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Seismic response of wrapped-face geosynthetic reinforced soil (GRS) wall comprising marginal backfill material

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ABSTRACT

This research investigates the dynamic behavior of GRS retaining walls using marginal backfill materials under seismic loading. A 6 m high wrapped-face GRS retaining wall is analyzed using finite element modeling subjected to the 1995 Kobe earthquake motion. The results reveal that increased backfill cohesion reduces lateral displacement in static analysis but amplifies deformation under pseudo-static conditions due to inertia effects. In case of dynamic analysis, cohesion reduces the impact of reinforcement stiffness on lateral displacement. Acceleration amplification exceeds critical levels at higher wall elevations, increasing stresses in the wall system. Stress distribution is concentrated in the bottom one-third of the wall due to overburden pressure, while the flexible wraparound face helps minimize stress concentration near the wall face. Backfill soils with higher cohesion exhibit reduced mobilized reinforcement loads in dynamic analysis as the presence of cohesion reduces the soil-reinforcement interaction. The potential failure surface in the bottom one-third aligns across all analysis types due to overburden pressure, with the reinforcement undergoing tensile failure regardless of backfill soil effects.

Keywords: Seismic response, Wrapped-face GRS wall, Marginal backfill, Finite element analysis, Failure mechanism

1 INTRODUCTION

Reinforced soil wall structures are widely adopted geotechnical solutions, offering viable alternatives to conventional retaining walls. These structures are preferred due to their cost-effectiveness, faster construction process, higher loading capacity, and ability to optimize space (Tatsuoka *et al*., 2014). Reinforced soil retaining walls can be reinforced using either natural or artificial geomaterials, with the choice of reinforcement material depending on the intended function and design requirements of the structure. For walls designed with long service life, artificial geomaterials such as geosynthetics are often preferred over natural materials due to their superior durability, consistency, and strength.

Geosynthetic-reinforced soil (GRS) walls represent a specific category of reinforced soil structures, utilizing geosynthetics as the primary reinforcement material. The key components of GRS walls include the backfill (reinforced fill), retained fill, facing, and reinforcements. According to FHWA guidelines (Berg *et al*., 2009), backfill materials for GRS walls should ideally consist of granular soils with fine content less than 15% and a plasticity index below 6%. Similarly, the NCMA (2010) allows the use of granular soils with fine content up to 35%. However, in regions such as hilly terrains and mountainous areas, the availability of granular materials that meet these specifications is often limited.

As a result, the use of marginal soils as backfill materials has gained attention. Marginal soils, which may not meet the strict specifications for granular materials, offer a cost-effective and accessible alternative in such areas. Their use reduces dependency on transporting granular materials over long distances, which can be both expensive and logistically challenging. While the use of marginal soils introduces considerations related to their cohesive and frictional properties, it enables the construction of GRS walls in locations where granular backfills are impractical or economically unfeasible.

The wall facing system in GRS walls can vary and typically includes concrete panel facings, modular block facings, segmental block facings, or wraparound facings. In this study, a geosynthetic wraparound facing system is employed, which offers flexibility and ease of construction. The seismic behavior of GRS walls can be investigated through various methods: experimental studies such as shake table tests and centrifuge tests (Ramakrishnan *et al*., 1998; Krishna & Latha, 2007), analytical approaches including pseudo-static and pseudo-dynamic analyses (Chehade *et al.*, 2021), and numerical modeling techniques like the Finite Element Method (FEM) and Finite Difference Method (FDM) (Sharma & Prashant, 2023). Among these, numerical modeling is particularly valuable when dealing with large-scale structures that are impractical to replicate in laboratory conditions. Numerical simulations provide a detailed and cost-effective means to analyze the performance of GRS walls under various loading conditions.

In this study, finite element modeling was conducted using RS2 (version 11.024) to examine the seismic performance of GRS walls reinforced with marginal backfill soils. The analysis included variations in reinforcement stiffness (810.2 kN/m, 1051.2 kN/m, and 1420 kN/m) and backfill cohesion (5 kPa, 10 kPa, and 16 kPa). The research focused on understanding the failure mechanisms, deformation behavior, and stress distribution within the GRS wall system under seismic loading conditions. Key parameters such as wall face displacement, acceleration amplification along the wall height, and potential failure surfaces were evaluated, with particular attention given to the influence of reinforcement stiffness and the shear strength properties of the marginal backfill.

