Finite Element Analysis of Multi-Tiered Reinforced Soil Walls Of Gotvand Dam Powerhouse under Earthquake Loading

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Abstract

Multi-tiered reinforced soil walls are now an innovation technology for the solution of earth retaining wall problems. This paper is focused on the numerical modeling of a reinforced soil wall with steel strip soil reinforcement taken from a series of structures constructed at the powerhouse of Gotvand dam located in south of Iran.

In this paper details of the numerical simulation and specifications of the materials that are used in a 31 m high reinforced soil wall that was built in 5-tiered configuration and located above the powerhouse of Gotvand dam are described. This paper presents the wall responses to a typical seismic loading. The lessons learned here have applications to other types of multi-tiered reinforced soil walls and are of value to designers who wish to: explore the mechanical behavior of these systems under static and earthquake loading and to generate data to fill the gaps in performance data from the limited number of monitored structures reported in the literature.

Keywords: Finite element method, Seismic analysis, Multi-tiered reinforced soil walls, Earthquake loading, Gotvand dam, Soil reinforcement, Powerhouse.

1. INTRODUCTION

Mechanically stabilized earth (MSE) walls also called reinforced soil walls, constructed with steel strip reinforcing elements and segmental concrete facing panels, are now an accepted technology in world-wide. The first wall of this type in Japan was constructed in 1972 (Hirai et al., 2003). There are now estimated to be more than 30,000 of these structures in Japan (Ochiai, 2007). A useful history of the development of this technology and relevant codes of practice in Japan can be found in the paper by Miyata and Bathurst (2012a). The first instrumented steel strip wall in Japan was constructed in 1978 that is 6m in height (Chida and Nakagaki, 1979) [9].

The behavior of MSE walls is complicated, and performing an accurate simulation of these walls using numerical modeling techniques (e.g., finite element and finite difference methods) is a challenge [11]. This challenge is due to the complex interactions between the soil and there in forcing elements, the soil and the facing panels and the segmental construction technique. A recent case study was reported by Damians et al. (2015) who used the finite element method to simulate the performance of a well-instrumented 17-m-high steel strip wall constructed in the USA (Runser etal.,2001). The numerical results were judged to be in reasonable agreement with a range of measured response features [12]. In contrast, there are many examples in the literature of numerical simulations of instrumented reinforced soil walls constructed with extensible polymeric reinforcement materials using the finite element method (Karpurapu and Bathurst,1995; Rowe and Skinner, 2001; amongst others) and the finite difference method (Hatami and Bathurst, 2005, 2006; Huang et al., 2009, 2010; Abdelouhab et al., 2011; amongst others).

There are many situations where reinforced soil walls are constructed in a tiered configuration for variety of reasons such as aesthetic, stability and construction requirement. Current design of reinforced soil walls shows that multi-tiered wall has a better performance in comparison to single tiered walls, especially when it is necessary to construct the high reinforced soil retaining wall with stable, economic and aesthetic consideration.

The current study presents the development and validation of a numerical model to reproduce the static and seismic responses of multi-tiered wall at the end of construction subjected to earthquake loading. Investigation of reinforced soil walls in multi-tiered configuration that built in water and power resources projects (multi-tiered reinforced soil walls that in powerhouse of Gotvand dam) is the most important goal of this study. The paper is to describe the methodology used to select the optimum material properties, to maximize the accuracy of the numerical predications, and to demonstrate the sensitivity of the numerical outcomes to arrange of input parameter values. The numerical finite element method program, ABAQUS (Version 6.11), has been used to perform the numerical simulations.

2. PROBLEM DEFINITION AND MODEL PARAMETERS

2.1. MULTI-TIERED REINFORCED SOIL WALLS

A 31 m high steel-reinforced soil wall in multi-tiered configuration (Figure 1) was built in 2004 that was located above the powerhouse of Gotvand dam (one of the biggest water & power project in south of Iran). These walls are in 5-tiered configuration and the facing of the walls was constructed using 1.5 m high cruciform-shaped concrete panels with a thickness of 180 mm. In the current study, comparisons between the static and seismic wall performance are restricted to the end of construction and dynamic loading was applied. The walls were reinforced by smooth steel strips that were 50 mm wide and 5 mm thick. The length of the steel strips varied with the elevation as given in Table 1.

