Civil Engineering Infrastructures Journal xx,xx
DOI: 10.22059/ceij.2026.395971.2317

ANALYSIS OF STRATIFIED HETEROGENEOUS DEPOSITED SLOPES SUBJECTED TO STATIC AND SEISMIC ACTION

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Received: 31/07/2025
Revised: 27/01/2026
Accepted: 19/03/2026

ABSTRACT:

Soil slopes are inherently heterogeneous, and their seismic stability is strongly influenced by soil layering, strength contrast, and layer thickness. This study investigates the stability of homogeneous and two-layered non-homogeneous slopes under static and seismic loading using the strength reduction finite element method in OPTUM G2. Stability charts are developed for slope inclinations of 25°, 35°, and 45°, upper-layer thickness ratios (T/D = 0.2–0.8), and combinations of fine and coarse-grained soils. Pseudo-static seismic loading is applied using $K_h = 0.1$ and $K_v = 0.05$. Results show that seismic loading reduces safety factors by about 20–35% compared to static conditions. Placing stronger fine-grained soil in the foundation layer increases safety factors by up to 25–40%. Coarse-grained soils exhibit translational failure, while fine-grained soils show rotational failure. Horizontal seismic forces dominate in fine-grained soils, whereas combined seismic effects are more critical for coarse-grained layers. The novelty lies in the unified stability and failure mode charts quantifying layer sequence, thickness ratio, and coupled seismic effects for stratified slopes.

Keywords: *Heterogeneous; Stratified; OPTUM G2; Translational; Rotational failure*

1. INTRODUCTION:

Slope stability is a fundamental concern in geotechnical engineering, as failures can threaten infrastructure and human safety. Failures may be triggered by rainfall, groundwater fluctuations, increased loading, or complex failure mechanisms, and even long-standing natural slopes may fail suddenly due to stress changes, strength reduction, or erosion (Wong et al., 2022; Tozato et al., 2022; **Popescu & Chakrabortty; 2024**). Consequently, reliable assessment of slope stability under both static and seismic conditions is essential. A wide range of analytical and numerical methods has been developed for slope stability evaluation, including limit equilibrium, upper and lower bound analyses, and finite element approaches for homogeneous and heterogeneous slopes (Mofidi et al., 2014; Aminpour & Maleki, 2024; **Jin, 2021; Shi et al., 2025**). The seismic response of layered slopes is strongly influenced by soil stratigraphy, slope geometry, and the combined effects of horizontal and vertical seismic excitations, which can substantially alter safety factors and failure mechanisms (Zhou et al., 2023; Rao et al., 2025; Jin & Liao, 2024). Strength reduction finite element methods, stability charts, and pseudo-dynamic simulations have been effective in capturing both practical and wave propagation effects (Sun et al., 2019; Hazari et al., 2020; Cui et al., 2022). Probabilistic, data-driven, and optimization-based methods, including machine learning and swarm intelligence, have further advanced slope stability assessment by incorporating spatial soil variability and failure probability, often integrating monitoring and earth observation data to refine predictions (Chakraborty & Dey, 2022; Zhang et al., 2022; Kumar et al., 2023; Thomas et al., 2023).

Earthquake-induced ground shaking remains a major threat, typically evaluated using pseudo-static, Newmark-based, and numerical methods, with stability charts and failure probability estimates developed for slopes and earth dams under seismic and drawdown conditions (Chatterjee & Choudhary, 2012; Malekpoor et al., 2020; Konovalov & Gensiorovsky, 2024; **Bayati et al., 2025**). Previous studies on layered and heterogeneous slopes have examined the influence of weak layer placement, layer sequencing, slope geometry, and soil properties under static and seismic loading using FEM, limit equilibrium, and lower bound methods (Qian et al., 2014; Ni et al., 2016; Sazzad & Moni, 2017; Feng & Yin, 2025; Karthik et al., 2022; Guanhua, 2023; Mirzazadeh & Hajiazizi, 2020; Sazzad et al., 2015). However, most studies assume fixed slope angles or neglect the combined influence of horizontal and vertical seismic excitations on heterogeneous, two-layered slopes (Chatterjee & Krishna, 2018; Sarkar & Chakraborty, 2019, 2021), highlighting a critical research gap.

