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Evaluation of Pseudo Static coefficient for Soil nailed walls on the basis of Seismic behavior levels

Majid yazdandoust[1*], Ali komak panah[1] and Reza Sadeghzadegan[2]
[1]Department of Civil Eng., Tarbiat Modares University, Tehran- 14115-111, IRAN
[2]Department of Civil Engineering, Parsian University, Qazvin- 14115-111, IRAN

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Abstract

The dependency of seismic behavior of geotechnical structures specifically soil nailed walls to the primary parameters of earthquakes, geotechnical parameters, and geometrical configuration and The independency of pseudo static method from factors affecting seismic behavior of the structures are the main deficiencies of this method. In this study, in order to modify the pseudo static method on the basis of seismic behavior of soil nailed walls, it has been tried to define the pseudo static coefficient as a function of main parameters of earthquakes, soil mass, and geometry of the structure. To do so, among the important factors of earthquakes (maximum acceleration, predominant period, effective time, magnitude), the predominant period and among geotechnical and geometrical characteristics (height of structure, length of nails, horizontal and vertical distance between of nails, geotechnical properties of soil, angel of slope), the height of structure have been picked up as primarily parameters. To choose appropriate coefficient for the specific earthquake record, and geotechnical and geometrical characteristics, the behavior of soil nailed walls in two modes of dynamic and pseudo static seismic behavior have been synchronized for wall horizontal displacements. Afterwards, pseudo static coefficient is defined as a function of predominant period and height of structure. Obtained results demonstrate the great impact of height of structure and predominant earthquake period on the pseudo static seismic coefficient. They include the fact that the increase in the height will bring the decrease in the pseudo static coefficient and the highest of coefficients and its variations yields by the natural period of the structure. This highlights the importance of investigating the seismic behavior of soil nailed walls for their natural periods.

Keywords: Seismic, behavior, geotechnical, soil, nailed, walls, pseudo.

Introduction

Soil nailing includes reinforcing and strengthening of in-situ soil through installation of steel bars excavation and grout injection around (figure-1). In other words, soil nailing is reinforcing of soil by tension members, i.e., nails, precise spacing so as to of a gravity structure and consequently to increase shear strength of soil and limit displacements.

Load transfer mechanism between nails and soil depends on the several parameters such as installation method, injection and excavation method, injection pressure, size and shape of reinforcement, geometric specifications of soil, particularly relative density and pre consolidation ratio, soil permeability and shear strength parameters of soil[1,2].

Mainly due to the advantages of soil nailing system, it has been the focus of a significant amount of studies in recent years and as such, many researchers devoted their efforts to study the effective parameters on the seismic performance of such structures. Vucetic et al.[3] showed the most probable failure mechanism under strong vibrations through conducting dynamic centrifuge tests on the nailed models. They showed that failure mechanism includes two sliding blocks and three failure surfaces (figure 2).

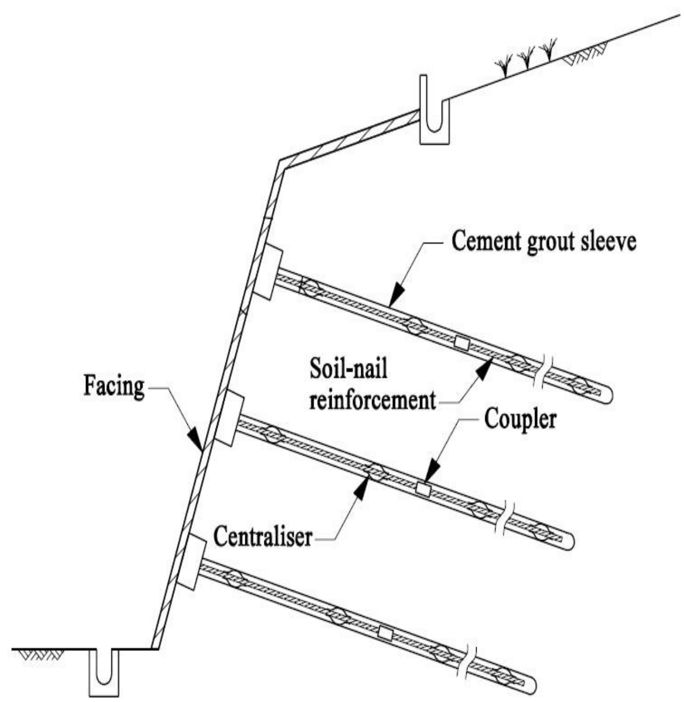


Figure-1
Cross section of a soil nailing system

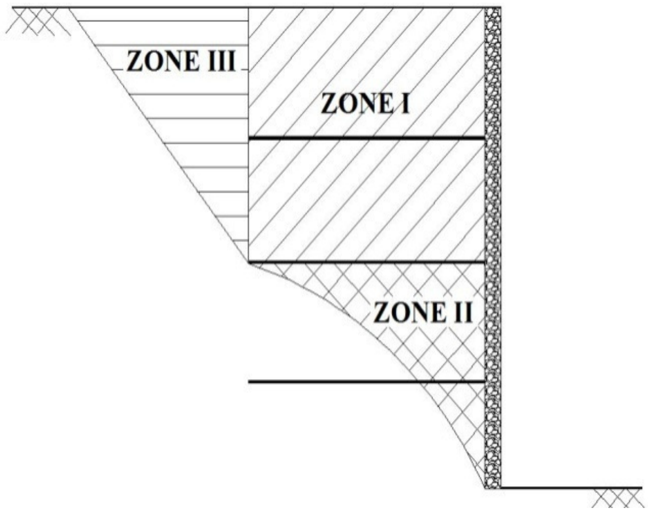


Figure-2
Failure mechanism in dynamic centrifuge test

Tufenkjian and Vucetic performing dynamic centrifuge tests to investigate the effect of nail length on the seismic performance of soil nailing system. They found that longer nails cause more stability against seismic loading and models with the ratio of length to height (L/H) higher than 0.6 showed favorable performance under cyclic loading[4,5]. Sabhahit et al., 1996 proposed a method for pseudo-dynamic analysis of nailed slopes. Comparison of pseudo static and dynamic analysis indicated that pseudo static method gives accurate results only for horizontal acceleration lower than 0.2, and for values higher than 0.2, pseudo-dynamic analysis should be applied[6]. Vela 1999 performed a study on a nailed soil wall in Felton and realized that middle height nails mainly carry the load[7]. Chokeir et al., extended the work of Juran[8] and developed a pseudo static analysis method. This method examines the effect of seismic loading on the location and maximum mobilized force nails under service stress. The obtained results revealed that dynamic force resulting from lateral pressure of soil behind failure surface, estimate of the over reality tensile forces in the nails.