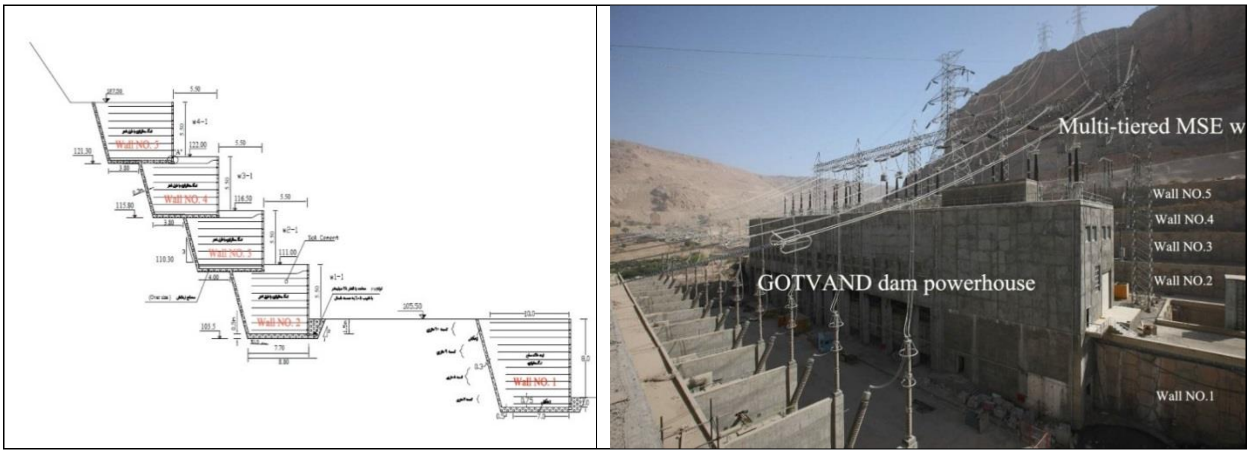


Figure 1. View and cross section of multi-tiered reinforced soil walls in Gotvand dam powerhouse

Table 1. Characteristic of each stage of multi-tiered reinforced soil walls in Gotvand dam powerhouse

Name of wall	Wall No. 1	Wall No. 2	Wall No. 3	Wall No. 4	Wall No. 5
Height (m)	9	7.5	6.2	6.2	6.2
Berm length (m)	33	5.5	5.5	5.5	5.5
Number of reinforcement layers	12	9	7	7	
Length of reinforcement layers (m)	7, 8, 9, 10	7	8	7	7
Vertical space of reinforcement layers (m)	0.75	0.75	0.75	0.75	0.75

The specifications of backfill and retained soil, reinforcements, and concrete facing panels which were used in numerical simulations are presented in Table 2-4.

Table 2. Characteristic of soils and rock

Parameter	Symbol	Unit	Rock	Soil (2)	Soil (1)
Soil Type	Type	-	-	Un-drained	Drained
Dry unit Weight	γ_{unsat}	kN/m^3	20	20	18.5
Saturated unit Weight	γ_{sat}	kN/m^3	21	21	20
Constitutive model of soil	*Model*	-	MC	MC	MC
Elastic modulus	E	MPa	1.7	0.1	0.1
Poisson's ratio	ϑ	-	0.462	0.3	0.3
Cohesion	C	kN/m^2	120	30	1
Internal friction angle	φ	Degree	36	36	36
Dilation angle	ψ	Degree	6	6	6
Cutoff tensile stress	$\sigma_{cutoff-t}$	kN/m^2	120	30	1