2. MATERIAL PROPERTY

2.1 Backfill material

Marginal soil can be defined as the soil having fines greater than fifteen percent or having plasticity index more than 6 as per FHWA (2009) guideline. In the present study, as already mentioned, marginal soil with varying cohesion are used as backfill material to investigate its influence while the other parameters are kept constant. The backfill soil is modelled as Mohr-Coulomb material that follows a non-associated flow rule (i.e. dilation angle is less than angle of internal friction of backfill soil during shearing).

2.2 Reinforcement material

The geotextile reinforcement is modelled using the geosynthetic liner elements available in RS2 finite element-based program. In this particular study, the geotextile reinforcement stiffness varied from 810.2 kN/m to 1420 kN/m. The geotextile element behaves as an isotropic linear-elastic material with no failure limit.

2.3 Interface characteristics

The interaction mechanisms between marginal backfill and geosynthetic material have been examined through pullout tests by Abdi and Arjomand (2011) and Esmaili *et al*. (2014). The interface between the geotextile and backfill soil material is modeled as per Mohr-Coulomb (M-C) criteria to describe the slippage of soil-geotextile interface. The interface system modeled using available joint property in RS2. The required input parameters are adhesion (c_a), angle of internal friction (φ), dilation angle (ψ), shear stiffness (k_s) and normal stiffness (k_n). The interface properties are adopted as reported by Yu *et al.* (2016).

3. FEM model of wraparound wall face

A two-dimensional finite element model is developed to study the seismic performance of GRS wall under dry conditions. The height (H) of the wall is 6 m with a vertical face (without a batter angle), and geotextile is used as reinforcement material in the wall. The wall is constructed with an equal lift of 0.3 m and geotextile us used as a wraparound to form the facing for each lift, having a wrap tail length of 0.6 m. The length of reinforcement is adopted as mentioned in earlier studies by Kilic *et al.* (2021), wherein the range (0.6-0.8)H is established for marginal soil backfill. In the present study, a 4.2 m length of reinforcement (i.e., 0.7 times the height of the wall) is used, as shown in Fig. 1.

A FE model requires proper implementation of boundary conditions. In accordance, the fore and far back end of the model is fixed in horizontal directions (roller connections) but permitted to move in vertical direction to allow the possible settlements. The lowermost part of the model is restricted from movement in both vertical and horizontal directions.

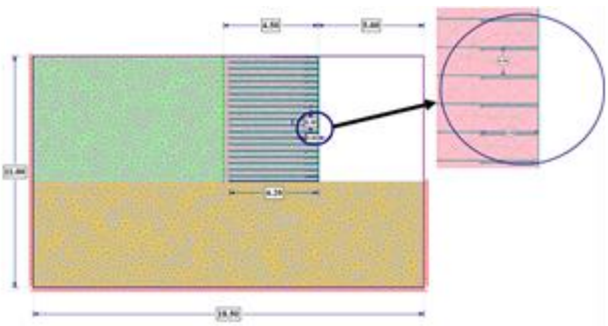


Fig. 1. Wraparound faced GRS wall FEM model

4. SEISMIC ANALYSIS

Seismic response of a wraparound faced GRS wall with marginal backfill soil is computed using RS2 software. The 1995 Kobe strong motion is used for the dynamic analysis and PHA of 0.344*g* (obtained from the same motion) is used as used coefficient of horizontal acceleration for pseudo-static analysis. In the present study, both static and pseudo-static analyses are also conducted to understand their corresponding discrepancy with the outcomes from dynamic analyses.

