Numerical study of facing type effects on reinforced soil walls response under service and seismic loads

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ABSTRACT: Recent research has shown that a large part of reinforced soil wall damages are attributed to inappropriate performance of their facing elements under static and dynamic loading conditions. Many facing factors such as material quality, construction procedure and quality, facing-reinforcement connection type, drainage conditions, etc., are influencing the stability of reinforced walls.
This paper presents a review and discussion first on the available numerical and laboratory studies in literature. The results of numerical study on a well-instrumented wall are presented next to evaluate the performance of common facing types under both service and seismic loads and the results are compared with the criteria and provisions mandated in the codes such as FHWA and AASHTO.
The results show that the facing type is having significant effects on the behavior of the reinforced soil wall and is one of the most important wall stability factors under seismic conditions. Moreover, the transfer of forces from reinforcement to the facing elements is very important and inappropriate performance of the load-transfer mechanism can lead to local and subsequently general instabilities. In addition, the results of the facing type effects on facing displacement profile, distribution of reinforcement forces and reinforced soil zone settlement under both static and dynamic conditions are evaluated and discussed.

Keywords: Reinforced soil wall, service and seismic response, geogrid, numerical model, dynamic analysis

1 INTRODUCTION

The reinforced soil walls have been widely used all around the world with different geometry and facing types. The study of reinforced soil walls behavior under service and seismic loading is significant. The seismic behavior of these walls is considered and well-evaluated in various design codes and standards such as AASHTO, FHWA and etc., and the design method is expressed in terms of seismic operation and seismicity.

Facing elements properties like stiffness, connection type to reinforcements, drainage condition and etc. have significant effects on wall behavior. According to AASHTO and FHWA, the facing elements are generally divided into six categories include: segmental precast concrete, wrap-around, modular block, full height concrete, gabion and tired facing wall. In this study four reinforced soil walls with different facing types include segmental precast concrete, wrap-around, modular concrete block and modular hollow concrete block are selected to study the effects of facing characteristics on the reinforced soil wall behavior under service and seismic loading.

Koerner et al. (2013) presented a collected database, statistics studies and recommendations about 171 failed mechanically stabilized earth (MSE) walls. This study shows the causes of occurred instabilities in reinforced soil walls. Maximum percentage of failing cases is related to walls with modular concrete block facing (71% of failing cases) and minimum percentage is related to walls with wrap-around facing (4% of failing cases). According to this research, most of walls failed in the first four years of their service time (86% of failing cases). This study shows that facing type has an important role in the behavior of reinforced soil walls and it should be considered in the design stage. In recent years, extensive research has been carried out on the effects of facing type on reinforced soil walls under service and seismic conditions.

Ehrlich et al. (2013) and Bathurst et al. (2006) presented the facing stiffness and toe resistance effects on the performance of geosynthetics reinforced soil retaining wall. According to these studies, the facing stiffness may play an important role in affecting the magnitude of the maximum axial force in reinforcement. Scotland et al. (2016) studied the facing deformation of wrapped geogrid-reinforced structures during the construction. Yu et al. (2017) presented comparative results of numerical results with laboratory results of two full-scale reinforced soil. In this study, numerical predictions for wall facing deformations, reinforcement strains and loads were generally in good agreement with measurements of the wrapped-face wall. Ren et al. (2016) evaluated the seismic behavior of reinforced-soil segmental retaining walls (SRW). According to the comparison between the results of shaking table test and the numerical model results, the numerical study can properly describe the seismic behavior of SRW with sufficient accuracy.

This paper investigates the behavior of four reinforced soil walls with different facing types under static and seismic excitations. The selected reinforced soil wall is one of the well-instrumented full scale wall which has been studied under static conditions in the laboratory by Miyata et al. (2015). FLAC 2D is used to simulate verification and parametric model. Many researchers have been used this software (El-Emam & Bathurst, 2004,Yu et al., 2009, Ren et al., 2016) because of its good accuracy in results. After discussion about verification model and its results, the results of four numerical models of reinforced soil walls include facing displacement, reinforced soil zone settlement and reinforcement axial force are presented to investigate the effects of facing type on the wall behavior under three conditions: end of construction, under service loading and under seismic excitation. At last the results are compared with the criteria and provisions mandated in the codes such as FHWA and AASHTO.

2 NUMERICAL STUDY INTRODUCTION

In this study four reinforced soil walls with different types of facing include: segmental precast concrete, wrap-around, modular concrete block and modular hollow concrete block, are studied and their results are compared. To understand the effects of facing type on wall behavior, all other parameters such as soil properties, length and properties of geogrid, height and geometry of the walls, boundary condition and loading, are considered constant in all models.