Chokeir used a simple mass and spring model to demonstrate the role of acceleration and frequency in inertia force in pseudo static analysis. He expressed the following equation for earthquake coefficient in the pseudo static analysis by ignoring damping factor:

$$k_h = \left[\frac{0.5}{1-\left(\frac{\omega}{\omega_n}\right)^2}\right]^{0.5} \times \left[\frac{a}{g}\right] \quad (1)$$

Where, k_h is pseudo static coefficient, a is design acceleration, ω is loading frequency and ω_n is natural frequency of structure [9,10]. Hong et al., conducted shaking table tests on five models with different slope to study the effects of vibration frequency, slope and length of nails on the seismic strength and failure mechanism. Nailed slopes showed ductile behavior during strong vibrations and the effect of slope on the displacement and seismic strength was notable and minor, respectively. Furthermore, it was observed that increase of nail length resulted in increase of seismic stability and decreases of displacement during strong vibrations. Failure surface was reported to be approximately two linear and pulling of lowermost nail caused the failure of structure[11].

Selection of Pseudo Static Coefficent as a Function of Seismic Performance Parameters: Due to the considerable cost and time saving of pseudo static analysis, this method can be reasonably considered as an equivalent to dynamic analysis. However, the disadvantage of pseudo static analysis lies in not considering earthquake, geometric and geotechnical parameters which affect the seismic performance of structures. Therefore, in order to overcome this disadvantage and consequently to consider the effect of seismic performance of soil nailing system in pseudo static analysis, it is inevitable to define a pseudo static coefficient which is a function of effective parameters on the seismic performance of the system (equation-2)

$$k_h = f(Seismic\ Performance) \quad (2)$$

While in all conventional methods in reliable codes, the pseudo static coefficient was only defined as a function of maximum acceleration (equation-3) that this reduces the accuracy of the method[12].

$$k_h = [1.45 - \frac{a_{max}}{g}] \quad (3)$$

In order to determine pseudo static coefficient as a function of loading period and height of soil nailing system, the seismic performance of system against horizontal displacements of surface in dynamic and pseudo static analysis has been used.

$$k_h = f(T, H) \quad (4)$$

Methodology

According to what mentioned above, the methodology in this study is presented in the following paragraphs.

Selection of mode: Since the height play a critical role in the seismic performance of soil nailing system, this variable was selected as the main variable in this paper. As such, four models with four different heights, namely 5, 10, 15 and 20 m, were used to study the effect of height on the pseudo static coefficient. Modeling of soil nailing system was performed using 2-D Ca^2 Software. This software was developed on the basis finite difference method in Tarbiat Modares University. In order to the effect of boundaries on the analysis results, the width of models was taken seven times of wall height. Furthermore, in order to the appreciable effect of foundation dimensions on deformations, the height and width foundation were assumed to be one-sixth and eight times of structure height, respectively[13,14]. A schematic view of soil nailing system is shown in figure-3.

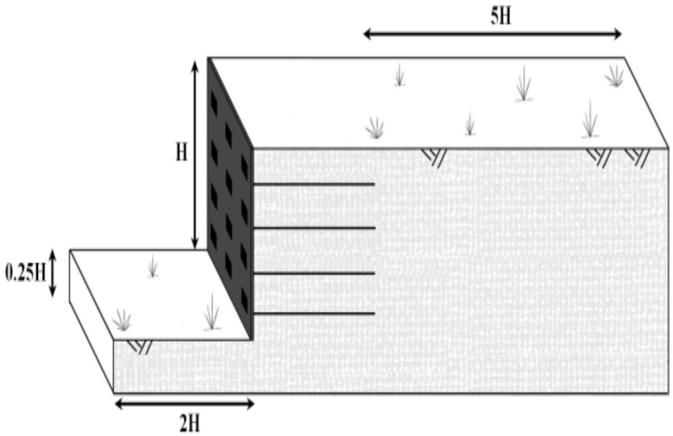


Figure-3
Dimensions of constructed models

For the sake of precise displaying of wave passage from the model, the mesh dimensions were considered one-tenth to one-eighth times of wave length of the largest frequency of inlet wave.

Geotechnical parameters: Since this study is aimed at investigating the seismic performance of soil nailing system in alluviums of Tehran City, therefore, the following geotechnical parameters in table-1 have been used for modeling. Moreover, the soil behavior was assumed to be elasto-plastic with plastic criterion of Mohr-Coulomb.

Table-1
Geotechnical specifications of alluviums in Tehran City

Parameter	Value	Unit
Specific weight	2050	(kg/m^3)
Bulk modulus	490	(kg/cm^2)
Elastic modulus	500	(kg/cm^2)
Shear modulus	188	(kg/cm^2)
Poisson's ratio	0.33	....
Cohesion	0.35	(kg/cm^2)
Internal friction angle	34	degree
dilation angle	5	degree

To prevent an increase in computation time due to use of the interface elements, for applied to the soil surface interaction, the equivalent elements are used.

This 5 cm thick material lied between soil and surface has specifications similar to soil but with lower plastic parameters as shown in table-2.

Table-2
Specification of interface elements

Parameter	Value	Unit
Bulk modulus	2050	(kg/m^3)
Elastic modulus	490	(kg/cm^2)
Shear modulus	500	(kg/cm^2)
Poisson's ratio	188	(kg/cm^2)
Cohesion	0.33	....
Internal friction angle	0.35	(kg/cm^2)
dilation angle	20	degree
Specific weight	0	degree

Reinforcement elements: FHWA Code has been utilized to determine the specifications of reinforcement elements including horizontal and vertical distances, length and diameter of nails. For this purpose, the nail length was taken 0.7 times of structure height. This is because this length is defined as an effective reinforcement length in the literature which prevents increase of force in the reinforcement elements[15]. The vertical and horizontal distances of nails were also assumed to be 2 m so as to prevent increase of bending moment and consequently increase of surface thickness. Finally, the diameter was determined based on the induced forces in nails[12,16]. The reinforcement elements were modeled in the software using cable elements with full Elasto-Plastic model. The specifications of steel elements are given in table-3. Furthermore, the injected materials around the cable element were selected in a way that provides a full bond between soil and reinforcement elements and prevent pulling out, tearing and failure. The specifications of these materials are presented in table-4.

