A FINITE ELEMENT VALIDATION APPROACH TO FULL-SCALE TESTING OF MODULAR BLOCK REINFORCED SOIL RETAINING WALLS UNDER SEISMIC LOADS

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ABSTRACT

Geosynthetic reinforced retaining walls have been increasingly popular due to their ease of field application and cost-effectiveness. When geosynthetic reinforced retaining walls are implemented in earthquake prone regions, their behavior under the action of seismic loads are needed to be considered. The analysis of such walls for design purposes could be conducted either by making use of limit equilibrium methods, where seismic loads are imposed as pseudo-static rigid body forces, or by performance based design in which displacement and deformations of the structure are considered. In order to evaluate deformation behavior of the geosynthetic reinforced walls, finite element analysis and physical tests (full-scale 1-G shaking tests, centrifuge tests) are conducted of the model structure. Considering that physical models have to be of limited size, it is not known how well they represent larger sized walls. In this study, a commercially available finite element package was used to investigate the effect of the height of the wall. In order to validate the Finite Element model, first a shaking table test results were tried to be simulated. So, finite element models of the tests undertaken by Ling et.al (2005) where the results of three 2.8 m high modular-block geosynthetic retaining walls were subjected to significant shaking using the Kobe earthquake motions. Each wall was excited with a one dimensional horizontal acceleration of 0.4g followed by 0.86g. Nonlinear numerical algorithms that incorporate a generalized plasticity soil model were implemented with finite element methods. The wall deformations, tensile forces in reinforcements, and accelerations obtained from the finite element modeling were compared with the experimental findings of Ling et. al and satisfactory agreement was found between the finite element models' results and experimental results. As a result, this model was used to investigate how the various parameters are affected with increasing wall height. Based on this study an evaluation was tried to be reached, whether laboratory size model walls can accurately model high retaining structures.

INTRODUCTION

Modular-block geosynthetic-reinforced soil (MB-GRS) walls are aesthetically pleasing and cost-efficient when compared to traditional reinforced earth walls. Modular block systems are becoming increasingly popular in the industry, mainly in transportation applications, and their increasing popularity necessitates the investigation of the seismic performance of MB-GRS walls. The AASHTO procedure (Elias and Christopher, 1996) allows for pseudo-static design up to a peak acceleration of

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0.3 g, beyond which a dynamic response analysis of the wall is recommended. When MB-GRS walls are designed for earthquake prone regions, time history analysis of the wall will prove useful in order to make safe designs. Several cases of partial or full collapse of MB-GRS walls have been reported in literature during recent earthquakes (e.g., Tatsuoka et al. 1998; Ling et al. 2001) which makes the seismic performance analysis of such walls imperative. The design of MB-GRS walls under earthquake loading involves an extension of the static force equilibrium analysis, with the earthquake inertia force considered as a pseudo-static event (Bathurst and Cai 1995; Ling et al. 1997; Ling and Leshchinsky 1998). Pseudo-static analysis has its shortcomings such as not being able to handle time history of the input ground acceleration motions and its amplifications on the soil mass. Further, the effects of repeated loadings on the soil behavior such as modulus reduction and increase of damping cannot be considered in pseudo-static analysis. When the above stated short comings of the pseudo-static analysis is considered, it is immediately realized that the dynamic analysis of MB-GRS walls is needed for reliable designs.

