

Mechanism-Based Screening of Seismic Instability in the Tarbela Reservoir Sediment Delta Using a Coupled QUAKE/W–SLOPE/W Analysis

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Research Article

Keywords: reservoir sedimentation, sediment delta, seismic slope stability, liquefaction susceptibility, Tarbela Dam

Posted Date: July 3rd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10120290/v1>

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Additional Declarations: No competing interests reported.

Abstract

Sedimentation at Tarbela Dam has formed a prograding underwater sediment delta that advances toward critical low-level tunnel intakes. Because the delta is layered, loose at its advancing front, and saturated under a high reservoir head, earthquake shaking can redistribute effective stresses and pore-water pressures non-uniformly, producing localized instability even when the body does not liquefy. This study presents a mechanism-based seismic screening of a representative delta cross-section using a coupled GeoStudio workflow, with QUAKE/W for the dynamic stress and pore-pressure response and SLOPE/W for the stability assessment, under horizontal peak accelerations of 0.28 g and 0.5 g, with parameters from published values for comparable saturated sediments. The output fields, namely effective stresses, pore-water pressure, a relative cyclic-demand susceptibility index, seismic deformation, and the critical slip response, are interpreted within a single overlay framework that locates where adverse indicators coincide. These consistently isolate the foreset toe and underlying bottomset contact as the controlling zone. Liquefaction is subordinate, localized at the fresh foreset toe rather than generalized across the consolidated body that decades of consolidation have stiffened. The indicative minimum factor of safety falls from about 1.4 statically to about 1.2 at 0.28 g and 0.95 at 0.5 g, placing the yield acceleration between the two levels; a sensitivity analysis confirms the foreset stays controlling despite parameter variation. The overlapping fields define an intake-relevant hazard pathway and support targeted mitigation through an underwater restraining dike, sediment bypass, and dredging. The study is a screening framework, not a final design prediction.

1. Introduction

Reservoir sedimentation is a persistent performance and safety constraint for large storage dams on sediment-laden rivers (Annandale 1987; Morris and Fan 1998; Schleiss et al. 2016). As deposits accumulate, the reservoir evolves from a deep basin into a deltaic system that advances toward the dam and its hydraulic structures. This is not solely a loss-of-storage problem; it also introduces local operational and safety concerns where a steep foreset slope migrates toward tunnel intakes and outlet works. Tarbela Dam on the Indus River in Pakistan is a globally cited example, where long-term sedimentation has been documented as a dominant factor governing reservoir serviceability and operational risk (Haq 2013; Roca 2012). The reservoir has already lost a large fraction of its original live storage, and recent assessments confirm a continuing decline (Hassan et al. 2022; Khan and Tingsanchali 2009).

A sediment delta typically comprises a relatively flat topset, a steeply inclined foreset, and a lower bottomset, which differ in grain size and drainage behaviour and therefore respond differently to cyclic loading. During earthquake shaking, the sediment body undergoes rapid stress redistribution and pore-pressure changes that reduce effective stress and available shear strength. The resulting instability does not require uniform liquefaction of the entire delta; it can develop as a localized mechanism within the foreset and underlying bottomset, where looseness, confinement, and drainage conditions are least

favourable. In intake-sensitive reservoirs, even limited underwater sliding can concentrate sediment near tunnel approaches and disrupt flow.

The specific concern of earthquake-triggered underwater slides at Tarbela, and the consequent risk of tunnel choking, has been recognized in project documentation, which discusses protective measures such as an underwater dike upstream of the right-abutment tunnel inlets to restrain the delta during a triggering earthquake (World Bank 1986). Such earthquake-triggered failures of loose, saturated submerged slopes share the mechanics of submarine mass movements documented more widely (Hampton et al. 1996; Locat and Lee 2002). This motivates examining the internal dynamic response of the delta and framing results around an intake-risk pathway rather than storage loss alone. A practical way to do so is a coupled numerical workflow in which the dynamic response is evaluated and then interpreted alongside the stability outcome (Seequent 2022a, b); such QUAKE/W-to-SLOPE/W coupling has recently been used to obtain time-resolved dynamic factors of safety for earth structures (Fuławka et al. 2025).

Despite its importance, mechanism-based interpretation of the internal delta response under seismic loading remains limited in the open literature for Tarbela, where most work emphasizes sedimentation forecasting and basin-scale management (Hassan et al. 2022) and does not connect dynamic stress response, pore-pressure evolution, susceptibility patterns, and stability within a single framework that can be read for intake safety.

The novelty of this study lies in treating the Tarbela sediment delta not only as a sedimentation-storage problem but as a coupled seismic-instability and intake-risk pathway. Unlike sediment-volume forecasting studies, the present work interprets dynamic effective-stress redistribution, pore-pressure distribution, cyclic-demand susceptibility, seismic deformation, and limit-equilibrium slip response within one overlay framework. This allows the controlling mechanism to be identified as a localized foreset instability along the weak bottomset contact rather than as generalized liquefaction of the whole delta. The contribution is therefore a low-data, transferable screening method for intake-sensitive, sedimented reservoirs in seismic regions, demonstrated here under two horizontal peak accelerations, 0.28 g and 0.5 g.

2. Study Area and Problem Definition

2.1 Tarbela Reservoir Sediment-Delta Context

Tarbela Reservoir has experienced sustained sediment inflow, producing a prograding delta that advances toward the Main Embankment Dam (MED). Published accounts indicate that the reservoir has lost approximately one-third of its original live storage to sedimentation, with continued losses in more recent surveys, and that the delta pivot point has migrated several miles toward the MED over recent decades (Hassan et al. 2022; Khan and Tingsanchali 2009; Roca 2012). The delta comprises a gently sloping topset, a steep foreset, and a deeper bottomset of finer material; field investigations describe the

deposits as loose silts and fine sands with standard penetration values generally below 30 (Haq 2013). The foreset is the primary concern for instability: it controls the delta-front geometry, concentrates loose saturated sediments, and lies on the advancing front where the geometry is least favourable for stability.

The reservoir boundary condition adopted here is the Maximum Operating Level (MOL) at elevation 1550 ft (472 m), which defines the reservoir head acting on the sediment mass. Operating policy has historically maintained a minimum level (about 1400 ft, 427 m), partly to limit delta advance through the stabilizing pressure of the water column on the deposit.