5.RESULTS AND DISCUSSION

This study analyzed the dynamic behavior of geosynthetic wraparound face walls reinforced with marginal backfill soils. The analysis included 27 models representing different combinations of backfill cohesion and reinforcement stiffness across various analysis types. However, for the sake of brevity, instead of providing details of every analyses separately, a selection of representative plots are included to effectively illustrate the key findings and trends. For each model, a stability check is conducted, and the critical strength reduction factor (SRF) for each model is determined, as shown in Table 1.

Table 1 SRF of numerical models with variations in backfill cohesion and reinforcement stiffness

		Reinforcement stiffness (kN/m)		
Cohesion (kPa)	**Analysis Type**	**810.2**	**1051.2**	**1420**
5	Static analysis	1.9	1.9	1.93
	Pseudo-static analysis	0.49	0.55	0.53
10	Static analysis	2.32	2.35	2.4
	Pseudo-static analysis	0.73	0.75	0.76
16	Static analysis	2.56	2.59	2.63
	Pseudo-static analysis	0.85	0.86	0.89

The results reveal that irrespective of the cohesion of the marginal backfill, the SRF of the wrap-face GRS wall improves with increasing reinforcement stiffness. This is attributed to the ability of stiffer reinforcements to distribute applied loads more uniformly throughout the soil mass. The even distribution of stresses reduces localized stress concentrations, which are potential triggers for failure. Additionally, the increased backfill cohesion enhances the soil's shear strength, further contributing to stability by mitigating lateral earth pressures acting on the wall. It may be noted for a particular backfill cohesion, the increase in the SRF is not as significant as is obtained with the change in the backfill cohesion. This indicates that the backfill cohesion (that naturally changes the stability of the reinforced fill medium by increasing its strength) is more influential in affecting the SRF than the reinforcement stiffness when marginal backfill is used in the GRS walls.

5.1 Lateral displacement of GRS wall

The lateral displacement of the GRS wall with wraparound face is analyzed for nine combinations of backfill soil strength parameters (cohesion, *c*) and geotextile reinforcement stiffness across all analysis types (i.e., static analysis, pseudo-static analysis, and dynamic analysis). Horizontal displacement results from static analyses reveal that the maximum displacement decreases with cohesion due to the increased shear strength of the soil. Fig. 2 shows the magnitude of lateral displacement for static, pseudo static and dynamic analysis (35th second; towards the end of strong motion) separately.

