The influence of nailing on the seismic response of a superstructure with underground stories

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Abstract. Soil nails are mainly designed for excavations for a limited time period and are not designed to withstand excavation forces permanently, specifically seismic forces. Despite this issue, when the excavation and retaining walls are completed the permanent effects of nails remain in the soil. This study investigates the effects of soil nailing in soft soils on the seismic response of a superstructure with four underground stories. The results show that soil nailing has a significant effect on the response of the superstructure which should be considered in future soil-structure interaction studies especially when soft soils are encountered.

Introduction

Soil-structure interaction studies have been improved considerably over the last decades. Due to the rapid development of computational calculations, it is now possible to investigate sophisticated soil and structure systems simultaneously [1]. For tall structures resting on soft soil the effects of considering soil structure interactions are significant and due to limited studies in this field there is no certain estimation for the response of the aforementioned systems [2].

Buildings with underground stories are known to have better seismic response than those without it. This is mainly caused by two reasons (1) the structure is generally resting on a denser and stiffer soil and (2) the integrity of the structure and the retaining wall commonly reduces the seismic loads to the structure. The effect of reduction of seismic loads can be related to the change of seismic base's location in the equivalent linear method.

Ganainy and Naggar studied the impact of underground stories for 5, 10 and 15 story buildings. The SSI effects for soft soil deposits led to a 10-25% increase in the base shear and moment demand of buildings, yet as the number of underground stories increased, the effects were decreased compared to fixed base conditions. This fact can be associated with the rigidity of the underground slabs and basement walls delivering a rigid box, hence fixing the structure [3]. Moreover, Saad et al. have conducted similar results for a ten-story building with 3 basements embedded in soft soils [4].

Soil nailing is widely used to reinforce geotechnical structures in problems such as slopes, excavation, etc. [5, 6], for example, numerous slopes have been stabilized in Hong Kong since 1970s with nails [7]. Although soil nails are commonly designed for static situations, their reinforcement increases the bearing capacity of soil, therefore their seismic effects are undeniable. In this paper the seismic effects of soil nailing has been investigated by studying a 20-story benchmark building with four underground stories. The building is resting on soft soil and the effect of nailing is analyzed by the seismic structural response in both situations. A two dimensional finite difference software, namely FLAC2D, has been adopted in this research which can model the soil and structure simultaneously to study their seismic interaction effects on each other.

Soil characteristics

To investigate the effects of nailing in soft soil, the soil profile of a mega project in Bangkok, namely Sukhumvit MRT station, has been selected (shown in Fig. 1). The details of the project can be found in previous studies (i.e. [8, 9, 10, 11]).

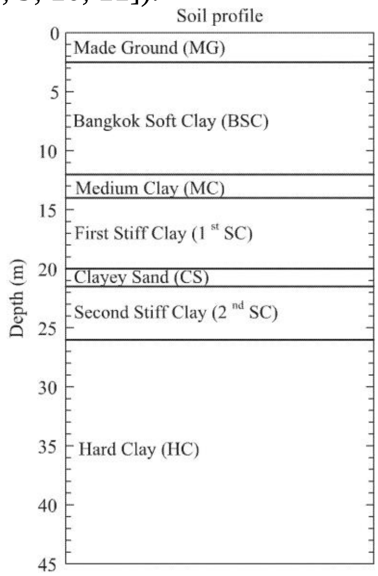


Fig. 1. Soil profile at the location of Sukhumvit Station [9]

The constitutive model selected for this study is a combination of two models: (1) Mohr-Coulomb model and (2) capped-hardening soil model (CYSoil model). The capped-hardening soil model is employed for modelling soft soil behavior. Although this model is much more complicated than the Mohr-Coulomb model, its parameters can be determined by common soil mechanics tests. The calibration process of this model for drained and undrained parameters of Bangkok soft clay has been performed by Bolouri Bazaz et al. with the use of a series of triaxial and odometer tests [12]. Table 1 and Table 2 show the parameters obtained for this study based on previous researches [8, 9, 12].

