PARAMETRIC STUDY ON BEHAVIOUR OF REINFORCED SOIL WALLS WITH COMBINED HORIZONTAL AND VERTICAL GEOSYNTHETICS

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ABSTRACT

The reinforced soil system employing geogrids, as a cost effective reinforcement technique, has come to play an important role in a variety of civil and geotechnical engineering applications. In regular reinforced soil walls, the reinforcements are usually laid horizontally in the soil. In this study, the behaviour of reinforced soil retaining walls with combined horizontal and vertical reinforcements are investigated experimentally as well as numerically. The results, indicating the effects of vertical reinforcement inclusion, are compared to conventional reinforcing types under static and dynamic loads. The performance of retaining walls employing vertical reinforcement in conjunction with horizontal reinforcement is convincing from the results of the shake table tests conducted by the authors. In this paper, PLAXIS, well-known geotechnical software, is used for conducting a series of parametric studies on behaviour of reinforced soil walls under construction and subject to earthquake loading, incorporating the vertical reinforcement. The vertical reinforcement layout and its strength are among the major variables of the investigation. The geometry of the model, soil properties and reinforcement characteristics have been kept identical in all different cases selected for parametric studies. The performance of the wall is presented for the facing deformation and crest surface settlement, lateral earth pressure, tensile force in the reinforcement layers and acceleration amplification. The vertical deformation, horizontal deflection, reinforcement force and earth pressure develop drastically under earthquake loading compared to the end of construction. The results show that these variables are considerably reduced when incorporating the vertical reinforcement in the system. In addition, the findings suggest better performance and higher structural safety for reinforced soil walls, when employing this proposed orthogonally horizontal-vertical geosynthetics.

1 INTRODUCTION

Reinforced soil walls have been built over the past several decades. Their growing acceptance over its conventional counterparts is mainly due to its cost effectiveness, which includes low material cost, short construction period, and ease of construction. Moreover, its acceptance has also been triggered by a number of technical factors, including aesthetics, reliability, simple construction techniques, good seismic performance, and the ability to tolerate large deformation without structural distress. According to Lo (2003), the construction of geosynthetic reinforced soil (GRS) walls in Australia started in the mid-eighties, while the construction of GRS walls for roads and rails commenced in 1991.

Case histories have indicated that properly built GRS walls performed better than traditional retaining walls during the previous large earthquakes (Hoe and Dov, 2005). Indeed, the satisfactory seismic performances of GRS walls may have contributed to the conservatism implemented in the latest practical design and analysis of these structures. The seismic responses can be examined by means of physical model tests or numerical modelling studies. Since it is uneconomical and impractical to examine the seismic response of a GRS wall via a series of full scale tests, using different types of soils and reinforcements under various seismic loads, a more cost effective and practical approach can be employing a reduced scale test followed by numerical modelling. Subsequently the numerical predictions should be validated based on physical model tests under controlled conditions.

A comprehensive numerical and experimental study has been conducted at the University of Technology, Sydney (UTS) to investigate the enhanced performance of reinforced soil wall by inserting vertical fortification under dynamic loads (Shrestha et al., 2011; Shrestha, 2013). To achieve the research objectives, the following methodologies were adopted:

1. Integrating past studies on the performance of GRS walls under seismic loads comprising case histories of post-earthquake investigations, physical model tests, and numerical modelling of GRS walls
2. Developing the concept of vertical reinforcement insertion in reinforced soil system, based on soil mechanics theories and analysing potential field construction procedures
3. Pre-verification of the concept of vertical reinforcement, using the finite element method, before commencing extensive laboratory experiments to evaluate the enhancement of reinforced soil wall with vertical reinforcement inclusion
4. Developing a meticulous methodology for constructing physical models, materials selection, model instrumentation and input parameters determination for dynamic experiments, using a large-scale shake table
5. Carrying out shake table tests and analysing the results of four different models, including: (i) a horizontally reinforced wall without vertical reinforcement, (ii) with vertical reinforcement, (iii) with reinforcement inclined towards the facing and (iv) with reinforcement inclined against the facing
6. Analysing the behaviour of GRS walls with PLAXIS software to compare the results against measurements, obtained from the experimental tests
7. Conducting parametric studies by varying the essential design parameters such as the soil friction angle, the reinforcement spacing and the stiffness of the backfill soil.