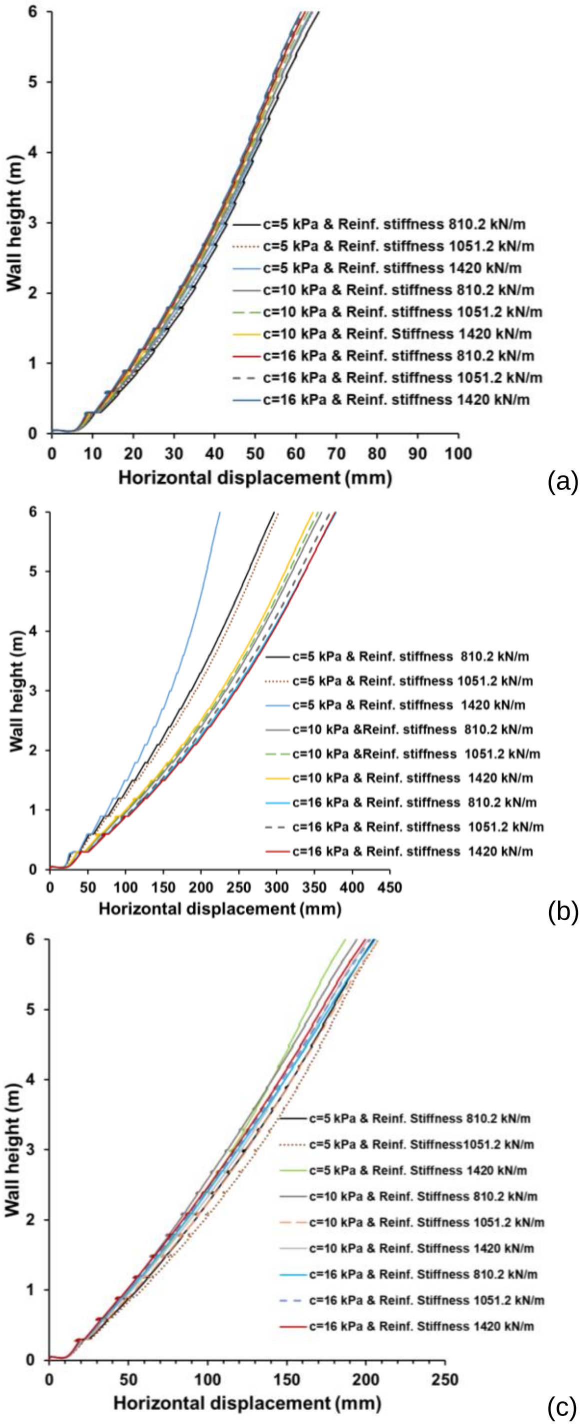


Fig. 2. Lateral displacement at wall face for (a) Static (b) Pseudo-static (c) Dynamic analyses

In pseudo-static and dynamic analyses, the lateral deformation tends to increase compared to static analysis due to the additional seismic forces considered, which amplify lateral earth pressure acting on the wall. These forces induce higher stress levels within the backfill soil, resulting in larger deformation.

Under pseudo-static scenario, marginal soil backfills with higher cohesion exhibit higher deformation. This is attributed to that fact that an increase in the cohesion of the marginal fill tends to induce relatively brittle behavior and thus becomes relatively poor in redistributing the stress (i.e. lateral earth pressure) effectively, thereby resulting in large deformation. However, in the case of dynamic loading, the marginal backfills exhibit lesser lateral deformation owing to their ability to resist small strain cycle and ability to dissipate energy during dynamic loading through internal damping, as can be viewed in Fig. 2. On the other hand, increment of reinforcement stiffness resulted with less lateral wall face displacement in all the case of analysis types.

5.2 Acceleration amplification

As shown in Fig. 3, the acceleration amplification factor at the end of the reinforcement, measured 4.4 m away from the wall face, indicates that in the bottom one-third of the wall structure, there is no significant amplification or de-amplification. This behavior is attributed to the stiffness provided by the surrounding soil, which effectively restrains variations in acceleration in this region. In contrast, at the wall face, measured 0.5 m from the top of wall, the amplification factor consistently exceeds 3, regardless of variations in backfill cohesion. This higher amplification near the wall face suggests that the soil and reinforcement closer to the face experience greater dynamic forces due to reduced restraint compared to the regions further from the wall face. Ling *et al.* (2003) noted that an amplification ratio exceeding 3 leads to significantly increased stresses on the reinforced wall structure. This effect becomes particularly pronounced near the top of the wall, both at the end of the reinforcement and at the wall face, especially in the upper one-third of the structure.

5.3 Lateral stress distribution

The lateral stress distribution contour shows that higher stresses occur at the bottom one-third of the wall due to the greater overburden of backfill soil. Near the wall face, no stress concentration is critically observed as shown in Fig. 4, which is attributed to the flexible behavior of the wraparound geotextile that allows stress relaxation.

