Stability and Seismic Response Analysis of Geocell Reinforced Slopes based on an Equivalent Composite Approach

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ABSTRACT

Geocell-reinforced slopes have proven to be one of the most efficient techniques of slope stabilization. However, the efficacy of utilizing geocell layers as fascia or reinforcement in slopes against seismic loading is yet to be intricately ventured. In this paper, numerical plane-strain modelling of geocell-reinforced slopes is carried out to study their response against seismic loading. Both pseudostatic analysis and non-linear time-history analysis are carried out considering a chosen strong motion history. Equivalent Composite Approach (ECA) is employed in modelling the 3-dimensional geocell layer as an equivalent 2-dimensional soil-geocell composite by introducing improved strength and stiffness imparted by the geocells. The improved strength is obtained from the additional confining pressure induced by the geocell pocket boundaries. The improved stiffness of the soil-geocell composite is calculated from the stiffness of the unreinforced slope material and the tensile modulus of the geocell material. Three different configurations of the placement of geocell layers are implemented to evaluate the response, where the geocell layers are introduced in the form of fascia, reinforcement, or a combination of both. The global stability of the reinforced slope sections is analysed using pseudostatic seismic coefficients assessed through different techniques, while the acceleration response and deformation of the slope face are analysed using an acceleration-time history input. The influence of geocell layers on the hysteresis behaviour of the slope face and on the development of potential slip surfaces is also investigated to yield motion specific observations.

Keywords: geocells, hysteresis behaviour, pseudostatic factor of safety.

1 INTRODUCTION

Geocells are made of high-density polyethylene (HDPE) strips ultrasonically welded to form a 3-dimensional honey-combed structure to hold the soils within. Due to its confinement effect (Bathurst and Rajagopal, 1993), geocells exhibit a lot of advantages as a reinforcement than the other types of planar geosynthetics. Application of geocells in retaining structures has attained a huge importance. A few layers of soil-infilled geocell pockets stacked one above the other can act as a flexible retaining structure (Chen and Chiu, 2008) while it can also be used as reinforcements or to provide a proper base for other type of retaining structures or embankments (Krishnaswamy et al., 2000). In this way, geocells can be employed for both internally and externally stabilized systems. Although geocell layers are now being widely used (Cowland and Wong, 1993; Emerseleben and Meyer, 2008; Pokharel et al., 2010; Kief et al., 2011; Sitharam and Hegde, 2013; Rajagopal et al., 2014) and are observed to be performing well under static loading scenarios (Mandal and Gupta, 1994; Dash et al., 2001; Zhou and Wen, 2008; Hegde and Sitharam, 2015), intricate studies related to seismic response of slopes reinforced or retained with geocells are still required for proper utilization of its benefits.

In this paper, geocell layers are introduced in the form of reinforcement, fascia and a combination of both. Pseudostatic stability analysis is performed to assess the stability of the slope sections adopted. A chosen ground motion is applied to study the non-linear response of the slope geometry in comparison with the natural slope. Geocell infilled soil layers are modelled as a composite soil using Equivalent Composite Approach (ECA) (Bathurst and Knight, 1998; Latha and Somawanshi, 2009; Hegde and Sitharam, 2013; Mehdipour et al., 2013; Jayanthi et al., 2022). Case specific observations have been made with respect to pseudostatic and seismic analysis of all the slope configurations adopted.

2 MODEL SPECIFICATIONS

The 2D plane-strain numerical model employed in this study has a slope face inclination of 40°. Geocell layers of 0.25 m thickness are used in the slope geometry

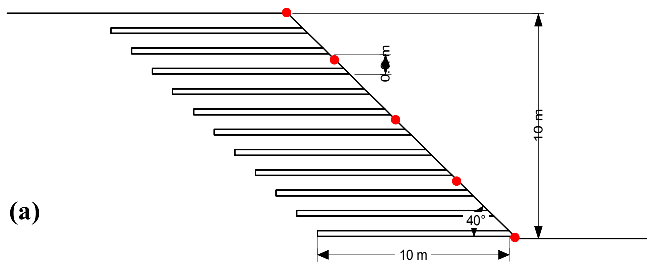
https://doi.org/10.3208/jgssp.v10.OS-14-04