Table 1. The drained and undrained properties of the soil profile [12]

Layer No.	**Soil Type**	**Depth**	**Density**	**Elasticity Modulus**	**Drained Parameters**			**Undrained Parameters**			
					c'	**φ'**	**υ**	**c**	**φ**	**S_u**	**υ**
1	MG	0-2.5	18	8	1	25	0.2	1	25	-	0.3
2a	BSC1	2.5-7.5	16.5	10	Capped Hardening Soil Model Parameters						
2b	BSC2	7.5-12	16.5	20.5							
3	MC	12-14	17.5	27.5	10	25	0.2	-	-	55	0.495
4	1^{st}SC	14-20	19.5	40	25	26	0.2	-	-	80	0.495
5	CS	20-21.5	19	53	1	27	0.2	1	27	-	0.25
6	2^{nd}SC	21.5-26	20	72	25	26	0.2	-	-	120	0.495
7	HC	26-60	20	240	40	24	0.2	-	-	240	0.495

Table 2. The drained and undrained parameters of Bangkok soft clay for the hardening soil model (CYSoil Model) for layers 2a & 2b [12]

Parameter	Drained Parameters	Undrained Parameters
P_r	100kPa	100kPa
K_r	5.87	4.41
m	0.9975	0.9975
R	4.5	4.5
α	0.87	0.87
c_p	0	0
φ_p	23.6	29
φ_0	0	10
ψ_p	0	0
${\varepsilon_s}^f$	0.293	0.293

The maximum dynamic shear modulus of soil also known as the small-strain shear modulus plays an important role on the seismic response of a soil-structure system. This parameter can be determined by many experimental or field tests [13]. In this study the dynamic shear modulus of the soil profile was acquired by the determination of the shear wave velocity resulted from a series of cross-hole and down-hole in situ tests [14, 15] ($G_{max} = \rho {V_s}^2$, where ρ is density and V_s is shear wave velocity). The shear wave velocity of the soil profile is illustrated in Fig. 2 [15]. The strain dependent modulus and damping factors of the soil are another aspect which considerably effect the seismic soil-structural response. These functions have been defined by a set of experimental tests performed by previous researches [16] and were implemented in FLAC by the equivalent-linear method and a sigmoidal model, namely sig3 [17]. The parameters are obtained as a=1, b=-0.5 & x_0=-0.67. Moreover, to overcome the deficiency of the predicted damping ratio than the experimental results in low cyclic shear strains, it is recommended to employ an additional 1% local or Rayleigh damping [17].

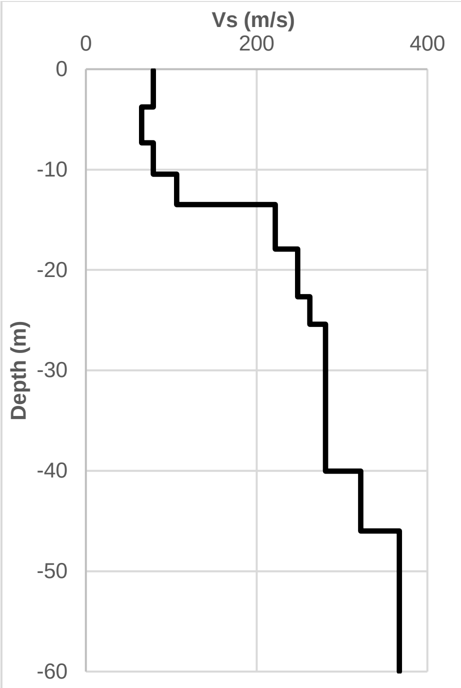


Fig. 2. Shear wave velocity of Bangkok subsoil [15]

Structural characteristics

A typical 20-story steel benchmark building has been taken into account for this study which consists of 5 and 6 bays in the N-S and E-W direction, each 6.1 meters in length [18]. The structure originally has 20 stories and two additional basements. In order to study the effects of underground stories, the 20-story superstructure has been considered with 4 basements. The specifications of the two additional basements are considered same as the original and this assumption has been verified following construction norms using SAP2000 [19]. Moreover, a 2m foundation has been considered following common regulations using SAFE [20].