2.2 Seismic Concern and the Intake Hazard Pathway

The Tarbela site lies in a seismically active region; seismicity studies indicate that a magnitude-6.5 earthquake could occur in the area, producing a peak bedrock acceleration as high as 0.5 g at the dam site. Two earthquake-related failure modes are of concern: a stress-driven stability failure of the foreset along the weak bottomset contact, and a liquefaction-type flow slide of the saturated sands. Either could mobilize material toward the low-level intakes and, in the worst case, choke power and irrigation releases until the tunnels could be cleared, an operation that could take months.

2.3 Objective and Scope

The objective is to interpret the coupled QUAKE/W–SLOPE/W outputs for a representative cross-section under 0.28 g and 0.5 g, and to identify intake-relevant hotspot zones where multiple adverse indicators coincide. The scope is a first-order screening: a single representative section, a simplified linear-elastic dynamic treatment, literature-based parameters, and the standard GeoStudio output fields, aiming to map the controlling mechanism rather than to deliver a fully calibrated triggering or deformation prediction. The assumptions are stated in Section 3.8 and revisited in Section 5.6.

3. Materials and Methods

3.1 Representative Cross-Section and Loading

A representative two-dimensional cross-section, extending from the topset through the foreset to the bottomset and the deeper foundation, was used as the analysis domain (Fig. 1). The sediment mass was assigned a bulk unit weight of 90 pcf (14.1 kN/m³), the value adopted in the project study material, and the reservoir head corresponds to the MOL of 1550 ft (472 m). Two horizontal peak accelerations were applied: 0.28 g, recorded during the 1991 (magnitude ~ 6.5) event, and 0.5 g, the probable design-level value for the site. The base of the model was restrained and lateral movement was restrained at the far field away from the MED. The original project documentation uses US customary units; SI equivalents are given in parentheses (1 ft = 0.305 m, 1 pcf = 0.157 kN/m³, 1 psf = 0.0479 kPa). Table 1 summarizes the principal inputs.

Table 1
Principal inputs adopted for the coupled GeoStudio analyses

Input item	Adopted value	Used for
Max. Operating Level	1550 ft (472 m)	Reservoir head / boundary
Sediment unit weight	90 pcf (14.1 kN/m ³)	Bulk weight of sediment
Acceleration, case 1	0.28 g	Moderate shaking
Acceleration, case 2	0.50 g	Design-level shaking
Constitutive treatment	Linear elastic	Dynamic stress response
Dynamic solver	QUAKE/W	Stress + pore pressure
Stability solver	SLOPE/W	Stability from stress state

3.2 Material Parameters

Site-specific cyclic test data were not available; therefore the dynamic stiffness, damping, and shear-strength parameters were adopted from published values for comparable loose, saturated delta and alluvial sediments (Kramer 1996; Seed and Idriss 1970) and are summarized in Table 2. Two units were distinguished: the loose fine-sandy foreset and the weaker, finer bottomset forming the basal contact along which a foreset failure would develop. The small-strain shear modulus G_{max} was estimated from a representative shear-wave velocity V_s and mass density ρ using Eq. (1), and the Young's modulus E from Eq. (2), in which ν is the Poisson's ratio:

$$G_{max} = \rho V_s^2$$

1

$$E = 2G_{max}(1 + \nu)$$

2

The adopted ranges are consistent with values reported for loose-to-medium saturated sands and soft silts (Idriss and Boulanger 2008). The foreset friction angle ϕ' was taken as 30° with c' of zero, and the weak bottomset as $\phi' = 24^\circ$ with a small c' , reflecting its role as the controlling basal surface.

Table 2
Representative material parameters.

Parameter	Foreset	Bottomset	Basis
Unit weight γ (pcf)	90	90	project value
Friction angle ϕ' (°)	30	24	Idriss and Boulanger (2008)
Cohesion c' (psf)	0	≈ 200	Idriss and Boulanger (2008)
Poisson's ratio ν	0.35	0.45	typical, saturated
V_s (m/s)	≈ 160	≈ 140	Seed and Idriss (1970)
$G_{\max}$ (MPa)	≈ 37	≈ 28	Eq. (1)
E (MPa)	≈ 100	≈ 82	Eq. (2)
Damping ξ (%)	5	5–7	Seed and Idriss (1970)

1 pcf = 0.157 kN/m³; 1 psf = 0.0479 kPa

3.3 Numerical Model Configuration

To support reproducibility, the modelling configuration is summarized in Table 3. The dynamic stage in QUAKE/W was initialized from an in-situ (gravity) stress state and driven by a horizontal motion scaled to the target peak acceleration; the resulting stress state was then imported into a SLOPE/W limit-equilibrium analysis. Entries marked as approximate were read from the representative section of Fig. 1 or follow standard screening choices, and define the analysis configuration rather than a site-calibrated model.

Table 3
Numerical model configuration for the coupled screening analysis

Item	Adopted setting
Software	GeoStudio (QUAKE/W, SLOPE/W)
Analysis sequence	Dynamic QUAKE/W → stress imported to SLOPE/W
Constitutive model	Linear-elastic (screening)
Units	US customary (ft, lb, pcf, psf); SI in text
Geometry (approx.)	Topset $\approx 0.02\text{--}0.03^\circ$; steeper foreset; sediment thickness up to ~ 200 ft (~ 60 m)
Reservoir / phreatic	MOL 1550 ft (472 m); phreatic surface at reservoir level
Boundary conditions	Base restrained; far-field lateral restraint away from MED
Input motion	Horizontal, scaled to PGA 0.28 g and 0.5 g
Material damping	$\approx 5\%$ (representative)
Initial stress	Gravity / in-situ initialization
SLOPE/W method	Morgenstern–Price (representative)
Slip search	Critical surface through foreset / bottomset contact

3.4 Dynamic Response Analysis (QUAKE/W)

The dynamic response was computed in QUAKE/W, which solves the equations of motion in the time domain and returns the redistribution of effective stresses and the pore-pressure response under earthquake loading (Seequent 2022a). The analysis returned the spatial distributions of effective vertical stress σ'_v , effective horizontal stress σ'_h , and pore-water pressure u , together with a relative susceptibility index and the seismic deformation pattern.