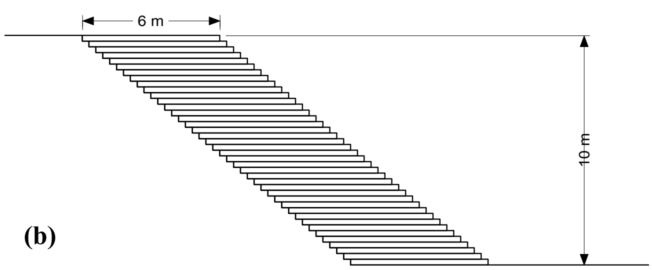
and the analyses are performed for four different reinforcement configurations: 1. Natural or Unreinforced slope (UR), 2. Reinforced Slope (R), 3. Slope with Fascia (F) and 4. Slope with Fascia and Reinforcement (F + R).

In the slope sections where geocells are used as fascia, the layers are placed just at the toe level and raised till the crest. The details of the slope geometry are given in the Fig. 1. All the three slope sections are designed by providing different length of reinforcements and fascia layers to achieve similar FOS under static conditions. The mesh element size is chosen after a thorough mesh sensitivity analysis for each slope configurations and it follows the criteria suggested by Kuhlemeyer and Lysmer (1973) for wave propagation problems. Further, local refinement has been done for the mesh elements around the geocell layers. The 3-dimensional structure of geocell layer infilled with soil is modelled as two-dimensional composite soil layer using Equivalent Composite Approach (ECA) with the composite soil having improved strength (Rajagopal et al., 1999) and stiffness (Latha, 2000) properties than the natural soil as mentioned in Table 1.

Table 1. Material Properties (Ujjawal and Hegde, 2020)

Parameters	Natural Soil	Composite Soil
Cohesion, *c* (kPa)	5	33
Internal friction angle, ϕ (˚)	32	32
Shear Modulus, *G* (MPa)	7.28	15.95
Damping ratio, ξ (%)	2.06	5.45
Poissons ratio, ν	0.33	0.33





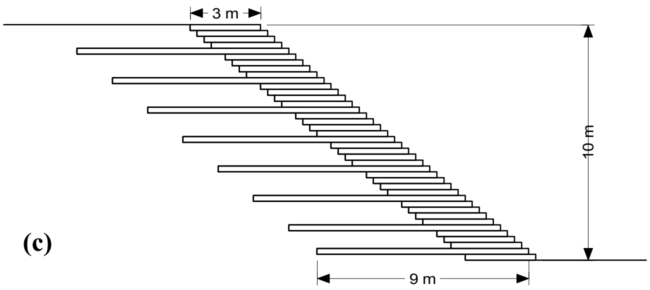


Fig. 1. Slope configurations with geocell layers as (a) Reinforcements, (b) Fascia and (c) Fascia and Reinforcement.

3 SESIMIC LOADING

3.1 Non-linear time history input

Seismic waves are applied at the base of the numerical model by inputting the acceleration time history curves of 2015 Nepal Gorkha earthquake ground motion (PGA = 0.186 g) whose time history and Fourier spectra are shown in the Fig. 2.

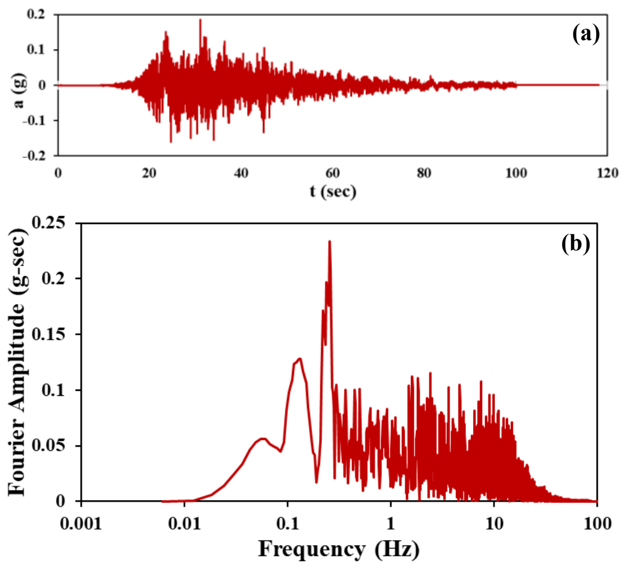


Fig. 2. (a) Acceleration time history and (b) Fourier spectra of 2015 Nepal Gorkha earthquake.