In the latest version of the finite difference software (FLAC2D) the possibility of considering an elastic-perfectly plastic model for structural elements has been provided. Hence, in this research this model has been employed for structural elements in terms of their plastic moment as M_p=Z.F_y where Z is the section modulus and F_y is the yield stress [21]. The damping of the structural system was considered as Rayleigh ($C = \alpha.M + \beta.K$; where C, M & K are damping, mass and stiffness matrices and α & β are constants) [17] where α & β were respectively calculated as 0.1435 and 0.0076 by means of modal analysis of the superstructure and 5% damping.

Soil and structural elements

The interface between soil and structural elements (i.e. foundation, piles and retaining wall) can be simulated by shear and normal coupling springs [22]. The structural elements and the grid are connected by means of force and motion via spring-slider system interface [17]. The characteristics of the interface system are presented as cohesive strength, frictional resistance, and stiffness in the normal and shear orientation. In addition, the normal coupling springs can simulate a gap between pile and soil during ground motion by considering a tension strength [22]. The definition of these parameters (Eqs. 1-7), derived from prior studies (i.e. [17, 22, 23, 24, 25, 26]) are presented as following:

$$cs_{ncoh} = 9\mathrm{c_{soil}}.D \tag{1}$$

$$cs_{nfric} = \varphi_{\mathrm{soil}} \tag{2}$$

$$cs_{nstiff} = \left(\frac{10\left[\mathrm{K}+\frac{4}{3}\mathrm{G}\right]}{\Delta \mathrm{z_{min}}}\right)D \tag{3}$$

$$cs_{nten} = \left(\frac{\mathrm{c_{soil}}}{\tan(\varphi_{\mathrm{soil}})}\right).D \tag{4}$$

$$cs_{scoh} = \mathrm{c_{soil}}.\mathrm{P} \tag{5}$$

$$cs_{sfric} = \varphi_{\mathrm{soil}} \tag{6}$$

$$cs_{sstiff} = \left(\frac{10\left[\mathrm{K}+\frac{4}{3}\mathrm{G}\right]}{\Delta \mathrm{z_{min}}}\right)P \tag{7}$$

Where, c_{soil} & φ_{soil} are the cohesion and friction angle of the adjacent soil, K & G are the bulk modulus and shear modulus of the adjacent soil, P & D are the perimeter and diameter of the structural element and Δz_{min} is the smallest width of the adjoining zone.

Selected earthquake records

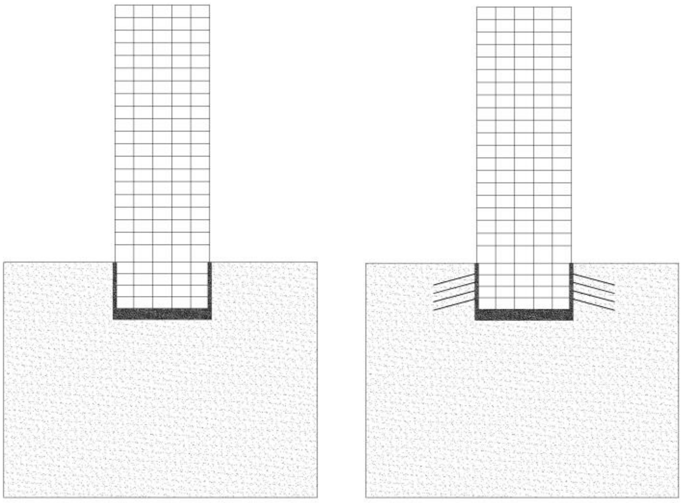
In this study seven earthquake records have been adopted. In order to minimize the amplification effects of soil, the earthquake records were selected from stations located on rocky grounds. A summary of the specifications of the earthquakes are presented in Table 3. Given that the earthquakes are applied at the bottom of the model, the earthquake records were scaled to match the ASCE class (A) response spectra corresponding to hard rock. S_1 and S_s were selected as 1.61 and 1.15 based on a site in downtown Los Angeles where the benchmark building has been originally designed according to them.

