Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2017) 1058-1070

ECCOMAS
Proceedia

COMPDYN 2017
6th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15–17 June 2017

REVIEW OF SEISMIC PERFORMANCE OF GEOSYNTHETIC REINFORCED SOIL RETAINING WALLS

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Keywords: Geosynthetic reinforced soil, seismic performance, retaining walls, numerical models, physical models, literature review

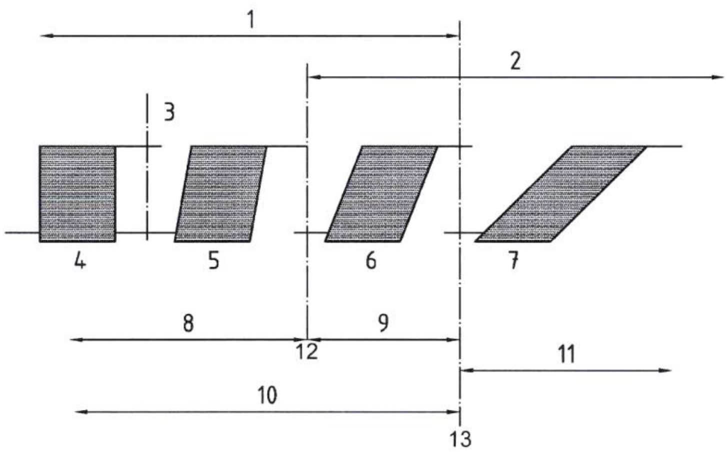
Abstract. *Geosynthetic reinforced soil (GRS) retaining walls have been increasingly used as alternative to concrete gravity retaining walls. In GRS retaining walls, the concrete mass, that resist to the destabilizing forces, is replaced by a mass of soil reinforced with geogrids or other polymeric material. One of the main advantages of GRS retaining walls is their lower cost when compared to concrete retaining walls. Furthermore, GRS retaining walls built in seismically active area have performed well during major earthquakes. The seismic design of GRS retaining structures is traditionally based on Mononobe-Okabe earth pressure theory with distinct approaches for the distribution of the dynamic lateral earth pressures. The lack of improvement in seismic design of GRS retaining walls has led in recent years to some physical and numerical studies, involving large or reduced scale model shaking table tests and powerful numerical tools. This paper presents a review of selected published work, including physical and numerical models, trying to identify the main parameters with greatest influence on the seismic performance of GRS retaining walls. The paper is focused on numerical simulations verified against results physical model tests. Post-earthquake investigations are also summarized. The main conclusions are highlighted and common trends are identified.*

Peer-review under responsibility of the organizing committee of COMPDYN 2017.
doi: 10.7712/120117.5476.18026

1 INTRODUCTION

Soil reinforcement applications using geosynthetics include reinforcing the base of embankments constructed on very soft foundations, increasing the stable slope angle of soil slopes and reducing the earth pressures behind retaining walls and abutments [1]. The design procedures for geosynthetic reinforced slopes and geosynthetic reinforced soil (GRS) retaining walls are traditionally different, although, as mentioned by Holtz [1], this difference is quite artificial and arbitrary.

According to the U. S. Department of Transportation, Federal Highway Administration [2], reinforced soil slopes are earth sloped structures with face inclinations of less than 70 degrees. Similarly, the British Standard BS 8006 [3] classifies the GRS structure as reinforced wall when the slope angle is greater than 70º. The European Standard EN 14475 [4] categorises reinforced soil structures according to Figure 1.



1 – Earth retaining structures
2 – Reinforced slopes
3 - Vertical
4 – Vertical wall
5 – Battered wall
6 – Inclined wall/Steep slope
7 – Shallow slope
8 – Some specific types of facings panels: panels, blocks, steel units, gabions
9 – Specific types of sloping panel
10 – Some common types of facings: planter units, wire mesh, wrapped around
11 – No facing. Erosion protection may be required
12 – Line of 4:1 face slope angle
13 - Line of 1:1 face slope angle

Figure 1: Classification of reinforced soil structures and facing systems (modified from [4]).