Table 3. Characteristic of steel strips reinforcements

Parameter	Unit weight	Elastic modulus	Poisson's ratio	Thickness	Dimensions
unit	kN/m^3	GPa	-	m	mm
quantity	78.5	210	0.25	0.18	5×50

Table 4. Characteristic of facing concrete panels

Parameter	Unit weight	Elastic modulus	Poisson's ratio
unit	kN/m^3	MPa	-
quantity	24	66.7	0.15

2.2. SEISMIC LOADING

The acceleration-time history employed is the horizontal component of the El-Centro earthquake of 1940, with a peak horizontal acceleration of 0.40g, as shown in Figure 2. Acceleration history was applied for 32 seconds for want of more computer time.

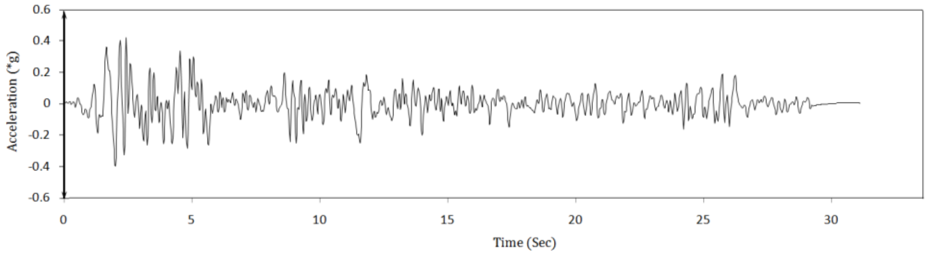


Figure 2. Time history of base reference input acceleration, (El-Centro earthquake, 1940)

3. FINITE ELEMENT METHOD PROCEDURE

The numerical simulations were performed using the 2-D finite element computer program ABAQUS 6.11. Figure 3 shows the ABAQUS numerical network used in this study. Plane strain conditions were assumed in this study and the finite element simulations were carried out. Wall geometry, arrangement of wall reinforcements, backfill and foundation soil properties, and facing type were simulated as were reported in the original case study [8]. The construction process was modeled using sequential bottom-up numerical network increments of 0.25 m thick.

