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ORIGINAL PAPER

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STABILITY ANALYSIS OF MAMAK DAM BEHAVIOUR UNDER VARIOUS WATER LEVELS IN THE RESERVOIR

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ABSTRACT

A dam is an engineered construction designed to store water primarily for human needs. When a dam fails, it has the potential to become a substantial disaster. Some primary causes of dam failure are excessive water leakage, landslides and earthquakes. In general, the current performance evaluation of the Mamak Dam falls into the “fairly good” category, even in the aftermath of the earthquake event with a magnitude of 6.5 Mw in 2018. In this study, the dam’s stability is analysed under seismic events, rapid drawdown and maximum daily rainfall infiltration. It is concluded that the upstream and downstream slopes were generally found to be safe in all design situations. Nevertheless, the impact of the maximum design earthquake (MDE) is notable in both pseudo-static and dynamic analyses, causing a reduction of over 50% in the factor of safety (FoS) – ultimately falling below the minimum safety threshold. Conversely, the operating basis earthquake (OBE) has a relatively minor effect on the FoS.

Keywords: dam stability, pseudo-static analysis, dynamic analysis, maximum design earthquake, MDE

INTRODUCTION

Apart from being a crucial resource to meet human needs, dams also have the potential to cause significant disasters if they fail (International Commission on Large Dams [ICOLD], 2019). A dam collapse can lead to devastating flash floods, resulting in extensive losses such as loss of lives, property, infrastructure and environmental devastation (Utepov et al., 2022). A study by the Indonesian Dam Safety Commission on 122 embankment dams revealed that 20% are considered at risk. Among these vulnerable dams, 59% have been in operation for over 25 years, while the remaining 41% are younger than 25 years (Komisi Keamanan Bendungan [KKB], 2020).

The Indonesian Agency for Meteorology, Climatology, and Geophysics have documented a long history of frequent and devastating earthquakes with a magnitude exceeding 6 Mw on Sumbawa Island from 1821 to 2021 (Badan Meteorologi Klimatologi dan Geofisika [BMKG], 2021). These seismic events have had severe consequences, leading to significant loss of life and extensive damage to infrastructure (Adi Kurniawan, Suarbawa & Septiadhi, 2017). Therefore, it is crucial to conduct a thorough seismic hazard analysis of Sumbawa Island to proactively address potential damages (Santoso & Agustawijaya, 2020). This study aims

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to evaluate dam stability during earthquakes and recommend measures if stability or water leakage becomes a concern. The analysis of dam stability includes operating basis earthquake (OBE) and maximum design earthquake (MDE), rapid drawdown and maximum daily rainfall intensity.

LITERATURE REVIEW

Pseudo-static analysis

This analysis emulates the effects of an earthquake's shaking by introducing an acceleration force that generates inertial forces. These inertial forces, which exert significant influence on the stability of embankment slopes, operate in both horizontal F_h and vertical F_v directions, acting at the centre of each segment. These forces are described as (Himanshu & Burman, 2019):

$$F_h = \left(\frac{a_h W}{\mathrm{g}} \right) = k_h W, \tag{1}$$

$$F_v = \left(\frac{a_v W}{\mathrm{g}} \right) = k_v W, \tag{2}$$

where:
F_h – inertial force in horizontal direction [N],
F_v – inertial force in vertical direction [N],
a_h – horizontal pseudo-static acceleration [m·s^{-2}],
a_v – vertical pseudo-static acceleration [m·s^{-2}],
W – weight of the slice [kg],
g – constant gravitational acceleration [m·s^{-2}],
k_h – horizontal seismic coefficient [-],
k_v – vertical seismic coefficient [-].

When seismic loading is taken into account, the determination of S_{res} and S_{mob} can be carried out in the following manner

$$S_{\mathrm{res}} = c' + \left(N - \mu - F_h \cos\alpha \right) \tan\phi', \tag{3}$$

$$S_{\mathrm{mob}} = W \sin\alpha + F_h \cos\alpha, \tag{4}$$

where:
S_{res} – seismic resistance coefficient [-],
S_{mob} – seismic mobilised load coefficient [-],
c' – effective soil cohesion [-],
N – number calculated as W multiplied by the cosine of α,
μ – pore water pressure [kPa],
α – inclination of the base [°],
ϕ' – effective frictional angle [°].