2.1 *Numerical model*

In Fig. 1, the models with different facing type (concrete panel, wrapped and concrete block) are shown. The total height of the walls is equal to 4 meters and the angle of wall facing is vertical. The concrete panel was 18 cm thickness and 1 meter height. Wrap-around facing is considered with length 0.6 m anchor length. The concrete modular block was 25 cm thickness and 50 cm height. The boundary condition is considered as Fig. 1 in static condition and free field condition for dynamic analysis according to parameters defined in FLAC2D (Cundall, 2014). Interface elements are added between concrete facing elements and also their connection to the soil. The initial condition for the seismic analysis is the static stability of the entire system that is maintaining the initial stresses while all the deformations are reset to zero. All soil and geogrid parameters are considered based on the original wall source reported by Miyata et al. (2015).

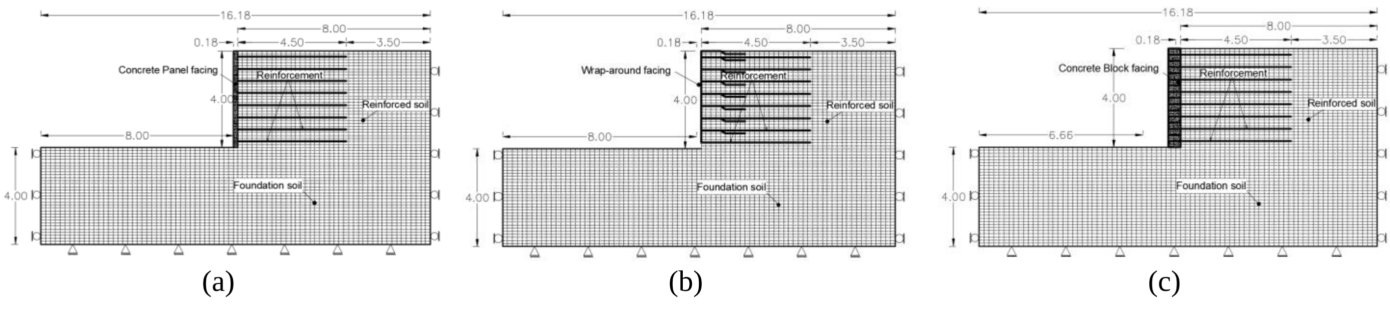


Figure 1. Grid, interface elements and boundary conditions of the numerical model (a) Concrete panel facing, (b) Wrap-around facing, (c) Modular concrete block facing

For simplicity the granular soil model is elasto-plastic with M-C (Mohr-Coulomb) failure criterion under static condition. Soil parameter values for the static model are summarized in Table 1. Soil Young's modulus is estimated on the basis of empirical relationships according to other soil mechanical properties reported by Miyata et al. (2015).

Table 1. Soil parameter for static analysis

Soil zone	Mohr- Coulomb parameters				
	γ (kN/m^3)	φ (°)	c (kPa)	E (MPa)	υ
Reinforced & Foundation Soil	16.2	38.0	2.0	80.0	0.3

In the dynamic analysis, the loading/unloading nonlinear hysteretic Massing rule was used to model the shear behavior of the soil, and to capture soil damping. This model has been used by (Cai, et. al. 1995) for dynamic finite element analysis of segmental retaining wall. The reinforcement geogrids are modeled by the elastoplastic cable elements in FLAC without compressive strength. The frictional behavior between soil and geogrid was simulated by assuming a grout layer thickness of zero, an interface soil/geogrid friction angle of 0.75φ, and zero cohesion. The reinforcement parameters used in the analysis are presented in Table 2.

Table 2. Geogrid parameters

Geogrid type	Geogrid parameters	
	T_{ult} (kN/m)	$J_{2\%}$ (kN/m)
Extruded biaxial polypropylene (PP)	32.0	170.0

Maximum allowable axial reinforcement forces are shown in Table 2. For simplicity, geogrid elastic modulus is calculated using secant method at the point of 10% strain using the tensile stress-strain graphs provided by the manufacturer. A variable-amplitude sinusoidal harmonic motion is used as an input at the bottom nodes of foundation soil for seismic excitations according to Eq. 1 and Fig. 2.

$$\ddot{u}(t) = k/2 \times \sqrt{\beta \, e^{-\alpha t} t^{\xi}} \, \sin(2\pi f \, t) \tag{1}$$

Where: α=5.5, β=55, ζ=12 are constant coefficients; f=frequency, t=time, k=peak amplitude of the input acceleration assumed as 0.4g, and frequency, f=3 Hz. The time, t, varies between 0 and 6 seconds.