Table-3
Specifications of steel elements

Specifications (Unit)		Diameter	Length	Angle	Horizontal distance	Vertical distance	Yielding stress	Elasticity modulus
		(cm)	(m)	degree	(m)	(m)	(Pa)	(Pa)
Height of structure (m)	5	2.5	3.5	10	2	2	4E8	2.1E11
	10	2.5	7					
	15	3	11					
	20	3	14					

Table-4
Specifications of injection materials

	Friction angle	Lateral stiffness	strength	Elasticity modulus
Unit	degree	(N/m/m)	(N/m)	(Pa)
Value	34	1.5E6	1.5E4	2.6E5

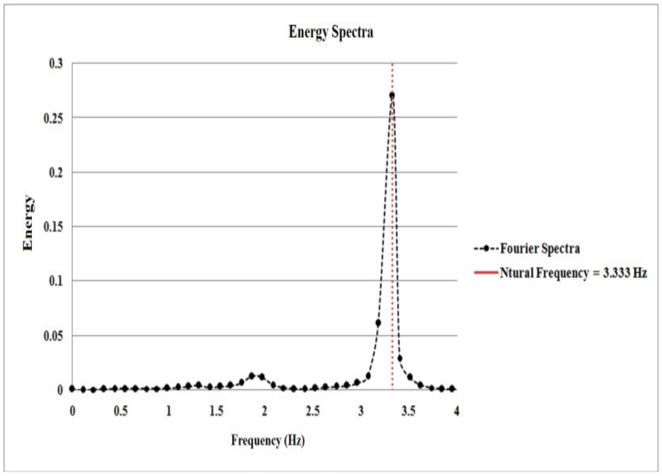
Surface: The parameters used for wall surface were according to FHWA Code and are listed in table-5. The surface modeling was also performed using beam element with elastic behavior model.

Table-5
Specifications of surface

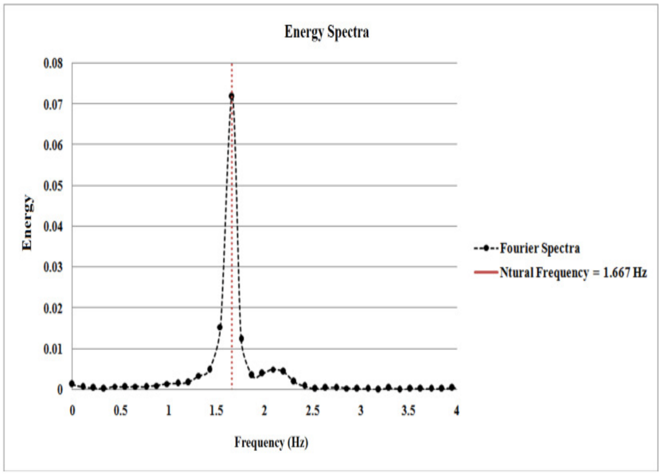
	Thickness	Moment inertia	Elasticity modulus	Density
Unit	(cm)	(cm4)	(Pa)	(kg/m3)
Value	10	3.32E-4	3.32E10	2400

Boundary and support conditions: Since the foundation is rigid, hinge supports were used in horizontal and vertical directions in the lower boundary of the model. For modeling the static condition, first, roller support is used for around the model then they are replaced by quiet boundaries in dynamic analysis. This causes that first static conditions model is satisfied and then to prevent of reflective waves, the quiet boundaries is replaced.

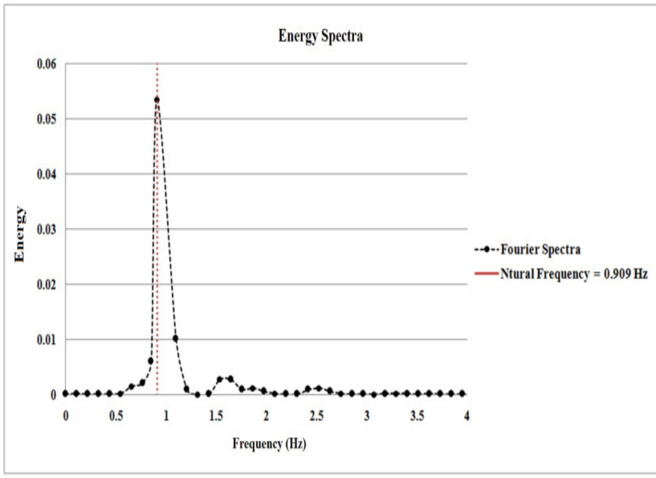
Pseudo static and Dynamic Analysis: Determination of natural period of structure: Occurrence of the maximum displacement of a structure under dynamic loading whit frequencies within the frequency range of structure's natural frequency causes that evaluation of the seismic performance of structures in natural frequency range is an indispensable. Hence, first, natural frequency of model should be determined and then on the basis of that, the range of loading frequency was selected. Determination of natural frequency of structures based on the free vibration resulting and energy spectra has been produced. According to this method, natural frequency is the frequency which produces the maximum energy. The energy spectrum and natural frequency of models are presented in figures-4 and table-6, respectively.