To address this, the present study investigates the seismic stability of homogeneous and non-homogeneous two-layered slopes using OPTUM G2. The objectives are to develop stability charts under static and seismic loading, evaluate the influence of horizontal and vertical seismic coefficients, and generate critical failure charts for varying slope configurations.

2. MODELLING OF SLOPES

2.1. Geometry model of slopes

This study examines two-layered slopes with varying inclinations (*β)* and soil configurations as shown in fig 1. The slope height (H) was fixed at 20 m to represent a high cut slope typical of hilly terrain and roadway excavations (Sarkar and Samanta, 2017). The model height and length were set to 2H and 9H, respectively, to ensure containment of the failure surface. Slope inclinations of 25°, 35°, and 45° were selected to represent gentle to steep conditions. Three soil types were used to model homogeneous and non-homogeneous slopes under two layering configurations: (i) Soil 1 in the upper layer with Soil 2 or Soil 3 below, and (ii) Soil 1 in the lower layer with 2 or Soil 3 above.

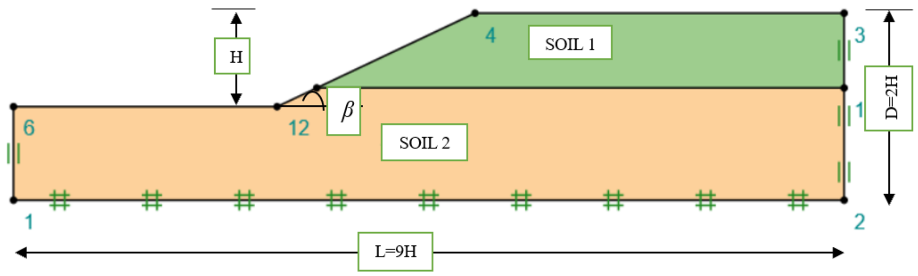

Figure 1: 2D model of two- layered non- homogeneous slopes.

2.2. Material properties

Three soils were used to model two-layered slope heterogeneity. Soils 1 and 2 were collected from Guwahati hills, while Soil 3 was taken from published studies. Soils 1 and 3 are fine-grained, and Soil 2 is coarse-grained, enabling simulation of homogeneous and non-homogeneous slopes to assess the influence of soil layering and properties on seismic stability, mentioned in table 1.

Table 1: Soil properties used in this study (Chatterjee and Krishna, 2018).

Properties	Soil 1	Soil 2	Soil 3
Classification	Fine-grained soil	Coarse-grained soil	Fine-grained soil
Dry weight (kN/m^3)	16	16	16
Angle of internal friction	30°	36°	18°
Soil cohesion (kPa)	10	0	25
Young Modulus (MPa)	5	5	5
Poisson ratio	0.3	0.3	0.3

2.3. Boundary and loading conditions

Two soil-layering configurations were analyzed, with lateral boundaries restrained horizontally and the base fully fixed. The models were subjected to static self-weight and dynamic seismic loading.

3. Methodology

The stability of two-layered slopes was analysed using OPTUM G2 (OPTUM G2, 2017), with the strength reduction method for slope angles of β = 25°, 35°, and 45° and various soil combinations. The model domain was set to a height of 2H and a length of 9H to ensure the failure surface remained within boundaries. Seismic loading was applied using horizontal and vertical coefficients of $K_h = 0.1$ and $K_v = 0.05$. Safety factors are reported as the average of upper- and lower-bound solutions for different T/D ratios, where T is the upper layer thickness and D is the total slope height. Mesh density was progressively refined to achieve convergent results.

4. Results and discussions

The numerical analyses reveal that slope stability under static and seismic loading is governed not only by soil strength parameters but also by the interaction between soil stratification, layer sequence, and failure mechanism. Rather than absolute safety factor values, the discussion below emphasizes the trends, controlling mechanisms, and their engineering implications.