In this paper items 2 and 7 are presented to illustrate the advantages of using a combined horizontal and vertical reinforcements in retaining walls. The experimental program results and model validation procedures will be published in the follow up paper.

2 FINITE ELEMENT MODEL

The finite element program PLAXIS 2D Version 9.0, was used for a two-dimensional analysis of deformation and stability analyses. The 2D Dynamics module and 15-node triangular elements were employed to analyse the propagation of waves through soil and their influence on retaining structures. This module provides a detailed analysis of seismic loading and vibrations due to construction activities. The wall was assumed to be 10 m high, with an inclined facing of 1(H) in 20(V), and had 7 m long reinforcement. This reinforced soil wall was modelled for a total height of 10 m to ensure an adequate distance from the assumed rough/rigid bottom boundary condition to the zone of influence was provided due to the construction of the wall. To increase the accuracy of outputs, the effect of stiffness on the boundary, 30 m below the surface, was considered, so the soil on the front and back sides were fixed at 30 m and 20 m, respectively. Because compaction close to the facing elements is usually poor, 0.5 m of soil in that vicinity (i.e. facing soil) was considered to be weaker than the rest of the reinforced soil.

Table 1: Sand and interface properties

Parameter	Name	Reinforced soil	Ground	Backfill	Facing	Unit
Material model	Model	Mohr-Coulomb				-
Type of material behaviour	Type	Drained				-
Soil unit weight	γ_{unsat}	19	18	17	17	kN/m^3
Young's modulus	E_{ref}	60000	50000	40000	30000	kPa
Poisson's ratio	ν	0.3	0.2	0.3	0.3	-
Cohesion	c	0.5	0.5	5	5	kPa
Friction angle	ϕ	38	33	30	32	degree
Dilatancy angle	Ψ	4	3	2	4	degree
Interface reduction factor	R_{inter}	0.85	0.75	0.67	0.7	-

The sand and interface properties of the model are given in Table 1. The initial geo-static stress in the foundation of the soil was based on its unit weight and the effective coefficient of lateral earth pressure at rest for each layer. There were four types of soil in the model, namely: backfill soil, reinforced soil, facing soil and natural ground. The reinforced soil was the material to be compacted between the layers of geogrids, the fill material was used as backfill between the reinforced soil wall and the natural ground, and the facing soil represents the relatively less compacted soil close to the facing elements. Interface reduction factors in the range of 0.67-0.85, were assumed for the interface between the soils and reinforcement, and the soils and facing elements. The interface reduction factor (R_{inter}) has been taken into account for the strength and stiffness decrease of the interface element in the corresponding soil layer. R_{inter} serves the model as a reduction factor in the soil-structure interface by reducing the cohesion (c), the friction angle (ϕ) and the shear modulus (G) values.

For vertical reinforcement modelling, the use of geogrid elements cannot represent the proposed vertical reinforcement, because it represents a planner form of reinforcement. The proposed reinforcement is similar to an anchor connecting two consecutive horizontal layers, which only works in tension, similar to other types of reinforcement. Therefore, node to node anchor was chosen in the numerical analysis. An anchor element designed in PLAXIS 2D version 9.0 should have both tensile and compressive strengths, but the additional reinforcement being proposed can only be activated in the case of tensile forces. Therefore, the values for compressive strength were chosen to be very small, because the program would not run for zero values in anchors. The vertical reinforcement, horizontal geogrids, and facing wall parameters are given in Table 2. The facing wall was constructed with 750 mm high and 180 mm thick concrete slabs.