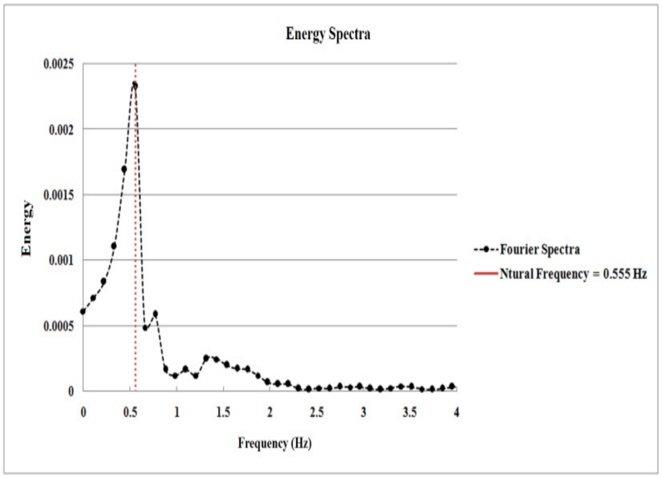
Energy spectrum for structure with 5m height



Energy spectrum for structure with 10m height



Energy spectrum for structure with 15m height



Energy spectrum for structure with 20m height

Figure-4
Energy spectrum

Table-6
Frequency and natural period of structure

		Natural frequency (Hz)	Natural period (Sec)
Height (m)	5	3.333	0.3
	10	1.667	0.6
	15	0.909	1.1
	20	0.555	1.8

Model according to soil nailing system: In order to model construction soil nailing system, first, the mesh was modeled based on the proposed dimensions in section 3.1.1 and static analysis.

Then, in order to catch the desired height, base on the proposed dimensions, the construction process is done by excavating, nail and surface installation, step by step (figure 5). In each step, system is analyzed for gravity loads or surcharge loads. In the static step, dynamic loads have no role in the system and static displacement would be removed at the end of the process.

Loading and dynamic analysis: The loading function used in this paper is an accelerograph expressed by equation-5. This type of loading has two main features: i.It is similar as much as possible to produced accelerograph during earthquake. This means that its amplitude gradually increases and then decreases. ii. It includes main parameters of earthquake which can be simply changed to evaluate the structure response.

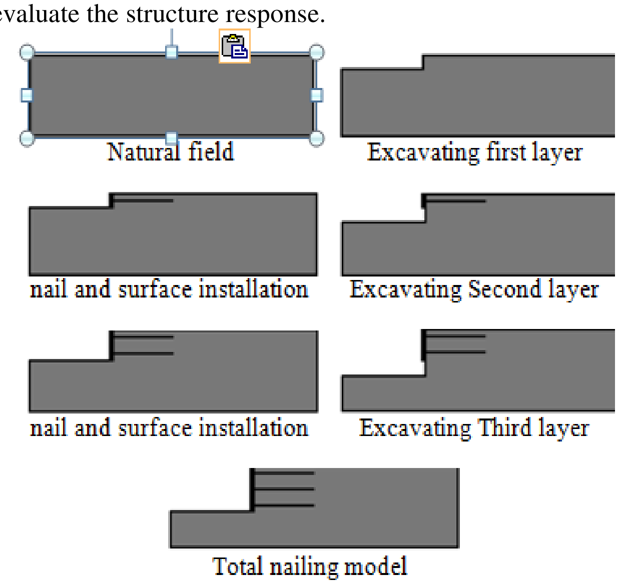


Figure-5
Steps to building a model

Where, *f* is loading frequency, *t* is loading time, *α*, *β* and *ζ* are loading variables which can be determined according to maximum acceleration.

Since selection of geotechnical parameters of Tehran City were used in the model and in accordance with seismic hazard maps of Iran, the maximum acceleration of Tehran is 0.35*g*, thus, *α*, *β* and *ζ* were taken in all dynamic loading in a way to produce maximum acceleration of 0.35*g*. The difference between natural frequency of soil nailing systems with different height and also necessity of studying the seismic performance of each system within the range of its natural frequency reveal the need for choosing a distinct dynamic loading for systems with definite heights. Therefore, regarding the natural frequency of structure, *α*, *β*, *f* and *ζ* were selected individually for each system in a way that the produced accelerograph has maximum acceleration of 0.35*g* and frequencies in the range of natural frequency of system. The values of above-mentioned variables are presented for each model in table 7. Figure 6 also shows accelerograph used in the analysis.

An important issue in the dynamic analysis is selection of damping mechanism. Since damping is a function of strain and not frequency in rock and soil materials, therefore, hysteresis models can exhibit more reliable results. In the present study, a constant hysteresis damping called local damping in the software was utilized. The damping was assumed to be 9.5%. It should be noted that large strain mechanism was applied in all models to modify density of soil mass in the event of occurrence large strains.

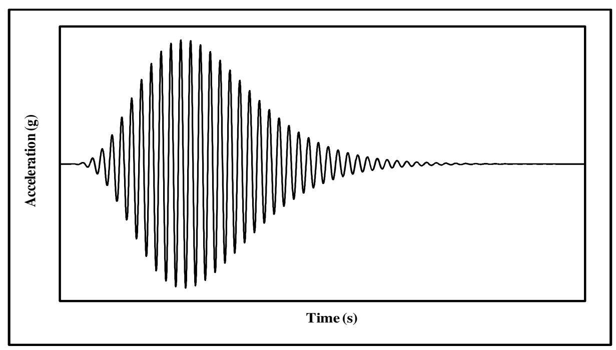


Figure-6
Dynamic loading with period equal to 0.2 sec

Table-7
Variables of dynamic loading

Structure height (m)							
5		10		15		20	
T	***β***	***T***	***β***	***T***	***β***	***T***	***β***
0.1	1.274	0.3	1.163	0.9	1.165	1.6	1.152
0.2	1.15	0.4	1.153	1.0	1.21	1.7	1.163
0.3	1.163	0.5	1.155	1.1	1.155	1.8	1.206
0.4	1.153	0.6	1.156	1.2	1.175	1.9	1.283
0.5	1.155	0.7	1.157	1.3	1.265	2.0	1.393
0.6	1.156	0.8	1.172	1.4	1.245	2.1	1.543
α=2.2 ζ =8 T= Loading period							

To evaluate the seismic performance of soil nailing system, after accomplishment of static analysis, reaching to equilibrium for system and removing the displacements, accelerations are applied to the foundation level and the dynamic analysis would be then performed.

Verification of accuracy of dynamic modeling: In order to verify the accuracy of dynamic modeling, the results of dynamic centrifuge tests conducted by Tufenkjian and Vucetic have been utilized[4,5]. And as such, the experimental model was modeled in Ca2 Software. Comparison of obtained results from experimental and numerical analysis indicated the accuracy of numerical modeling (figure-7).