3.2 Pseudostatic seismic coefficients

Horizontal seismic coefficients used to perform pseudostatic stability analyses are obtained using four different techniques. These include 1. Effective Acceleration (EA) obtained using the significant duration proposed by Trifunac and Brady (1975), 2. Effective acceleration using Bolt’s method (Bolt, 1969), 3. Sustained Maximum Acceleration (SMA) and 4. Indian Standard Code (IS 1893: 2016). EA and SMA are calculated corresponding to the Nepal Gorkha ground motion. Table 2 gives the values of the seismic coefficients calculated through different techniques.

Table 2. Pseudostatic seismic coefficients

	Seismic coefficients
Trifunac and Brady (1975)	0.027
Bolt (1969)	0.031
Sustained Maximum Acceleration (SMA)	0.156
IS 1893: 2016	0.18

4 SEISMIC RESPONSES

Seismic responses of all four slope sections (UR, R, F and FR) have been analysed. Responses at the slope face are recorded in terms of peak values of acceleration, displacement, lateral stress and strain generated during the earthquake motion (Fig. 3). Five monitoring points are located and their responses are plotted along the slope height.

4.1 Acceleration and Displacement response

The response values of peak acceleration increased from toe to crest signifying the occurrence of acceleration amplification as the seismic wave propagates from toe to crest. Similarly, the displacement response is also increased by a considerable amount as the seismic wave propagated towards the crest.

The peak response recorded for acceleration as well as displacement is almost the same for all cases of reinforcement conditions. This is attributed to the design of slope sections for similar stability criteria causing the slope sections to exhibit similar responses when subjected to a strong motion.

It can be observed that the inclusion of geocell layers in any form did not change the acceleration as well as the displacement response of the slope face (Fig. 3a and 3b). This observation is only with respect to the earthquake motion chosen in this study but not for a generalized design. It is a common notion that application of geocell layers in slope sections would expectedly improve the performance of the slope by reducing the acceleration and displacement than that experienced by the system in its natural state. Hence, the particular observation made in context of this earthquake motion seems more motion-specific rather than a generalized one. Further studies would be required with other earthquake motions to reach a more intricate understanding.

4.2 Peak lateral stress and strain response

It is observed that the lateral stress and strain exerted at the slope face are controlled by a significant amount due to the presence of geocell layers. It can be observed from Fig. 3(c) and 3(d) that the slope geometries with geocell layers as fascia have experienced a notable reduction in lateral stresses and strains at the slope face.

In addition, the toe region of natural slope experiences the higher stresses and strain level. It is understood that the seismic waves propagate from the base to first reach the toe part before travelling towards the crest. During this process, the stresses developed get distributed, exerting a relatively lesser stress and strain level at the crest. Furthermore, the slope sections with geocell layers also experiences higher lateral stresses at the toe region much greater than the natural slope. The geocell layers placed at the toe level increase the stiffness and act as stress attractors. Placement of a few more geocell layers beneath the toe is expected to avoid such occurrence of lateral stress concentration at the toe.

From all these 4 plots, it can be stated that the lower half of the slope face exhibits more flexibility as indicated by larger increment in amplification and stress-strain behaviour, thereby indicating larger relative response in comparison to the upper part of the slope. This indicates that more attention is needed to arrest the seismic response towards the toe of the slope.