In order to quantify the behavior of reinforced earth retaining walls under the action of seismic loads, physical model tests (centrifuge and large scale shaking table tests) have been performed by various researchers including but not limited to Murata et. al. (1994), Matsuo et. al. (1998), Koseki et. al. (1998), El-Emmam and Bathurst (2004), Ling et. al. (2005), Guler and Enunlu (2009), and Guler and Selek (2014). Murata et. al. (1994) tested 2.5 m high 1/2 scale model walls with gabion/rigid concrete panel facing blocks. 1-1.4m high models with hard facing panel. Reinforcement length, L/H = 0.4 and 0.7. Matsuo et. al. (1998) tested a model wall with inclined facing. 5 Hz sinusoidal base acceleration with stepwise increase in amplitude was the input excitation that was given to the wall. Koseki et. al. (1998) tested 0.5 m high propped-panel models with phosphor-bronze reinforcement strips (with L/H = 0.4) connected together in a grid form. El-Emmam and Bathurst (2004) worked with 1 m high 1/6 scale models with rigid facing panels. A stepped amplitude sinusoidal function at 5 Hz predominant frequency was used as base excitation by these authors. Ling et. al. (2005) tested 2.8 m high full-scale GRS segmental retaining wall models. Both vertical and horizontal components of the Kobe earthquake accelerogram were applied to the model. Guler and Enunlu (2009) reported the results from 1:2 scale 2-m-high model GRS walls, with concrete facing blocks tested with full amplitude El Centro and sinusoidal harmonic motion excitations. Guler and Selek (2014) have studied effects of change in peak ground acceleration, reinforcement length and spacing, model scale, treatment of the top two facing block layers on the accelerations on the wall face, maximum displacements of the wall face during shaking, permanent displacements, and strains in reinforcement.

The seismic performance of MB-GRS walls have also been investigated by various researchers by making use of finite element analysis such as Ling et. al. (2010) and Liu (2011). While finite element analysis can provide an insight to the nature of the problem at hand, the results acquired form an idealized finite element analysis can merely be a rough estimation of the physical actuality of the phenomena that is dealt with. In most cases finite element analysis necessitates that its results are validated by physical tests. Therefore it is logical to validate finite element models with actual test data and use the validated models to understand the behaviour of similar structures. In this study, the effects of wall height on various parameters have been investigated. The physical tests that are conducted by Ling et. al. (2005) are modeled by means of FE analysis and in turn the validated model is used to understand the behavior of walls with various geometries. Based on this study an evaluation was tried to be reached, whether laboratory size model walls can accurately model high retaining structures.

METHODOLOGY

In an attempt to study the effect of wall height on the deformation characteristics of MB-GRS, a nonlinear dynamic finite element modeling scheme was employed by using the PLAXIS finite element package. The models that were developed throughout the course of the study incorporated a steel encasement, backfill material, geogrid, modular blocks, interfaces (soil-geogrid, soil-modular block,

block-block and block-geogrid), foundation soil, and EPS board to simulate the shaking table results of Ling et.al. (2005).

The steel encasement that was used in the physical tests by Ling et. al. (2005) was intended to give lateral confinement to the backfill material. To limit the horizontal deformations of the back-wall, the steel encasement was constrained by the steel bracings. In order to achieve the same degree of rigidity, the steel encasement that was used was resembled by a steel cluster with a thickness of 10 cm behind the backfill and an the modulus of elasticity of this cluster was taken as $2x10^9$ kPa with a Poisson's ratio of 0.35. In the finite element models, during the dynamic analysis, it was observed that the base and the top point of the steel cluster did not displace relative to each other under the action of the base excitation used. This ensured that the back-wall implemented in the finite element analysis served its intended purpose.

The sand that was used in Ling et. al. (2005) was modeled by hardening soil model with small strains. This type of soil model was chosen for its inherent ability to mimic the modulus reduction in the soil due to straining and the subsequent increase in the damping ratio which is termed hysteretic damping. In order to come up with the parameters of hardening soil model with small strains, the triaxial test data that was presented in Ling et. al. (2005) was used which is presented in Fig.1. By making use of the data presented in Fig.1., the material properties of the backfill material were calculated. The properties of the sand were given by Ling et.al. as follows. unit weight = 14.3 kN/m^3 at a moisture content of 9.5 %; the maximum void ratio: 1.291; the minimum void ratio: 0.781 and the relative density 52-56%.

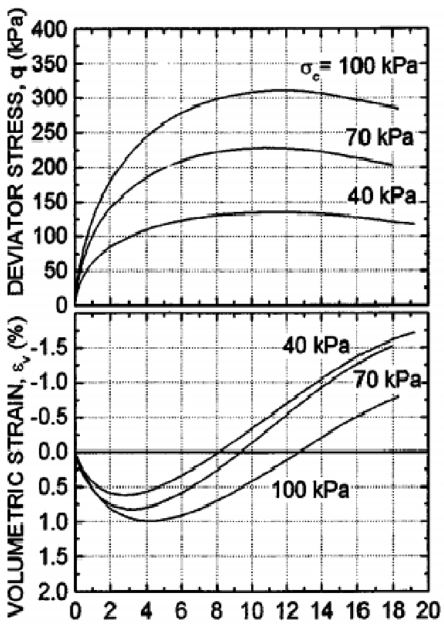

Figure 1. Triaxial test data of the sand used in Ling et. al. (2005)

In an attempt to model the above prescribed backfill sand in PLAXIS, the parameters that are tabulated in Table.1. are used to construct the hardening (isotropic hardening) soil model with small strain stiffness.