Dynamic analysis

Many geotechnical engineering problems – like those related to structures such as retaining walls, tunnels, earth dams, and embankments – are typically analysed using two-dimensional dynamic simulations utilising the finite element method (FEM). The equation describing the motion of elements is provided as follows:

$$[M]\{\ddot{U}\}+[C]\{\dot{U}\}+[K]\{U\}=\{R(t)\}, \tag{5}$$

where:
$[M]$ – mass matrix,
$[C]$ – damping matrix,
$[U]$ – axial displacement of nodal points within the model,
$[K]$ – stiffness matrix, including the material and geometric nonlinearities,
$\{R(t)\}$ – axial forces acting on the model's points.

The Newmark step-by-step method is a contemporary approach employed for solving motion equations, particularly in the context of dynamic seismic analysis. This method was first introduced by Newmark in 1965. It involves calculating displacement and velocity through the utilization of the following equations:

$$u_{t+\Delta t}=u_t+\dot{u}_t\Delta t+\left[\left(\frac{1}{2}-\alpha\right)\ddot{u}+\alpha\ddot{u}_{t+\Delta t}\right]\Delta t^2, \tag{6}$$

$$\dot{u}_{t+\Delta t}=\dot{u}_t+\left[\left(1-\beta\right)\ddot{u}_t+\beta\ddot{u}_{t+\Delta t}\right]\Delta t, \tag{7}$$

where:
u_t – displacement vector at time t,
$\dot{u}_t$ – velocity vector at time t,
$\ddot{u}_t$ – acceleration vector at time t.

The stability of the solution in accordance with the implicit Newmark scheme (as outlined by Hu in 1997) relies on certain parameters. These parameters, namely Δt (representing the time increment) and α and β (acting as control parameters for numerical accuracy), must conform to specific conditions to ensure a stable solution. Such a condition is:

$$\beta\geq 0.5;\ \alpha\geq 0.25\left(0.5+\beta\right)^2. \tag{8}$$

In the conventional Lagrange's method, as described by Chaudhary and Bathe in 1986, setting β to 0.5 yields satisfactory results in the calculations. The average acceleration method is also employed alongside Newmark's method to solve the motion equations.

To prevent undesired wave reflections at the model boundaries, it is necessary to lay down specific boundary conditions. These conditions are established following the principles of the Lysmer–Kohlmeyer's model, which dictates the computation of the normal stress and shear stress absorbed by a damper as outlined as follows (Brinkgreve & Vermeer, 1998).

$$\sigma_n=-c_1\rho V_P\dot{u}_x, \tag{9}$$

$$\tau=-c_2\rho V_S\dot{u}_y, \tag{10}$$

where:
σ_n – normal stress [N·m^{-2}],
c_1 – relaxation coefficient employed to enhance wave absorption in the normal direction at the boundary [-],
ρ – mass density [kg·m^{-3}],

V_P – longitudinal wave velocity [m·s^{-1}],
$\dot{u}_x$ – particle motion velocity in the x direction [m·s^{-1}],
τ – shear stress [Pa],
c_2 – relaxation coefficient employed to enhance wave absorption in the tangential direction at the boundary [-],
V_S – shear wave velocity [km·s^{-1}],
$\dot{u}_y$ – particle motion velocity in the y direction [m·s^{-1}].

Determination of seismic load

The process of establishing the design earthquake magnitude for earth dams includes evaluating the safety risk factor based on ICOLD (2018) and the Indonesian guidelines for stability analysis of earth-fill dams under seismic loads (Department of Human Settlements and Regional Infrastructure, 2004). According to the provided description, the weight factor is determined to assess the total risk factor (Fr_{tot}) as indicated in Table 1.

Considering the risk class, the Mamak Dam is designated with an OBE with a return period of 100–200 years and a MDE with a return period of 10,000 years. The earthquake coefficient method is employed for analysis. The analysis procedure follows the Indonesian Guidelines for stability analysis of earth-fill dams due to seismic loads (Department of Human Settlements and Regional Infrastructure, 2004).

Modified earthquake coefficients by Indonesia seismic hazard map

In the analysis of earthquake coefficients using the 2017 Indonesian earthquake zone map, the process involves determining earthquake acceleration at the base rock by considering dam location and frequency. For the Mamak Dam with acid tuff and welded tuff (hard rock), the site class coefficient (F_{PGA}) is equal to 0.8. A summary of the horizontal and vertical modified earthquake coefficients is shown in Table 2.