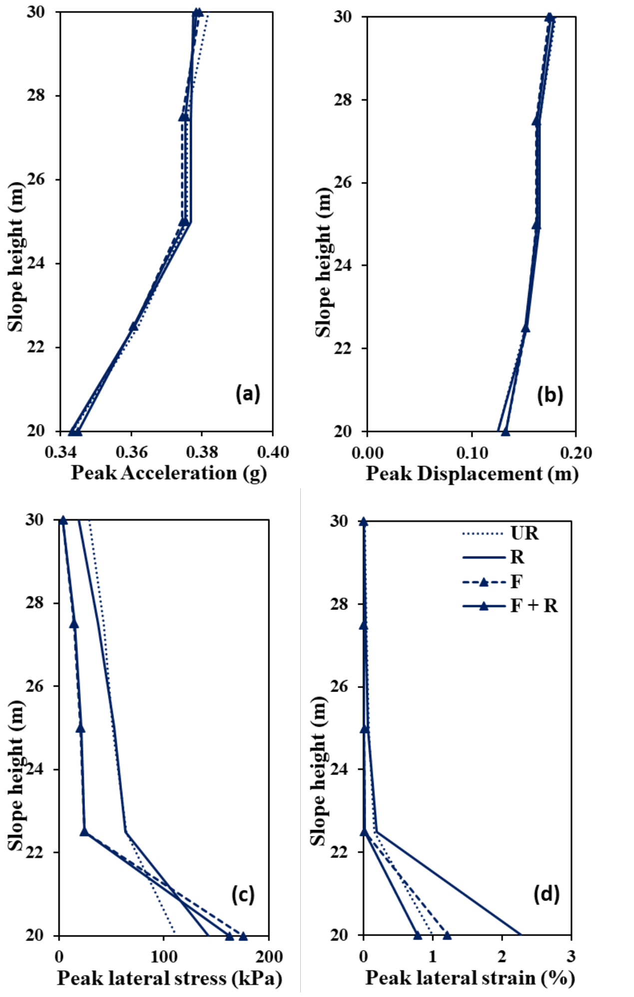


Fig. 3. Responses of slope face for different geocell configurations.

4.3 Hysteresis behaviour of the slope face

Hysteresis curves have been plotted for points at crest, mid-height of the slope face and toe for every slope configuration to study the shear behaviour of the slope face during the earthquake motion.

Fig. 4(a) shows the hysteresis curves of crest for all four reinforcement configurations. All the hysteresis curves are plotted starting with the existing stress and strain conditions before the application of the input motion. Hence, the hysteresis loops can be noticed to be located at different levels of shear stress.

It is evident that the unreinforced slope has covered wider range of shear stress as well as shear strain. The crest point has experienced the minimum amount of shear stress when geocell layers are laid in the form of reinforcements. Further, the cases ‘F’ and ‘F + R’ have the minimal shear strain experienced but with shear stress higher than the reinforced case. It can also be noted that the shear stiffness of the slope section has increased due to the presence of fascia.

At the mid-height of the slope, there is no difference in shear behaviour between the unreinforced and the reinforced slope. However, with fascia, the soil elements at the mid-height of the slope face shifts to a lower stress state for a given strain level.

When it comes to the shear behaviour of the toe region, the hysteresis loop shifts laterally to a higher strain level soon after the occurrence of PGA. This is true for the unreinforced and reinforced case. In the cases with fascia, the hysteresis loop has shifted diagonally indicating the increase in shear stress experienced post-peak and a strain level that is much lesser than the unreinforced and reinforced sections.

As a whole, it is notable from all three points of the slope face that geocell layers as fascia reduce the strain level experienced by the elements of the slope face. Moreover, introducing geocell layers as fascia increases the shear stiffness of the elements at the slope face.

It can also be observed from the shear behaviour of all three monitoring points that the crest point remains in elastic state exhibiting linear behaviour throughout the seismic motion. This behaviour is observed even in the case of natural slope where no stabilization has been implemented. The strain percentage is even very minimal for the crest point to stay in an elastic state. Towards the bottom of the slope, the soil elements in the free surface exhibits a non-linear behaviour which is very obvious in the toe region. Presence of geocell layers also reduces the initial conditions of shear stresses prevailing in the system even before the instance of the input motion.