3.5 Definition of the Liquefaction-Susceptibility Index

The susceptibility index used here, I_{LS} , is treated as a relative cyclic-demand indicator extracted from the QUAKE/W output, not as a calibrated factor of safety against liquefaction. It is interpreted as a spatial ranking in which higher values indicate zones where the seismically induced cyclic demand more closely approaches the assumed cyclic resistance, written schematically as

$$I_{LS} = \frac{\tau_{cyc}}{\tau_{res}}$$

where τ_{cyc} is the induced cyclic shear stress and τ_{res} a reference cyclic resistance. Because site-specific cyclic-resistance curves and CPT/SPT-based values were unavailable, the index is used only to identify relative hotspots within the model domain; values greater than unity are interpreted as elevated relative susceptibility, but not as confirmed liquefaction triggering (Seed and Idriss 1971; Seed and Lee 1966; Youd et al. 2001). Representative ranges are given in Table 4.

Table 4

Interpretation of the relative susceptibility index

Index range	Interpretation	Where observed
≤ 1.0	low relative susceptibility	consolidated delta body
1.0–2.0	elevated relative susceptibility	transition zones
≥ 2.0	highest relative susceptibility	fresh foreset toe

3.6 Stability Assessment (SLOPE/W)

The stability of the foreset and underlying layers was assessed in SLOPE/W using the stress state from the dynamic analysis, maintaining consistency within a single workflow (Seequent 2022b). The Morgenstern–Price procedure used here satisfies both force and moment equilibrium (Morgenstern and Price 1965), one of several rigorous limit-equilibrium formulations (Bishop 1955; Spencer 1967). Critical slip surfaces were searched through the foreset and along the weaker bottomset contact, and the minimum factor of safety (FoS) was evaluated for each loading level. Because the analysis imports the non-uniform dynamic stress field rather than a single sustained body force, it provides a more representative estimate of the seismic stability margin than a uniform pseudo-static idealization.

3.7 Output-Driven Hotspot Overlay Framework

The interpretive contribution is a simple overlay applied to the standard outputs. Four indicators, the effective-stress reduction tendency, the dynamic horizontal-stress concentration, the elevated pore-water pressure, and the susceptibility index, are compared spatially to locate where adverse conditions coincide. A zone in which several indicators are simultaneously unfavourable is treated as a candidate hotspot and is then checked against the independently computed critical slip surface and the deformation field, turning a set of contour plots into a defensible, repeatable argument about the controlling mechanism and its location.

3.8 Assumptions

Three assumptions apply. First, the linear-elastic treatment captures the dynamic redistribution of stresses but not the full nonlinear, hysteretic generation of excess pore pressure, so the pore-pressure and susceptibility fields are indicative screening indicators. Second, a single representative section is used, so the results describe the controlling mechanism rather than a section-by-section hazard map. Third, parameters are adopted from literature, so the factors of safety in Section 4 are indicative and characterize the stable-to-failure transition rather than an exact design factor.

4 Results

All contour magnitudes were read directly from the model output figures; units are pounds per square foot (psf; 1 psf $\approx$ 0.0479 kPa), consistent with the adopted unit weight of 90 pcf over the sediment column.

4.1 Effective Vertical Stress

The effective vertical stress field σ'_v (Fig. 2) increases with depth, from about 14,000 psf ($\sim$ 670 kPa) in the shallower topset to roughly 20,000 psf ($\sim$ 960 kPa) in the deeper bottomset toward the toe. The contour spacing is broadly regular, but a localized perturbation appears at the foreset crest, where the contours deflect downward (18,000–19,000 psf, $\sim$ 860–910 kPa), the first indication that the foreset transition concentrates the dynamic response.

4.2 Effective Horizontal Stress

The effective horizontal stress field σ'_h (Fig. 3) differs markedly from the vertical field. Elevated horizontal stress concentrates along the upper foreset face and crest, with a pronounced near-vertical band at the crest, while the base and toe carry lower horizontal stress. This concentration coincides with the vertical-stress perturbation of Fig. 2 and indicates that the foreset transition is where shaking most strongly perturbs the in-situ stress state.

4.3 Pore-Water Pressure Response

The pore-water pressure field u (Fig. 4) is governed mainly by depth below the phreatic surface, with sub-horizontal contours increasing from about 12,000 psf ($\sim$ 575 kPa) near the surface to about 26,000 psf ($\sim$ 1245 kPa) at the deepest bottomset beneath the topset–foreset transition. This deep, high-pressure zone reduces effective stress along the bottomset contact that underlies the foreset, the same surface along which a stress-driven failure would develop.

4.4 Liquefaction Susceptibility

The relative susceptibility index I_{LS} (Fig. 5) isolates the foreset toe as the most vulnerable zone, reaching about 2.2–2.6 in the loose sediments there, annotated in the output as the liquefaction-prone foreset delta, while the large consolidated body returns about 0.4–1.0. Following Eq. (3), values approaching 2 at the foreset toe indicate that cyclic demand approaches the resistance of the freshest, loosest material, whereas the bulk body retains a comfortable margin. Susceptibility is thus localized at the advancing front rather than distributed through the deposit.

4.5 Seismic Deformation of the Delta

The deformed configuration under 0.5 g loading (Fig. 6) shows net movement of the delta toward the MED, with the largest amplitudes through the foreset. The orientation is consistent with the documented historical advance of the delta and indicates that strong shaking accelerates, rather than reverses, the trend that already concerns operators. The same zone that concentrates horizontal stress (Fig. 3) and carries the highest susceptibility (Fig. 5) also accommodates the largest movement.

4.6 Slope Stability Response

The stability analysis locates the governing slip mass through the topset crest, foreset, and weak bottomset contact (Fig. 7). The figure shown corresponds to the 0.28 g case and is included to illustrate the governing failure mechanism. At this loading level, the section remains stable with a reduced margin (FoS $\approx$ 1.2). At the higher 0.50 g loading level, the same foreset–bottomset mechanism remains controlling, but the minimum factor of safety decreases further to approximately 0.95, indicating an imminent-failure condition (Table 5). Thus, the controlling mechanism is unchanged, while the stability margin decreases with increasing seismic demand.

Table 5
Indicative minimum factors of safety for the foreset failure surface (parameters of Table 2)

Loading scenario	Min. FoS	Condition
Static (no shaking)	$\approx$ 1.4	Stable
0.28 g (1991 event)	$\approx$ 1.2	Stable, reduced margin
0.50 g (design)	$\approx$ 0.95	Imminent failure

Although only the 0.28 g critical slip figure is shown, the 0.50 g case was evaluated within the same SLOPE/W framework and returned the same governing mechanism with a lower minimum factor of safety.