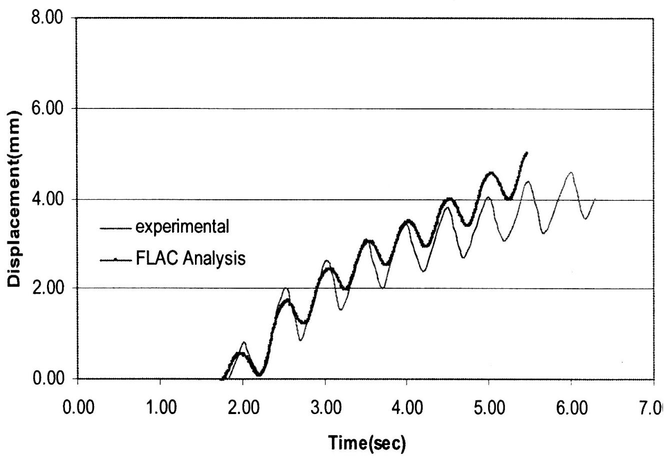


Figure-7
Comparison between experimental and numerical results

Loading and pseudo static analysis: In order to obtain more accurate results, the pseudo static loading applied in Ca^2 Software was in accordance with FHWA. This is illustrated in figure 8.

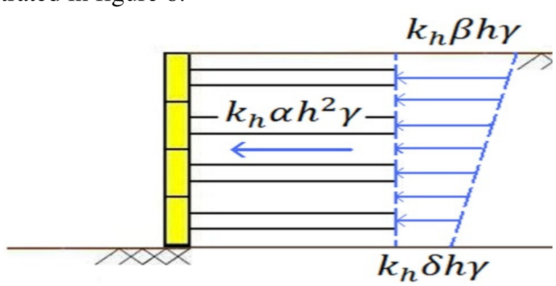


Figure-8
Recommended pseudo static loading in FHWA

To evaluate the seismic performance of soil nailing system in pseudo static condition, after accomplishment of static analysis, reaching to equilibrium for system and removing the displacements, each model is analyzed base on the specified pseudo static coefficient and mentioned loading.

Results and Discussion

The results were presented in two phases, dynamic and pseudo static.

Results of dynamic analysis: The results of dynamic analysis of structures within the range of natural frequency are shown in the form of surface horizontal displacement in figure-9.

The following conclusions are drawn from the results of this study: Rotation of structure around as a dominant mode of deformation of soil nailing system. Notable effect of height on the horizontal displacement of structure. Notable effect of loading period on the horizontal displacement of structure. Increasing influence of loading period on the horizontal displacement of structure in structure's natural frequency range. Increasing influence of changes loading period on the horizontal displacement Due to Increasing of height of structures. Reducing the influence of loading period on the horizontal displacement away from the natural frequency

Results of pseudo static analysis: In order to determine the coefficient of pseudo static base on the loading period and height system, coefficients are chosen in such a way that they produce the performance same seismic performance in dynamical certain conditions. The pseudo static coefficients are depicted in figures-10 and 11.

Moreover, according to the considerable agreement between the results of dynamic and pseudo static analysis, it can be concluded that pseudo static loading recommended by FHWA can be a reliable alternative for dynamic loading.

In the base of results of pseudo static and dynamic analysis, pseudo static coefficient can be as a function of loading period. These functions are expressed by figures-12 to 14.

Conclusion

The obtained results revealed that pseudo-static coefficient is highly affected by structure height and increase of height will result in notable decrease of pseudo-static coefficient. Therefore, it can be concluded that using a constant pseudo-static coefficient for a soil nailing system with different heights will lead to an overestimated and costly design. Moreover, the effect of loading period on the pseudo-static coefficient is considerable and this reduces as height increases. Accordingly, selection of loading period with lower height in a soil nailing system has a high level of importance.

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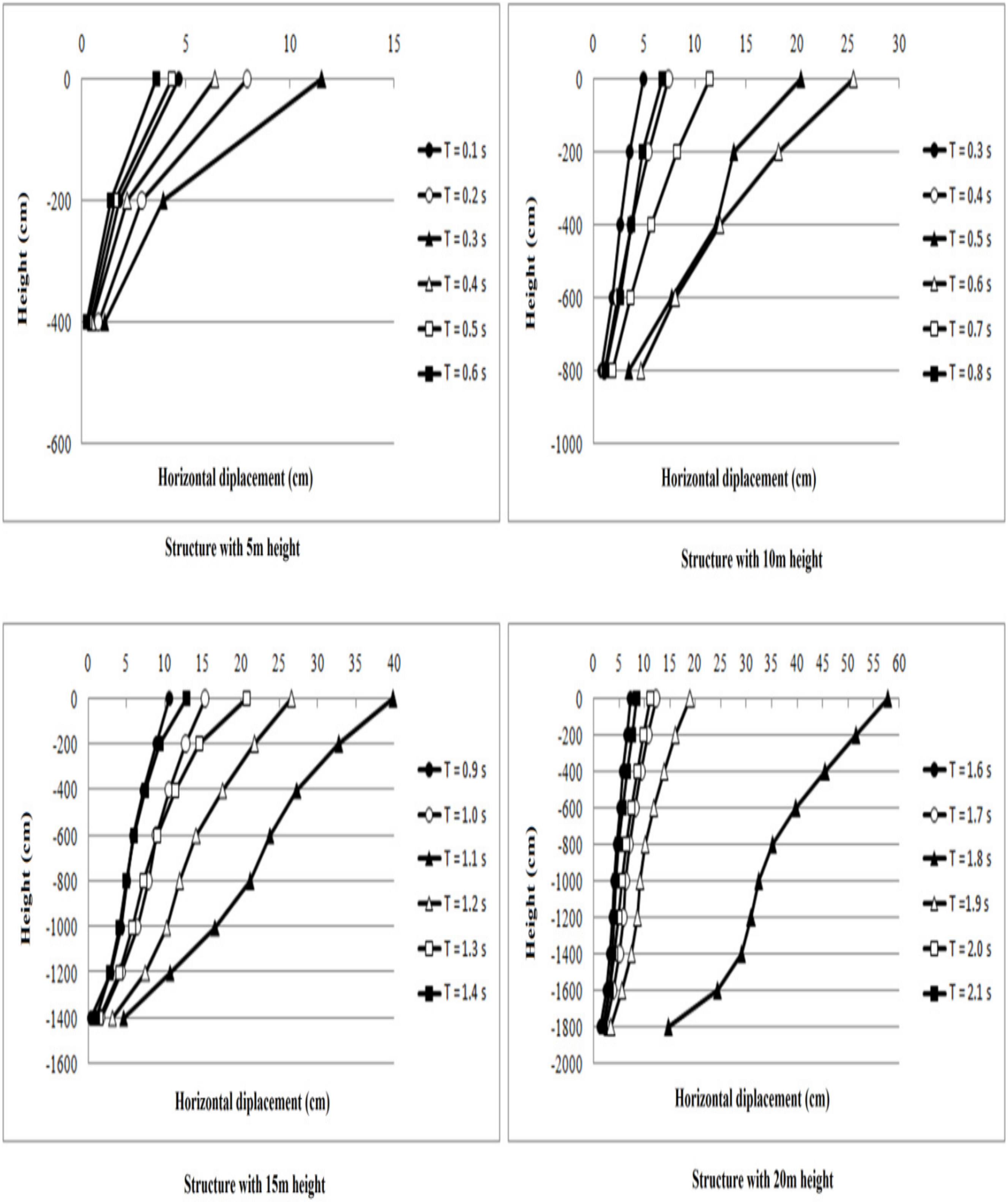