Fig. 5 shows the evolution of shear stress during the earthquake for crest, mid-height and toe of the slope section with fascia ‘F’. In order to obtain a clear view of the shear stress time histories, the in-situ stress state is considered as the initial shear stress magnitude. Due to the directivity of the developed shear stresses in relation the Cartesian coordinate system, the in-situ stresses are obtained negative at the specified points. On a relative scale to the in-situ shear stress, the shear stress magnitudes would have extended in both positive and negative directions. Among the three locations, crest experiences the minimum stress reversal while the toe region behaves non-linearly covering a wider range of shear stresses during the stress reversal. A clear transition of stress change is seen between the initial and the final residual stress persisting around the toe.

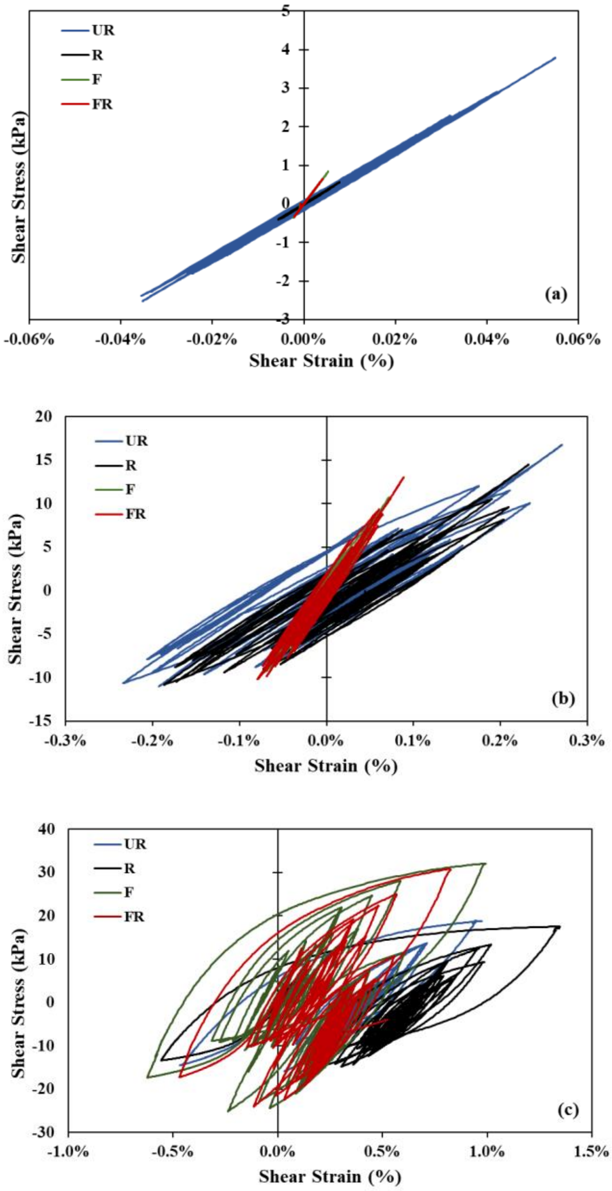


Fig. 4. Hysteresis curves for (a) Crest, (b) Mid-height and (c) Toe.

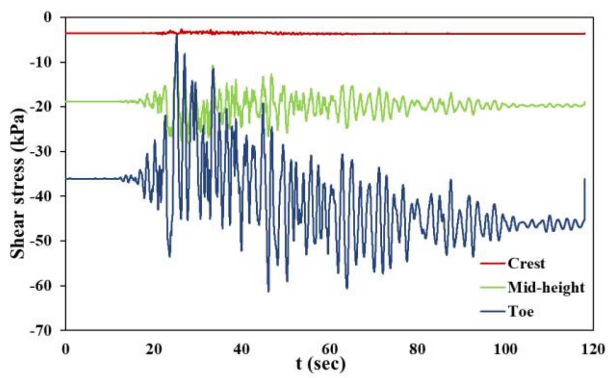


Fig. 5. Shear stress time histories of Crest, Mid-height and Toe for fascia ‘F’.