GRS structures can be constructed using distinct reinforcement materials and facing systems (Figure 1). The reinforcement can be materialized by inextensible steel strips or relatively extensible polymeric materials, such as geotextiles, geogrids or strips. This literature review is limited to extensible reinforcements and GRS retaining walls.

GRS retaining walls are nowadays a well-understood technology. The design of these structures under static loading conditions are also well-established and the accuracy of internal design methods has been assessed through the construction of full-scale instrumented structures. Post-earthquake investigations have shown that GRS retaining walls, in general, have behaved well during earthquakes.

GRS retaining walls have had a good performance during strong earthquakes (Loma Prieta 1989, Northridge 1994, Kobe 1995, Chi-Chi 1999, El-Salvador 2001) as reported by several researchers [5, 6, 7, 8, 9]. Their good seismic performance is currently attributed to the ductile behaviour of the reinforced soil mass and the conservatism of the current seismic design methods.

As reported by [5] GRS retaining walls survived the Loma Prieta earthquake of 1989 with estimated ground accelerations ranging from 0.3g to 0.7g. After the Northridge earthquake minor signs of movement were reported in two GRS structures located close to the centre of shaking, while any evidence of damage was identified on structures located farthest from the epicentre [6]. The Hyogoken-Nambu (Kobe) Earthquake caused serious damage to conventional masonry retaining walls, unreinforced concrete gravity-type retaining walls and cantilever-type steel-reinforced concrete retaining walls, while geogrid-reinforced soil retaining walls, having a full-height concrete facing, performed very well during the earthquake [7].

In contrast, the Chi-Chi earthquake, in Taiwan, caused serious damage to reinforced-soil retaining walls using keystones as facing [8]. According to [8] the failure of these modular-block reinforced soil retaining walls could be attributed to several factors, such as, a lack of professional design used in the GRS walls, the insufficient strength and stiffness of the connection pins between the modular blocks and reinforcement, the installation of structures, like lampposts, at the vicinity of the modular-blocks.

On the basis of a survey of hundreds of modular block retaining walls in San Salvador area, only two required repair [9]. Both damaged walls suffered from failure at the top of the structures resulting from changes to the design after construction. According to [9], one wall suffered from an error after construction that resulted in the top layer of reinforcing being cut and partially removed. Where the top of the wall was properly designed and constructed, the wall performance was very good. The other wall suffered from a translation failure of the entire reinforced soil zone. This was also the result of a change in design after construction.

The seismic design of GRS retaining structures is traditionally based on Mononobe-Okabe earth pressure theory with distinct approaches for the distribution of the dynamic lateral earth pressures ([2, 10]). In recent years the lack of improvement in seismic design of GRS retaining walls led to some physical and numerical studies, involving large or reduced scale model shaking table tests and powerful numerical tools. This paper presents a literature review of selected published work related to the seismic performance of GRS retaining walls, comprising physical and numerical modelling.

2 PHYSICAL MODELS

The study of the performance of physical models of GRS retaining walls under cyclic loading conditions can improve the understanding of the real behaviour of these structures during earthquakes. However the complexity and high costs associated with the physical models lead to the frequent use of numerical tools to understand the behaviour of GRS retaining walls under earthquake loading. To validate the results and conclusions of these numerical models, they must be properly calibrated through numerical simulations verified against physical models.

The stress field in the backfill material cannot be reproduced in reduced-scale models, but these tests can be very helpful to better understand the behaviour of GRS retaining walls provided that the results are interpreted carefully considering the scale effects.

Table 1 summarises selected experimental studies carried out on GRS retaining structures to evaluate their seismic performance, recently published (after 2005) in well reputed peer-reviewed scientific journals.

The seismic response of geosynthetic reinforced retaining walls through shaking table tests carried out on models of modular block and rigid faced reinforced retaining walls was presented by [11]. Effects of backfill density, number of reinforcement layers and reinforcement type were studied.