The geogrid that was used by Ling et. al. (2005) had an elastic stiffness of 680 kN/m. The geogrid reinforcements that were used in the modeling of GM-GRS wall had the same stiffness as the one used by Ling et. al (2005).

Table 1. The soil properties used in finite element modeling

E_{50}^{ref} (kN/m^2)	10230
E_{oed}^{ref} (kN/m^2)	9240
E_{ur}^{ref} (kN/m^2)	30680
ν_{ur}	0.2
c (kN/m2)	1
φ	38^o
ψ	5
m(power factor)	0.9
G_o (kN/m^2)	62500
$\gamma_{0.7}$	0.001

Fig. 2 shows the configuration and the connection strength of the modular blocks that was used by Ling et. al (2005). The blocks were 24 cm high, 30 cm deep and 45 cm wide. The mass of the empty block was 34 kg. The modulus of elasticity of the modular block in this study was reported as 2x10^6 kPa. In the modeling effort the modular blocks were assigned the same modulus of elasticity. The concrete blocks are much stiffer and stronger than soils, thus they are assumed as a linear elastic material. The modular blocks used in the investigation undertaken by Ling et. al. (2005) happened to have a 5 cm wide lip on the outer edge which gave a batter of 78^o to the wall facing. In the wall models the batter angle of the wall and the modular block configuration was identical to the one in the physical tests.

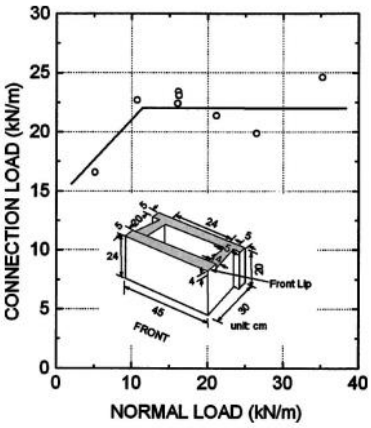

Figure 2. The configuration of the modular blocks that were used by Ling et. al. (2005)

The interfaces in Ling et. al. (2005) were naturally occurring due to the interactions of various materials. In order to model these interactions interfaces were assigned in PLAXIS. The thin-layer interface elements were assigned between block to block surfaces and block to soil surfaces. Mohr – Coulomb model was applied for block-soil interaction derived from the soil model with an interface friction angle of 27^o. Linear elastic interface was defined between blocks with the factor R=0.7 that reduced the strength of the block at the interface.

Foundation was defined as a linear elastic material with a modulus of elasticity 2x10^4 kPa and ν=0.3. EPS boards were used in these FE models as wave absorbers, in the modeling program's absorbent boundaries became redundant in these limited geometry. The reflection boards were defined as a low stiffness, high damping capacity soil with hardening soil model with small strain stiffness soil model. It is assumed that the reflection board cluster with its relatively small thickness (10 cm) to the rest of the model, did not perform its intended purpose which is to absorb waves and prevent their reflection back to the model.

The production period of the wall with 20 cm lifts was defined with staged construction phenomena. For dynamic excitation prescribed displacement option was used to define the seismic load which was a significant duration of a E-W component of the Kobe earthquake which lasted 14 seconds (illustrated in Fig. 3).