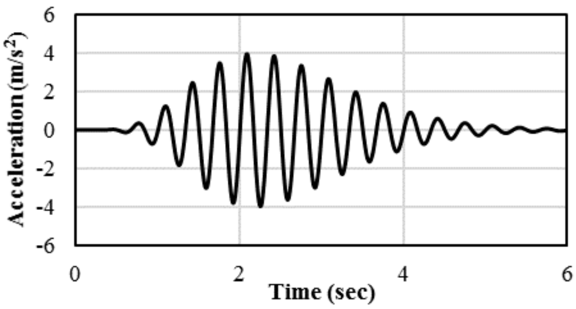


Figure 2. Harmonic wave shape

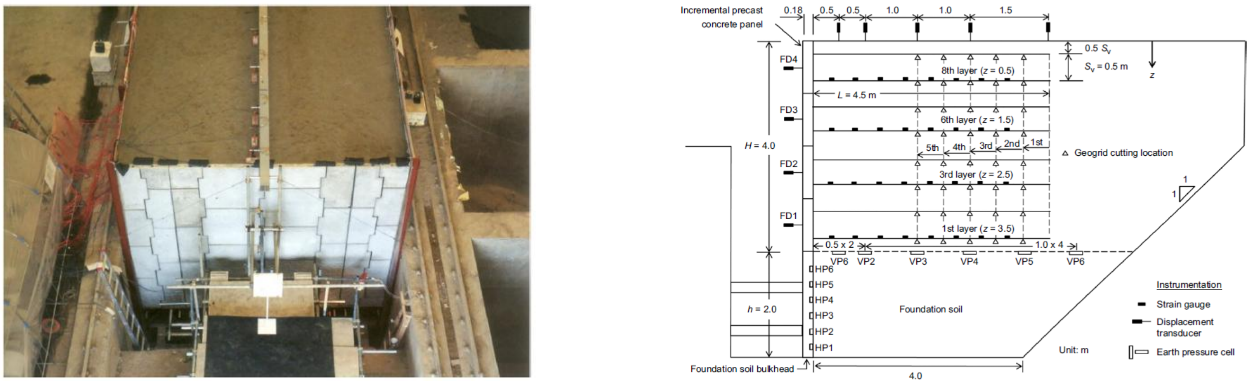
2.2 *Model verification*

FLAC has been used successfully to model reinforced soil walls under both static and seismic conditions (e.g. Hatami and Bathurst 2001, 2005, 2006; El-Emam et al. 2004). In this paper, the results of a well-instrumented reinforced soil wall system reported by Miyata et al. (2015) are used to validate numerical model.

Miyata et al. (2015) presented the performance of three geogrid-reinforced soil walls with different facing type before and after foundation failure. This study reported the results of three 4 m height and 5 m width full-scale instrumented geogrid-reinforced soil walls constructed with different facings. The walls were seated on 2 meter deep foundation layer that was laterally supported at the base of the wall face by a rigid bulkhead. Following end of construction, the bulkhead was moved outward in stages to simulate loss of foundation support in the vicinity of the wall toe. Bulkhead loads, wall deformations, backfill settlements, reinforcement loads and earth pressures were recorded at the end of construction and during bulkhead displacement.

2.2.1 *Introduction of full-scale wall test*

The selected walls were instrumented with foil-type electrical resistance strain gauges bonded directly to the top and bottom of the reinforcement, horizontal facing displacement transducers mounted against the facing and backfill surface, earth pressures cells at the foundation level and mounted flush with the inside surface of the bulkhead. As shown in Fig. 3 the foundation bulkhead was located in a test pit below the toe of the reinforced soil wall structures. The panel wall facings were seated directly on the instrumented footing. The seating of the two vertical walls on the foundation bulkhead prevented vertical displacement of the wall toe from occurring. The same fine sand with a fines content of 8% was used for the backfill and foundation soil (D85 = 1.2 mm, D50 = 0.33 mm, D10 = 0.078 mm, C_u = 4.5, C_c = 1.6). Compaction was carried out in 0.25 m thick lifts using a walk-behind (65 kg) vibrating plate compactor. Consolidated-drained triaxial tests were carried out to estimate strength parameters for the backfill. From these tests a cohesion value of 2 kPa and a peak friction angle of 38° were deduced.



(a) (b)

Figure 3. Incremental concrete panel wall: (a) photograph of full-scale test wall; (b) Instrumentation cross-section view

An extruded biaxial polypropylene (PP) geogrid with an ultimate tensile strength of T_{ult}= 32 kN/m was placed at a vertical spacing of 0.50 m. Vertical incremental concrete panels with height of 1 m and thickness of 0.18 m were used for the facing. The reinforcement stiffness value was taken as 170 kN/m at 2% strain (J2%) based on in-isolation load–strain–time properties for this material and construction time. The compacted soil unit weight was γ = 16.2 kN/m^3. More details are available in the papers by Miyata et al. (2015).