Figure-9
Seismic performance of soil nailing system in the form of horizontal displacement against loading period

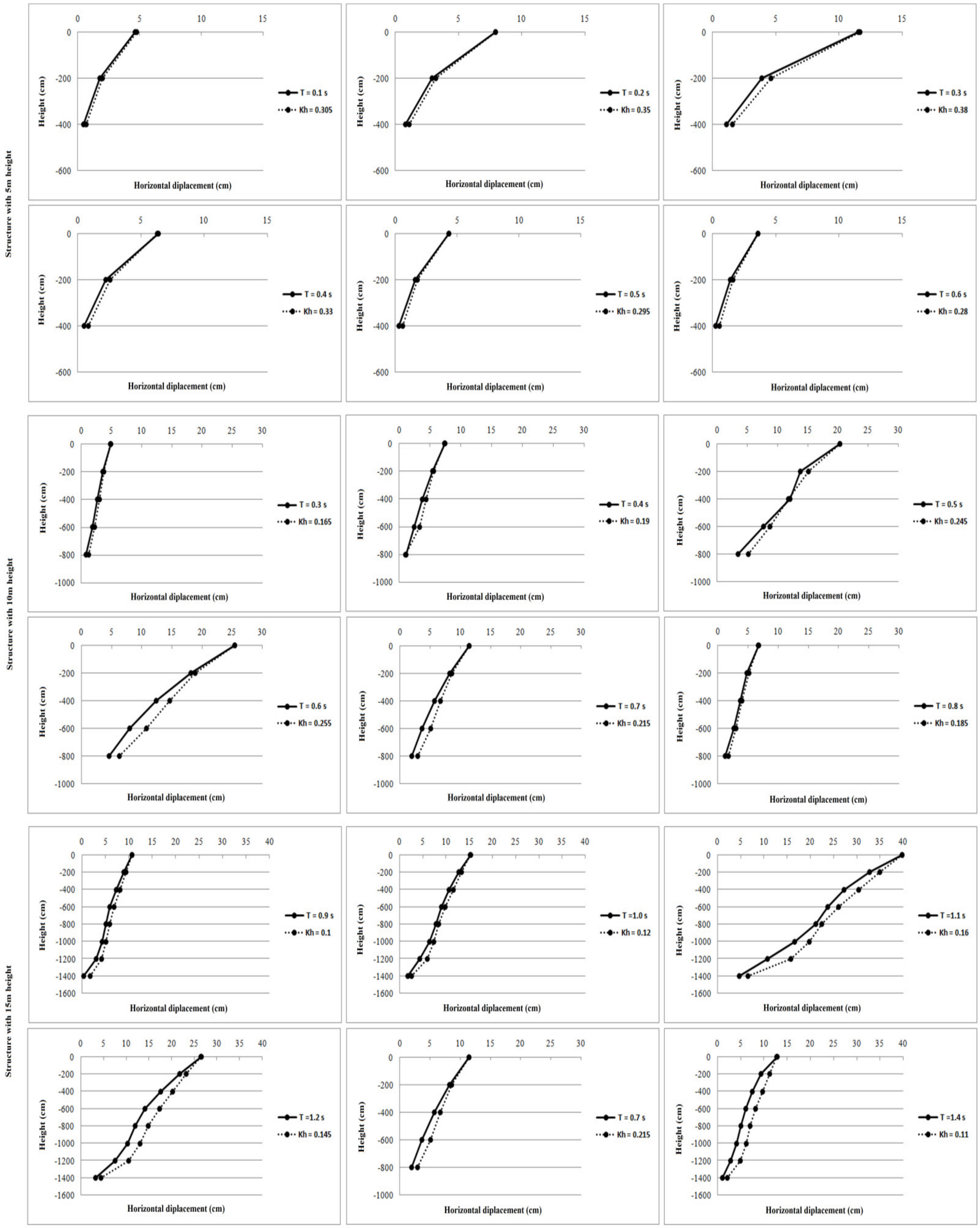

Figure-10

Horizontal displacement of the structure under pseudo- static loading with different period and pseudo static coefficient