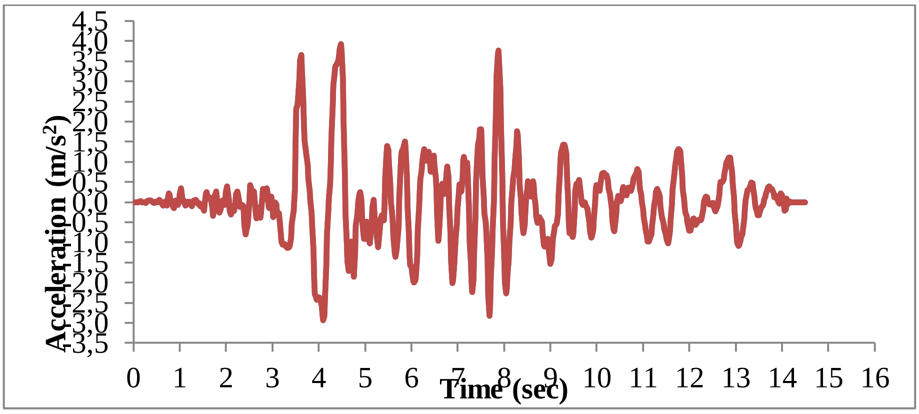

Figure 3. Dynamic excitation for finite element model (Japan Meteorological Agency, Kobe Station, Kobe Earthquake, 1995, EW component, significant duration of about 14.4 s)

RESULTS AND DISCUSSION

In the initial phase of the FEM investigation the physical model wall that was tested by Ling et. al. (2005) was modeled by utilizing PLAXIS. The parameters pertaining to finite element model was derived from the parameters reported by Ling et. al. (2005). The finite element model's behavior under the action of seismic loads was in close agreement with that of Ling et. al. The peak horizontal displacement that was measured in physical model is plotted alongside with the finite element model's outputs in Fig. 4. The trend of the horizontal deformations throughout the length of the wall is presented in Fig. 5. In the same figure the wall deformations are seen to be most pronounced in the top portion of the wall.

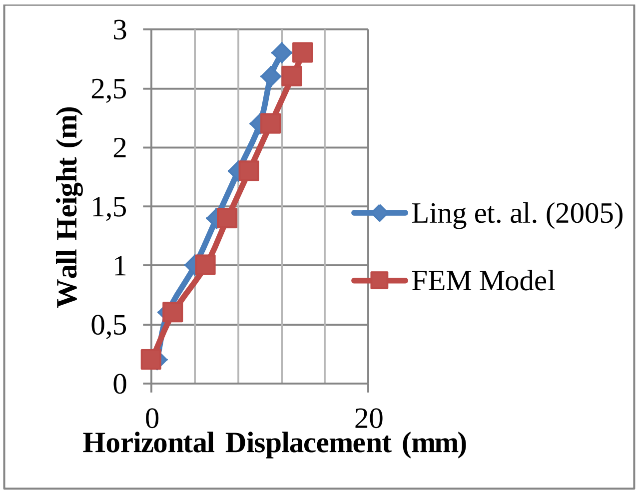

Figure 4. Peak horizontal displacement in the FEM model and Ling et. al. (2005)