Table 2: Properties of the vertical reinforcement and geogrids

Elements	Parameter	Symbol	Value	Unit
Vertical Reinforcement	Normal stiffness	EA	1500	kN
	Spacing out of plane	L_s	1	m
	Strength	$F_{max, compression}$	0	kN
		$F_{max, tension}$	2.5	kN
Horizontal Geogrids	Normal stiffness	EA	5000	kN/m
	Tensile strength	N_p	100	kN/m
Facing Elements	Normal stiffness	EA	7.00E+07	kN/m
	Flexural rigidity	EI	1.45E+07	kNm^2/m
	Equivalent thickness	d	0.18	m
	Load intensity	W	10	kN/m/m
	Poisson's ratio	ν	0.2	-

The values of all the interface reduction factors were chosen such that they were weaker than the two materials in contact with each other. They were reduced from 67% to 85% to reflect a reasonable reduction in the strength of the interface. The results of this analysis are discussed in detail in the next section.

The generation of plane strain mesh by PLAXIS used followed by a robust triangulation procedure to form 'unstructured meshes'. These meshes are considered to be numerically efficient compared to regular 'structural meshes'. Elements with 15 nodes provide accurate calculations of stresses and failure loads. The earthquake was modelled by imposing a prescribed displacement at the bottom boundary, and the default absorbant boundary conditions were applied at the furthest vertical boundaries to absorb outgoing waves. The generation of refined mesh is shown in Figures 1 and 2.