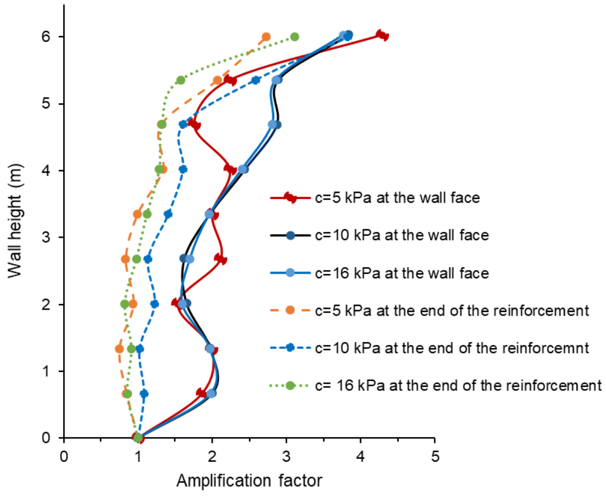


Fig. 3. Acceleration amplification factor along wall height

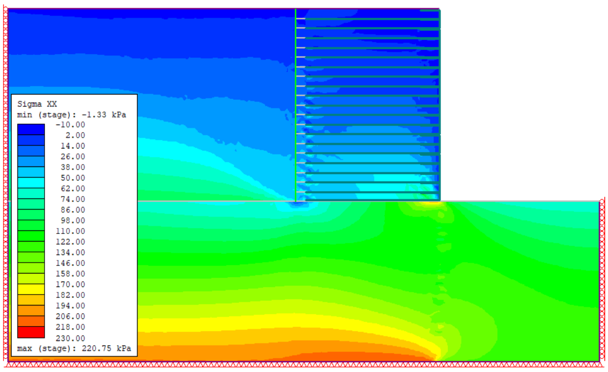


Fig. 4. Horizontal stress countours in the GRS wall model

5.4 Peak reinforcement load

The peak reinforcement load along each reinforcement layer is plotted against the wall height to identify the type of failure in the reinforcement, either pullout or tensile failure, based on the variations in cohesion and reinforcement stiffness. The plot is designed to illustrate the maximum mobilized reinforcement load and pinpoint the probable failure locations within the reinforcement layers. For a reinforcement stiffness of 810.2 kN/m, the maximum reinforcement loads for a backfill with cohesion values of 5 kPa, 10 kPa, and 16 kPa are presented in Fig. 5.

In case of dynamic analysis, it is found that the mobilized reinforcement load decreases with increasing backfill cohesion. This reduction is attributed to the fact that enhanced cohesion in the backfill soil reduces the soil-reinforcement interaction and, consequently, the mobilized load. Conversely, in pseudo-static analysis, the mobilized reinforcement load increases with higher backfill cohesion. This behavior is due to the significant displacement caused by inertia effects, particularly in the lower one-third of the reinforcement layers, where tensile failure becomes dominant.