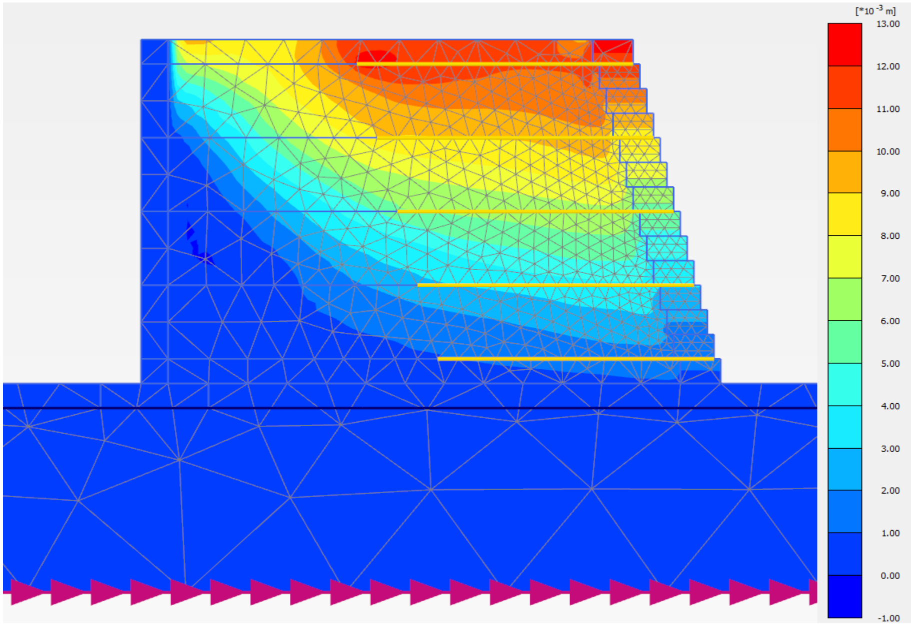

Figure 5. The deformation characteristic of 2.8m high wall model

Amplification response found from the finite element tests showed slight discrepancies from the shaking table tests. General trend of acceleration amplification in the study conducted by Ling et. al. (2005) for Kobe excitation scaled to 0.86g was 1.34. The average amplification factor throughout the wall height in the finite element model was 1.52. In Fig. 6. the input acceleration that was induced on the FE model is illustrated with red markers and the acceleration response of the topmost modular block is illustrated in blue.

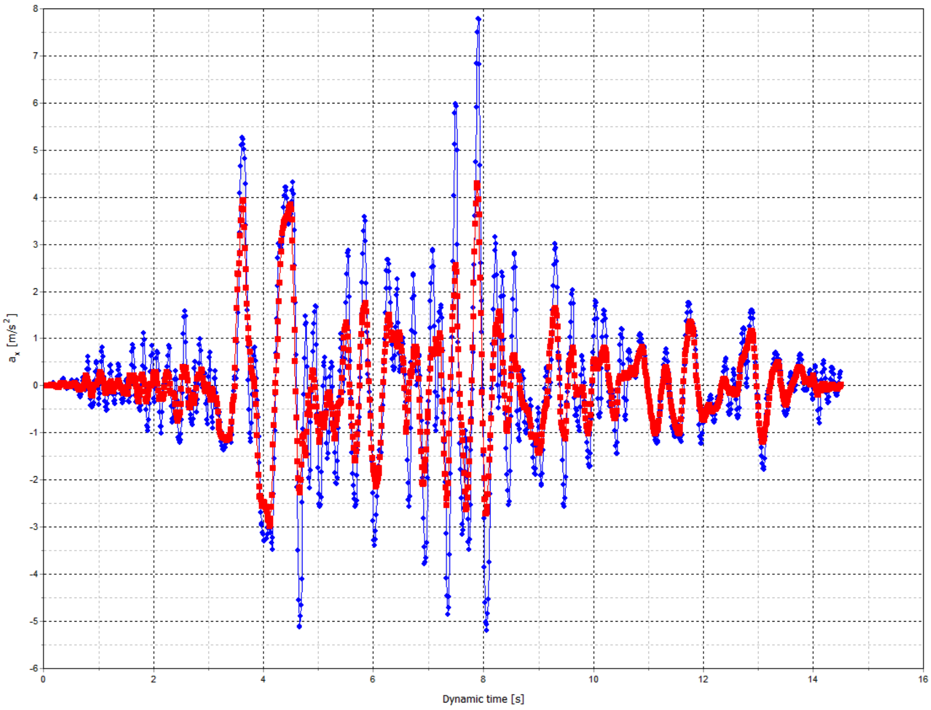

Figure 6. Acceleration time histories of input motion and wall response at the topmost modular block

The tensile forces in the geogrid reinforcements are given in Fig. 7 both for the FE model and for the physical test for a wall with a height of 2.8 m. As can be seen from this figure the magnitudes of tensile forces estimated by the FE model are in close agreement with the physical tests.