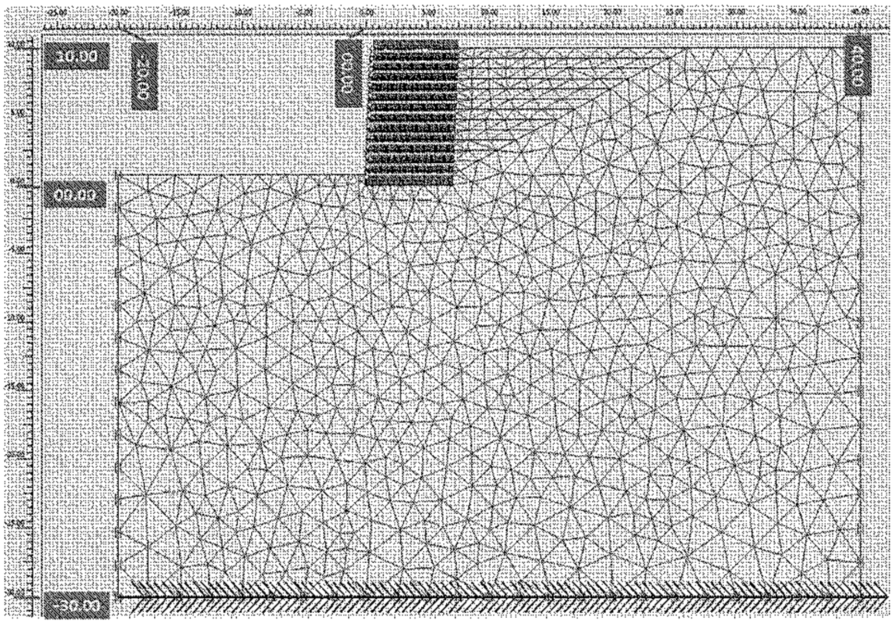


Figure 1: Plane strain finite element mesh of the model

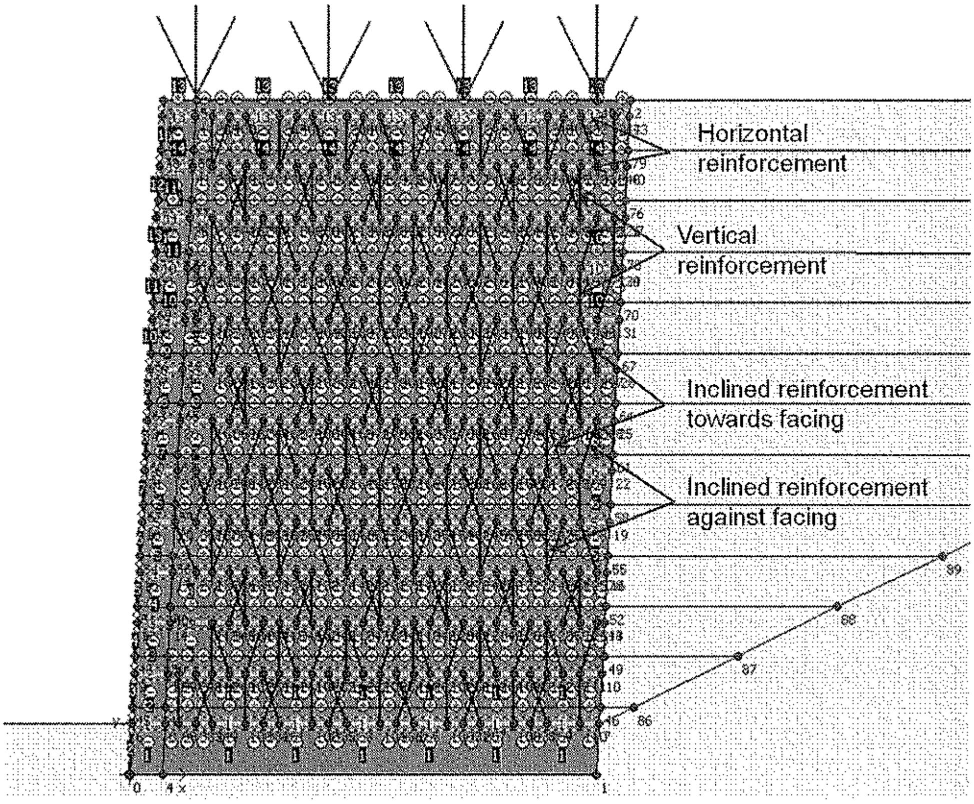
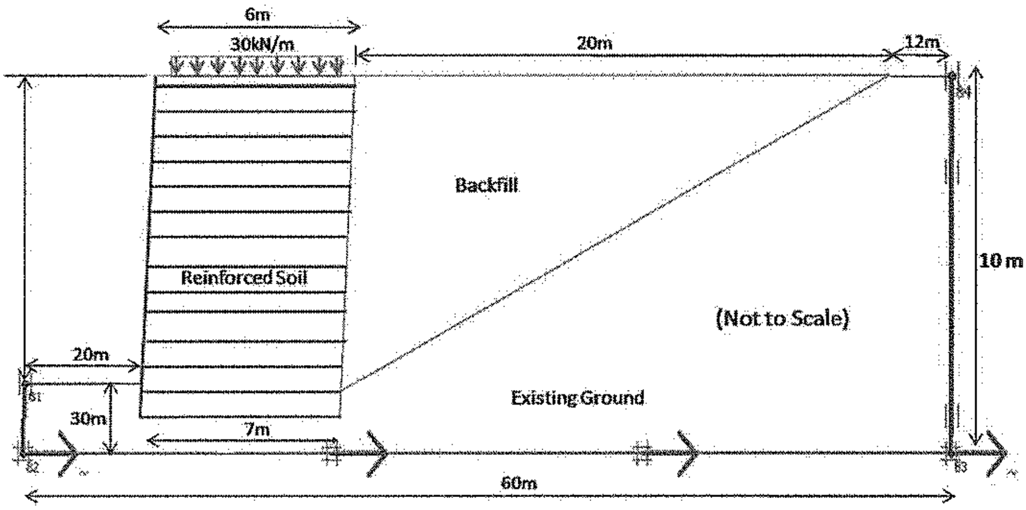
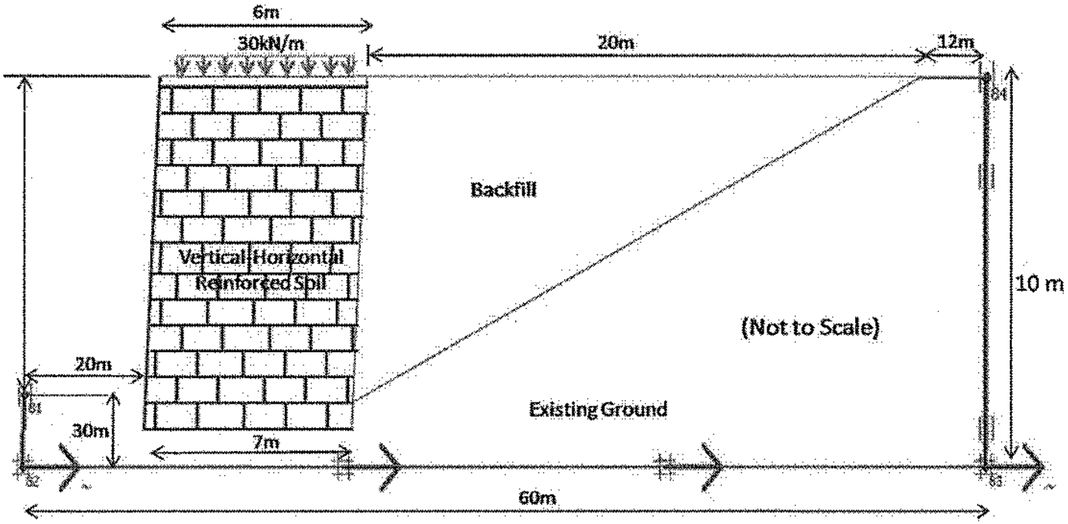


