Investigation of the Effect of Seismic Loading on Displacements of Multi-Tiered Reinforced Soil Walls in Iran Major Hydropower Projects

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Abstract

Reinforced Soil Wall (RSW) is one of the flexible structures that have good performance during earthquakes. Investigating the displacement behavior of RSWs in earthquake is an important issue in dynamic behavior of these structures. In this paper, one of the reinforced soil walls that are constructed in IRAN major hydropower projects is selected. These walls are modeled in Finite element method (FEM) based software, and the performance analysis in several conditions included: end of construction, statically analysis, dynamic analysis are done. In order to investigate the effect of different seismic loadings, two earthquake records of seismic loading are applied to numerical simulations. Comparing the results of seismic analysis of walls illustrates difference of seismic performance of reinforced soil wall under different seismic loadings specially in displacements of these structures.

Keywords: Multi-tiered Reinforced Soil Walls, Seismic Displacement, Dynamic Analysis, Finite Element Method, Gotvand dam.

1. INTRODUCTION

There are different types of retaining walls (e.g. gravity, cantilever and tieback walls) and they are used to secure embankments against sliding, or as key elements of harbors. Tall retaining walls are often constructed as what is called reinforced soil retaining walls or in multi-tiered configuration [3]. This type of retaining wall consists of a facing with a reinforced soil zone behind it (Kramer, 1996). Reinforced soil walls are mechanically stabilized earth retaining systems that are technically proven and a cost effective alternative to the conventional concrete walls [1]. Traditionally, the reinforcements are consisted of thin steel elements but today the use of geogrids is becoming more common. During an earthquake, the retaining wall is subjected to inertial forces due to the backfill inertia. Reinforced soil walls must be designed to withstand the static lateral earth pressure, in addition to forces that are applied in case of an earthquake (Kramer, 1996). As summarized in Rowe and Ho (1998), lateral facing displacement consists of the contributions from deformation of reinforced soil zone, displacement at the back of reinforced soil zone, displacement due to foundation yielding (Skinner and Rowe, 2003, 2005; Rowe and Taechakumthorn, 2008; Bergado and Teerawattanasuk, 2008; Li and Rowe, 2008; Viswanadham and König, 2009; Huang and Luo, 2010; Rowe and Taechakumthorn, 2011), compaction (e.g., Hatami and Bathurst, 2006; Bathurst et al., 2009), slack in reinforcement connection, and dislocation of facing blocks. With proper quality control, slack in reinforcement connection and block dislocation can be minimized [12].

Reinforced soil walls are often used along coastal highways and riverbanks, for docks, sea walls, dams and spillways [2]. Flooding, tides, impounded water and rapid water level drawdown all create complex hydraulic loading conditions that benefit from the open facing joints and free-draining backfill characteristics of reinforced soil walls. In addition, the precast facing panels can move slightly relative to each other, giving the wall system flexibility, resiliency, and the ability to resist storm-driven waves, debris and even pack ice.

Investigation of reinforced soil walls that built in water and power resources (e.g. dams and powerhouses) projects shows that the main applications of these structures are as below:

1. Soil slope stability
2. Construction of bridge abutment
3. Protection soil and rock slopes against sliding
4. Soil improvement for construction or development of main or access roads

Some of the reinforced soil walls that were designed and constructed in IRAN dam projects are given in Table 1 and Figure 1.

Table 1- A number of the most important reinforced soil walls that were designed and constructed in Iran dam projects

No.	Project name	Location	Date of completion	Total area (m^2)
1	Powerhouse of Seymareh dam	Iran, Eilam	2010	500
2	Rural road in Alborz dam	Iran, Mazandaran	2004	2708
3	Access road to Cham Gordalan dam	Iran, Eilam	1999	538
4	Khoda Afarin dam	Iran, Tabriz	2005	1270
5	Powerhouse of Gotvand Dam	Iran, Khozestan	2004	6000
6	Development of access road in Bakhtiari dam	Iran, Ahwaz	2012	4200
7	Retaining wall in Lorestan Roodbar dam	Iran, Lorestan	2012	2000
8	Geogrid MSE walls in Dorood dam	Iran, Lorestan	2014	2000

Powerhouse of Seymareh dam

Access road to Cham Gordalan dam

Development of access road in Bakhtiari dam

Rural road in Alborz dam

Figure 1. Pictures of reinforced soil walls in Iran dam projects

2. CHARACTERISTICS OF MATERIALS, ASSUMPTIONS AND ANALYSIS METHOD

2.1. CHARACTERISTICS OF MATERIALS

Materials used for modeling the multi-tiered reinforced soil walls, is defined according to prototype condition [15]. Three type of materials is modeled including: two types of granular soil that are used to modeling backfill soil (soil type 1) and retained and foundation soil (soil type 2), one type of rock to modeling bed rock, one type of concrete to modeling segmental facing panels and one type of steel to modeling reinforcements. Physical and mechanical properties of backfill soil, reinforcements, and concrete facing panels which were used in numerical modeling are shown in Table 2-4. It is worthy to note that the ground water table level is -82.5 m that has no effect on soil parameters.