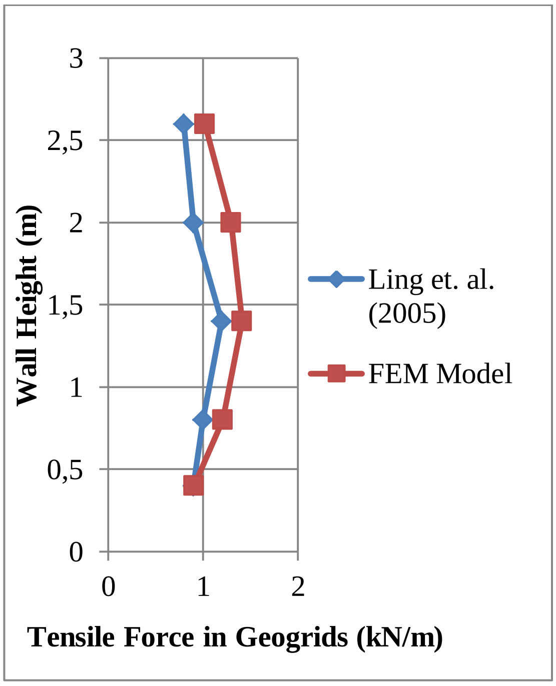

Figure 7. Tensile forces in geogrids measured by Ling et. al. (2005) and FE model

One of the main goals of the forthcoming study is to investigate the effects of blow up of the finite element model and observe the behavioral differences in the geogrid reinforced wall. For this purpose, the wall height was increased to 4.6 m and 6.4 m. In these walls the spacing of the geogrids in the vertical direction (s_v) was kept constant as well as all associated material properties. In order to keep L/H ratio (reinforcement length/height of the wall ratio) constant, the reinforcement length was increased as the wall height increased. The width of the model was also increased as the height increased.

The wall displacements for varying wall heights are illustrated in Fig. 8. Among the investigated walls, the wall with a 2.8 m wall height had a deflection to wall height percentage of 0.5 which corresponds to the ratio of the relative displacement of the topmost modular block relative to the toe of the wall in horizontal direction to wall height. The wall with a height of 4.6 m had 1.5% as the displacement to height ratio. The wall with a height of 6.4 m had 3.3% as the displacement to height ratio. It was observed that increase in wall height was accompanied with increasing deflection to wall height ratios.
The maximum tensile forces in the geogrids from the FE models with varying heights are given in Fig. 9. The model wall (H = 2.8 m) that was validated with the physical test results of Ling et. al. (2005) had a maximum geogrid tensile force of 1.75 kN/m. For the model wall with a 4.6 m wall height, the maximum tensile stresses in the geogrids were 3.7 kN/m. The maximum tensile stress in the geogrid reinforcement for the 6.4 m high wall was 7.5 kN/m. It was observed that the maximum tensile stress under the action of the seismic excitation increased with increasing wall height. The levels of tensile stress in geogrid reinforcements were within tolerable range for earthquake resistant design.