Table 3. The selected earthquakes and their specifications

Earthquake Incident	**Station Name**	**Alias**	**Magnitude (Mw)**
San Fernando (1970)	Pasadena - Old Seismo Lab	San	6.61
Morgan Hill (1984)	Gilroy - Gavilan Coll	Mor1	6.19
Morgan Hill (1984)	Gilroy Array #1	Mor2	6.19
Loma Prieta (1989)	UCSC	Lom	6.93
Northridge-01 (1994)	LA – Wonderland Ave	Nor1	6.69
Northridge-01 (1994)	Vasquez Rocks Park	Nor2	6.69
Iwate-Japan (2008)	IWT010	Iwa	6.9

Model characteristics

In this study, two models were simulated in two dimensional finite difference program (FLAC2D), one with nailing and one without it. The effects of nailing were investigated by comparing the structural response of both models in terms of base shear, peak horizontal acceleration, drift and displacement. The geometric dimensions of the model, were selected as 250 meters width and 60 meters deep [22, 27, 28] and the structural elements have been scaled in perpendicular direction to fulfil proper 2D modeling [22, 17]. The schematic illustration of the aforementioned models are presented in Fig. 3 (a) without nailing and (b) with nailing. The characteristics of the retaining walls have been obtained regarding FHWA-NHI-14-007 [29]. The retaining wall is assumed a 15 m deep concrete reinforced wall with a thickness of 0.3 m for the model with nailing and 0.5 m for the model without them. It is noted that in both models the retaining wall is connected to the superstructure. For the model with nailing, the nails are considered as 12 m with an angle of 15 degrees and the vertical and horizontal space of the nails are 1.5 m and 2 m respectively. The nails are assumed as 240 MN/m2 ribbed steer bar with a diameter of 32 mm.



(a) (b)

Fig. 3. Different modes of study

Results and discussions

The two dimensional soil-structure interaction models presented in the previous section have been analyzed in the time domain, undergoing seven scaled earthquake records by the direct method in finite difference software FLAC2D. This section presents and discusses the results of the superstructure. The response is expressed in terms of “Max” and “Mean” values which are the maximum and average of the maximum values obtained in each earthquake, respectively. The results disclose the significant effects of nailing in soft soils for superstructures.

In the current study, base shear is the maximum lateral force of the ground level taken place in a seismic motion. Comparison of the base shear gives a view on the shear force induced in a structure during an earthquake. The base shear of both models is illustrated in Fig. 4. It can be seen that the mean and max values of base shear have been decreased about 9% and 7% respectively by assuming nailing in soft soils.

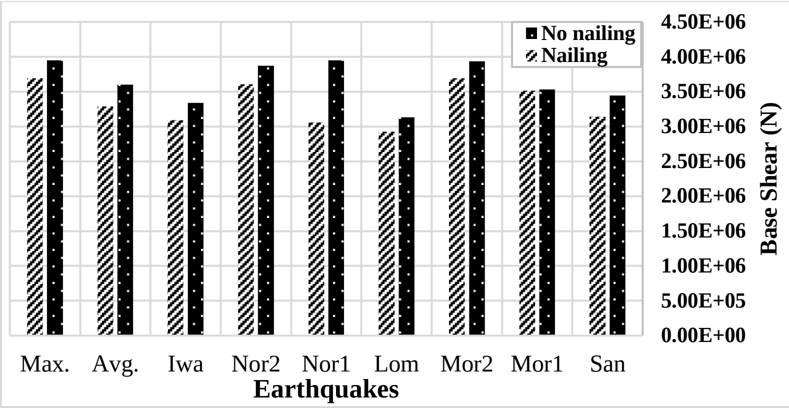


Fig. 4. The comparison of base shear in six studied models

The peak horizontal acceleration (PHA) of the left-side nodes of the structure have been recorded during every seismic motion. PHA corresponds to the maximum values obtained for the horizontal accelerations of each node. The mean and max values of PHA are illustrated in Fig. 5. It should be noted that on an average basis the PVA of the superstructure with nailing has decreased about 7% regarding to the superstructure without nailing.