2.2.2 *Numerical Modeling for Verification*

Fig. 4 shows the geometry, boundary conditions, loading, reinforcement arrangement, interface elements, and finite difference grid for numerical simulation of the full-scale wall that used for numerical validation. The bulkhead is modeled with a region of weak soil and the connection of foundation soil to concrete bed is modeled using an interface.

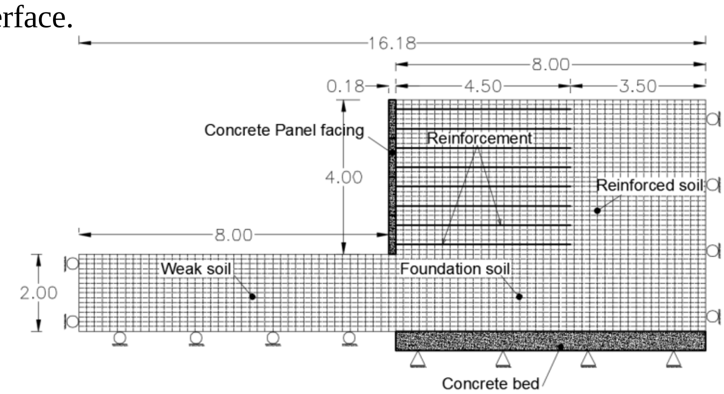


Figure 4. Grid and boundary conditions of the numerical model for verification study

2.2.3 *Result of Verification*

Fig. 5 presents measured results from the physical model and the numerical model predictions for the facing displacement against horizontal displacement of bulkhead. Fair agreement is observed between the measured and predicted results but the occurrence of some errors is undeniable. These negligible errors are due to: (1) Lack of some numerical model parameters (especially Young's modulus of soil that is estimated on the basis of empirical relationships), (2) Bulkhead replacement with weak soil in numerical model, (3) The precision of interface properties between soil foundation and concrete bed.

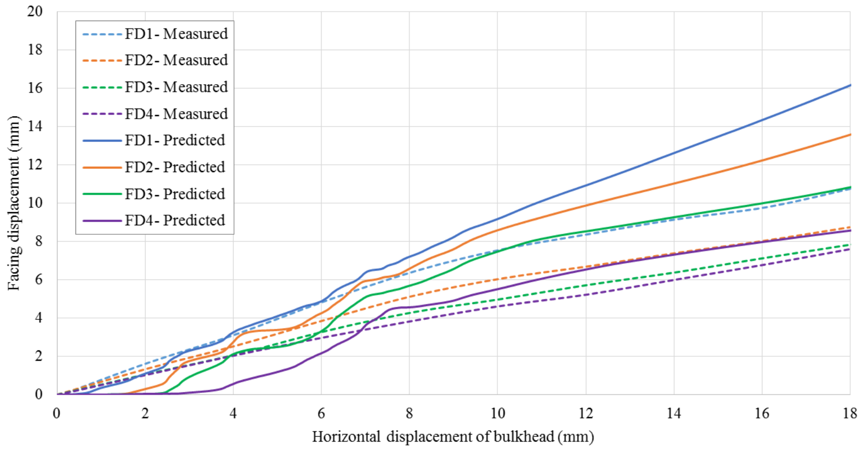


Figure 5. Facing displacement vs horizontal displacement of bulkhead (Comparative results of laboratory and numerical model)

3 RESULTS

3.1 *Static and seismic analysis results*

In this section, the behavior of reinforced soil walls after construction, under service loading and seismic conditions has been studied. The effects of facing characteristics on the wall behavior under different loading condition are discussed.

3.1.1 *Facing horizontal displacement*

Fig. 6 shows the profile of horizontal displacement of the walls after construction, under service and seismic loads. In service loading condition, the wall with concrete panel facing has maximum horizontal displacement and the walls with concrete block facing have minimum displacement. Fig. 5(a) and 5(b) show that all four walls except the wall with concrete panel facing have bulging form of horizontal displacement. In seismic condition, the wall with wrap-around facing has minimum displacement and the wall with concrete panel facing has maximum value. The horizontal deformation pattern is almost linear in seismic condition. The reason of occurrence of maximum displacement in the wall with concrete panel facing is due to use of rigid facing with flexible reinforcement. Because of this manner, in real situation for constructing a wall with concrete panel facing, the reinforcements must be pre-tensioned during construction. In general, the wall with wrap-around facing has a good behavior in seismic conditions due to its high flexibility.