Table 1. Dam safety evaluation criteria for risk factor

Risk impact	Weight factor	Risk class/Importance	
Reservoir capacity (ML×10^3)	4	60 > C > 2.0	high
Dam height [m]	5	500 < L < 2 000	high and strong importance
Evacuation requirements – number of persons (amended as per Reference 3)	12	no emergency action plan (12)	extreme importance
Potential downstream damage (to existing structures)	13	major national highway/interstate//power station	high and strong importance
Availability of construction and maintenance records	3	no procedures	extreme importance
Availability of processed instrumentation and surveillance records	3	no data	extreme importance
Level of effort extended in previous safety evaluations	2.5	reports submitted irregularly	high and strong importance
New or future downstream development	0.5	local planning in place	equal importance
Flood capacity-related deficiencies	2	concrete gravity	moderate importance
Static stability-related deficiencies	6	active surface seepage	moderate importance
Earthquake resistance-related deficiencies	8	peak ground acceleration beyond 0.25 g and no fault within 10 km	high
Total score (Fr_{tot})		59	
Risk class of the Mamak Dam		(111) high	

Source: PT. Virama Karya (2020).

Table 2. Summary of horizontal seismic coefficient (k_h) and vertical seismic coefficient (k_v)

Return period (T) [s]	$y = 0.25\ h$		$y = 0.5\ h$		$y = 0.75\ h$		$y = h$	
	k_h	k_v	k_h	k_v	k_h	k_v	k_h	k_v
200	0.204	0.082	0.170	0.068	0.155	0.062	0.140	0.056
10 000	0.571	0.228	0.476	0.190	0.434	0.174	0.392	0.157

Source: Halim (2023).

CHARACTERISTICS OF THE MAMAK DAM

The Mamak Dam was constructed in 1990 in Mamak Village, Sumbawa Island, Indonesia, at coordinates 117°34′42″ East and 8°41′29.2″ South. The Mamak Dam serves multiple functions, including hydropower generation, irrigation, and local water supply. The Mamak Dam has four embankments – namely, the main dam, Saddle Dam-1, Saddle Dam-2 and Saddle Dam-3 (Fig. 1). The Mamak Dam is composed of several essential elements – the impervious core (constructed from earth fill), filter layer, transition layer, random rock, selected rock and rock fill (Fig. 2).

Fig. 1. Bird's view of the Mamak Dam

Source: PT. Raya Konsult (2022a).

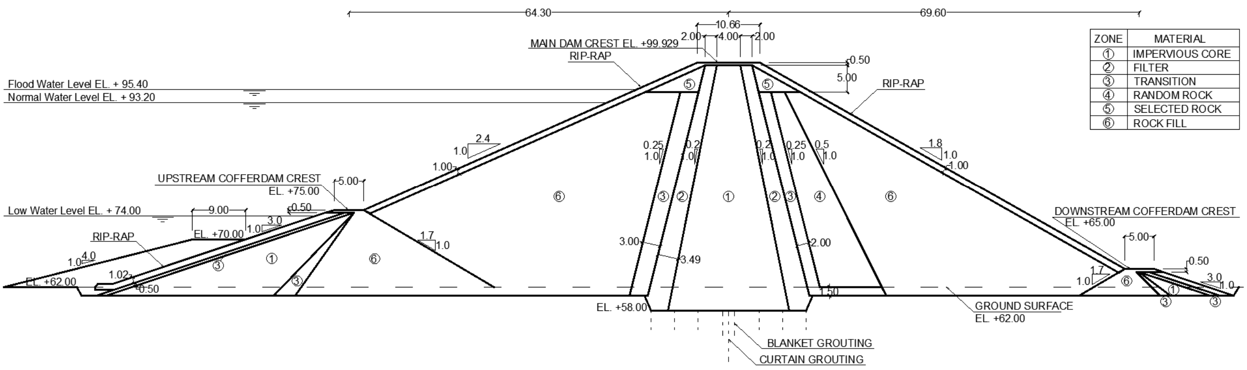

Fig. 2. Cross-section A–A of the Mamak main dam

Source: Halim (2023).