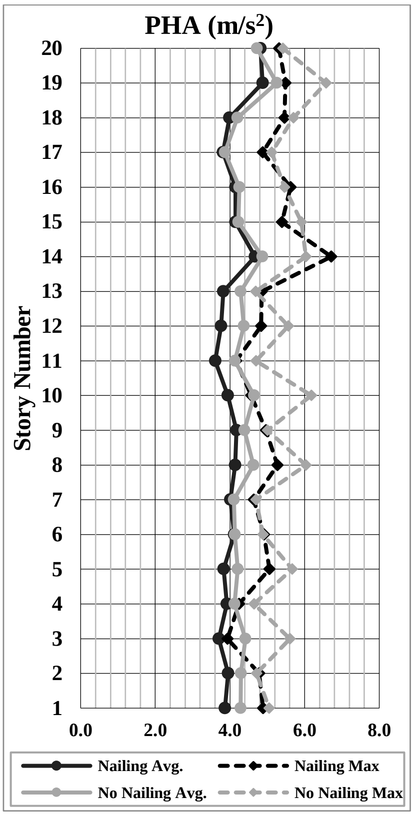


Fig. 5. The peak accelerations observed in the superstructure

Displacements of structures during earthquakes are important because of the disruptive impacts of adjacent structures on each other. Besides structural inter-story drifts throughout earthquakes are substantial to study for the case of sustainability and integrity of the structure. Hereon the drift and displacements of the left column of the superstructure have been observed to give a perspective on the seismic structural response. Fig 6 shows the mean and max values of drift and displacements. It can be seen that the drifts and displacements of the superstructure decrease 10% and 40% averagely by considering nailing.

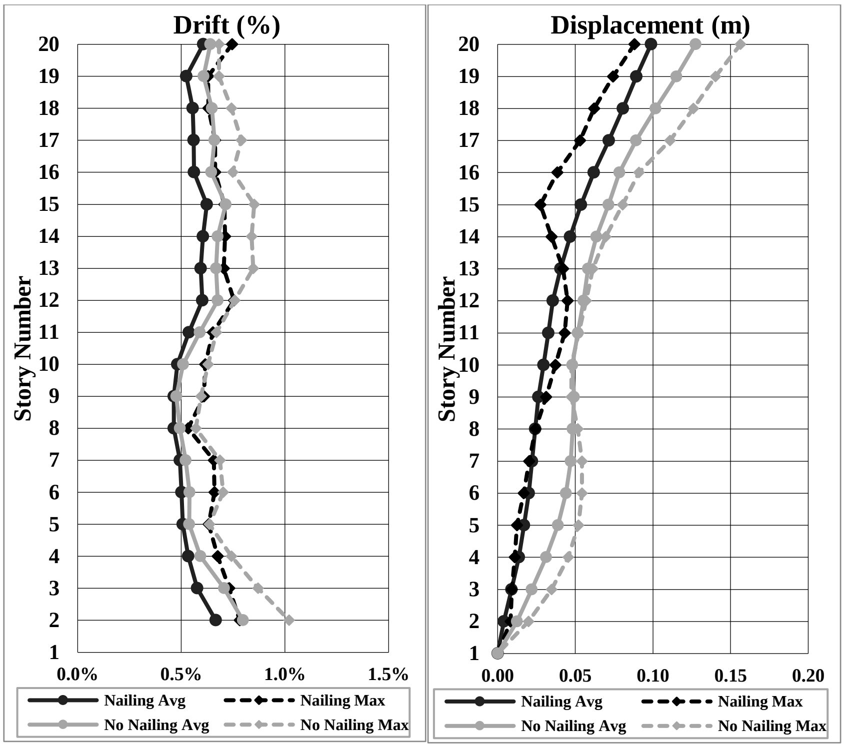


Fig. 6. Drift & displacements of the structure

Conclusion

In this study the effects of nailing on the seismic performance of a superstructure with four underground stories adjacent to soft soils has been discovered. Nailing is designed to withstand the destruction of excavation for a limited time period and it is not designed to resist earthquake forces, but as the excavation process is completed and the retaining walls are constructed the permanent effects of the nails remain in the soil. This study shows that the permanent effects of nails are significant to the seismic performance of the superstructure and is reduces the seismic response of it. For the situation discussed in this research the reduction is up to 7-10 percent. Therefore, this issue can be considered for future studies of soil-structure interaction in superstructures, especially when they are encountered with soft soils.

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