One of the main conclusions reported by [11] is that modular block walls performed better than the rigid faced walls for the same level of base shaking. Shaking table tests have shown that:

- increasing the backfill density reduces the deformations significantly for both rigid faced and modular block walls, being the benefit more pronounced in modular block retaining walls;
- reinforcements are more effective in reducing the deformations in modular block walls.

Ref.	Test	Model height (m)	Reinforcement	Backfill material	Input motion	Studied parameters
[11]	Reduced-scale shaking table tests	0.6	Biaxial geogrids	Poorly graded sand (C_c = 0.896; C_u = 3.30)	Sinusoidal	- backfill density - number of reinforcement layers - reinforcement type
[12]	Reduced-scale shaking table tests	0.8	Polyethylene strips	Firuzkooh sand, poorly graded (C_c = 0.88; C_u =1,87)	Stepped-amplitude sinusoidal (5Hz)	- reinforcement length -reinforcement arrangement
[13]	Reduced-scale shaking table tests	0.7	Plastic geogrid	Nanjing fine sand (Cc = 1.07; Cu = 2.31)	Seismic motions	- ground motion
[14]	Reduced-scale shaking table tests	0.5	Bar-mat (flexible)	"Longstone" sand, poorly graded (C_u = 1.42; D_{50} = 0.15mm)	Seismic motions	- backfill density - seismic motion
[15]	Reduced-scale shaking table tests	0.6	Polypropylene woven geotextile	Poorly graded sand (C_c = 1.054; C_u = 3.553)	Sinusoidal	- backfill density - wall facing system - frequency of ground motion
[16, 17]	Reduced-scale shaking table tests	1.0	PVC-coated polyester geogrid	Synthetic olivine sand (C_c = 1.27; C_u = 2.5)	Stepped-amplitude sinusoidal	- reinforcement stiffness - reinforcement length - reinf. vertical spacing - facing geometry - facing mass - facing toe boundary
[18]	Large-scale shaking table tests	2.8	Polyester geogrid	Fine sand (C_u = 2; D_{50} = 0.27mm)	Kobe earthquake motions	- reinf. vertical spacing - reinforcement length

Table 1: Summary of physical model tests.

Shaking table tests performed by [11] have also evidenced that the acceleration amplification is non-uniformly distributed along the height of the wall and it is not affected by the wall facing and inclusion of reinforcement.

As mentioned by the authors, the seismic response of modular block walls could be influenced by the frequency of shaking and the interface shear between stacked modular blocks, parameters not evaluated in this study.

The seismic behaviour of soil retaining walls reinforced with polymeric strips was studied by [12] through of 1-g shaking table tests. The study has involved the effect of reinforcement length, number of steps and shape of the reinforcement arrangement (zigzag vs. parallel) on the failure mode, wall displacements and acceleration amplification.

These small scale model tests have shown that the internal failure mechanism in the reinforced zone involves a bulging mode and this convex deformation of the facing (bulging) causes a concave settlement profile, being the maximum value of the settlement recorded in the backfill zone where failure begins. As regards the reinforcement arrangement in the wall height, the study has suggested that the most appropriate reinforcement distribution for reinforcement length is the step arrangement (length increases from the bottom to top of the wall by steps: 0.5H, 0.7H, and 0.9H). The acceleration amplification factor increases from the bottom to the top of the wall, though the use of extensible reinforcements prevents further increase in the acceleration amplification factor.

The seismic performance of geogrid reinforced retaining walls, with rigid facing system, constructed with a saturated sand was reported by [13]. Findings of this study show that the existence of the geogrids decreases the seismic settlement of the backfill surface. On one hand, the backfill surface settlement in the reinforced zone was much smaller than in the unreinforced zone, and on the other hand, the backfill surface settlement of reinforced walls was also much smaller than that of unreinforced retaining walls. The geogrid layers decreased the development of excess pore water pressures and accelerated the dissipation of excess pore water pressures.