Backfill soil

Design codes typically recommend that the backfill soil is a granular soil so that it is free draining. A number of possibilities exists with respect to choice of constitutive model for the soil. In the present paper linear elastic-plastic with Mohr-Coulomb failure criterion is considers.

Table 2- Characteristic of soil and rock

Parameter	Symbol	Unit	Rock	Soil (2)	Soil (1)
Soil condition	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

Reinforcements

Steel-strips with 5mm×50mm area and 5mm thickness were used for reinforcement of the backfill soil. The wall comprises several layers of steel strips that are extended.

Table 3- Characteristic of steel strips reinforcements which were used in numerical modeling

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

Facing

Segmental concrete panels with 1.5m×1.5m area and 0.3m thickness were used for construction of the multi-tiered reinforced soil walls that are considered as case study in this paper.

Table 4- Characteristic of facing concrete panels which were used in numerical modeling

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

2.2. SEISMIC LOADING

Acceleration that used in this dynamic analysis belongs to Coalinga, El-Centro earthquakes. It was an attempt to use accelerations that were registered on stone base so that it may be consistent with rigid foundation in the models (Figure 2). These two earthquake have same frequency content and different time duration and same peak ground acceleration (PGA) equal 0.4g.

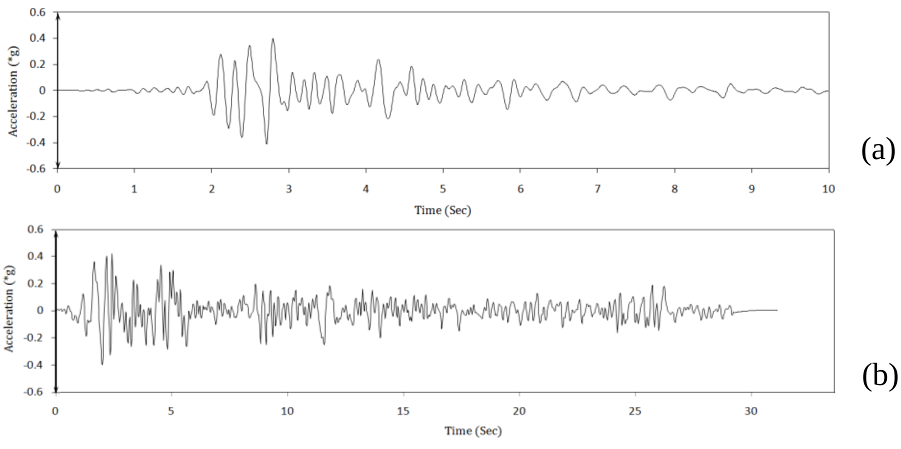


Figure 2. Time-acceleration diagram for: a-Coalinga earthquake (1983), b-El-Centro earthquake (1940)

2.3. ASSUMPTIONS

For dynamic analysis some assumptions included below items as are considered. The dry materials, Mohr-Coulomb for constitutive model of soil and rock, rolled connection as connection of reinforcement to facing panels and nonlinear dynamic analysis is assumed in numerical modeling.

3. THE CASE STUDY

In this paper, one of the highest reinforced soil walls in multi-tiered configuration is selected that are designed and constructed in one of the Iran major hydropower projects. This 31-m-high multi-tiered wall is built to support the soil slopes that are around the powerhouse of Gotvand dam project. Figure 3 shows a typical view of multi-tiered reinforced soil walls around the Gotvand dam powerhouse.

Figure 3. View and cross section of multi-tiered reinforced soil walls in Gotvand dam powerhouse

4. METHOD OF SEISMIC ANALYSIS

The finite element package ABAQUS Explicit, version 6.11 was used to perform two dimensional finite element analysis. The mesh of the wall without facing units, includes 1346 elements and 2035 nodes, and the wall with facing has 402 elements and 608 nodes (Figure 4). The wall is 31 m height in 5-tiered configuration and comprises concrete masonry units connected together by a cementing material, a uniform granular backfill, and several layers of steel-strip reinforcement extending into the backfill soil (Figure 1). The elements are discretized into 3-node quadrilateral elements (triangular) for backfill soil and facing panels and 2-node quadrilateral elements (beam) for reinforcement elements.