4.7 FoS–Acceleration Trend and Yield Acceleration

Figure 8 plots the indicative minimum FoS against the horizontal peak acceleration. The trend is monotonic and crosses unity between 0.28 g and 0.5 g; linear interpolation places the yield acceleration, the level at which FoS = 1, near 0.45 g. This value is indicative and follows directly from the three screening cases rather than from a continuous time-history search.

4.8 Sensitivity Analysis

Because the parameters are adopted rather than measured, a sensitivity analysis was performed by varying each adopted value within its plausible range in the stability check while holding the geometry and the dynamic stress pattern fixed (Table 6). The indicative FoS shifts as expected, decreasing with lower bottomset strength and stiffness and increasing with higher damping, but in every case the critical

zone remains the foreset-toe and bottomset contact. The central conclusion of a localized foreset hazard is therefore robust to the parameter assumptions, even though the absolute FoS is not.

Table 6
Indicative sensitivity of the 0.5 g stability result to adopted parameters

Case	Change	Min. FoS	Critical zone unchanged
Base (Table 2)	—	≈ 0.95	—
Bottomset $\varphi' = 22^\circ$	-2°	≈ 0.88	Yes
Bottomset $\varphi' = 26^\circ$	+ 2°	≈ 1.02	Yes
Bottomset $c' = 0$	-200 psf	≈ 0.90	Yes
Foreset $\varphi' = 28^\circ$	-2°	≈ 0.93	Yes
Unit weight = 95 pcf	+ 5 pcf	≈ 0.92	Yes
Foreset $V_s = 120$ m/s	-40 m/s	≈ 0.92	Yes
Damping = 10%	+ 5%	≈ 0.98	Yes

Indicative values obtained by varying one adopted parameter at a time in the screening stability check; rounded and intended to show direction and robustness, not precise magnitudes.

4.9 Integrated Hotspot Overlay

Figure 9 synthesizes the results as an overlay on the delta section. The dynamic horizontal-stress concentration at the foreset crest, the susceptibility peak at the foreset toe, the high pore-pressure and low effective stress along the bottomset contact, the MED-directed deformation, and the SLOPE/W critical slip surface all fall within the same foreset-toe-to-bottomset band. The spatial coincidence of these methodologically distinct indicators is the central result and defines the controlling, intake-relevant hazard zone.

5. Discussion

5.1 The Foreset Hotspot

Read individually, each field tells part of the story; read together through the overlay (Section 3.7 and Fig. 9), they converge. The foreset crest-to-toe band concentrates horizontal stress (Fig. 3), shows the local vertical-stress perturbation (Fig. 2), carries the highest susceptibility (Fig. 5), and accommodates the largest deformation (Fig. 6). The deep bottomset beneath it carries the highest pore pressure and lowest effective stress (Fig. 4), providing a weak basal surface, and the independently computed critical slip mass (Fig. 7) passes through exactly this zone. The agreement among four dynamic indicators, the pore-pressure regime, and a separate limit-equilibrium solver is the central result: the hazard is localized and robustly identified.

5.2 Why Liquefaction Is Subordinate

Liquefaction triggering is conventionally framed as a comparison between the cyclic stress ratio imposed by the earthquake and the cyclic resistance ratio of the soil (Seed and Idriss 1971; Youd et al. 2001). The bulk of the Tarbela delta has consolidated for roughly four decades under a high reservoir head; sustained confinement increases relative density and lateral effective stress, both of which raise the cyclic resistance (Idriss and Boulanger 2008); for the finer bottomset, liquefaction-susceptibility criteria for silts and clays further suggest limited triggering potential (Boulanger and Idriss 2006; Bray and Sancio 2006). Consequently the demand-resistance ratio in the consolidated body remains low (index ~ 0.4–1.0), and only the freshest material at the foreset toe retains a high ratio (~ 2.2–2.6). The hazard is therefore better characterized as a localized foreset problem driven by stress and geometry than as a generalized liquefaction problem.

5.3 Governing Mechanism and Intake Pathway

With liquefaction subordinate, the governing mechanism is a stress-driven failure of the foreset along the weak, high-pore-pressure bottomset contact, which becomes imminent at design-level shaking. Because the foreset is the part of the delta closest to and advancing toward the intakes, a triggered failure would mobilize loose sediment precisely where it can reach the intake approaches. Table 7 traces each model output to its engineering meaning and intake consequence, making the hazard pathway explicit.

Table 7
Hazard pathway from model output to intake consequence

Model output	Hotspot	Engineering meaning	Intake consequence
Eff. horizontal stress	foreset crest	stress concentration	initiates instability
Pore-water pressure	deep bottomset	reduced effective stress	weak basal contact
Susceptibility index	foreset toe	cyclic demand near resistance	local mobilization
Deformation	toward MED	seismic movement direction	sediment toward intakes
Critical slip surface	foreset–bottomset	governing failure	possible choking

5.4 Field Corroboration

Although the study is numerical, independent field observations support its premise. Hydrographic surveys conducted immediately before and after the 2005 earthquake recorded sediment shifts of up to about two feet (~ 0.6 m) over parts of the topset and deposition of roughly 2.2 feet (~ 0.67 m) near the MED attributable to the event (WAPDA 2005). The range-line elevations and the computed bed changes

are listed in Table 8 (change taken as the post-event minus pre-event elevation). These event-driven changes confirm that earthquake shaking redistributes delta sediment toward the MED, the direction the model predicts, at a magnitude consistent with a sensitive, mobile foreset.

Table 8
Range-line bed elevations before and after the 2005
earthquake (WAPDA 2005)

Range line	Sep 2005 (ft)	Oct 2005 (ft)	Change (ft)
1	1202.5	1203.6	+ 1.1
2	1203.0	1203.6	+ 0.6
3	1205.0	1204.6	-0.4
4	1208.7	1208.6	-0.1
5	1210.0	1209.6	-0.4
6	1216.0	1215.6	-0.4
7	1222.3	1221.6	-0.7
8	1229.4	1228.6	-0.8
9	1239.4	1238.6	-0.8
10	1248.0	1247.6	-0.4
11	1258.4	1260.6	+ 2.2
12	1275.4	1277.6	+ 2.2
13	1356.4	1357.6	+ 1.2
14	1373.6	1371.6	-2.0
15	1377.5	1377.6	+ 0.1
16	1380.0	1379.6	-0.4
17	1377.0	1375.6	-1.4
18	1379.5	1377.6	-1.9

1 ft = 0.305 m.