3.1.2 *Reinforced soil zone settlement*

Fig. 7 shows the vertical displacement of reinforced zone (top and bottom) after construction and under seismic load. Fig. 7 shows that the facing type has no significant effect on settlement of the bottom of reinforced soil zone. But its effect on settlement of the top of the zone is evident. According to Fig. 7(a) and 7(b) the walls with wrap-around and concrete panel facing have similar settlement and values. The displacement of walls with concrete block facing is less than other modeled walls especially in vicinity of facing elements; It shows that high friction between the soil and the concrete and also high rigidity of the block facing, relatively prevents the soil from settling in the vicinity of facing. In general, by increasing the rigidity of the wall facing, settlement of the top of the reinforced soil zone decreased, in both static and seismic conditions. This effect is not noticeable in the bottom of this zone.

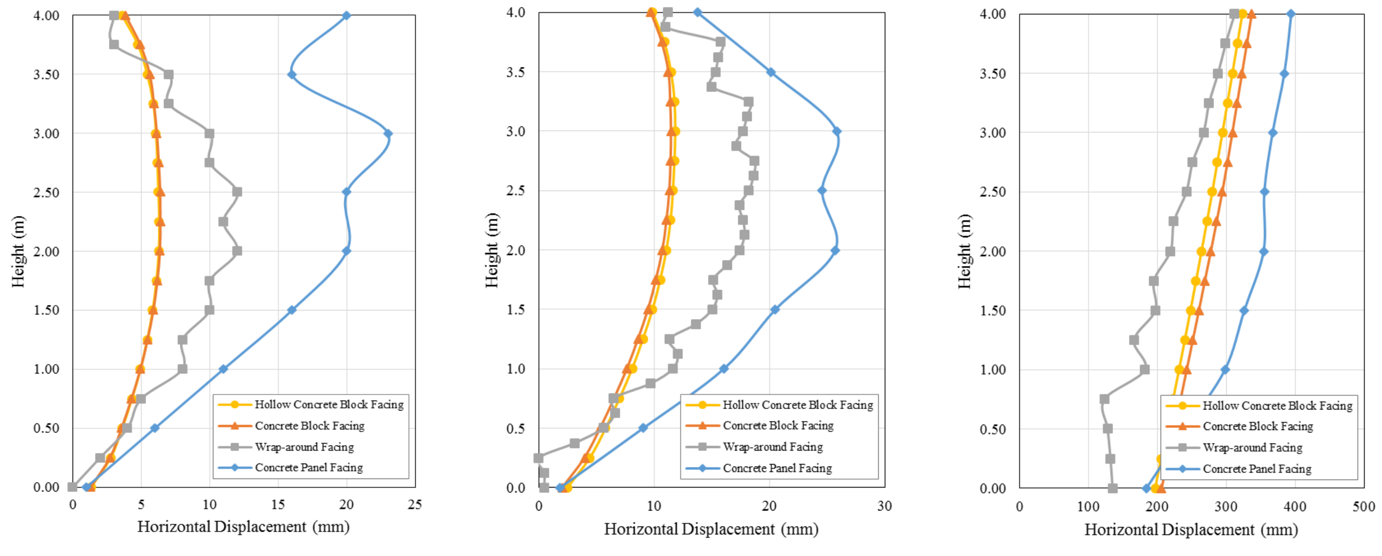


Figure 6. Profile of horizontal displacement for four models (a) after construction, (b) under service load (q=10 kPa), (c) under seismic load