Figure 2: General model of the reinforced soil wall used in the numerical analysis

The calculations involved two stages; stage one was a normal plastic calculation, where the reinforced walls constructed; and stage two was associated with a dynamic analysis, where an earthquake was simulated. To maintain uniformity of the model in all cases, several inclined and vertical reinforcement patterns were built in the input stage, followed by the generation of mesh, and a respective pattern was chosen for the output as an exact comparison of the results in different cases. For simulating seismic loads on the models, the load of 1995 Kobe earthquake, based on a 50-second accelerogram, was used. The geometry of the numerical models is shown in Figure 3. It can be noted that reinforced walls with vertical reinforcement inclined towards the facing or inclined against the facing are not shown in this figure.



(a) Conventional horizontal reinforcement



(b) Vertical-horizontal reinforcement

Figure 3: General models of the reinforced soil wall, (a) a horizontally reinforced wall without vertical reinforcement and (b) a reinforced wall with vertical and horizontal reinforcement

Figure 4 illustrates a sample output of PLAXIS analysis for vertical deformations of a reinforced retaining wall without inclusion of vertical reinforcement in a shaded form. The horizontal and vertical displacements in each layer of the wall, from 0 to 10 m high, are shown in Figures 5a and 5b, depicting the height of the retaining wall versus deformation. The results indicate that using additional vertical elements over conventional soil reinforcement significantly reduces horizontal and vertical deformations. Overall, the findings of numerical analyses clearly indicate that the application of vertical reinforcement in a reinforced soil system enhances its performance not only under static loads but also under seismic loads. The insertion of vertical reinforcement increases the integrity of the reinforced wall, creates block actions, and reduces horizontal and vertical displacements.