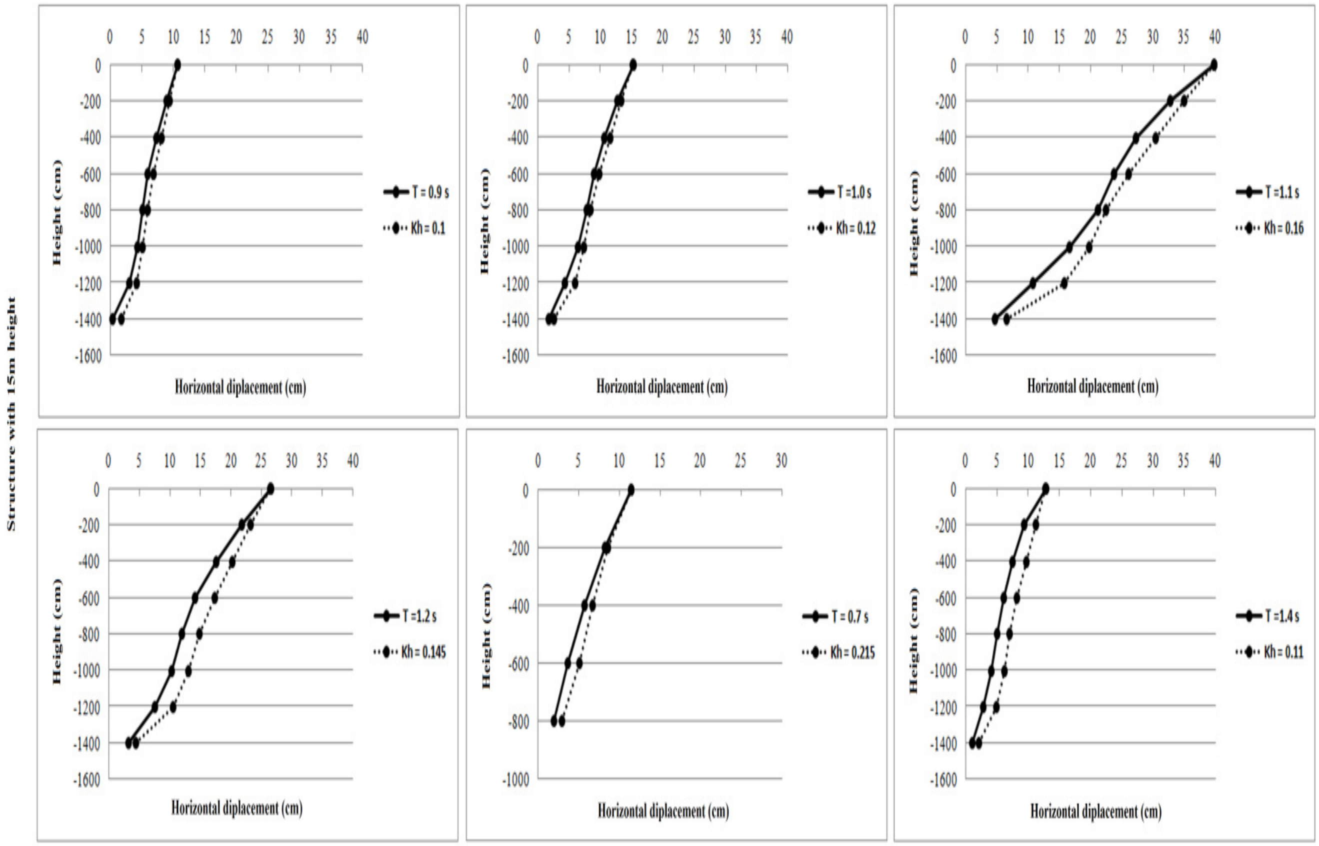

Figure-11
Horizontal displacement of the structure under pseudo- static loading with different period and pseudo static coefficient