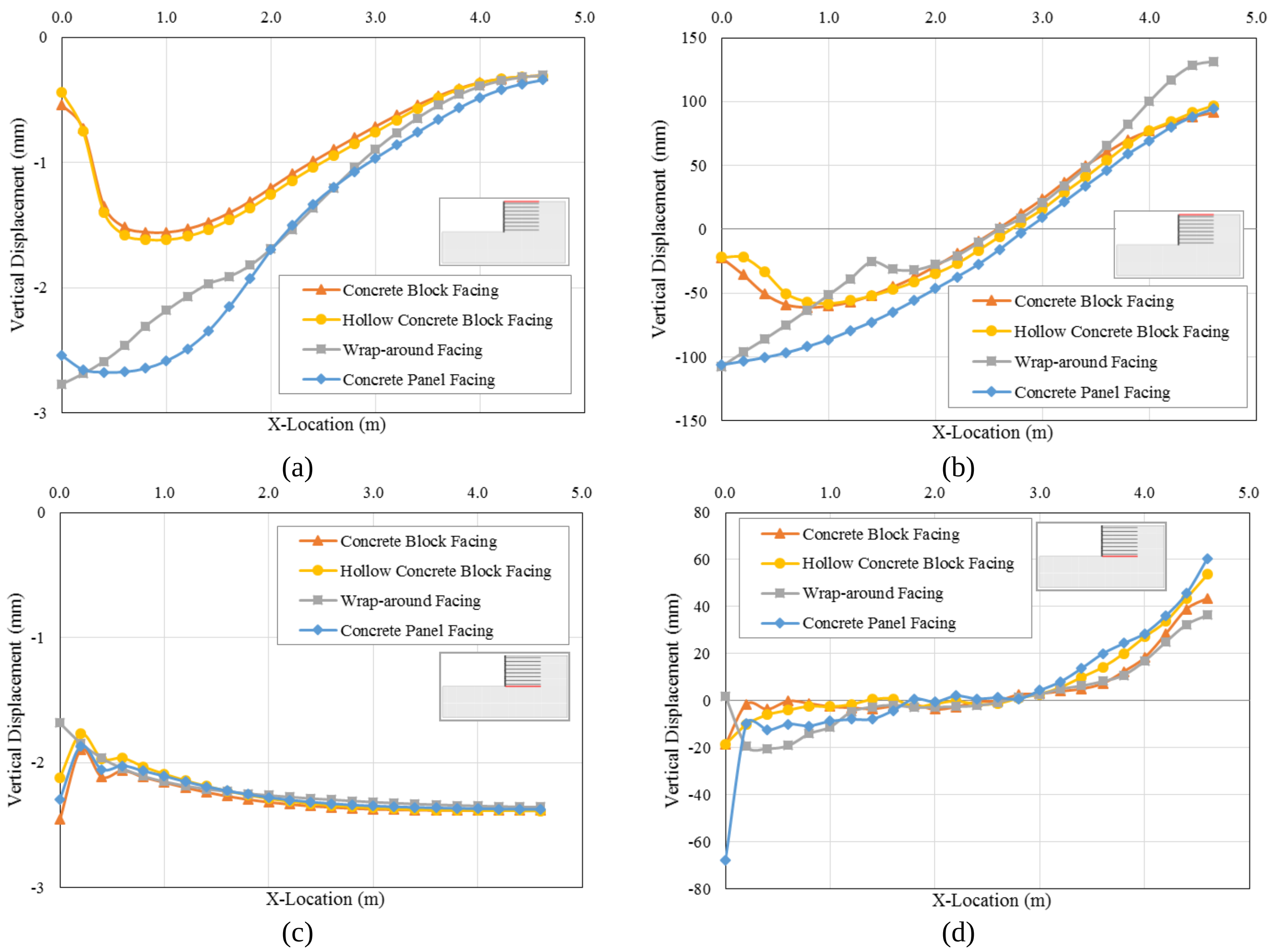
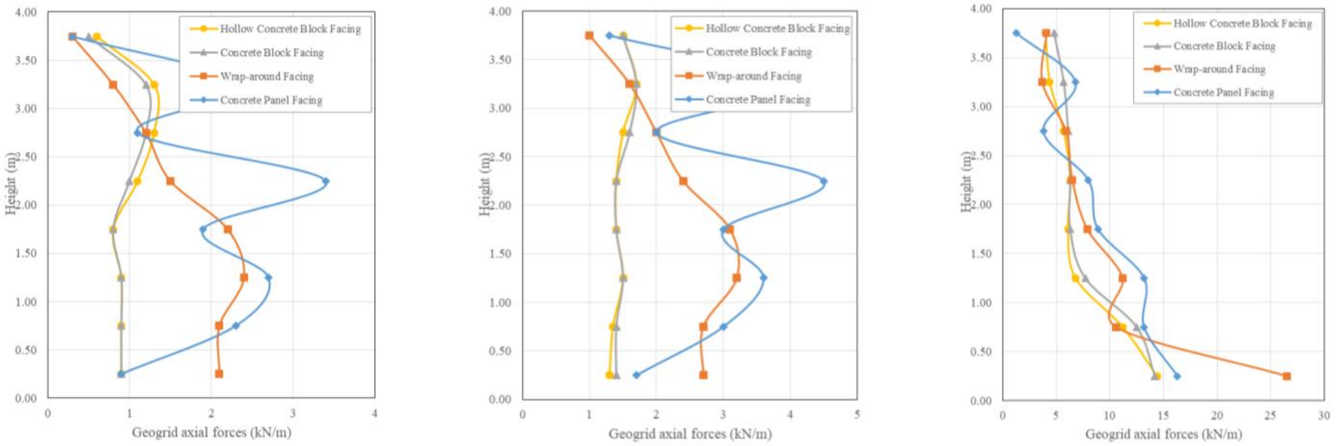


Figure 7. Reinforced soil zone settlement (a) Top of the zone- after construction (b) Top of the zone- under seismic load, (c) Bottom of the zone- after construction, (d) Bottom of the zone- under seismic load

3.1.3 *Geogrids axial forces*

Fig. 8 shows the profile of maximum axial force in geogrids, in the walls after construction, under service load and under seismic excitation. Under static loading condition, the maximum force in the wall with wrap-around facing occurred at the 0.3 of the wall height, in the wall with concrete panel facing accrued in middle of the wall height and in the wall with concrete block facing (both solid and hollow) occurred in the 0.75 of the wall height. However in seismic condition, the maximum axial force of reinforcement in all four occurred in the first layer; Also as the height increased, the maximum force is reduced in all four walls. In the wall with wrap-around facing, the maximum axial forces change rapidly because the geogrids play a role as the facing elements.