The Mamak Dam covers a catchment area of 108 km^2. When at full water level (FWL), it can hold 29.839 million m^3 of water, with a live storage capacity of 27.671 million m^3, along with a dead storage capacity of 2.167 million m^3. At flood water level (FWL), the water spread area is 2.357 km^2. Key water level benchmarks include FWL at elevation +95.40 m, normal water level (NWL) at elevation +93.43 m and low water level (LWL) at elevation +74.00 m. The deepest bed level is recorded at elevation +58.00 m. The main dam, along with its cofferdams, reaches a height of 36.959 m, with a crest level of elevation +99.93 m, extending over a length of 203.01 m and a crest width of 10.66 m. Additional saddle dams are Saddle Dam-1 (33.929 m tall, crest level elevation +99.93 m, 205.394 m long, crest width 10.245 m), Saddle Dam-2 (10.929 m tall, crest level elevation +99.56 m, 54.611 m long, crest width 9.832 m) and Saddle Dam-3 (16.538 m tall, crest level elevation +99.80 m, 85.986 m long, crest width 10.154 m), as detailed by PT. Raya Konsult (2022b).

Earthquake records in the Mamak Dam

In seismic analysis, two distinct ground acceleration time histories specific to the location are utilised (Fig. 3). The maximum ground acceleration in the horizontal (x) and vertical (y) directions are 0.550 times the acceleration due to gravity (0.550 g) and 0.363 times the acceleration due to gravity (0.363 g), respectively.

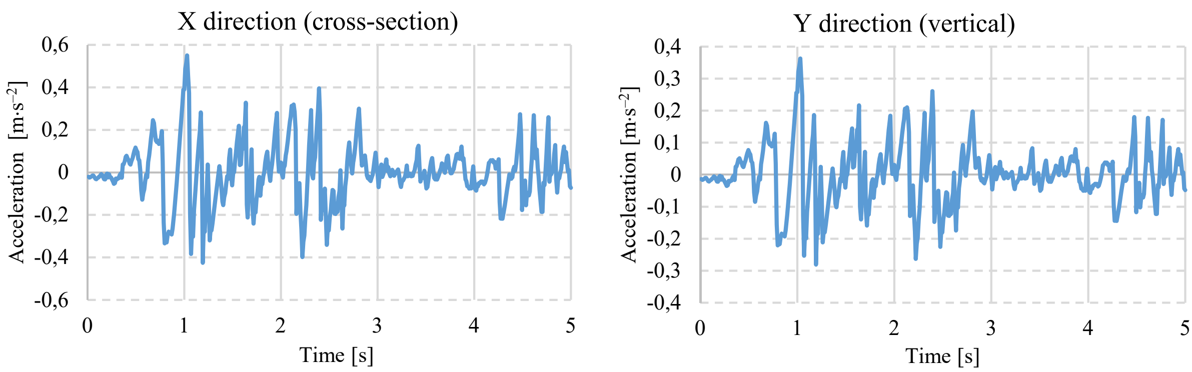

Fig. 3. Accelerometer used in dynamic analysis of the Mamak Dam

Source: PT. Raya Konsult (2022c).

Rainfall intensity in the Mamak Dam area

In order to investigate the effect of any climatic changes on the slope stability of the Mamak Dam, the maximum average daily rainfall was collected from PT. Raya Konsult (2022b) and is given in Table 3. Based on Table 3, the assumed precipitation intensity is 0.164 m daily.

Table 3. Maximum average daily rainfall in the Mamak Dam area

No	Year		Maximum daily rainfall [mm]
1	1996		80
2	1997		116
3	1998		130
4	1999		130
5	2000		109
6	2001		72
7	2002		100
8	2003		103
9	2004		87
10	2005		106
11	2006		82
12	2007		60
13	2008		68
14	2009		147
15	2010		112
16	2011		79
17	2012		96
18	2013		64
19	2014		164
20	2015		51
21	2016		118
22	2017		95
23	2018		98
24	2019		93
25	2020		86
		Max	164
		∑	2 445
		AVG	98

Source: PT. Raya Konsult (2022b).

Geotechnical design parameters

To provide a refined set of inputs for the numerical model, geotechnical parameters are organised based on the designated zones typically found in embankment dams. The geotechnical parameters of the main dam, Saddle Dam-1, Saddle Dam-2, Abutment-1 and Abutment-2 – which are implemented in the numerical model – are given in Table 4.