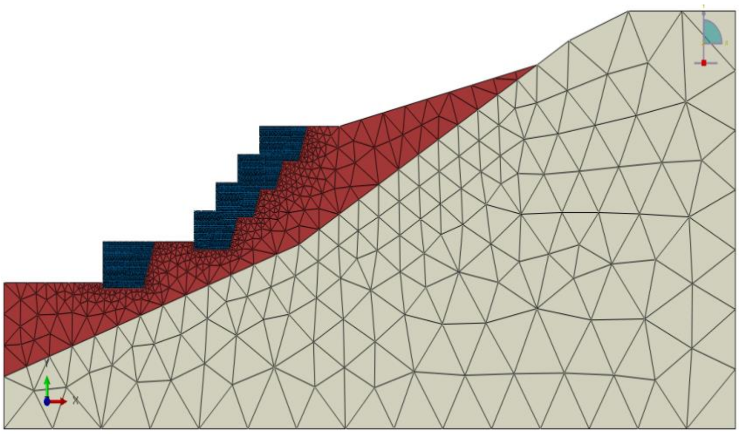


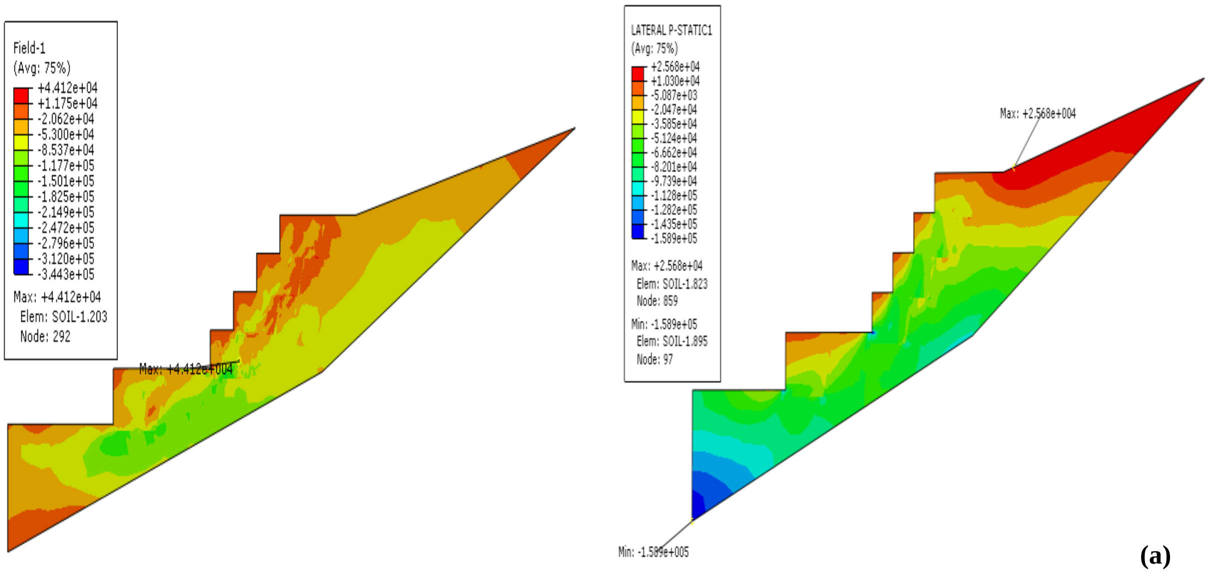
Figure 3. View of numerical grids

4. NUMERICAL RESULTS

In this section, comparison between static and seismic analyses for steel-reinforced soil walls is done. The results of seismic analysis are presented and the different analysis parameters are compared.

4.1. DISTRIBUTION OF LATERAL PRESSURE

Figure 4 shows the horizontal stress in walls at the end of construction for static analysis (Figure 4-a) and dynamic loading (Figure 4-b). It can be observed that the horizontal stress fluctuated near the lines of the active earth pressure. The fluctuation of the horizontal stress distribution in the numerical analysis is thought to be caused by the dynamic shearing forces between the horizontal soil layers.



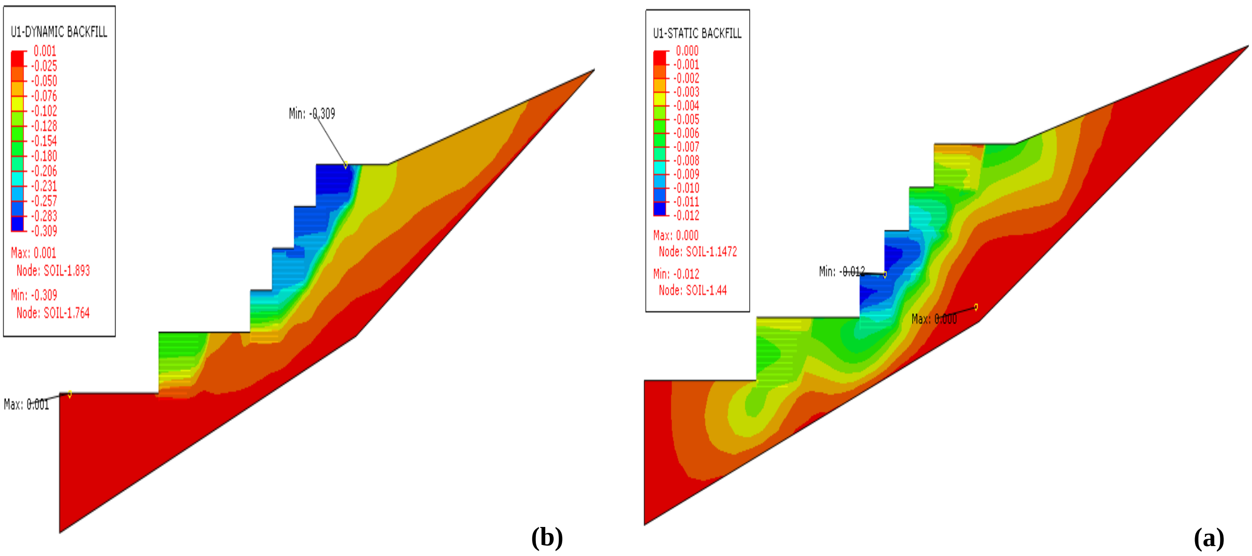
(a)