Seismic waves with long-time high acceleration values from the far field had greater effects on the seismic behaviour of the reinforced retaining wall than those from the near field, therefore, according to [13] far field or mid far-field earthquakes should be considered in the design of geogrid reinforced retaining walls.

The seismic performance of a bar-mat retaining wall was investigated experimentally and theoretically by [14]. A series of reduced-scale shaking table tests are conducted, using a variety of seismic excitations (real records and artificial multi-cycle motions) and the problem was analysed numerically. Shaking table results have evidenced that the response of the reinforced walls is "quasi-elastic" for small to medium intensity seismic motions. According to [14], for these ground motions, the permanent lateral displacements of the wall do not exceed a few centimetres (at prototype scale) and the settlements are very small. For larger intensity seismic motions, plastic deformations occur and an active failure wedge behind the reinforced area is developed (not completely). Only under unrealistic conditions (a large number of strong cycles with large amplitude) the active failure wedge behind the reinforced soil block develops completely, which means that only in such cases a conservatively designed reinforced wall reaches its ultimate capacity [14].

The results of shaking table tests carried out on wrap-faced and rigid-faced reinforced soil model walls are presented by [15]. The influence of backfill relative density on the seismic response of these models was studied. Wrap-faced GRS retaining walls were also tested for different base excitations.

Findings of these experiments have shown that the effect of backfill density on the seismic performance of GRS retaining walls is pronounced only at very low relative density and at higher base excitation. When tested at higher base excitation, the walls constructed with higher backfill relative density showed lesser face deformations and greater acceleration amplifications compared to the walls constructed with lower densities. The backfill density effect was more pronounced in wrap-faced GRS walls and the displacements in these walls were many times higher compared to those recorded in rigid-faced GRS walls.

The behaviour of GRS retaining structures under working stress and seismic loading conditions has been studied over many years in Royal Military College of Canada (RMC) [16, 17, 19, 20]. The influence of facing geometry, facing mass and facing toe condition on simulated earthquake response of GRS retaining walls was reported by [16]. The influence of reinforcement stiffness, reinforcement length and vertical spacing was presented by [17].

The toe boundary condition and facing panel configuration were found to have a significant effect on model response [16]. For the same boundary condition (hinged toe - movement in the vertical and horizontal direction restrained but free to rotate - or sliding toe - slide horizontally and rotate and vertical movement restrained) and the same base excitation level, a wall with an inclined facing displaced less than an identical vertical wall. Regardless of toe boundary condition, the accumulated facing lateral displacements at the top of vertical walls were smaller for walls with facing panel less massive (smaller thickness).

The acceleration amplification was amplified through the facing panel and the backfill soil and the evolution of the amplification factors with the wall height was nonlinear.

Regarding the magnitude and distribution of reinforcement connections loads and total earth force (sum of connection loads and horizontal toe load) the study reported by [16] pointed out that:

- the horizontally restrained toe in reduced-scale models attracted approximately 40% to 60% of the total horizontal earth load during base excitation, demonstrating that a stiff facing column plays an important role in resisting dynamic loads under simulated earthquake loading;
- the distribution and magnitude of connection loads over the wall height were in general poorly predicted using current FHWA and NCMA guidelines;
- for model walls with an unrestrained toe, the predicted total earth forces using the FHWA method were smaller than the measured values;
- for model walls with a restrained toe, both NCMA and FHWA design methods significantly under predict the total earth force.

Reduced-scale shaking table tests carried out by [17] led to the following main conclusions:

- the lateral displacements of the model walls decrease with increasing reinforcement length, reinforcement stiffness and number of reinforcement layers;
- increasing the reinforcement length and decreasing the reinforcement stiffness reduces the total seismic earth forces acting at the back of the facing;
- the magnitude of the total reinforcement connection loads decreases with increasing reinforcement length, decreasing stiffness reinforcement stiffness and increasing vertical spacing;
- the acceleration amplification factor decreases with increasing reinforcement length and increases with reinforcement vertical spacing. There is a critical acceleration value from which the amplification factors increased significantly.