Table 4. Geotechnical parameters of the Mamak Dam

Type	Zone	Soil classification	Saturated permeability coefficient (k_s) [m·s^{-1}]	Zone area ($A = k_y/k_x$) [m^2]	Unit weight (γ) [kN·m^{-3}]	Effective cohesion (c') [kPa]	Effective frictional angle (φ') [°]
Embankment zone	earth-fill zone	clay	5.82E-06	0.5	17.52	12.00	27.10
	filler zone	sand	3.28E-03	1.0	20.90	0	32.00
	transition zone	sand	3.60E-02	1.0	18.09	0	28.14
	random zone	clay	3.80E-04	1.0	18.90	6.00	30.10
	selected rock	rock	–	1.0	18.67	0	37.00
	rock-fill zones	rock	–	0.4	21.70	4.15	36.15
	rip-rap	rock	3.30E-03	1.0	25.00	5.00	37.00
Abutment	Abutment-1 Abutment-2	clay	1.00E-04	1.0	17.11	2.30	28.75
Foundation	downstream area	clay	1.00E-04	1.0	18.00	35.00	41.00
	below DS	sandy clay	1.00E-04	1.0	17.04	10.00	32.00

Source: PT. Raya Konsult (2022a).

The assessment of stability is conducted for both the slopes on the upstream and downstream sides of each embankment (Fig. 4). Then, the outcomes of the analysis are compared with the safety standards and guidelines.

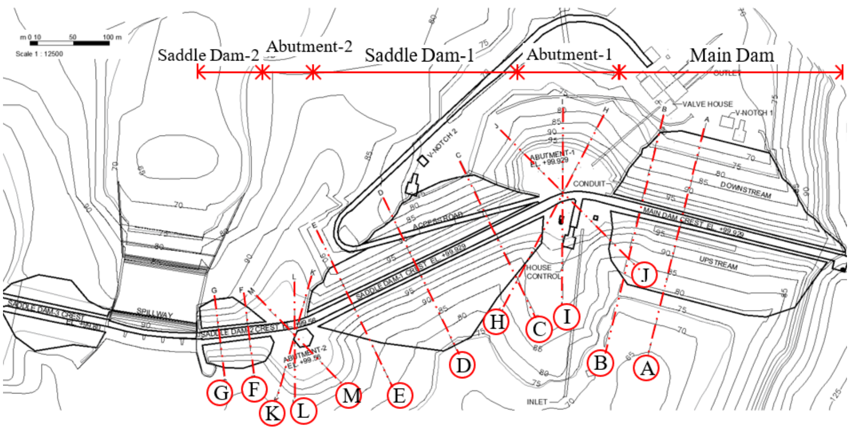

Fig. 4. Location of the cross-sections on the dam plane for slope stability

Source: Halim (2023).

ANALYSIS OF RESULTS

Pseudo-static analysis results

In the upstream slope, cross-sections A–M exhibit FoS values ranging from approximately 1.737 to 3.740 in the absence of earthquakes, indicating generally stable conditions in the area of the main dam, Saddle Dam-1, Saddle Dam-2, Abutment-1 and Abutment-2 (Table 5). The inclusion of earthquake considerations results in decreased FoS values for these sections. With the effect of OBE, FoS obtained by each cross-section ranges from 1.197 to 1.881. The FoS of the whole cross-sections further decreases with MDE earthquake effects, and none of them are considered as safe.

In the downstream slope, cross-sections A–M maintain FoS values above 1.2 without earthquakes, indicating acceptable stability, except for cross-sections H and I (Abutment-1) due to a higher slope inclination. Decreasing the slope inclination is needed. Similar to upstream slopes, the FoS of the whole cross-sections for upstream slope stability analysis further decreases with MDE earthquake effects, and only one of them is considered safe, which is Abutment-2 because the height of Abutment-2 is not as high as other dam parts. It is evident that earthquake effects significantly decrease the FoS for all sections, warranting the implementation of appropriate engineering measures to enhance long-term slope stability.

