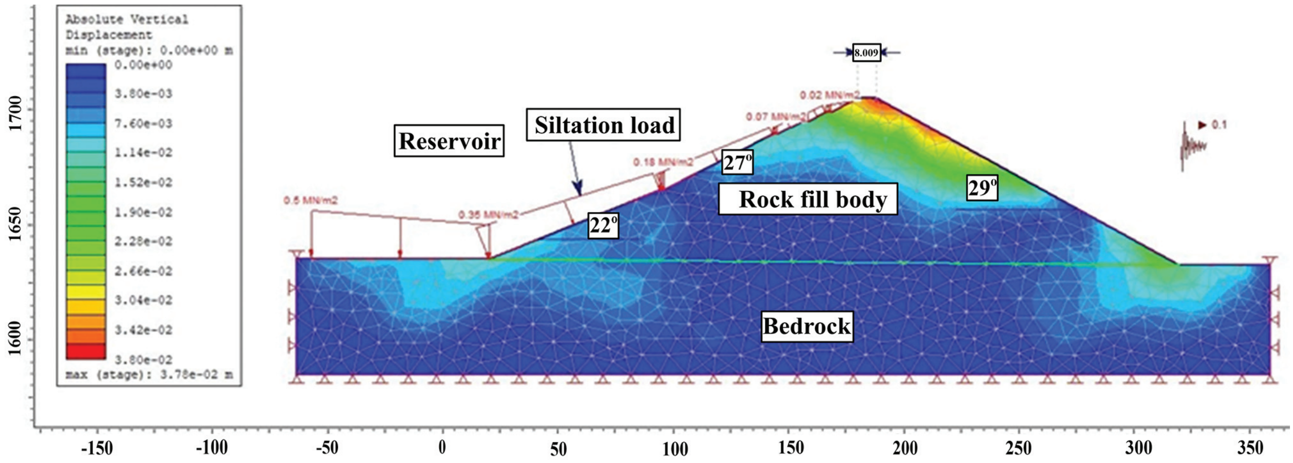

Fig. 12 FEM assessment for vertical displacement of Midi Dam body under the effect of siltation and seismic load

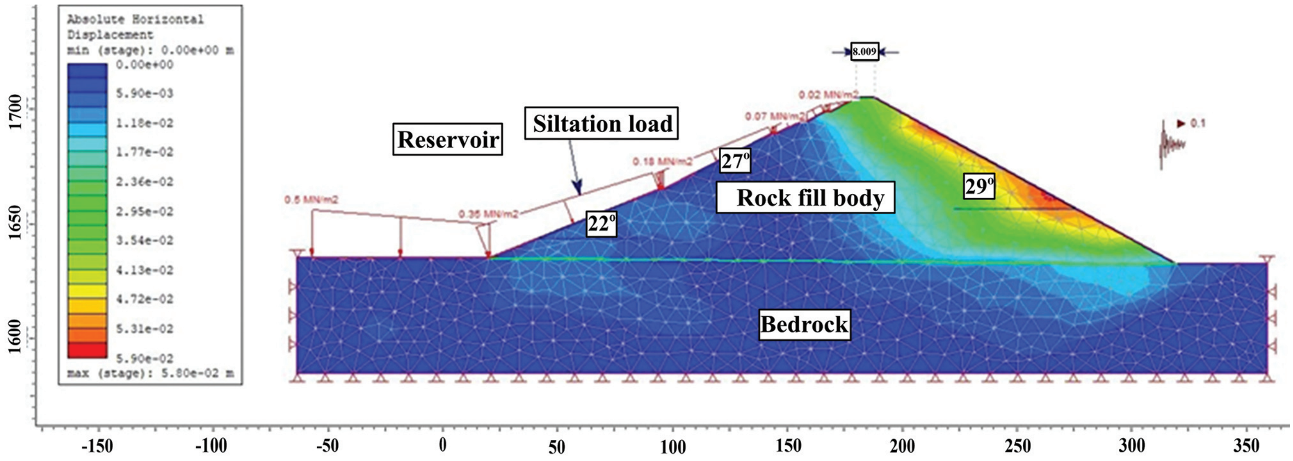

Fig. 13 FEM assessment for horizontal displacement of Midi Dam body under the effect of siltation and seismic load