5.5 Acceleration Level and Yield Acceleration

The 0.28 g case produces an adverse but sub-failure state ($FoS \approx 1.2$), whereas the 0.5 g case drives the section to an imminent-failure condition ($FoS \approx 0.95$). Because the factor of safety crosses unity between these levels, the yield acceleration is bracketed between 0.28 g and 0.5 g, with interpolation

placing it near 0.45 g (Fig. 8). In the Newmark sliding-block framework (Newmark 1965; Jibson 2011), accelerations above this level accumulate permanent downslope displacement, which displacement-based procedures can estimate (Bray and Travarasrou 2007), rather than producing instantaneous collapse, consistent with the distributed, MED-directed deformation of Fig. 6. The design-level event, rather than the moderate recorded event, therefore governs the intake hazard.

5.6 Limitations and Future Work

The screening nature of the study points to a clear path for strengthening the conclusions, summarized in Table 9. The most valuable step is to re-run the dynamic analysis with an equivalent-linear or nonlinear effective-stress model (Schnabel et al. 1972), supported by measured modulus-reduction and damping curves and a recorded input motion, so that excess pore-pressure generation and a defensible factor of safety against liquefaction can be computed. Adding limited site characterization, such as relative density, fines content, and SPT- or CPT-based cyclic resistance (Boulanger and Idriss 2014), would convert the relative susceptibility map into an absolute triggering assessment and replace the indicative factors of safety with calibrated values.

Table 9
Limitations and how future work would resolve them

Limitation	Effect on interpretation	Future resolution
Literature-based parameters	FoS indicative, not design value	site sampling, CPT/SPT, lab cyclic tests
Linear-elastic dynamics	excess pore pressure not fully captured	equivalent-linear / nonlinear model
Single section	no reservoir-wide map	multiple cross-sections
No recorded motion	frequency effects not represented	site-compatible time histories
Relative index	not absolute triggering	CRR/CSR from CPT/SPT
No displacement analysis	permanent movement not quantified	Newmark / coupled analysis

6. Engineering Implications and Mitigation Options

Because the hazard is localized at the foreset and expresses itself as an intake pathway, mitigation can be targeted rather than reservoir-wide. Three directions, consistent with the long-standing Tarbela management discussion (TAMS 1982; World Bank 1986) and broader reservoir sediment-management practice (Khan and Tingsanchali 2009; Mahmood 1987; Morris and Fan 1998; Schleiss et al. 2016), follow from the results.

1. Underwater restraining dike. A rock-fill dike retaining the delta would eliminate the foreset slope; the topset would then rise to the dike crest at its very gentle natural gradient, removing the steep driving geometry identified as controlling. Provided the dike is designed for the design-level seismic

loading, residual effects on the near-horizontal topset would be confined to a shallow zone of limited strain potential.

2. Sediment bypass and flushing. A low-level bypass that flushes incoming sediment during the high-inflow season attacks the supply that feeds foreset advance, sustaining live storage while reducing the rate at which the hazardous front approaches the intakes.
3. Dredging. Targeted dredging in the intake approach and at the foreset toe addresses the specific zone flagged as most susceptible and can serve as a maintenance measure alongside the structural and operational options.

Screening also implies, independent of capital works, that monitoring of foreset geometry (for example, repeat hydrographic survey) and reservoir-level management during high-seismicity periods are sensible interim risk-reduction measures.

7. Conclusions

A coupled QUAKE/W–SLOPE/W screening of a representative Tarbela delta cross-section, interpreted through an output-driven overlay under 0.28 g and 0.5 g horizontal accelerations, supports the following conclusions.

1. The seismic hazard is localized, not diffuse. Four dynamic indicators, the deep low-effective-stress bottomset, and an independent critical slip surface converge on the foreset toe and bottomset contact as the controlling zone.
2. Liquefaction is subordinate. Consolidation under the reservoir head raised the cyclic resistance of the bulk delta (index ~ 0.4 – 1.0); only the freshest foreset-toe material is elevated (~ 2.2 – 2.6). The governing mechanism is a stress-driven foreset failure along the weak bottomset contact.
3. Stability decreases with shaking. The indicative minimum FoS falls from about 1.4 statically to about 1.2 at 0.28 g and about 0.95 at 0.5 g, placing the yield acceleration near 0.45 g; a sensitivity analysis shows the foreset remains critical across the assumed parameter ranges.
4. The mechanism defines an intake pathway. A localized foreset failure can mobilize sediment toward the low-level intakes and choke releases; the 2005 survey corroborates the modelled, MED-directed sediment response.
5. Mitigation can be targeted. An underwater restraining dike, sediment bypass and flushing, and dredging address the foreset hazard directly, and the low-data overlay method is transferable to other intake-sensitive, sedimented reservoirs.

The absolute factors of safety reported here should not be used as design values without site-specific calibration; their value is to identify the controlling mechanism and hazard zone, and the framework is intended as a screening tool that requires multi-section and laboratory validation before operational use.

Declarations

Acknowledgements

The authors acknowledge the Tarbela Dam Project for the study context and data used in the original analysis.

Statements and Declarations

Funding

No funding was received for conducting this study.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Ethics approval

Not applicable. This study did not involve human participants, their data or biological material, or animals; it is based on numerical modelling and previously published information.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Clinical trial registration

Not applicable. This study is not a clinical trial.

Author Contributions

Saad Hanif contributed to conceptualization, methodology, numerical interpretation, writing, and revision. Abdullah Arshad contributed to methodology, analysis support, and review. Muhammad Adnan Hanif contributed to technical review, interpretation of findings, and manuscript revision. Qudeer Hussain contributed to critical review, validation of engineering interpretation, and manuscript revision. All authors read and approved the final manuscript.

Data Availability

The data supporting the findings of this study, comprising the model output figures and the adopted parameters, are included within the article. Further details are available from the corresponding author on reasonable request.