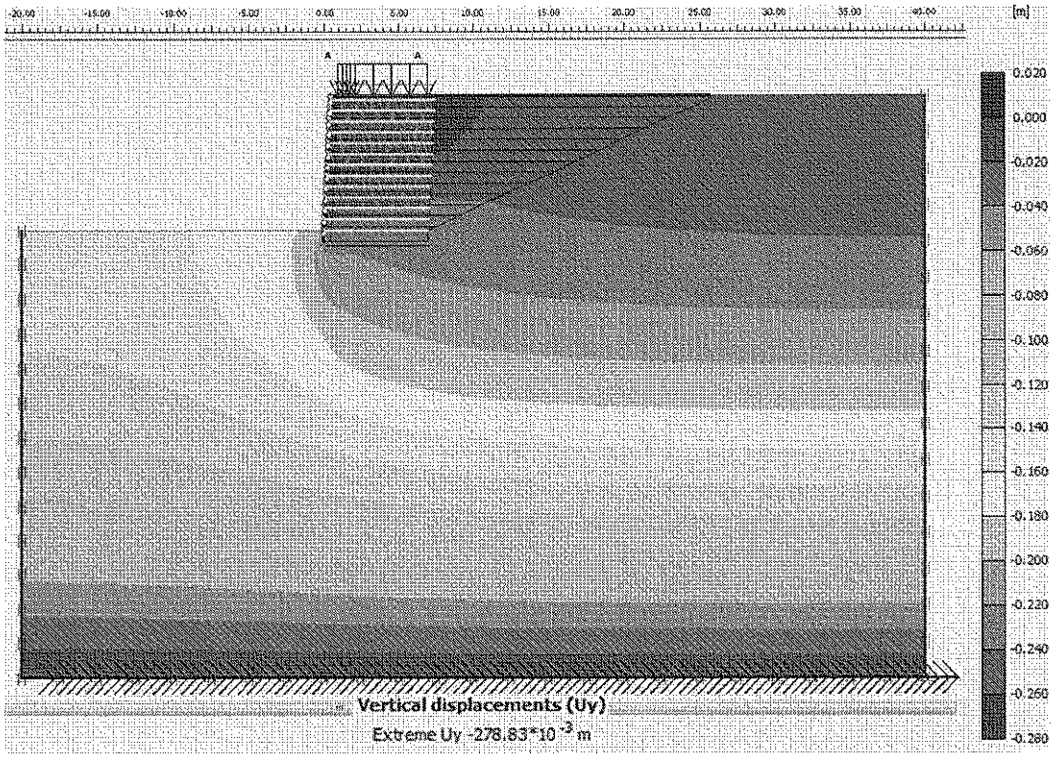
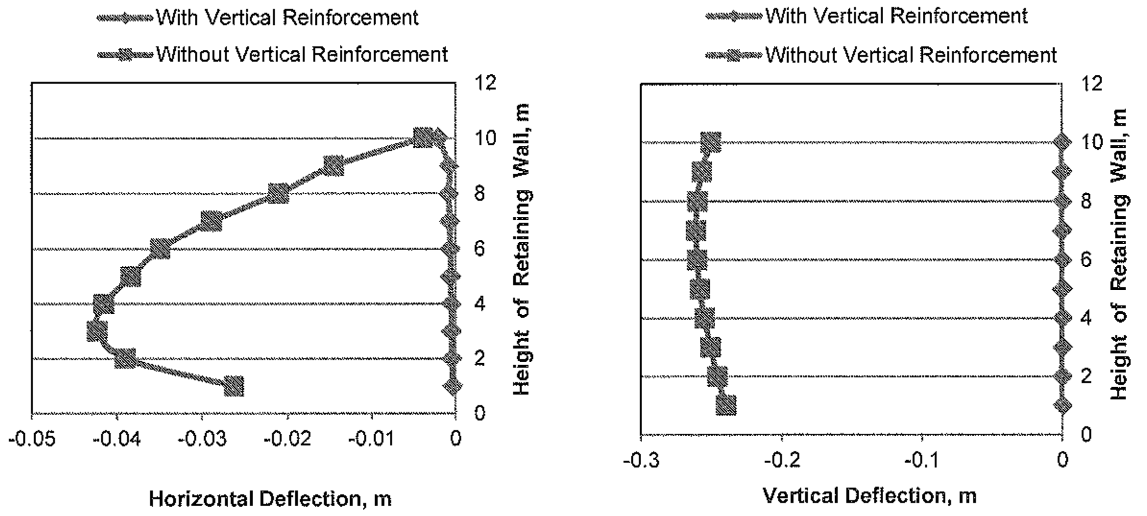


Figure 4: Vertical displacements of reinforced wall without applying the vertical reinforcement



(a) (b)

Figure 5: Comparison of vertical and horizontal deformations of reinforced walls, (a) horizontal deflections and (b) vertical deflections

3 PARAMETRIC STUDIES

A number of parametric studies of reinforced soil walls subject to dynamic behaviour have been reported in previous studies (e.g. Ling et al 2005; Hatami and Bathurst 2006). Hatami and Bathurst (2000) studied the fundamental frequency of reinforced soil walls and showed that they were not affected by different structural components under moderate earthquakes of 0.2 m/s^2. Bathurst and Hatami (2001) provided a detailed review of the numerical modelling of reinforced soil walls. Bathurst and Hatami (1999) presented numerical studies using a finite difference approach for propped soil walls reinforced with panels, and where the effects of the height, the stiffness and spacing of the reinforcement were investigated. Ling et al. (2004) analysed the construction of a full scale reinforced soil retaining wall 6 m in height and the dynamic analysis of five centrifugal models with prototype heights of 7.5 m. The results indicated that the layout of the reinforcement including its length and spacing, played an important role in determining how well the wall performed.