Multi-tiered soil walls reinforced with steel-strips, are analyzed in 3 steps as below:

1. Static analysis
2. Frequency analysis is done for detecting the model basic frequencies and Rayleigh (seismic) coefficients.
3. Seismic analysis is done to study the walls dynamic performance.

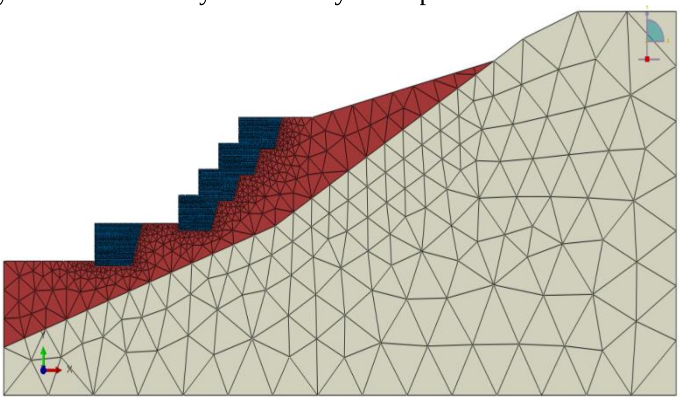


Figure 4. View of numerical grids

5. NUMERICAL RESULTS

Dynamic finite element analyses were carried out to simulate earthquake loading on a multi-tiered reinforced soil wall subjected to earthquake. The numerical analysis was carried out to investigate the dynamic behavior of multi-tiered reinforced soil wall. The comparison between the other previous results and the numerical calculation shows that the numerical method proposed in this paper can properly describe the seismic behavior of multi-tiered reinforced soil wall with sufficient accuracy. Some relevant physical mechanical parameters, such as the horizontal displacement of the facing segmental panels, the settlement of the backfill surface, the lateral earth pressure acting on the facing panels, the tensile forces in the steel-strips and the acceleration response, were all reproduced well by the numerical analysis. In the main part of numerical analyses, the influences of earthquake loading, specially deformation of walls, is investigated by comparing of first and second dynamic analysis results. Thus, the proposed numerical method in this paper can provide an effective evaluation method for the dynamic design of multi-tiered soil walls reinforced with steel-strips. The numerical results of seismic analyses can be explained in the following sections as below.

5.1. MAXIMUM OF SEISMIC ANALYSIS PARAMETERS

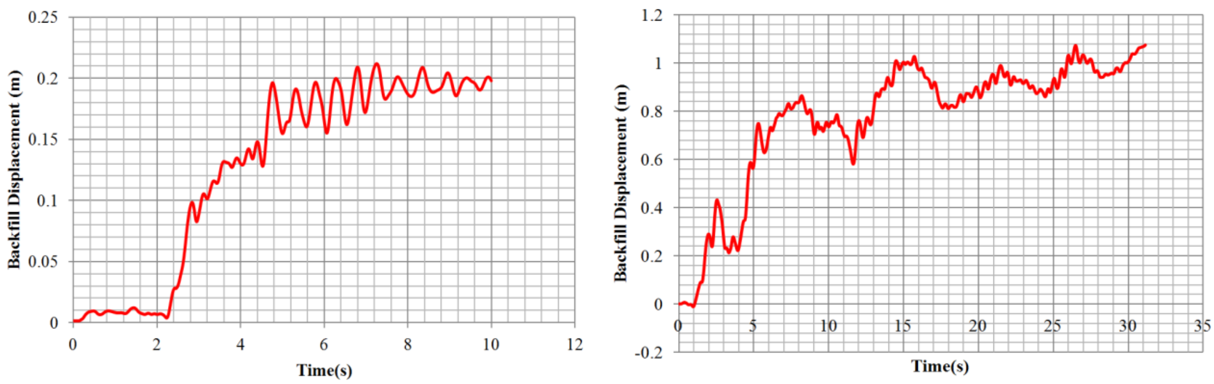
The maximum value of the most important seismic analysis parameters that obtained from dynamic analysis is presented in Table 5.