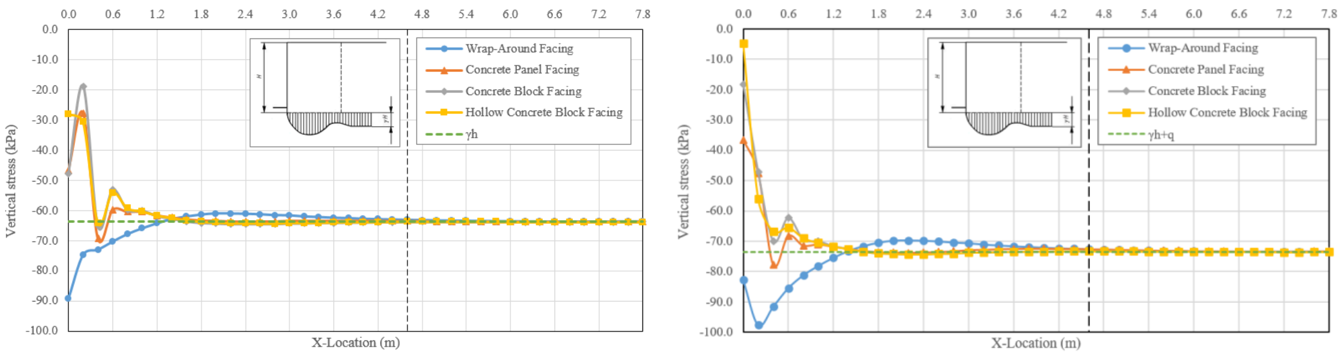
(a) (b) (c)

Figure 8. Profile of maximum geogrid axial force (a) After construction, (b) Under service load (q=10 kPa), (c) Under seismic load

3.2 *Comparing numerical results with design code criteria*

3.2.1 *Vertical stress under reinforced soil zone*

According to BS Standard (BS8006, 2010), real vertical stress imposed at the base of reinforced and retained soil zone is similar to the graph showed in upper section of Fig. 8 and bearing capacity based upon Meyerhof distribution may be assumed. Fig. 9 shows the pressure imposed at retained and reinforced soil zone base for all different facing, after construction and under service load (q=10 kPa). In the wall with wrap-around facing the result are similar to what mentioned in the design code. In other walls with stiffer facings, vertical stress reduced in the area near facing; It shows that, some soil weight is maintained by friction between the facing and the soil.



(a) (b)

Figure 9. Vertical stress imposed at the base of the walls for all different facing types (a) After construction, (b) Under service load (q=10 kPa)

3.2.2 *Connection force*

Fig. 10 shows the connection force according to numerical model results (Fig. 10 (a-2, a-3, b-2, b-3, c-2, c-3)), calculated from maximum axial load by BS (BS8006, 2010) code formula (Fig. 10 (a-1, b-1, c-1)) after construction and under service load. As it is shown, at the end of construction and under service load the walls with concrete panel facing and concrete block facing have good compatibility with the results from BS code formula.