4.1. Homogeneous soil slopes subjected to Static and Seismic loading conditions

This section presents the safety factors and critical slip surfaces of homogeneous slopes (β = 25°, 35°, 45°) under various loading conditions, as assessed using Optum G2.

4.1.1 Safety Factor Assessment:

Soil 1 exhibits the highest safety factors for slopes of 25°, 35°, 45°, while Soil 2 is the least stable, with stability decreasing as slope angle increases. Fine-grained soils exhibit higher stability than coarse-grained soils due to the combined contribution of cohesion and friction, particularly for gentler slopes. Optum G2 results for a 26.57° homogeneous slope under static loading agree with previous FE studies (Chatterjee and Krishna, 2018), whereas LEM slightly overestimates safety factors due to its assumptions (Rawat and Gupta, 2016a, 2016b), clearly depicted in table 2. Table 3 shows that seismic effects decline with slope steepness; horizontal seismic loading dominates for fine-grained soils, while coarse-grained Soil 2 is more affected by combined seismic forces. Under seismic loading, safety factors reduce by approximately 20–35%, highlighting the sensitivity of slopes to inertial forces even when material properties remain unchanged.

Table 2: Comparison of safety factor for homogeneous slopes of 26.57° (Static load)

	Present study	**Past study (Chatterjee and Krishna, 2018)**	
Soil type	**OPTUM G2**	**LEM-MP**	**FEM-SRM**
Soil 1	1.6765	1.79	1.69
Soil 2	1.456	1.591	1.51
Soil 3	1.5075	1.587	1.51

Table 3: Comparison of safety values for homogeneous slopes acted by Static and Seismic load

	Load	**Static load**	**Seismic load**	
Soil slope (β)	**Soil Type**		**K_h =0.1**	**K_v =0.5 K_h**
25°	Soil 1	1.764	1.407	1.409
	Soil 2	1.562	1.226	1.211
	Soil 3	1.568	1.251	1.264
35°	Soil 1	1.305	1.096	1.1
	Soil 2	1.04	0.844	0.826
	Soil 3	1.254	1.055	1.076
45°	Soil 1	1.032	0.884	0.891
	Soil 2	0.718	0.531	0.542
	Soil 3	1.055	0.911	0.931

4.1.2. Critical failure surfaces

The observed failure mechanisms are strongly soil-dependent as noted in table 4. Fine-grained soils (Soil 1 and 3) show circular rotational failures, with Soil 1 shallow and Soil 3 deeper due to cohesion. Coarse-grained Soil 2 exhibits shallow translational failure near the toe, reflecting its negligible cohesion and dominance of frictional resistance. Patterns remain consistent across slopes and loading, validating Optum G2 results.

Table 4: Failure surface chart for homogeneous soil slope.

Soil slope/ Soil type	**25°**	**35°**	**45°**
Soil 1	Circular toe, shallow rotational failure	Circular toe, shallow rotational failure	Circular toe, shallow rotational failure
Soil 2	Translational/Slope failure along the face of slope	Translational/Slope failure along the face of slope	Translational/slope failure along the slope face
Soil 3	Circular toe, deeper rotational failure	Circular toe, deeper rotational failure	Circular toe, deeper rotational failure

4.2. Non-Homogeneous Two-Layered Soil Slopes under Static and Seismic Loading:

The assessment of two-layered, non-homogeneous soil slopes considers two cases: (i) a fixed top layer with a variable bottom layer, and (ii) a fixed bottom layer with a variable top layer. In both cases, Soil 1 is fixed, while Soil 2 and Soil 3 are varied

4.2.1. Safety factor for soil combination 1 and combination 2:

The stability of two-layered non-homogeneous slopes (25°–45°) with T/D ratios of 0.2–0.8 was analysed under static and seismic loading using Optum G2 and clearly noted in table 5,6 respectively. Summarizing all, it can be concluded, placing strong fine-grained soil as the foundation layer enhances safety factors for all slopes, loading conditions, and T/D ratios (0.2–0.8). For coarse-grained soil, foundation placement gives similar safety factors at low T/D ratios (0.2–0.4) and higher values at higher T/D ratios (0.5–0.8).