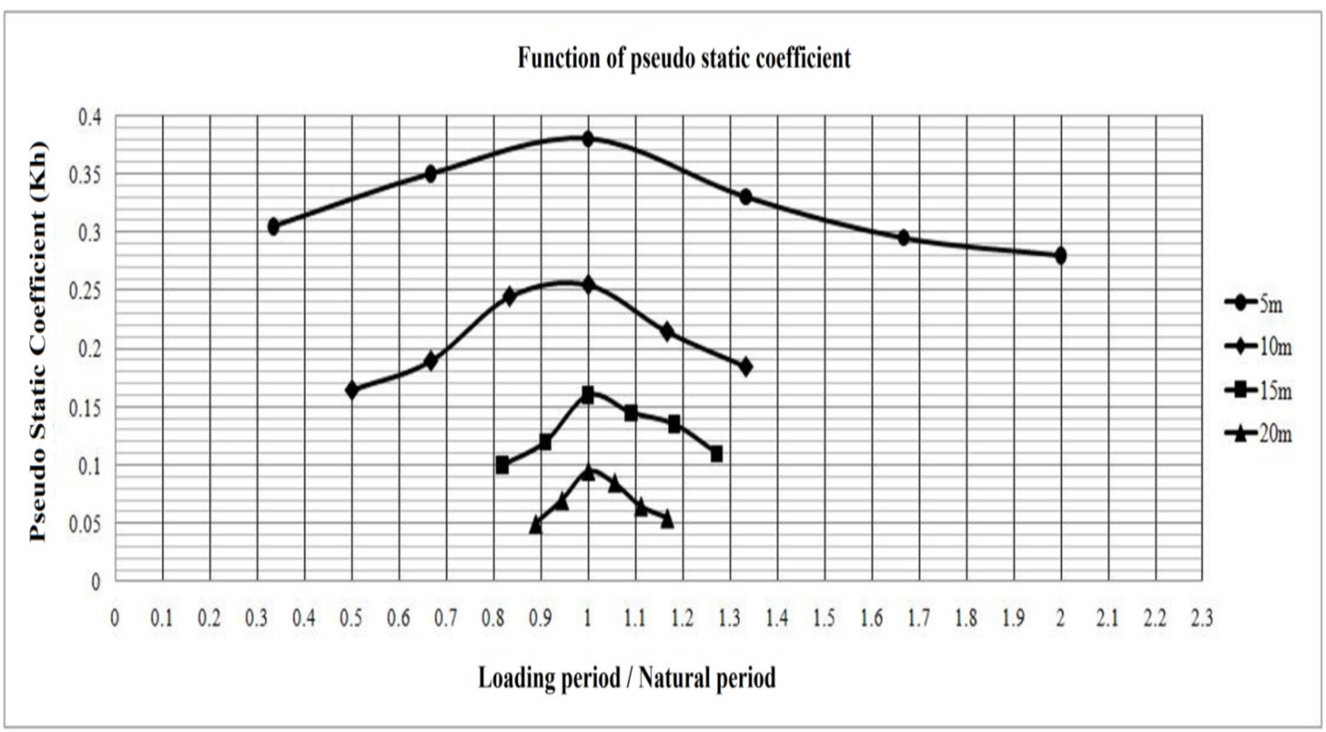

Figure-12
Variations of pseudo-static coefficient against loading period

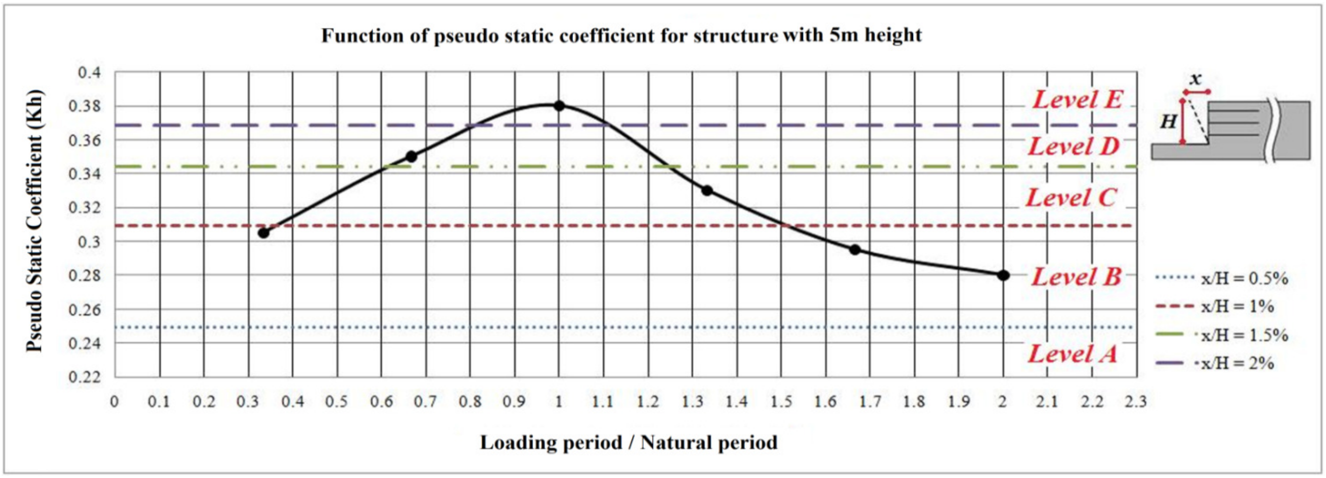

Figure-13
Variations of pseudo-static coefficient against loading period base on seismic performance

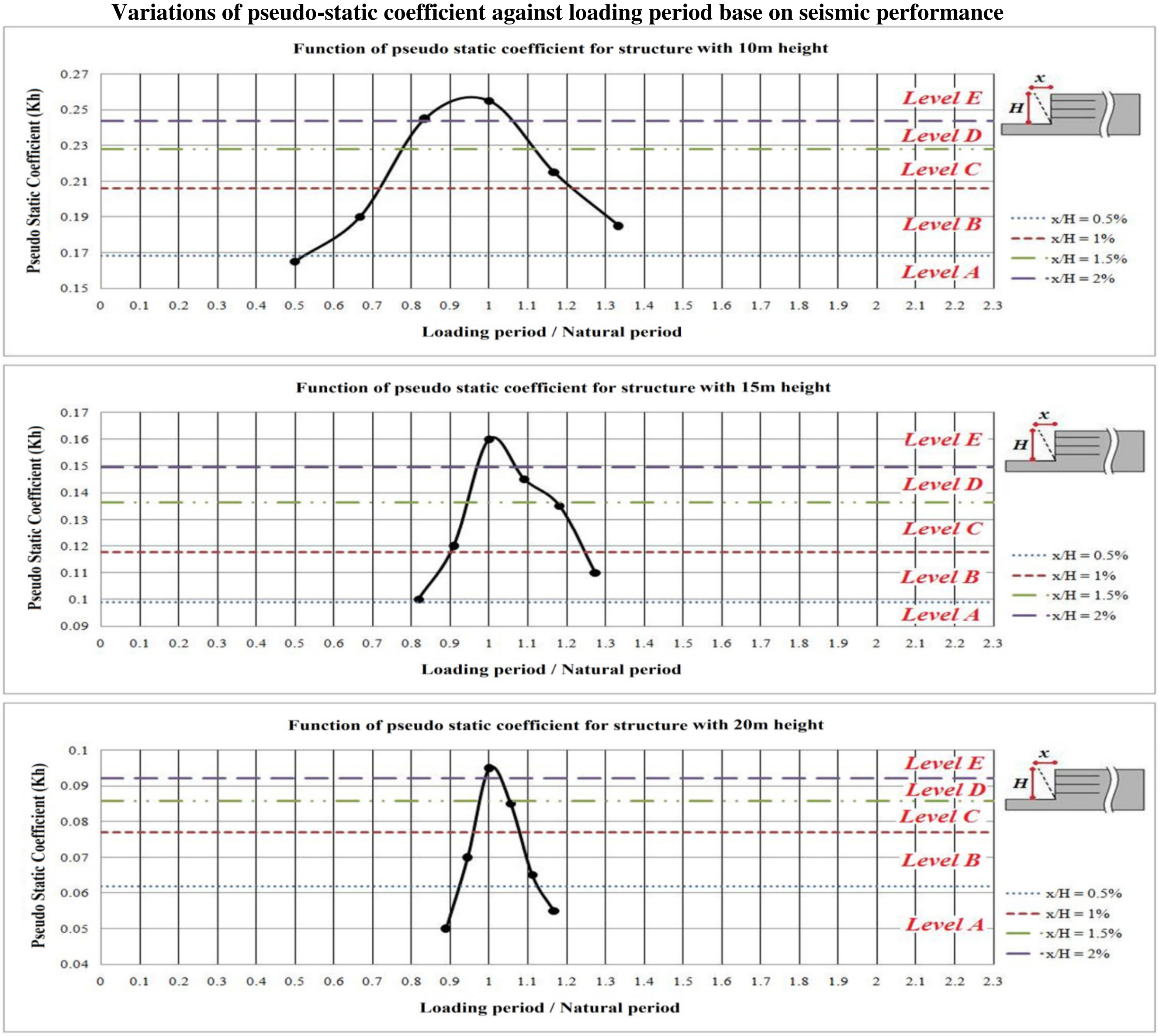

Figure-14
Variations of pseudo-static coefficient against loading period base on seismic performance

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