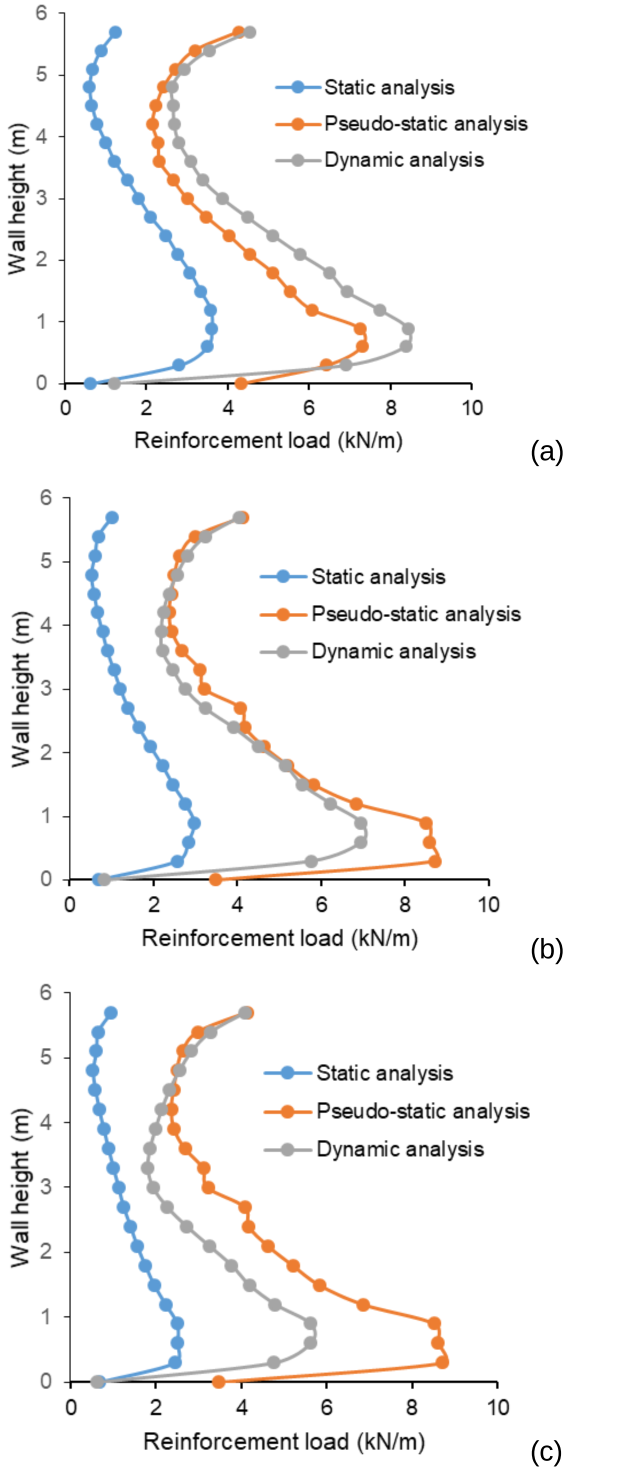
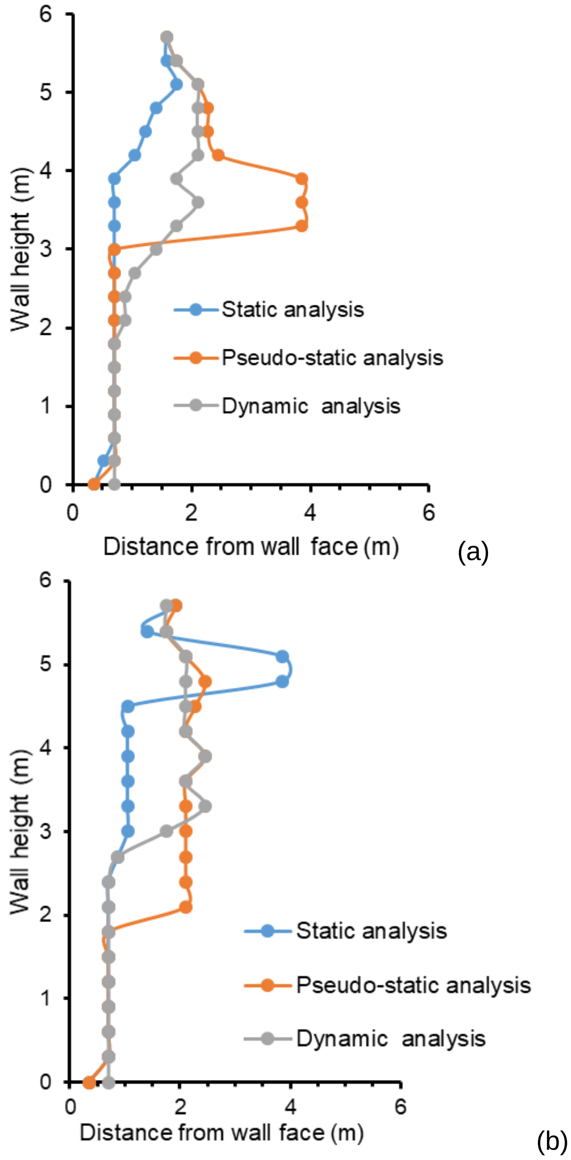


Fig. 5. Mobilized peak reinforcement load for GRS wall with backfill cohesion (a) 5 kPa (b) 10 kPa (c) 16 kPa

5.5 Potential failure surface

The potential failure surface, representing the locus of maximum axial loads in each layer of reinforcement, across all analysis cases, reveals important trends influenced by the backfill cohesion. It is noted that irrespective of backfill cohesion, the failure surface in the bottom one-third of the structure consistently aligns across all types of analysis. This behavior is primarily due to the overburden pressure, which causes the reinforcement to experience tensile failure irrespective of the backfill soil properties, as illustrated in Fig. 6.

In static analysis, the failure surface near the top of the structure tends to shift further away from the wall face. This phenomenon occurs due to the combined effects of reduced overburden pressure and substantial lateral displacement at the top of the wall. These factors lead to reinforcement failure by pullout, where the reinforcement forces are mobilized away from the face of the wall. The movement of the failure surface suggests that the system's response is dominated by the interplay between soil-reinforcement interaction and the changing stress distribution along the height of the wall.