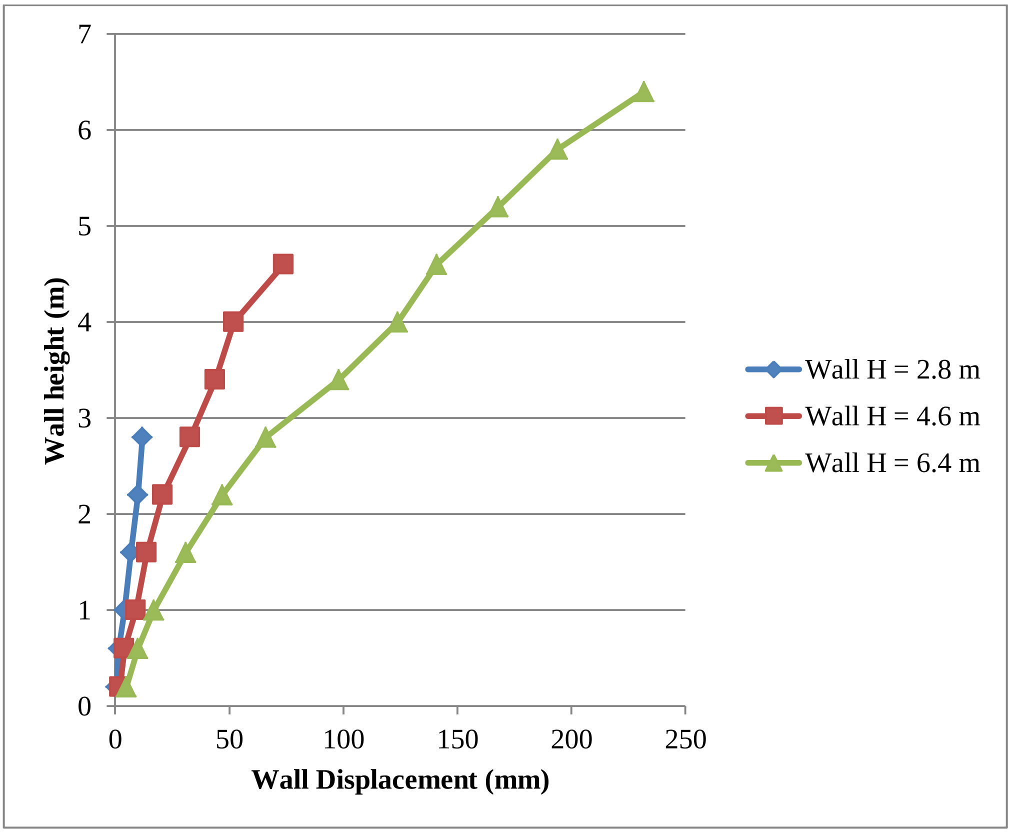

Figure 8. Wall displacements for FE models for varying wall heights

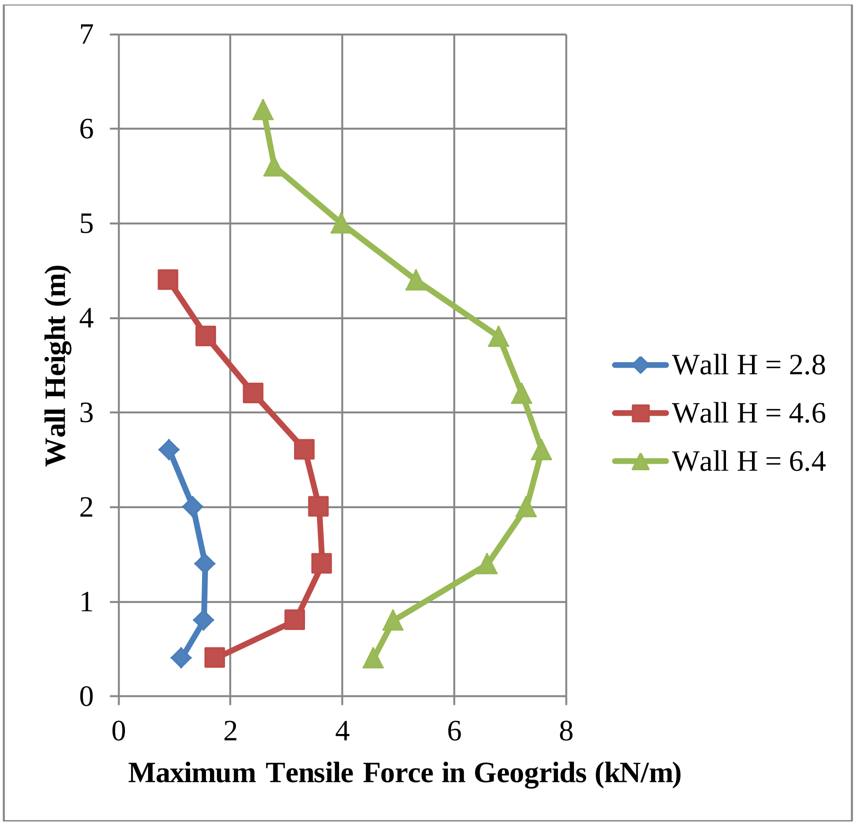

Figure 9. Maximum Tensile forces for FE models for varying wall heights

CONCLUSIONS

It was shown that the FE model could accurately predict the physical model results in terms of wall face displacements, accelerations, and tensile stresses in the geogrids. By making use of the validated FE model, models for varying wall heights has been implemented in order to investigate the seismic behavior of walls with 4.6 m and 6.4 m wall heights.

As can be seen, the tensile forces in the reinforcement increased with increasing wall height. This increase is not proportional to the increase in wall height; however the distribution within the wall height shows similar trends. Also the maximum displacement on the wall face was found to be increasing with increasing wall height. The ratio of maximum fall face displacement to wall height increased with increasing wall height. The deformation on the geogrids also increased with increasing wall height.

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