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Figures

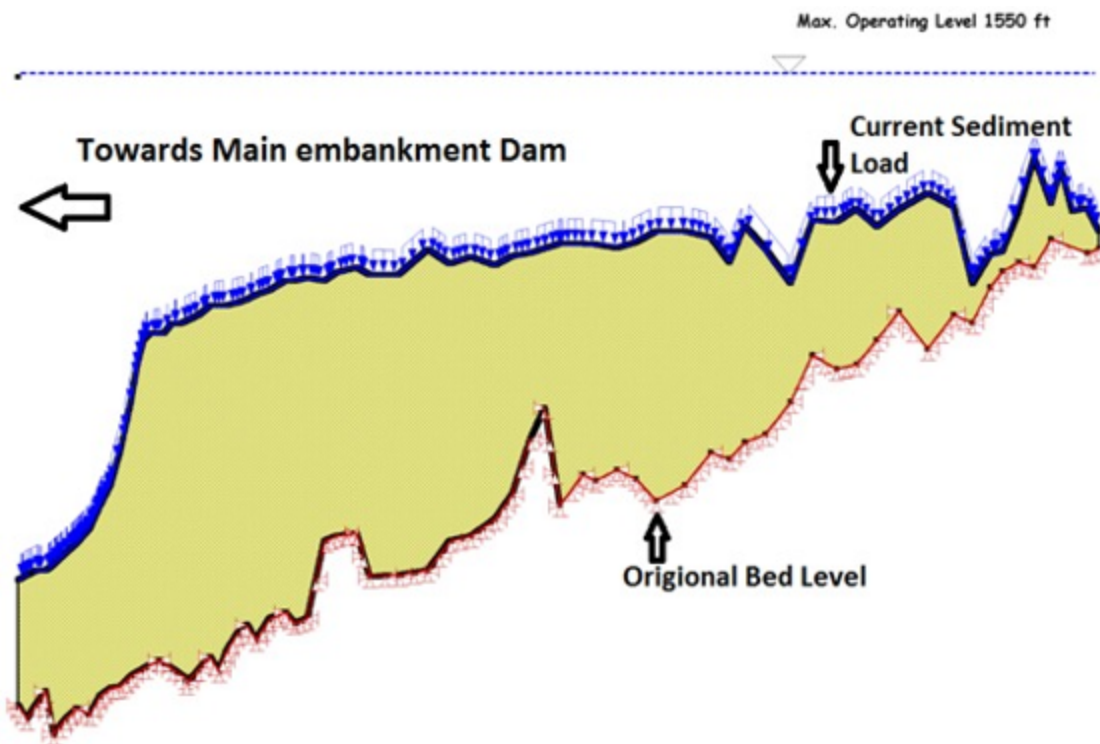


Figure 1

Representative QUAKE/W model cross-section of the Tarbela sediment delta, showing the current sediment surface, the original bed level, and the reservoir Maximum Operating Level (1550 ft); the steep foreset faces the Main Embankment Dam (left)

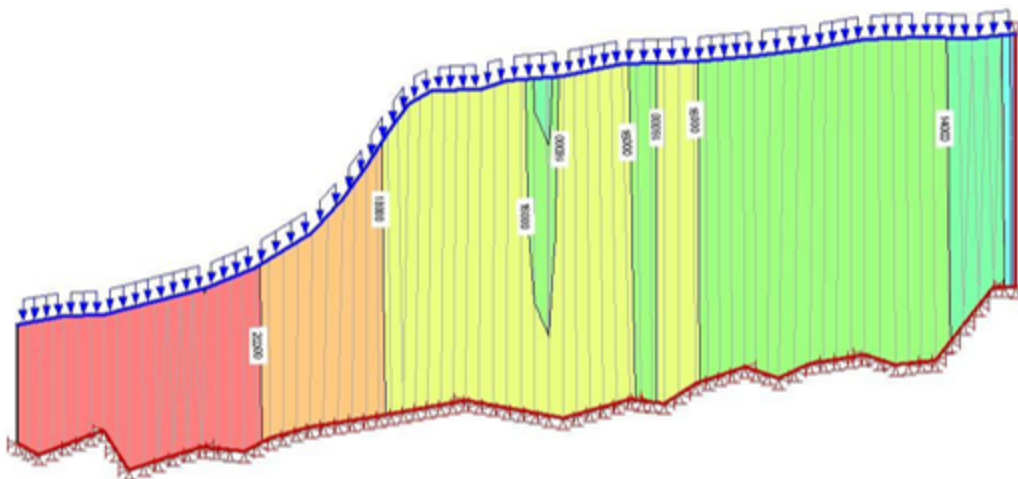


Figure 2

Effective vertical stress field (psf); magnitudes increase with depth from ~14,000 psf (topset) to ~20,000 psf (bottomset/toe), with a localized perturbation at the foreset crest

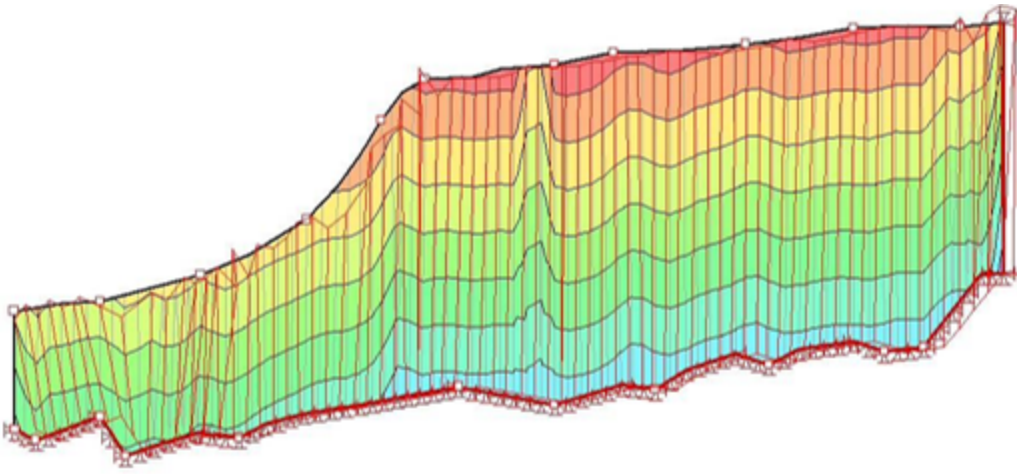


Figure 3

Effective horizontal stress field; the highest values lie along the upper foreset face and crest, with a near-vertical concentration band at the crest, while the base and toe carry lower stress