Large-scale shaking table tests carried out on 2.8 m high modular-block geosynthetic-reinforced soil model walls were reported by [18]. These tests were performed at the large-scale shaking table of the Japan National Research Institute of Agricultural Engineering.

The three models were subjected to significant shaking using Kobe earthquake motions. Two of them were excited with a one-dimensional horizontal maximum acceleration of 0.4g followed by 0.86g, and the third model was submitted also to a vertical acceleration record.

Under moderate earthquake loading (peak acceleration of 0.4g), the GRS retaining walls showed negligible deformation. When submitted to very strong shaking (peak acceleration of 0.86g) the walls still performed well.

This study has shown that the wall performance under earthquake loading could be improved by increasing the length of the top reinforcement layer, reducing vertical reinforcement spacing and grouting the top blocks to ensure firm connection to the reinforcement [18]. The lateral displacements were largest at the top of the wall and a larger settlement occurred in the unreinforced zone of backfill. The vertical earthquake loading did not much affect the wall deflection but increased the vertical stress under the backfill and blocks, the reinforcement load and the connection load.

According to [18] the results of these shaking table tests have demonstrated that FHWA and NCMA design methods underestimate the seismic capacity of flexible GRS wall systems.

3 NUMERICAL ANALYSES

The studies on the numerical modelling of the seismic behaviour of GRS walls can be divided into two categories: parametric analyses using numerical models that were not verified against physical tests, and studies that were based on numerical simulations verified against results of centrifuge shaking table tests, full-scale or reduced-scale shaking table tests. This literature review comprises only the latter type of numerical analyses and those published after 2001. Table 2 summarises selected numerical simulation on seismic performance of GRS retaining walls.

The seismic behaviour of GRS retaining walls has been numerically investigated using mainly FLAC or FLAC3D codes [21, 22, 26, 29, 30], DIANA-Swandyne-II [24, 25, 27], DYNA3D or LS-DYNA [23, 28] and ABACUS [14]. Different elements were assumed to model the reinforcement layers (cable elements, shell elements, bar elements, truss elements and beam elements), assuming in general elastic or elastic-plastic behaviour. Regarding the interface between the backfill and the reinforcement, as well as, the backfill constitutive models different approaches have also been considered (Table 2). Most of these numerical analyses have achieved a reasonable prediction of the seismic performance of GRS models.

The main conclusions among the studies carried out with FLAC code include:

- a simple elastic-plastic soil model may be sufficient to predict the seismic performance of GRS retaining walls provided that the backfill soil properties are selected accurately. Plane strain properties of the backfill material should be used [21, 22, 31];
- a constant reinforcement stiffness value was shown to be a reasonable assumption for numerical modelling of the geogrid reinforcement [31]. The in-isolation material properties are suitable to model the reinforcement stiffness but the assumption of a perfect bond between the reinforcement and soil may contribute to differences between predicted and measured loads [22];
- current pseudo-static seismic design methods underestimate the size of the soil failure zone behind the wall facing and consequently underestimate the reinforcement anchorage lengths close to the top of the wall [21, 22];
- current active earth pressure theories applied to reinforced soil walls significantly overestimate the horizontal reinforcement forces [26];
- the magnitude and distribution of reinforcement connection loads during static and dynamic loading are influenced by the toe boundary condition [22];
- the horizontal displacement of wall and the vertical displacement of the backfill increase with the decrease of the wall stiffness [29];