(b)

Figure 4. Distribution of lateral pressure: (a) end of construction, (b) dynamic loading

4.2. DEFORMATION OF BACKFILL SOIL

The residual horizontal displacements of backfill soil in static and dynamic loadings are displayed in Figure 5. The seismic analysis results have larger horizontal displacement than the statically analysis, implying that the dynamic excitation has a slight influence on the overall horizontal displacement, especially in high elevation in multi-tiered walls.



(b)

(a)

Figure 5. Horizontal displacement of backfill soil: (a) end of construction, (b) dynamic loading

4.3. DISTRIBUTION OF TENSILE FORCE IN REINFORCEMENTS

Figure 6 indicates the calculated tensile forces along the steel strips at the end of static and dynamic analysis. It can be observed that the dynamic analysis gives slightly higher values than static analysis in the upper part of the wall, and give slightly lower values than those in the lower part of the wall. However, because the tensile forces are relatively small, the difference was only about 15% of the strength of reinforcements. As shown in Figure 6-b in seismic analysis, maximum tensile load is occurred in the first stage of multi-tiered walls.

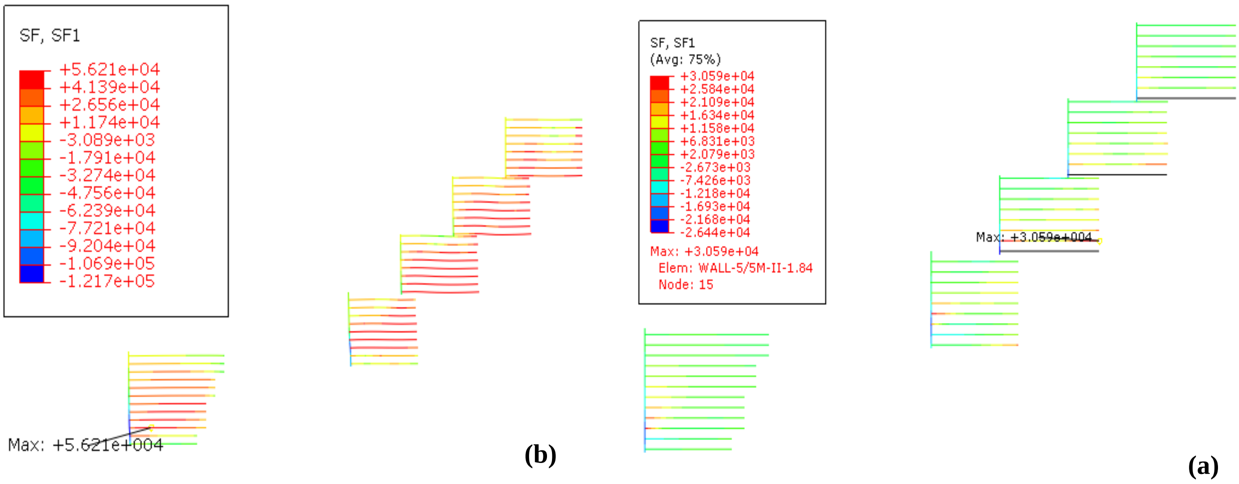


Figure 6. Distribution of maximum tensile forces at different heights in walls at: (a) end of construction, (b) dynamic loading

4.4. STRAIN OF REINFORCEMENTS

Figure 7 illustrates the strains of steel-strips at different layers of wall No.1 to wall No.5 at the end of the construction (Figure 7-a) and at the end of earthquake loading (Figure 7-b). In both loadings the maximum strain of reinforcements is occurred in the first reinforcement layer of wall No.2.