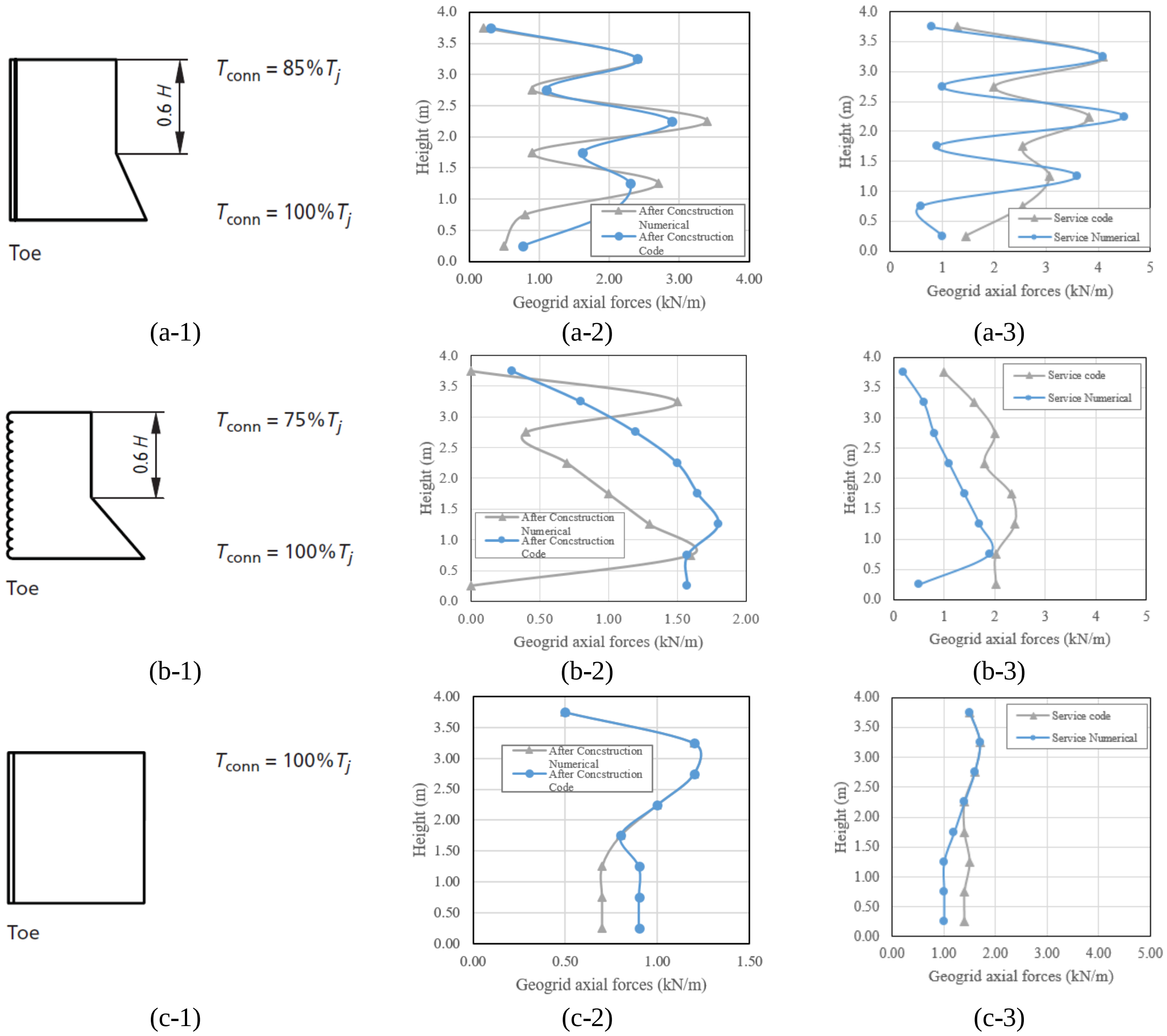


Figure 10. Comparative connection forces from numerical model result and BS code formula: (a) Concrete panel facing, (b) Wrap-around facing, (c) Concrete block facing

4 SUMMARY AND DISCUSSION

This paper investigated the role of the facing element type on the static and dynamic behavior of reinforced soil walls by studying four walls with different facing types. The reported results are related to finite difference numerical models carried out by FLAC. At first, the effects of facing type on the behavioral characteristics of the wall, include wall facing displacement, vertical displacement of the reinforced soil zone and geogrid forces, under post-construction condition, under service load and under seismic condition, are investigated. The results showed that the facing type and its stiffness have significant effects on the static and dynamic behavior of the wall. It shows that making the right choice in facing type is very important in seismic regions.

Considering the importance of the design code criteria of reinforced soil walls, the results of numerical analysis were compared with the results of the design code formula. The results showed, although in many cases there are differences between the results of numerical modeling and the results of the design code formula, but the effects of facing type on the behavior of reinforced soil walls are partly covered by the design code.

5 CONCLUSIONS

The most important findings are summarized below:

1- The facing type has significant effect on the horizontal displacement of the wall under both static and dynamic condition. All walls except the wall with concrete panel facing have bulging form of horizontal displacement in static condition. In seismic condition, the horizontal deformation pattern is almost linear. The wall with wrap-around facing has a good behavior in seismic conditions due to its high flexibility.

2- The effect of the facing type on the top settlement of the reinforced soil zone is significant under both static and dynamic condition. This effect is insignificant on the bottom of the reinforced soil zone. The greatest effect on the displacement is related to the vicinity of the facing.

3- The facing type has a significant effect on the position of the maximum geogrid force in the wall height. Generally, with increasing facing stiffness, the maximum geogrid force is created at a higher elevation. In the wall with wrap-around facing, the maximum axial forces change rapidly because the geogrids play a role as the facing elements.

4- The distribution of soil pressure under the reinforced soil zone is very similar to the prediction of the design code. In the walls with stiffer facing, the pressure of the soil near the facing is much less.

5- The connection force in the walls with stiffer facing from numerical model results is compatible with predicted results by design code formula.

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