A scaled down reinforced wall, 650 mm high with horizontal reinforcement spaced every 100 mm was used as the baseline case in this study. All soils (reinforced soil, backfill/retained soil, and foundation soil) were considered to be cohesionless. The unit weight and the friction angle of all soils were assumed to be 18 kN/m^3 and 35°, respectively. Table 3 summarises the properties the values used in the baseline case and the ranges used in the parametric study.

Table 3: Variation of key parameters

SN	Parameters	Soil modulus, E MPa	Friction angle, ϕ°	Vertical spacing, VS mm
1	Soil stiffness	5	30	100
2		10	30	100
3		15	30	100
4		20	30	100
5	Soil friction angle	5	28	100
6		5	30	100
7		5	32	100
8		5	34	100
9	Vertical reinforcement spacing	5	30	50
10		5	30	100
11		5	30	150
12		5	30	200

Four Young's moduli of 5 MPa, 10 MPa, 15 MPa, and 20 MPa were assessed in the parametric study of soil wall vertical reinforcement. The dynamic responses of the maximum horizontal displacement of these moduli are illustrated in Figure 6, with the results showing that the magnitude of dynamic response decreased with an increase in Young's Modulus. The calculated displacements are in agreement with the concept that a reinforced soil wall built with a higher modulus of elasticity would be more stable than with backfill that was not as stiff.

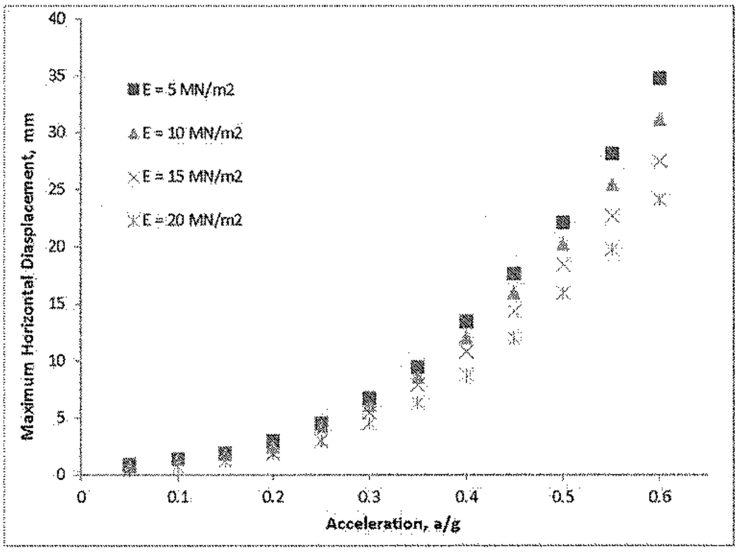


Figure 6: Effect of Young's modulus on the maximum horizontal displacement

Five soil friction angles: 26°, 30°, 32°, 34° and 36° were evaluated in the parametric study. The dynamic response of the maximum horizontal displacement with vertical reinforcement for those soil friction angles are compared in Figure 7. The results indicate that the magnitude of dynamic response increased when the friction angle decreased. The calculated displacements are in agreement with the notion that a reinforced soil wall built using backfill with higher friction angles would be more stable than backfill with a lower friction angle. Similar results were reported by Lee et al. (2012) in a parametric study of reinforced soil walls with horizontal reinforcement under real multi-directional ground shaking.