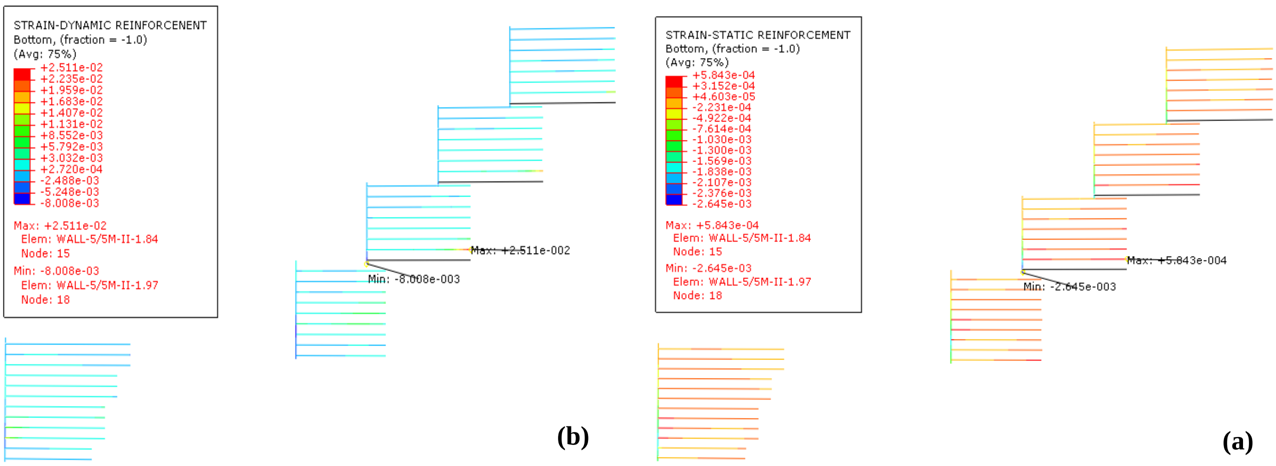


Figure 7. Strains of the reinforcements: (a) end of construction, (b) dynamic loading

4.5. SHEAR ZONE

Figure 8 shows typical plots of shear zones in the multi-tiered reinforced soil walls for seismic conditions. In this numerical study, there was no evidence of a well-defined failure surface intersecting all reinforcement layers as may be expected from conventional tied-back wedge and nonlinear slip surface methods of analysis (Bathurst and Alfaro 1997). This was true even for models with the lowest reinforcement stiffness. Rather, the reinforced soil zone acted as a parallel-sided monolithic mass. Further study is required to determine if the pattern of internal failure will change with greater reinforcement spacing [5].