Table 5- Maximum values of seismic analysis parameters

Parameter	Unit	Coalinga earthquake	El-Centro earthquake
Maximum horizontal displacements of walls	m	-0.197	-1.073
Maximum settlements of walls	m	-0.127	-0.506
Maximum strain along reinforcements	%	+0.800	+3.700
Maximum horizontal displacement of walls during earthquake	m	-0.210	-1.100
Maximum horizontal displacement of facing walls during earthquake	m	-0.210	-1.100

5.2. HORIZONTAL DISPLACEMENTS OF WALLS

The magnitudes of deformation occurred during and after construction subjected to earthquake loading is important in the performance of reinforced soil walls. However, there is no standard method for prediction of the lateral deformations [11]. Horizontal movements depend on compaction, reinforcement extensibility, reinforcement length, reinforcement to facing connection details, and deformability of the facing system (Mitchell and Christopher, 1990). The contour of horizontal displacements of walls after is presented in Figure 5.



Coalinga earthquake   El-Centro earthquake

Figure 5. Horizontal displacements of walls

Two shapes of a deformed reinforced soil wall, named bulging and tilting were observed in the typical dynamic analyses [4]. The shape of a deformed wall depends to the dynamic loads and wall characteristics. Tilting shapes are created when the earthquake is very strong and/or the wall is not stiff. Bulging shapes could be seen when the earthquake is not strong and/or the wall is very stiff .Typical wall deformation in this study is bulging shape and is shown in Figure 6.

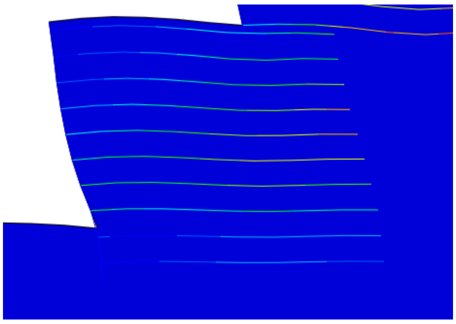
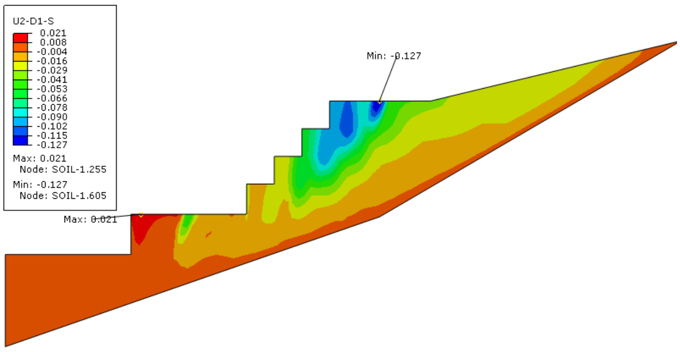


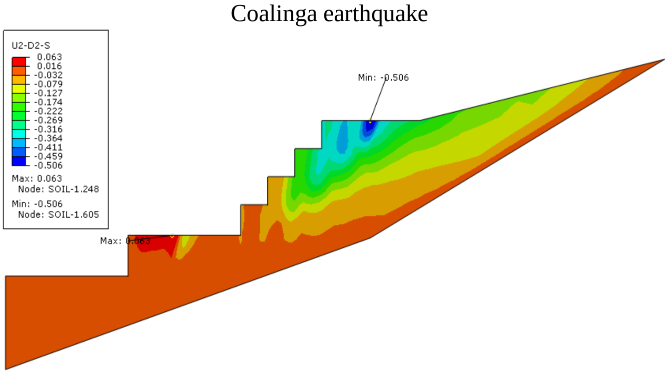
Figure 6. View of typical wall deformation

5.3. SETTLEMENTS OF WALLS

The vertical deformation of reinforced soil wall depends on the ground condition supporting the wall. In real situation, the settlement of reinforced soil walls does not significantly cause the failure, if the settlement is even throughout the wall elevation and at the backfill zone [13]. However, differential settlement of wall on localized spot area in the wall elevation may cause the opening between the interlocking concrete facing panels. In 2D finite element analysis, where the plane strain assumption is applied, differential settlement along wall elevation is unable to be predicted. On the other hand, vertical deformation along cross sectional of wall can be modeled. The contours of wall settlements subjected seismic loading (after first and second seismic loading) are illustrated in Figure 7.