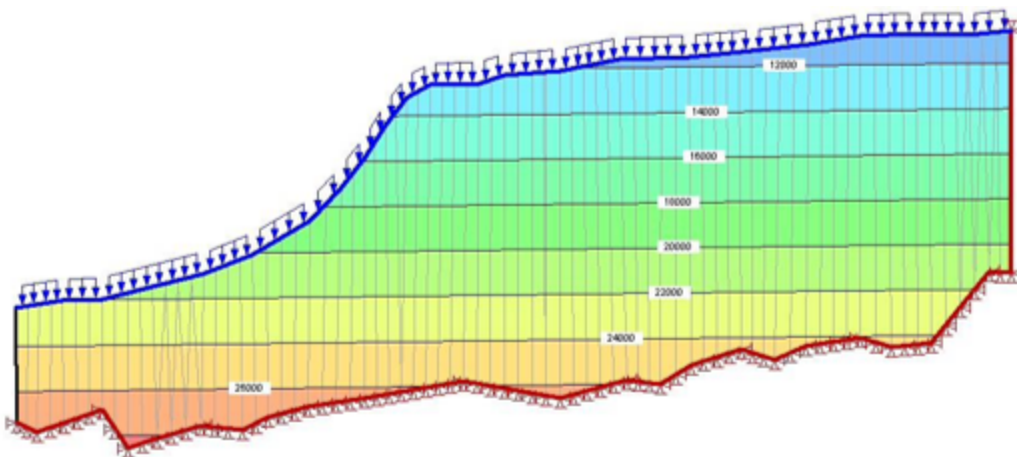


Figure 4

Pore-water pressure field (psf); sub-horizontal contours increase from ~12,000 psf near the surface to ~26,000 psf at the deep bottomset

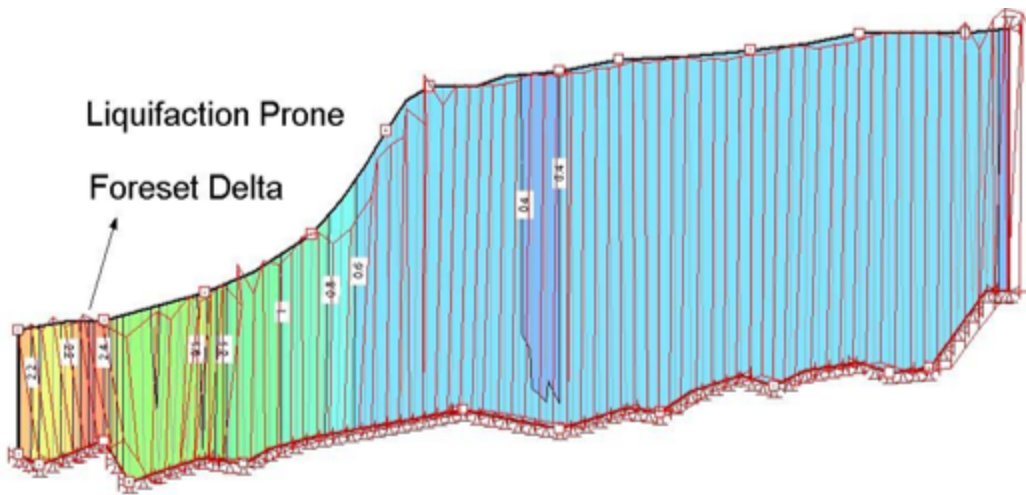


Figure 5

Relative liquefaction-susceptibility index; the foreset toe carries the highest values ($\sim 2.2-2.6$, annotated “liquefaction-prone foreset delta”), whereas the consolidated body returns low values ($\sim 0.4-1.0$)

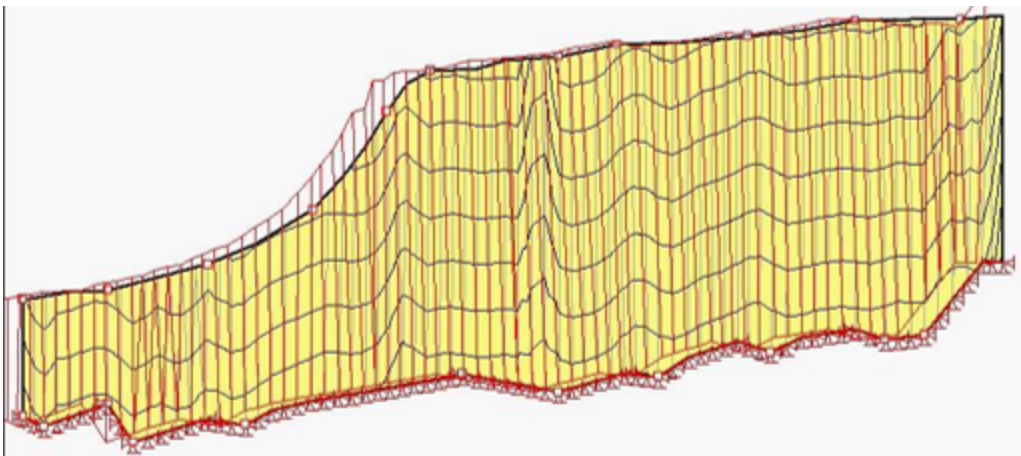


Figure 6

Seismic deformation (deformed mesh) under 0.5 g horizontal loading; net movement is directed toward the Main Embankment Dam, with the largest amplitudes through the foreset.