Ref.	Code	GRS facing type	Reinforcement model	Backfill model	Interface model	Input motion	Validation test
[21, 22]	FLAC	Full-height rigid facing	Elastic-plastic, cable elements	Mohr-Coulomb, elastic-plastic strain-softening	Grout layer	Sinusoidal (5Hz)	Reduced-scale shaking table
[23]	DYNA3D	Concrete blocks	Linear elastic, shell elements	Ramberg-Osgood	Sliding interface (penalty-function based contact surface)	Sinusoidal (3Hz)	Full-scale shaking table
[24]	DIANA-Swandyne-II	Modular blocks	1D bounding surface, bar elements	Pastor-Zienkiewicz	Slip element	Kobe record	Full-scale shaking table
[25]	DIANA-Swandyne-II	Facing panels	Bounding surface model	Generalized plasticity soil model	Thin layer elements with elastic perfectly plastic sliding behaviour	Sinusoidal (2Hz)	Centrifugal shaking table
[26]	FLAC	Full-height rigid facing	Elastic-plastic, cable elements	Nonlinear hysteretic model (Masing rule)	Grout layer	Sinusoidal	Reduced-scale shaking table
[27]	DIANA-Swandyne-II	Modular blocks	1D bounding surface	Generalized plasticity soil model	Thin layer elements with elastic perfectly plastic sliding behaviour	Kobe record	Full-scale shaking table
[28]	LS-DYNA	Concrete blocks	Plastic-kinematic model, shell elements	Geologic cap model	Penalty-based contact	Kobe record	Full-scale shaking table
[14]	ABACUS	Facing panels	Truss elements	Modified kinematic hardening model	Perfect contact with soil (no sliding or pullout)	Seismic motions	Reduced-scale shaking table
[29]	$FLAC^{3D}$	Full-height rigid facing	Isotropic linear elastic, three nodded shell elements	Mohr-Coulomb, hyperbolic modulus	Spring-slider surface	Sinusoidal (3Hz)	Reduced-scale shaking table
[30]	FLAC	Wrap-faced	Linear elastic, beam elements	Mohr-Coulomb, hyperbolic model	Linear spring-slider system	Sinusoidal (3Hz)	Reduced-scale shaking table

Table 2: Summary of numerical simulation on seismic performance of GRS retaining walls.

- after shaking two types of strained zones can be observed: a high strain zone near the wall facing and a low strained zone extending into the retained backfill. The variation of length and stiffness of reinforcement, number of reinforcement layers and backfill soil affects marginally these strained zones [29];

- backfill soil with higher friction angle and dilation angle (a denser backfill) shows a better seismic performance [30];

- the effect of soil-reinforcement interaction parameters is more prominent than the effect of reinforcement stiffness on the seismic performance of wrapped-face reinforced soil retaining walls [30].

The finite element method program DYNA3D was used by [23] to simulate the experimental results of shaking table tests performed on segmental (modular) blocks reinforced walls (Table 2). The simple Ramberg-Osgood model was considered suitable to simulate the nonlinear hysteretic behaviour of soil.

This verified numerical model was used by [32] to investigate the effects of wall facing details on the seismic behaviour of a segmental reinforced retaining wall subjected to a El Centro earthquake record. The results of this study have revealed small lateral facing deformations, connection loads and axial strains in the geosynthetic layers, suggesting that this particular GRS retaining wall would not experience any significant distress if subjected to the El Centro earthquake.

Lee et al. [28] used the finite element method program LS-DYNA to numerically simulate the dynamic performance of three large-scale shaking table walls reported by [18]. Discrepancies between the calculated results and measure wall response were attributed to the deficiencies of the constitutive models and idealization of the numerical model. However, these primitive constitutive models have the advantage of limited material parameters.

The nonlinear dynamic finite element code DIANA- Swandyne-II was used by [24, 25, 27] to model large-scale shaking table tests and centrifugal shaking table tests. The sand was modelled by [25] and [27] with a generalized plasticity model based on the concept of critical state which requires 16 parameters.

The first study, presented by [24], has shown that damping properties used in the finite element analyses were extremely important to simulate the dynamic behaviour of the GRS walls.

Numerical analyses carried out by [25] showed that the generalized plasticity model for granular soil and the adopted geosynthetic model were relevant for expressing the monotonic and cyclic behaviour of soil and reinforcement and a good prediction of the results was achieved. The numerical analyses also confirmed that the length and spacing of reinforcement play an important role in minimizing wall deformations and strains in the reinforcements. The amplification of acceleration seemed to be minimally affected by the reinforcement layout.