Table 5. Pseudo-static analysis during normal water level

Cross-section	Upstream slope stability analysis			Downstream slope stability analysis		
	FoS without earthquake	FoS with earthquake (OBE)	FoS with earthquake (MDE)	FoS without earthquake	FoS with earthquake (OBE)	FoS with earthquake (MDE)
A	2.237	1.282	0.736	1.651	1.251	0.855
B	1.938	1.286	0.818	1.275	0.992	0.735
C	2.151	1.332	0.802	1.347	1.029	0.739
D	2.079	1.428	0.918	1.670	1.248	0.865
E	2.223	1.507	0.994	1.586	1.219	0.854
F	2.203	1.528	0.990	1.649	1.215	0.818
G	2.208	1.505	1.015	1.721	1.292	0.883
H	2.954	1.488	0.825	1.135	0.787	0.563
I	3.740	1.881	1.011	1.115	0.459	0.323
J	3.180	1.700	1.058	1.532	1.157	0.894
K	3.444	1.622	0.923	2.488	1.705	1.103
L	2.392	1.357	0.791	2.682	1.525	0.965
M	1.910	1.197	0.718	2.190	1.553	1.033

FoS – factor of safety, OBE – operating basis earthquake, MDE – maximum design earthquake.

Source: Halim (2023).

In this study, a comprehensive slope stability analysis was conducted on both the upstream and downstream slopes of the Mamak Dam. The analysis included pseudo-static analysis under normal conditions – without earthquake effects – as well as conditions with earthquake effects, specifically for the OBE and MDE. Additionally, a rapid drawdown scenario was considered, with a 12-day duration for the water level to decrease from the FWL to the LWL. To assess the stability during drawdown, three specific days (Day 4, Day 8 and

Day 12) were selected for evaluation, representing critical stages in the drawdown process. On day 4, the water level dropped from the FWL at elevation 95.40 m to 88.26 m. By Day 8, the water level had further decreased to 81.14 m, and by Day 12, it had reached the LWL at 74.00 m.

The results of the analysis indicated that both the normal condition (without earthquake effects) and the scenario with OBE produced safe outcomes, with acceptable values of FoS. However, the analysis with MDE showed unsafe results, indicating that the embankment would likely fail under such seismic conditions. The findings suggest that while rapid drawdown alone does not significantly affect the dam's stability, the combination of rapid drawdown with an MDE event could lead to dam failure. Therefore, the critical condition for this dam is the simultaneous occurrence of rapid drawdown and a major earthquake (MDE), which could compromise the safety of the structure. The analysis of results during rapid drawdown from flood water level to low water level on Day 12 are given in Table 6.

Table 6. Analysis due to rapid drawdown from flood water level to low water level T-12

Cross-section	Upstream slope stability analysis			Downstream slope stability analysis		
	FoS without earthquake	FoS with earthquake (OBE)	FoS with earthquake (MDE)	FoS without earthquake	FoS with earthquake (OBE)	FoS with earthquake (MDE)
A	1.856	1.226	0.768	1.802	1.373	0.944
B	1.964	1.425	0.950	1.535	1.187	0.833
C	1.725	1.240	0.838	1.506	1.144	0.812
D	2.060	1.443	0.942	1.639	1.222	0.847
E	2.244	1.585	1.039	1.661	1.249	0.854
F	2.202	1.529	0.992	1.649	1.215	0.818
G	2.297	1.623	1.064	1.721	1.292	0.883
H	2.149	1.357	0.882	1.320	1.112	0.716
I	2.343	1.531	0.969	1.221	0.928	0.660
J	2.241	1.479	1.023	1.893	1.394	1.026
K	2.663	1.619	1.025	2.488	1.705	1.103
L	2.209	1.541	1.058	3.399	1.891	1.144
M	1.627	1.211	0.832	2.190	1.553	1.033

FoS – factor of safety, OBE – operating basis earthquake, MDE – maximum design earthquake.

Source: Halim (2023).

Dynamic analysis results

The results of the dynamic analysis, considering factors of safety (FoS) for upstream and downstream slopes under varying water elevations (FWL, NWL, LWL), present concern regarding the stability of the evaluated cross-sections. In accordance with established engineering standards such as DIN 19700-12 (Deutsche Institut für Normung [DIN], 2004), the minimum required FoS for slope stability is 1.1. Most of the cross-sections did not meet the required minimum FoS due to the impact of MDE (Table 7).