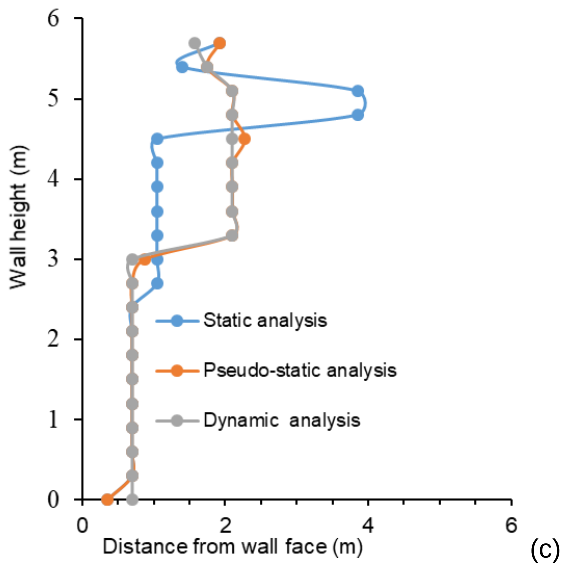


Fig. 6. Potential failure surface for GRS wall with reinforcement of stiffness 810.2 kN/m and backfill cohesion of (a) 5 kPa (b) 10 kPa (c) 16 kPa

For the GRS wall with 16 kPa cohesion for backfill material, potential failure surface profiles for both the pseudo-static and dynamic analyses aligned with each other. That is due to the fact that in dynamic analysis, the cyclic seismic forces are less likely to degrade cohesive bonds as compared to purely frictional soils. Thus, the failure path remains similar to that obtained from pseudo static analysis.

It is important to note that the failure surfaces in the GRS wall do not follow the conventional inclined wedge failure. This deviation occurs because the combination of cohesion in the backfill soil and seismic forces shifts the potential failure surface toward the wall facing and becomes more vertical. In GRS walls, the presence of reinforcement prevents outward bulging, forcing seismic-induced failure to follow a steeper path.

6 CONCLUSIONS

The present study investigates the stability, lateral displacement, acceleration amplification, mobilized reinforcement load, and potential failure mechanisms of wrap-face geosynthetic-reinforced soil (GRS) walls. The analysis considers variations in backfill soil cohesion and reinforcement stiffness across static, pseudo-static, and dynamic analysis types. The findings emphasize the critical role of backfill cohesion and reinforcement stiffness in determining the overall performance of GRS walls.

- Stability of wraparound face GRS walls improves with increased reinforcement stiffness and backfill cohesion, resulting in higher SRF values.
- Increased cohesion exhibits reduced lateral displacement in static analysis but illustrates increased deformation in the case of pseudo-static analysis due to inertia effects. In dynamic analysis, an increase in cohesion diminishes the effect of reinforcement stiffness on lateral displacement owing to damping.
- Backfill soils with higher cohesion exhibit reduced mobilized reinforcement loads in dynamic analysis due to reduction in the soil-reinforcement interaction.
- Amplification increases at higher elevations of the wall due to decreased confinement near the upper portion.
- Stress contours show higher concentrations in the bottom one-third of the wall due to greater overburden pressure. Minimal stress noted near the wall face is attributed to flexible wraparound geotextile allowing stress relaxation.
- The potential failure surface in the bottom one-third aligns across all the analysis types that is attributed to overburden pressure. The reinforcement is expected to undergo tensile failure regardless of backfill cohesion.
- The higher cohesion content in marginal backfill GRS wall leads the potential failure surface aligned for dynamic analysis and pseudo static analyses, due to less degradation of cohesive soil in cyclic loading as compared to that obtained for cohesionless soils.
- The failure surfaces developed in GRS walls comprising marginal backfill do not customarily follow the conventional inclined planar failure wedges, especially due to the presence of reinforcement, which prevents outward bulging of the wall face.

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