The validated finite element model was used by [33] for conducting a series of parametric studies on the behaviour of GRS walls under construction and subject to earthquake loading. Based on this parametric analyses, [33] concluded that the lateral displacement and the wall crest settlement were affected by factors such as soil cyclic behaviour, reinforcement layout and earthquake motions. The wall crest settlement was larger behind the rear end of reinforcement. The loads in the reinforcement layers were influenced by the earthquake record and vertical spacing of reinforcement layers. Amplification of acceleration was affected by the soil behaviour and earthquake motions but not by the reinforcement layout. The effects of reinforcement vertical spacing were more significant compared to the length of the reinforcement.

The selection of Rayleigh damping coefficients for the soil was later investigated by [27], concluding that for models with a peak acceleration of 0.4 g, a 15% damping value produced the most satisfactory results. For models with maximum acceleration of 0.8 g, the damping was lowered to 5%. Predicted wall deformations, backfill settlement, reinforcement loads and acceleration response were compared to measured values. Their analyses have shown that the tensile loads in the reinforcement were slightly overestimated. These authors have also concluded that the effect of Rayleigh damping on the response of numerical models required further investigation.

A modified kinematic hardening model was developed and encoded in the finite element code ABACUS by [14]. After calibrating model parameters, the retaining walls, tested through reduced-scale shaking table tests (see Table 1), were analysed at model scale, assuming soil parameters for small confining pressures. After validating the numerical method the problem was analysed at prototype scale assuming soil parameters for standard confining pressures. According to the authors following this procedure, the results of shaking table testing were indirectly ‘‘converted’’ to real scale.

A good prediction of the results of the shaking table tests were achieved with the numerical prediction (model scale). The numerical analysis underestimated the cyclic component of the horizontal wall displacement, but the residual displacement was similar to the experimental results for all cases examined.

4 FINAL REMARKS

The paper summarizes recent studies related to the seismic performance of GRS retaining walls involving full-scale or reduced-scale shaking table model tests and numerical simulations verified against results of physical model tests. Post-earthquake performance of GRS walls was also briefly summarized.

Overall, it could be argued that the seismic performance of GRS retaining structures has been very good, being the cases of inadequate behaviour due mainly to insufficient strength and stiffness of the connection pins between the modular blocks and reinforcement and changes to the design after construction.

Based on the studies reviewed in this paper the following main conclusions can be drawn:

- Physical and numerical models have been shown that current pseudo-static seismic design methods underestimate the size of the soil failure zone behind the wall facing and consequently underestimate the reinforcement anchorage lengths close to the top of the wall. On the other hand, classical earth pressure theories applied to reinforced soil walls overestimate the reinforcement forces.

- Far field or mid far-field earthquakes should be considered in the design of GRS retaining walls, since the seismic waves with long-time high acceleration values from the far field had greater effects on the seismic behaviour of GRS retaining walls than those from the near field.

- The performance of GRS retaining walls under earthquake loading could be improved by increasing the length of the top reinforcement layer, reducing vertical reinforcement spacing and grouting the top blocks (in case of modular block walls) to ensure firm connection to the reinforcement.

- A simple elastic-plastic soil model may be sufficient to predict the seismic performance of GRS retaining walls provided that the backfill soil properties are selected accurately.

- The increase of the reinforcement length lead to the decrease of seismic lateral displacements, total seismic earth forces acting at the back of the facing, magnitude of the total reinforcement connection loads and acceleration amplification factor.

- The effect of backfill density on the seismic performance of GRS retaining walls is pronounced only at very low relative density and at higher base excitations.
- The effect of soil-reinforcement interaction parameters seems to be more significant than the effect of reinforcement stiffness particularly on the seismic performance of wrapped-face reinforced soil retaining walls.

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