Table 7. Dynamic analysis results (maximum design earthquake)

Cross-section	Flood water level		Normal water level		Low water level	
	FoS upstream slope	FoS downstream slope	FoS upstream slope	FoS downstream slope	FoS upstream slope	FoS downstream slope
A	0.708	0.814	0.711	0.830	0.919	0.790
B	0.790	0.675	0.793	0.728	0.925	0.808
C	0.772	0.694	0.777	0.728	0.868	0.830
D	0.865	0.806	0.893	0.840	0.917	0.840
E	0.949	0.829	0.969	0.829	–	–
F	0.932	0.793	0.965	0.793	–	–
G	0.971	0.858	0.990	0.858	–	–
H	0.793	0.505	0.800	0.538	0.793	0.505
I	0.975	0.232	0.986	0.298	0.980	0.658
J	1.036	0.849	1.033	0.869	1.025	1.030
K	0.891	1.078	0.898	1.078	–	–
L	0.751	0.911	0.766	0.940	–	–
M	0.663	1.008	0.693	1.008	–	–

FoS – factor of safety.

FoS – factor of safety.

Source: Halim (2023).

Conversely, the OBE had a relatively minor effect on FoS value, with all cross-sections under OBE conditions considered to be safe (Table 8).

Table 8. Dynamic analysis results (operating basis earthquake)

Cross-section	Flood water level		Normal water level		Low water level	
	FoS upstream slope	FoS downstream slope	FoS upstream slope	FoS downstream slope	FoS upstream slope	FoS downstream slope
A	1.266	1.206	1.257	1.226	1.291	1.348
B	1.284	0.914	1.261	0.967	1.400	1.175
C	1.315	0.979	1.307	1.004	1.333	1.224
D	1.394	1.160	1.403	1.223	1.418	1.223
E	1.515	1.152	1.482	1.194	–	–
F	1.482	1.190	1.503	1.190	–	–
G	1.493	1.267	1.480	1.267	–	–
H	1.459	0.710	1.463	0.762	1.459	0.710
I	1.849	0.332	1.856	0.434	1.565	0.936

Table 8 (cont.)

Cross-section	Flood water level		Normal water level		Low water level	
	FoS upstream slope	FoS downstream slope	FoS upstream slope	FoS downstream slope	FoS upstream slope	FoS downstream slope
J	1.699	1.102	1.675	1.132	1.508	1.416
K	1.613	1.680	1.597	1.680	–	–
L	1.331	1.440	1.332	1.500	–	–
M	1.155	1.528	1.172	1.528	–	–

FoS – factor of safety.

Source: Halim (2023).

Rainwater infiltration-based stability assessment results

In terms of rainwater infiltration-based stability assessment, FoS values without the impact of earthquake and rainfall infiltration and FoS values with the impact of only rainfall infiltration exceed the required minimum FoS (1.2–1.5), indicating that the whole structure of the dam remains stable during heavy rainfall, although flooding is occurring. However, when it comes to the OBE with rainfall infiltration, the FoS in the cross-sections of the main dam and Abutment-1 falls below safety criteria. Furthermore, with the impact of MDE and rainfall infiltration, most of the cross-sections do not meet the required minimum FoS (Table 9).

Table 9. Rainwater infiltration-based stability assessment during flood water level

Cross-section	FoS without earthquake and rainfall infiltration	FoS with rainfall infiltration	FoS with earthquake (OBE) and rainfall infiltration	FoS with earthquake (MDE) and rainfall infiltration
A	1.599	1.533	1.477	1.000
B	1.626	1.563	1.158	1.000
C	1.824	1.722	1.155	1.000
D	2.317	2.147	1.267	1.000
E	4.208	3.750	1.776	1.000
F	2.856	2.288	2.580	2.238
G	5.474	4.771	3.522	1.721
H	1.599	1.494	1.122	1.000
I	1.649	1.501	1.172	1.000
J	1.649	1.499	1.160	1.000
K	3.704	3.519	1.809	1.000
L	4.404	3.618	1.821	1.000
M	3.750	3.438	1.969	1.000

FoS – factor of safety, OBE – basis earthquake, MDE – maximum design earthquake.

Source: Halim (2023).