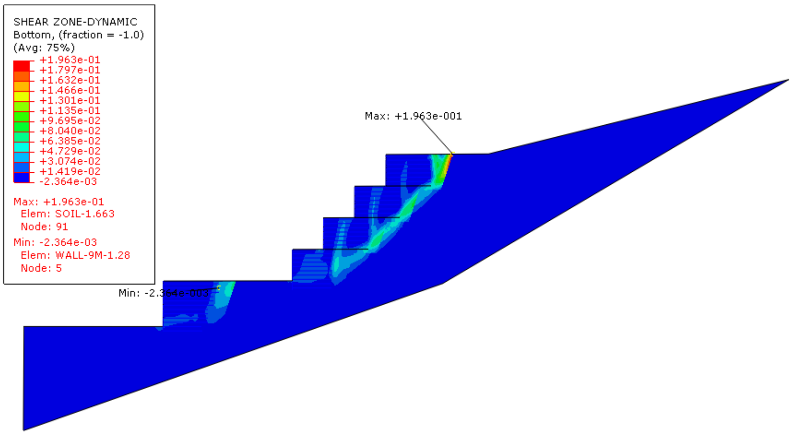


Figure 8. Shear zone at end of dynamic loading

4.6. DISTRIBUTION OF BACKFILL ACCELERATIONS

Figure 9 shows the accelerations at different elevations of the reinforced soil area, whose locations are depicted in Figure 9, during the second vibration stage. It can be observed from the results that the accelerations were amplified along with the increase of height, which is also coincident with the numerical analysis. These results again proved the fact that the accuracy of the dynamic FEM analysis conducted in this paper is quite high. The distribution and magnitude of peak accelerations in the backfill soil is of interest in pseudo-static seismic design methods because a coherent distribution of the ground acceleration is considered to be responsible for the additional destabilizing force that must be resisted by reinforced structures during a seismic event [4].

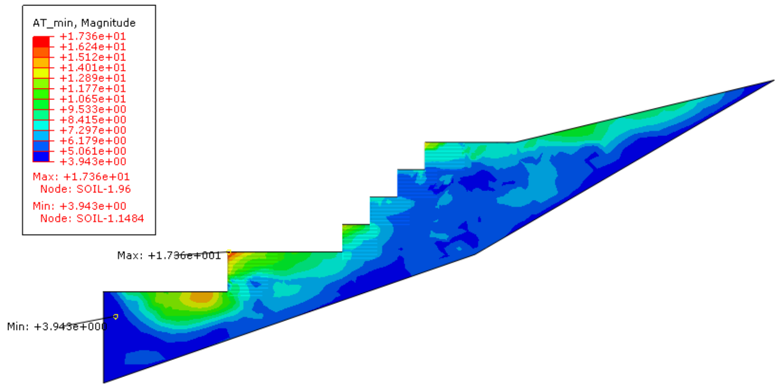


Figure 9. Acceleration responses subjected to reinforced soil walls during seismic loading

5. CONCLUSIONS

In this research, a multi-tiered reinforced wall with steel strip soil reinforcement was designed and built in 2004, is investigated under seismic loading. The results of static analysis are compared to seismic analysis using the finite element program ABAQUS. In this paper, the static and dynamic analyses on reinforcement forces and numerical analysis using finite element method, and the results have been presented.

1. Based on the obtained results, the backfill lateral pressure due to seismic loading is two times more. Also the location of maximum backfill soil lateral pressure is differed from reinforced soil at wall No.5 under static loading to reinforced soil at wall No. 2 under dynamic loading.
2. In seismic analysis results, the maximum magnitude of strain of reinforcements, deformation of reinforced backfill soil, the maximum magnitude of reinforcements tensile force is respectively 100, 11, 1.84 times more than static analysis. The location of maximum magnitude of strain of

reinforcements is in second layer of reinforcements in both static and dynamic analysis, the maximum deformation of reinforced backfill soil is in wall No.5 in both static and dynamic analysis and location of reinforcements tensile force maximum is differed from second layer at wall No.3 under static loading to third layer at wall No. 1 under dynamic loading.

3. The reinforcement loads increased from top of the wall to base in each single wall and with increasing height from wall No.1 to wall No.5. At the region of one third of base of the wall, the reinforcement forces were bigger than the top.
4. Dynamic loading induces more forces in reinforcement in comparison to static loading. At the top of the wall, the dynamic and static forces were almost similar, but with an increase in depth, the difference became slightly more. This result is similar to increasing the height of wall by increasing the number of stages in multi-tiered walls. The earthquakes with maximum base input acceleration had more effect on the difference between static and dynamic forces.
5. The magnitude of strip-backfill soil interface stiffness had a minor effect on both the tensile loads in the steel strips and the vertical facing load at the toe.
6. Backfill soil horizontal accelerations due to dynamic analysis is 3.4 times more than maximum time history accelerations that applied to numerical model, that it shows the resonance in some points of reinforced soil mass.

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