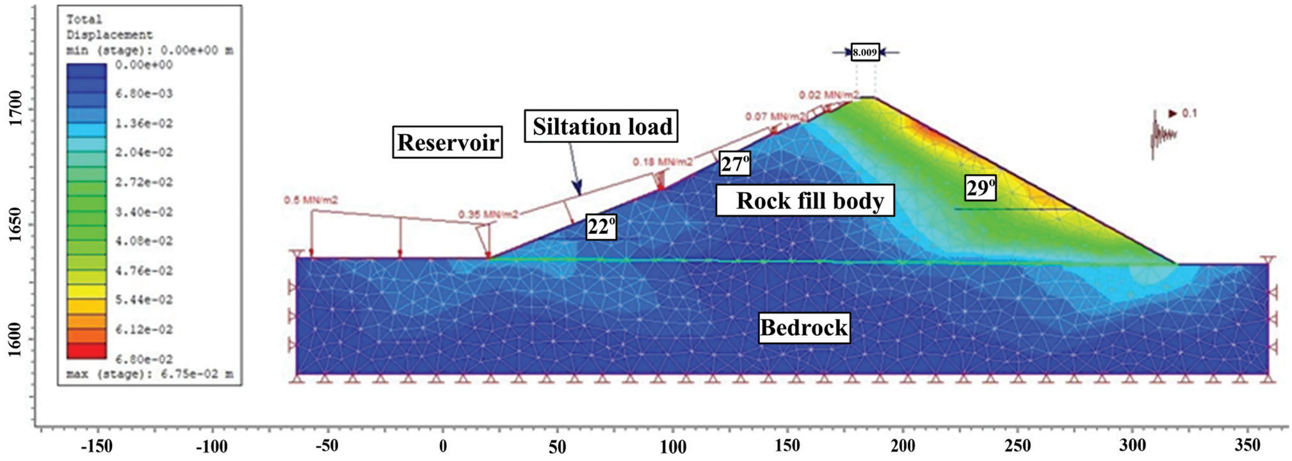

Fig. 14 FEM assessment of Midi Dam body total displacement under the effect of siltation and seismic load

Table 3 Parameters used in the FEM

Material name	Material colour	Initial element loading	Unit weight (MN/m^3)	Elastic type	Poisson's ratio	Young's modulus (MPa)	Use residual Young's modulus	Failure criterion	Material type	Peak tensile strength (MPa)	Peak friction angle (degrees)	Peak cohesion (MPa)	Residual tensile strength (MPa)	Residual friction angle (degrees)
Rock Fill	🟥	Field Stress and Body Force	0.021	Isotropic	0.3	2360	No	Mohr Coulomb	Plastic	0	39	0	0	39
Bedrock	🟦	Field Stress and Body Force	0.023	Isotropic	0.32	6647	No	Mohr Coulomb	Plastic	0	42	0	0	42

Table 4 Accepted safety values for stability of dam body, upstream and downstream slopes

Operating status	Dam body	Upstream cofferdam	Downstream cofferdam
End of construction, earthquake free	> 1.5	> 1.2	> 1.2
End of construction, earthquake (a:0.1 g)	> 1.0	> 1.0	> 1.0
Operating status, earthquake free	> 1.5	> 1.2	–
Operating status, earthquake (a:0.1 g)		> 1.0	–
Operating status, earthquake (a:0.16 g)	>1.0	–	–

and SRF: 1.37. Comparisons were made between the safety numbers established for the Midi Dam and those established by the State Hydraulic Works (DSI) for the dams which are thought to be stable (Table 4). The fact that the SRF determined as a result of the compared analysis is greater than the 1.2 safety number accepted for the stability of the dams indicates that there will be no instability problems for the Midi Dam under study.

As a result of the vertical, horizontal, and total displacement analyses for the end-of-operation situation, in the stress-strain analysis performed under the end-of-operation siltation load and seismic loads in the Midi Dam body, the maximum vertical displacement of the dam body at the base of the foundation under the effect of siltation load was 3.88 cm, the horizontal displacement was 4.95 cm, and the total displacement was 5.18 cm (Figs 9, 10 and 11). The maximum vertical displacement, horizontal displacement, and total displacement of the dam body at the base of the foundation were calculated using seismic load and siltation load and were found to be 3.78 cm, 5.80 cm, and 6.75 cm, respectively (Figs 12, 13 and 14).

DISCUSSION

Upon reviewing the existing literature, it is evident that previous studies predominantly assessed the stability of embankment dam bodies through the utilization of limit equilibrium assessments (Lam, Fredlund 1993; Duncan 1996; Shivamanth *et al*. 2015; Wu *et al*. 2020; Gordan *et al*. 2022). In order to conduct these assessments, engineers are required to assess the strength properties of the materials used in the dam, which encompass cohesion, internal friction angle, and other pertinent variables. This study facilitated a more detailed analysis of the stability and deformations of the dam body compared to previous investigations. This was achieved by using seismic data, which are geophysical methods, to determine the elasticity modulus and Poisson's ratio. The inclusion of these measurements inside the research region contributed to an enhanced level of reliability in the study.

CONCLUSIONS

Stress-strain analyses and body stability analyses were carried out using the finite element method, taking into account the data obtained from geophysical applications (SRT and MASW) on the Midi Dam body and the parameters obtained from laboratory studies. As a result of these analyses:

- The safety numbers determined as a result of the stability analysis of the dam body were SRF: **2.03** and SRF: **1.37**, and since it is higher than the 1.2 safety number accepted for the stability of the dams, no instability problem is expected in the dam under investigation.
- When the dam body was examined in terms of displacements, in the vertical, horizontal and total displacement analyses using seismic load and siltation load, the maximum vertical displacement (settlement amount) of the dam body at the foundation base was **3.78** cm, horizontal displacement was **5.80** cm and the total displacement amount was **6.75** cm. Vertical, horizontal and total displacements determined by numerical analysis methods did not pose a problem in terms of the statics of the dam body, and it was concluded that this situation was also supported by the stability of the body in the analyses made.
- In order to accurately assess the stability and deformation of rock-fill dams, it is advisable to employ geophysical techniques that offer the advantages of on-site measurements and cost-effectiveness. These approaches can provide a valuable assistance in conducting studies aimed at determining the stability of such dams.

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