Table 5: Proposed stability charts depicting safety factors for various soil combination (static load)

		Combination 1		**Combination 2**	
	Top layer	**Soil1**		**Soil2**	**Soil 3**
Ratio	**Bottom layer**	**Soil2**	**Soil 3**	**Soil1**	
T=0.2D	β=25°	1.565	1.549	1.561	1,808
	β=35°	1.039	1.226	1.0415	1.3625
	β=45°	0.7295	1.02	0.786	1.096
T=0.4D	β=25°	1.565	1.61	1.561	1.704
	β=35°	1.046	1.273	1.042	1.305
	β=45°	0.735	1.045	0.726	1.068
T=0.5D	β=25°	1.731	1.707	1.561	1.589

	β=35°	1.281	1.309	1.038	1.252
	β=45°	1.013	1.03	0.719	1.05
T=0.6D	β=25°	1.771	1.766	1.561	1.569
	β=35°	1.307	1.308	1.034	1.254
	β=45°	1.032	1.032	0.724	1.054
T=0.8D	β=25°	1.765	1.765	1.562	1.574
	β=35°	1.311	1.308	1.036	1.254
	β=45°	1.032	1.032	0.729	1.055

Table 6: Proposed stability charts depicting safety factors for various soil combination and change in T/D ratio (seismic load)

		Combination 1				**Combination 2**			
	Top layer	**Soil 1**				**Soil 2**		**Soil 3**	
	Bottom layer	**Soil 2**		**Soil 3**		**Soil 1**			
Ratio	**Soil slope**	**K_h=0.1**	**K_v =0.5 K_h**	**K_h=0.1**	**K_v =0.5 K_h**	**K_h=0.1**	**K_v =0.5 K_h**	**K_h=0.1**	**K_v =0.5 K_h**
T=0.2D	β=25°	1.226	1.2115	1.234	1.244	1.227	1.212	1.4445	1.448
	β=35°	0.8451	0.8388	1.027	1.042	0.836	0.8257	1.147	1.1545
	β=45°	0.5975	0.5924	0.8787	0.8941	0.542	0.54785	0.9465	0.95845
T=0.4D	β=25°	1.2295	1.2145	1.2795	1.287	1.226	1.2105	1.361	1.371
	β=35°	0.8499	0.84335	1.061	1.0725	0.847	0.8322	1.099	1.1135
	β=45°	0.6031	0.5965	0.8974	0.9088	0.569	0.5167	0.9253	0.94176
T=0.5D	β=25°	1.384	1.3775	1.337	1.339	1.224	1.206	1.269	1.2805
	β=35°	1.0745	1.075	1.0935	1.099	0.845	0.8071	1.0525	1.068
	β=45°	0.8712	0.8784	0.8751	0.8924	0.55	0.5511	0.9105	0.9277
T=0.6D	β=25°	1.407	1.407	1.411	1.4075	1.223	1.208	1.251	1.2665
	β=35°	1.0935	1.0985	1.094	1.0985	0.844	0.8286	1.0545	1.0715
	β=45°	0.8835	0.8911	0.8849	0.8901	0.532	0.5642	0.9109	0.9296
T=0.8D	β=25°	1.4085	1.4085	1.4087	1.4085	1.222	1.2125	1.252	1.262
	β=35°	1.094	1.0995	1.094	1.0995	0.844	0.8081	1.055	1.071
	β=45°	0.8851	0.89	0.8851	0.8913	0.549	0.5639	0.9109	0.9335