Coalinga earthquake

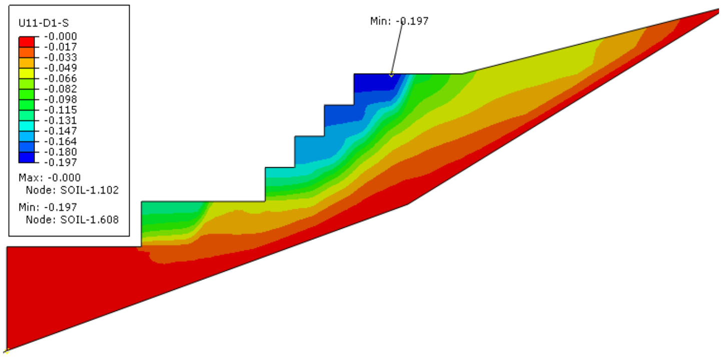


El-Centro earthquake

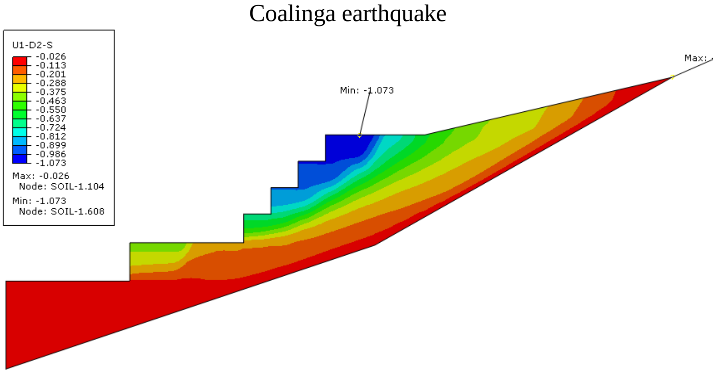
Figure 7. Contour of horizontal settlement of walls

5.4. MAXIMUM HORIZONTAL DISPLACEMENTS OF WALLS DURING EARTHQUAKE

This section gives the deformed shape of the diaphragm wall at different time steps in the dynamic analyses. It gives the information about relative permanent displacement and permanent tilt of the gravity wall. This information is useful for displacement base design procedures. Figure 8 shows the maximum horizontal displacements of walls during earthquake at first and second seismic loading.



Coalinga earthquake

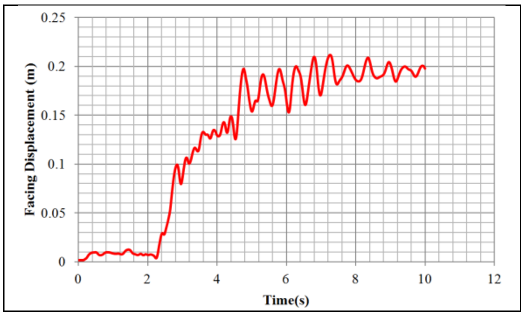


El-Centro earthquake

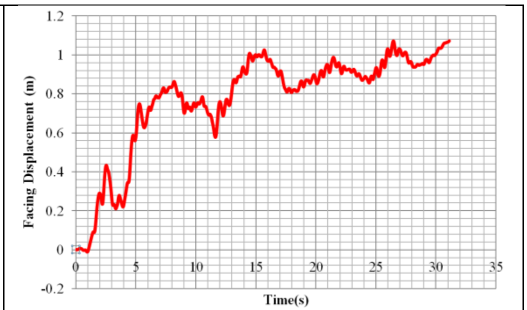
Figure 8. Contour of horizontal displacements of walls

5.5. MAXIMUM HORIZONTAL DISPLACEMENTS OF FACING PANELS DURING EARTHQUAKE

The time history of maximum horizontal displacements of facing panels in multi-tiered reinforced soil walls subjected to 0.40g excitation that is graphed in Figure 9, shows that the displacements around static displacement over the ground motion duration, and are not permanent at the end of the excitation. As is graphed in Figure 9 is the fluctuating displacement at the middle level of the wall. The increasing in the displacement of the top, rightly so, results from the increasing acceleration along the wall height.



Coalinga earthquake



El-Centro earthquake

Figure 9. Time history diagram of maximum horizontal displacements of facing panels during earthquake

5.6. MAXIMUM STRAIN OF REINFORCEMENTS AFTER EARTHQUAKE

Figure 10 shows the distribution of reinforcement strain after seismic loading. In each part of this figure, maximum strain of reinforcements after seismic analysis in one stage of multi-tiered soil wall is presented (wall No.1 to wall No.2). As shown in Figure 10, with increasing the height of walls, the value of reinforcement strain is increasing because of ground horizontal amplification. The value of reinforcement strain in first layer of steel-strips is about zero because of their high stiffness and reinforcement strain is increasing with increasing the wall height and reinforcements elevations as is shown in Figure 10.