5 PSEUDOSTATIC STABILITY ANALYSIS

Stability analyses have been carried out for all slope configurations using the seismic coefficients calculated through different techniques, as mentioned in Table 2. Effective and sustained maximum acceleration is obtained corresponding to the chosen ground motion. The seismic coefficient calculated according to IS 1893:2016 is based on the zone factor allotted to different seismic zones of India. The zone factor chosen in this study is for seismic zone V indicating the maximum seismically active zone.

Factor of safety (FOS) obtained by applying the seismic coefficients to different slope configurations has been shown in Fig. 6. It can be noticed that any of the geocell applications adopted herein has led to the increase in the stability of the slope as compared to its unreinforced state. Interestingly, it is observed that all three reinforcement configurations have almost the same value of FOS for a given seismic coefficient. It is owing to the fact that all three slope sections are designed to achieve similar FOS under static conditions and thereby, when subjected to pseudostatic loading, it yields similar FOS. However, given different geometric configurations as mentioned, the critical slip surfaces of each of the three slope sections would be different.

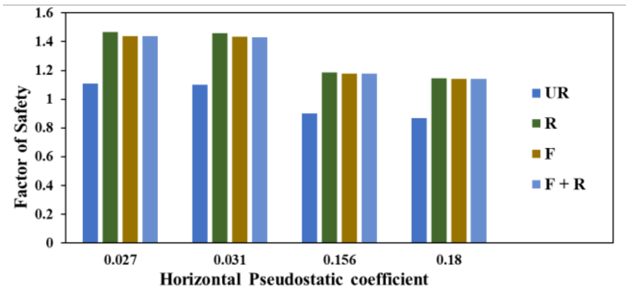


Fig. 6. Factor of Safety with respect to different pseudostatic coefficients.

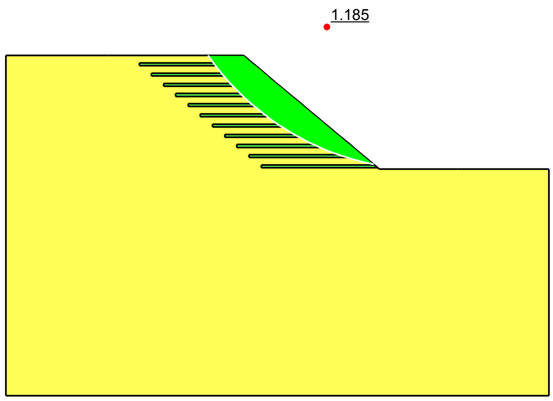


Fig. 7. Slope section with geocell reinforcement 'R' for $k_h = 0.156$.

Fig. 7 shows the critical slip surface and the corresponding factor of safety of reinforced slope 'R', in the case of sustained maximum acceleration ($k_h = 0.156$).

Application of geocells is increasing the global stability even under seismic conditions. However, further studies are required to understand the reason behind similar FOS for all the different configurations adopted. Although the shear behaviour of the slope face is predominantly controlled by the presence of fascia, when it comes to the global stability of the slope, geocell layers as reinforcements also come into effect as it intervenes the generation of the potential slip surfaces.

6 CONCLUSIONS

By using different types of configurations in applying geocells in the slope face, the motion specific observations revealed no significant alteration in the acceleration and displacement responses. However, the utilization of reinforcements played a role in the dissipation of lateral stresses and strains at the free surface of the slope. It is believed that this would depend on the strong motion characteristics and further studies with different such characteristics would be required to arrive at a generalized observation.

Proceeding from crest to toe, the behaviour of the free surface of the slope face changes from elastic to non-linear especially beneath the mid-height of the slope under non-linear dynamic analysis.

Pseudostatic analysis revealed that geocells placed only as reinforcements too contributes to the global factor of safety of the slope section while the shear behaviour of the slope face was predominantly controlled by the presence of geocell layers as fascia.

Slope sections designed for a similar stability criterion under static loading conditions yield similar FOS and seismic responses under pseudostatic and seismic loading scenarios respectively.

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