4.2.2. Critical failure surface:

The critical failure surfaces of non-homogeneous two-layered slopes were analyzed for inclinations of 25°, 35°, and 45° at various T/D ratios. For β = 25° (T/D = 0.5), when Soil 1 occupied the top layer with Soil 2 or Soil 3 at the base, a toe failure mechanism was observed, with coarse Soil 2 displacing less material than fine Soil 3. When Soil 1 was placed at the bottom, top-layer Soil 2 produced translational failure confined to the slope face, whereas Soil 3 induced deeper rotational failure shown in fig 2. These results indicate that the slip surface is largely controlled by the properties of the bottom layer. For β = 35° (T/D = 0.4), failure was confined to the slope face when the top layer was stronger (Soil 1), while a cohesive bottom layer (Soil 3) resulted in a deeper slip surface and greater soil displacement as shown in fig 3. For β = 45° (T/D = 0.6), top-layer Soil 1 caused circular toe failure regardless of the bottom soil. Coarse Soil 2 on top led to translational failure along the slope face, while fine Soil 3 produced deeper circular slip surfaces. At this T/D ratio, non-homogeneity had minimal influence, and the slope behavior resembled that of the homogeneous top soil layer. Overall, the stronger layer controls the geometry and depth of the critical slip surface, confirming that failure in layered slopes is mechanism-driven rather than geometry-driven, in agreement with previous FEM studies (Chatterjee and Krishna, 2018).

Moreover, seismic loading alters not only safety factors but fundamentally changes failure mechanisms. Slopes that fail by deep rotational modes under static conditions frequently transition to shallow or translational failures under seismic action, underscoring that seismic design must explicitly account for failure mode shifts rather than rely on static stability assessments alone as noted in table 7.

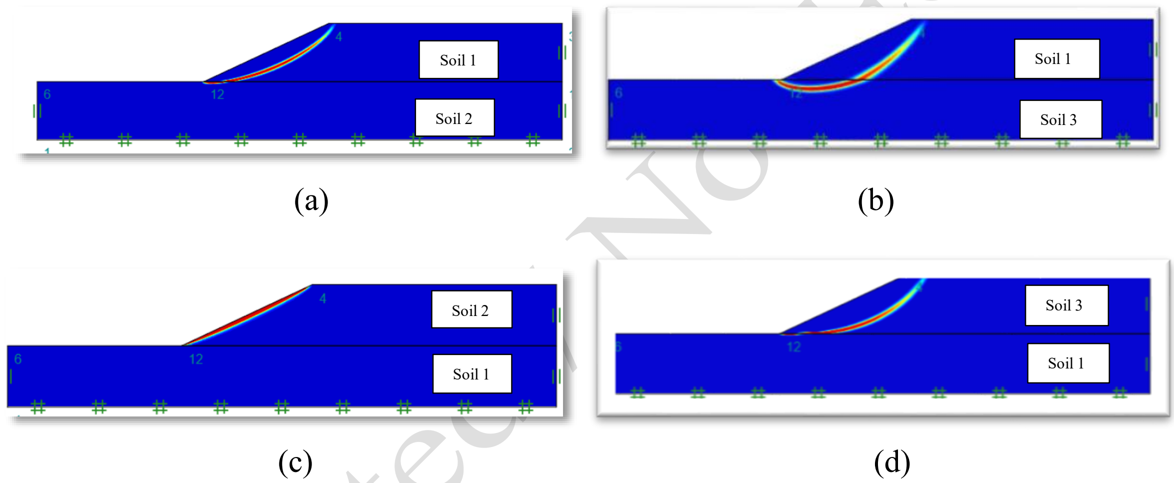

Figure 2: Shear dissipation pattern with fixed top layer (a), (b) and bottom layer (c), (d) for T/D = 0.5 at soil slope 25°.