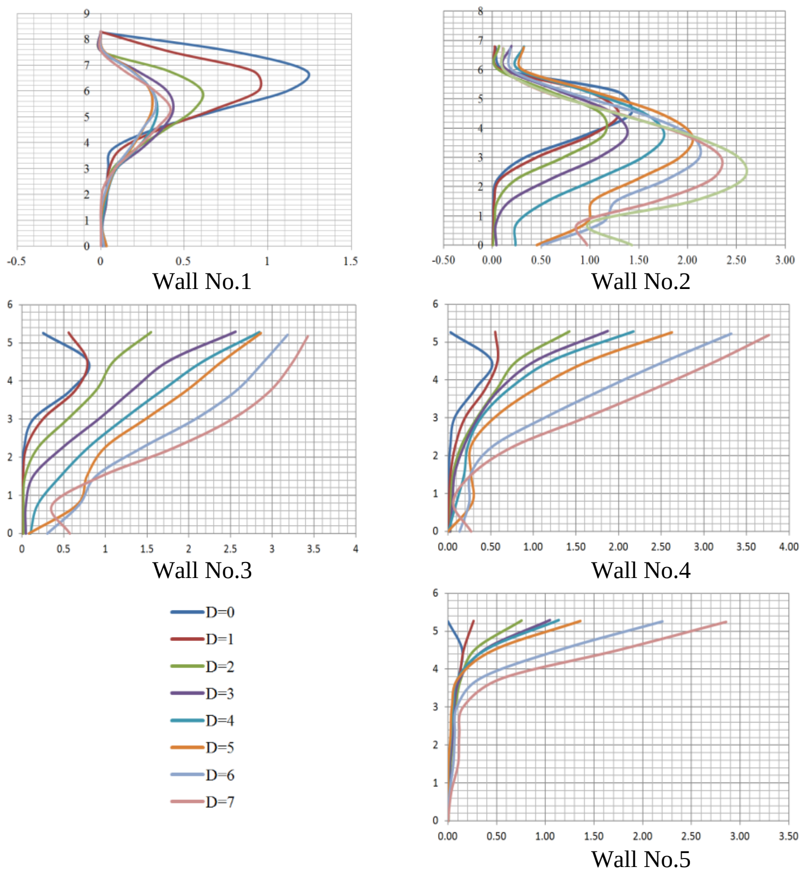


Figure 10. Maximum strain of reinforcement along wall height in each stage of multi-tiered soil walls after El-Centro earthquake

6. CONCLUSIONS

This paper describes the results of the numerical study of multi-tiered reinforced soil in Gotvand dam powerhouse. The analyses are performed using the finite element methods as describes section 4. Based on the obtained results, the following conclusion may be drawn.

1. It was found that deformations of reinforced soil zone and displacement at the back of reinforced soil zone are the two main components of lateral facing displacement for medium-high to high reinforced soil walls. The deformation of reinforced soil zone was only slightly affected by reinforcement length, but was largely determined by reinforcement spacing and reinforcement stiffness that can be unified by the global reinforcement stiffness.
2. Reinforced soil walls can undergo large displacements due to resonance, when exposed to earthquakes with significant energy content at frequencies similar to their first-mode of response, even when the total energy content of the earthquake is not large. It is very important in reinforced soil walls in multi-tiered configuration and tall wall specially.
3. Soil stiffness played an important role in the lateral deformation when soil strength was not mobilized owing to large reinforcement stiffness and/or small reinforcement spacing (Leshchinsky and Vulova, 2001). Soil strength took over as the important role when soil deformation was large due to higher soil stress because of low stiffness reinforcement, large reinforcement spacing or high retaining wall.
4. In typical seismic analysis of reinforced soil wall two shapes of a deformation, named bulging and tilting were observed. Bulging shapes could be seen when the earthquake is not strong and/or the wall is very stiff .Typical wall deformation in this study is bulging shape.
5. The most important parameters that are affecting the value of reinforcement strain are: the layout of reinforcements, reinforcement axial stiffness (EA), wall elevation, wall surcharge and etc.

6. The results state that the assumptions of available seismic design codes are highly conservative, due to ignoring allowable displacements after earthquake occurrence. Consequently, performance based design concept would result in more suitable and economical structure.
7. The displacement based performance of single reinforced soil walls is differed from multi-tiered reinforced soil walls [13]. Therefore multi-tiered reinforced soil and their seismic performance must be analyzed and investigated before designing and construction.

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