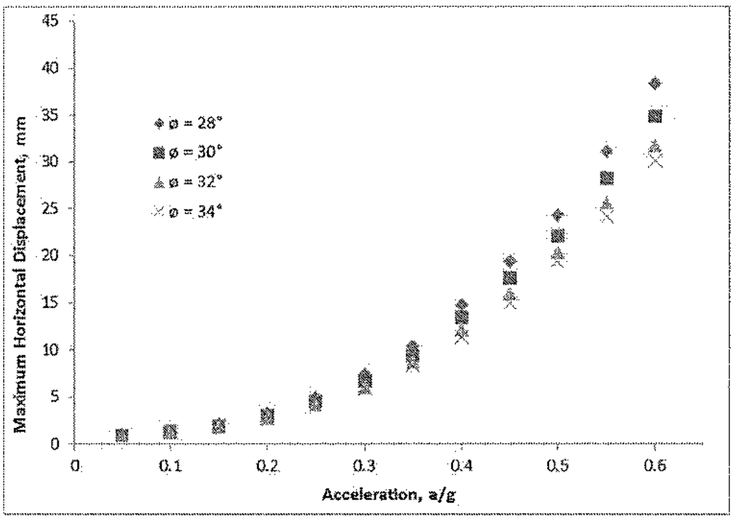


Figure 7: Effect of the soil friction angle on the maximum horizontal displacement

Four options for vertical reinforcements, including 50 mm, 100 mm, 150 mm and 200 mm spacing, were explored in the parametric study. The dynamic response of the maximum horizontal displacement for these four reinforcement spacing are plotted in Figure 8. The finite element results indicate that the maximum horizontal deflection with vertical reinforcement spaced at 50 mm and 100 mm were close to each other. Accordingly, it can be concluded that closely packed vertical reinforcement (i.e. small spacing) would not add any extra benefits to a wall system. Hence, it may be concluded that vertical reinforcement can be spaced more than twice that of the horizontal reinforcement. In addition, the spacing should be varied based on how the dynamic load accelerates.

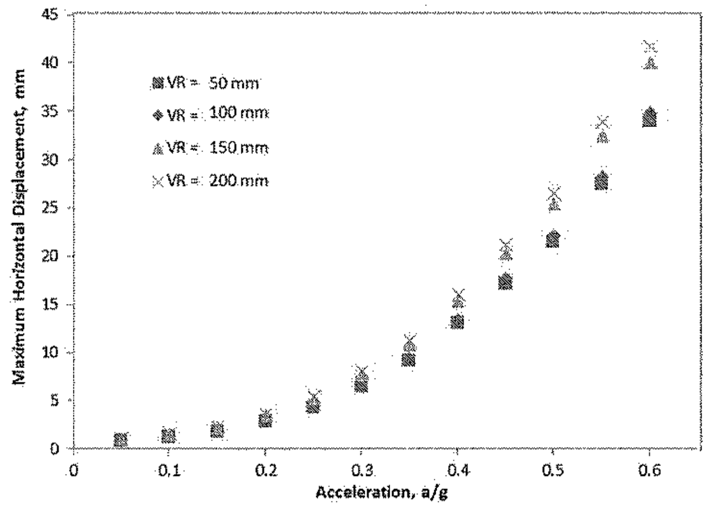


Figure 8: Effect of the spacing of vertical reinforcement on the maximum horizontal displacement

4 CONCLUSIONS

This paper presents a new approach for reinforced soil walls by inserting vertical reinforcements to the conventional system. It is designed to connect the horizontal reinforcement layers together. In this system, the selected granular material is compacted over the horizontal reinforcement up to a given height and then another layer of horizontal reinforcement is laid down, after which the vertical reinforcement is inserted vertically or at an angle with vertical, as per the design requirements. Each layer is then tied with another and thus acts as one integrated wall system, which reduces the total force at the back of the facing panels. This study focused on investigating the dynamic performance of reinforcing soil wall, enhanced by inserting vertical reinforcement. For this purpose, shake table tests were carried out, following an extensive laboratory experiments for materials selection to construct the models. The results of the shake table experiments and the corresponding numerical predations will be available in follow up papers.

A validated finite element model, using PLAXIS-2D Dynamics, was developed to conduct a series of parametric studies to study the behaviour of a soil wall with vertical reinforcement insertion. The results of the parametric study were similar to the outcomes of previously published parametric analyses using common GRS wall with horizontal reinforcement only. As expected, the results where the friction angles were varied indicated that the dynamic response increased in magnitude as the friction angle decreased. Similarly, the dynamic response also decreased with an increase in Young's Modulus. The results of varying the spacing of vertical reinforcement showed that vertical elements spaced less than twice of the horizontal reinforcement spacing, would not add any extra benefits to a reinforced wall system.

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