It was observed that the pore water pressures generated due to rainwater infiltration added to the seepage, resulting in deformations of the dam faces and reducing the stability of the earthen dams. Heavy rainfall can lead to the occurrence of overtopping in dams. To prevent overtopping in dams, there is a concept known as early release – this concept involves a policy suggesting the construction of gates in the spillway. The flood is predicted based on hydrological data. The minimum freeboard is analysed afterwards. The condition of early release is meant to prevent situations where the water level exceeds 50% of the minimum freeboard.

CONCLUSIONS

This study provides stability analysis based on a case study of the Mamak Dam. Analyses were conducted on both the inclining side facing the reservoir and the declining side of the earth embankment across a total of 13 different sections. The analyses included an examination of the slopes for both continuous seepage conditions (steady state) and temporary seepage conditions (transient state) to simulate rapid drawdown conditions and the impact of rainwater infiltration. Also, seismic loading impact was accounted for through both pseudo-static and dynamic analysis methods. Two values of horizontal seismic coefficients (k_h), two values of vertical seismic coefficients (k_v) and two independent ground acceleration time histories were considered in the analyses. The design situations of each cross-section encompassed different water elevations, rapid drawdown, seismic loadings and rainfall intensity.

The following conclusions have been drawn from the present work:

- The upstream and downstream slopes of all cross-sections have been generally found safe for slope stability analysis in different water elevation cases, rapid drawdown and rainfall intensity design situations. Nevertheless, the simultaneous occurrence of a major earthquake (MDE) and each case significantly decreases the FoS for all sections.
- The impact of the MDE was notable in both pseudo-static and dynamic analyses, causing a reduction of over 50% in the FoS for static and dynamic conditions – ultimately falling below the minimum safety threshold. Conversely, the OBE had a relatively minor effect on the FoS value, with all cross-sections under OBE conditions considered to be safe.
- The rainwater infiltration-based stability assessment shows that the Mamak Dam remains stable during heavy rainfall, even in flooding conditions. However, when rainfall infiltration is combined with an OBE, the FoS in the main dam and Abutment-1 falls below safety criteria. Under the combined effects of MDE and rainfall infiltration, most cross-sections fail to meet the required FoS, indicating a significant risk to the dam's stability during such extreme events.

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Authors' contributions

Conceptualisation and methodology: Z.L., M.L. and N.H.; validation: N.H.; formal analysis: N.H.; investigation: N.H.; resources: N.H.; data curation: N.H.; writing – original draft preparation: N.H.; writing – review and editing: Z.L., M.L. and N.H.; visualisation: N.H.; project administration: N.H.

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ANALIZA STATECZNOŚCI ZAPORY MAMAK PRZY RÓŻNYM POZIOMIE WODY W ZBIORNIKU

STRESZCZENIE

Zapora ziemna jest konstrukcją inżynierską, którą projektuje się w celu retencjonowania wody głównie na potrzeby ludzkie. W przypadku awarii zapory istnieje ryzyko wywołania znacznych strat ludzkich, ekonomicznych i środowiskowych. Główne czynniki prowadzące do uszkodzeń zapory to między innymi niekontrolowane przecieki, osuwiska i trzęsienia ziemi. Ogólny stan stateczności zapory Mamak wpisuje się w kategorię „akceptowalny", nawet po trzęsieniu ziemi o magnitudzie 6,5 Mw w 2018 roku. W niniejszej pracy przeanalizowano stateczność zapory podczas zdarzeń sejsmicznych, szybkiego obniżania wody w zbiorniku oraz maksymalnej dziennej intensywności opadów deszczu. Stwierdzono, że skarpy od strony górnej i dolnej wody były bezpieczne we wszystkich sytuacjach projektowych. Niemniej jednak wpływ maksymalnego trzęsienia ziemi o projektowanej wielkości (MDE) jest zauważalny zarówno w analizach pseudostatycznych, jak i dynamicznych, prowadząc do zmniejszenia współczynnika stateczności (FoS) o ponad 50%, ostatecznie poniżej minimalnego progu bezpieczeństwa. Z kolei trzęsienie ziemi o działaniach operacyjnych (OBE) ma stosunkowo niewielki wpływ na FoS.

Słowa kluczowe: stateczność zapory, analiza pseudostatyczna, analiza dynamiczna, maksymalne trzęsienie ziemi o projektowanej wielkości, MDE