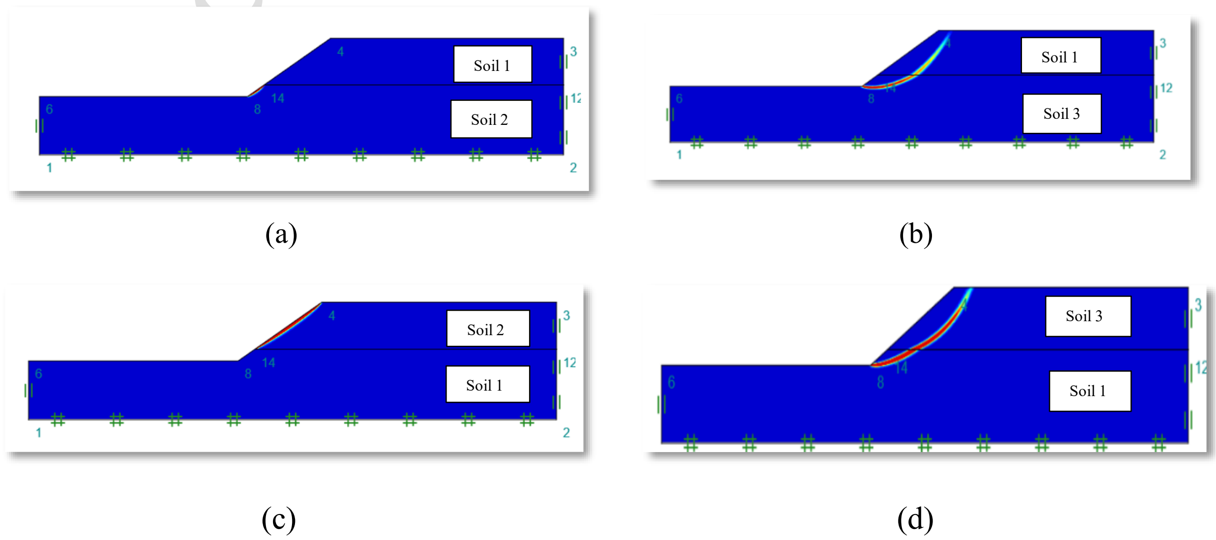

Figure 3: Shear dissipation pattern with fixed top layer (a), (b) and bottom layer (c), (d) for T/D = 0.4 at soil slope 35°.

Table 7: Critical failure surface for non-homogeneous slopes acted by seismic loading with change in T/D ratio

Soil slope	**Soil combination**		**T=0.2D**	**T=0.4D**	**T=0.5D**	**T=0.6D**	**T=0.8D**
25°/35°/45°	**Soil 1**	**Soil 2**	Translational toe failure extending to top-layer interface.	Translational failure confined only to soil 2	Shallow rotational circular toe failure	Shallow rotational circular toe failure	Shallow rotational circular toe failure
		Soil 3	Circular toe failure: shallow above interface, deep below	Circular toe failure: shallow above interface, deep below	Shallow rotational circular toe failure	Shallow rotational circular toe failure	Shallow rotational circular toe failure
	Soil 2	**Soil 1**	Translational failure from interface to crest in Soil 2	Translational slope/face failure	Translational slope/face failure	Translational slope/face failure	Translational slope/face failure
	Soil 3		Circular toe failure: deep above interface, shallow below	Circular toe failure: deep above interface, shallow below	Deep rotational circular toe failure.	Deep rotational circular toe failure.	Deep rotational circular toe failure.

5. Conclusions

This study examined the stability of homogeneous and two-layered non-homogeneous soil slopes under static and seismic loading using the strength reduction finite element method in OPTUM G2. Stability charts, safety factors, and failure mechanisms were developed for varying slope inclinations, soil combinations, and layer thickness ratios and validated against published FEM and limit equilibrium results. From an engineering standpoint, the results confirm that soil layering and foundation strength strongly govern slope stability and failure mode under seismic loading. Placing stronger or stiffer soil in the foundation layer improves stability by confining the failure surface to the upper layer, whereas coarse-grained soils in the top layer promote translational failures along the slope face. The proposed stability and failure charts offer a practical tool for preliminary design, enabling engineers to assess critical soil configurations and the relative influence of horizontal and combined seismic coefficients without extensive numerical modelling. The applicability of the results is limited to two-dimensional, dry slopes with idealized two-layered soil profiles and pseudo-static seismic representation. Effects of groundwater, rainfall infiltration, time-history seismic loading, soil anisotropy, strain softening, and large deformations were not considered. Consequently, the charts are best suited for preliminary evaluation and comparative assessment rather than final design.

For future research, extension to three-dimensional and multilayered slopes, inclusion of groundwater and rainfall effects, and fully coupled dynamic analyses using real earthquake records are recommended. Incorporating advanced constitutive models, progressive failure mechanisms, and probabilistic frameworks would further enhance the reliability and practical relevance of seismic slope stability assessments.

Conflicts of Interest

There is no vested interest for the author.

Funding Statement

The work received no specific grants from any funding agency.

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