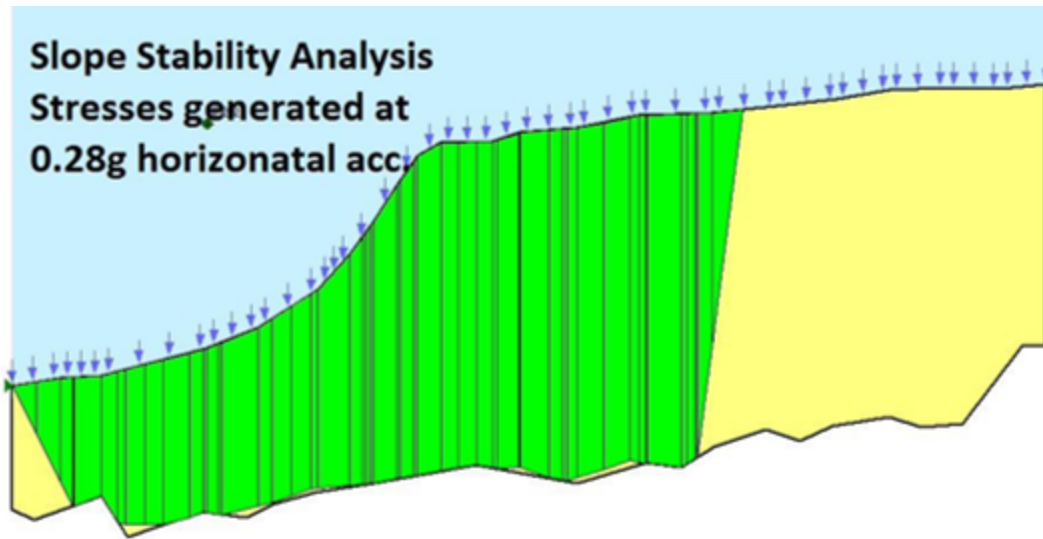


Figure 7

Representative critical slip surface obtained from SLOPE/W for the 0.28 g dynamic stress state. The figure is shown to illustrate the governing foreset–bottomset failure mechanism. At the higher 0.50 g loading level, the same mechanism remains controlling, while the minimum factor of safety decreases further to approximately 0.95 (Table 5)

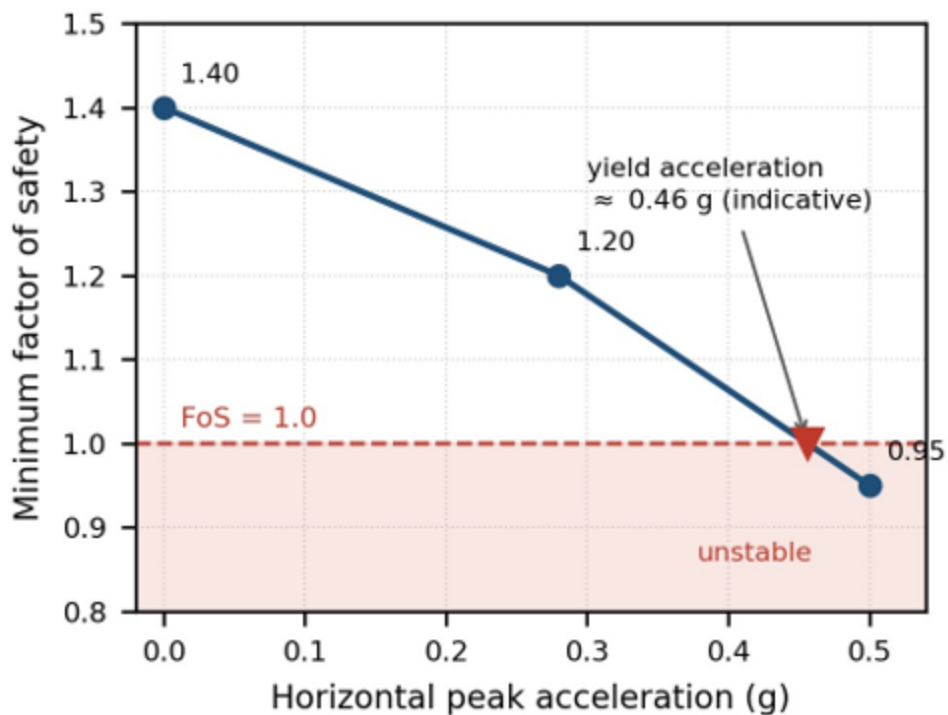


Figure 8

FoS–acceleration trend showing the transition from stable to imminent-failure conditions; the yield acceleration is estimated by interpolation between the 0.28 g and 0.50 g cases and should be interpreted as indicative

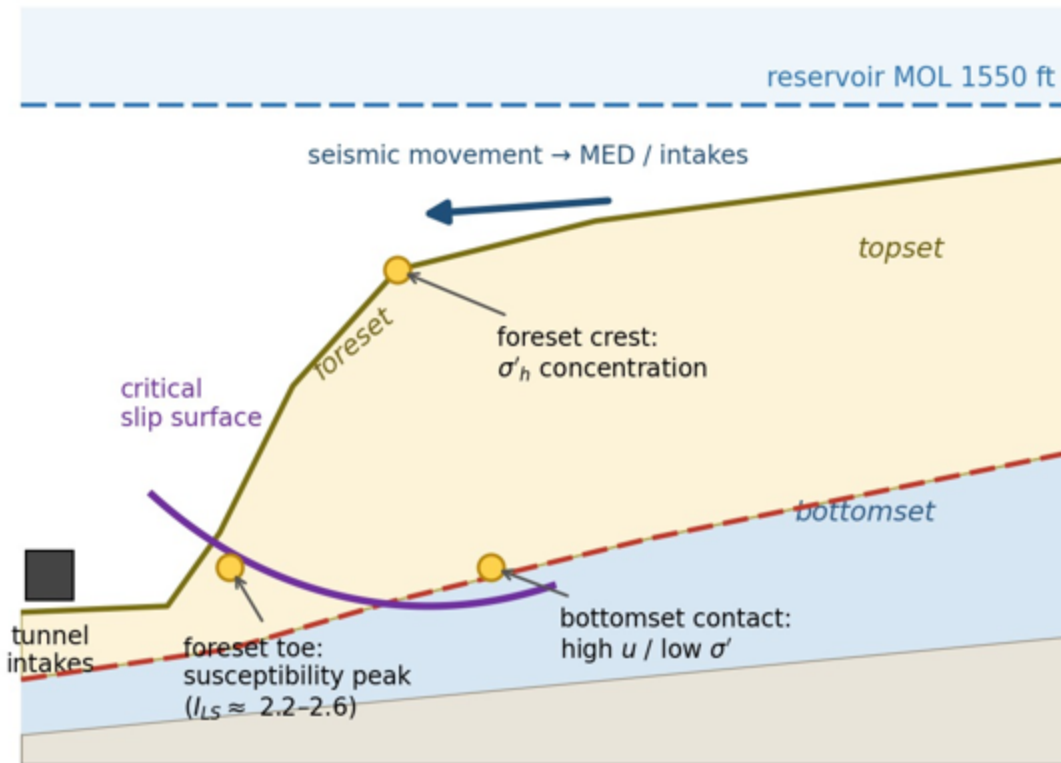


Figure 9

Integrated hotspot overlay showing the coincidence of dynamic horizontal-stress concentration (foreset crest), susceptibility peak (foreset toe), elevated pore pressure and low effective stress (bottomset contact), the critical slip surface, and the MED-directed deformation