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A Study on Correlation between Safety Factor of Pile-Slope Systems and Seismically Induced Displacements of Pile Groups

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ABSTRACT

This paper presents a study on the seismic behavior of pile groups located in soil slopes that are also known as pile-slope systems. The main objective of the present study is to explore a reasonable and practical correlation between the safety factor of soil slope and seismic lateral displacements of pile groups in the slope, in order to achieve a better understanding and a framework for seismic analysis and design of pile groups in soil slope. To this end, a parametric study based on 3D numerical analysis for a number of pile groups in soil slopes under different conditions has been carried out to investigate the seismic behavior of pile-slope systems. Some findings and conclusions are drawn that are intended to provide insight into the seismic behavior of pile-slope systems.

KEYWORDS: Pile group, Soil slope, Pile-slope system, Seismic behavior, Pseudo-static safety factor.

INTRODUCTION

Many coastal and harbor structures, bridges, high-rise buildings and transmission towers are constructed on soil slopes and supported by pile groups. These structures may be subjected to induced lateral loads due to the seismic movements of slope. In such conditions, the existing analysis and design methods are mostly complex and time consuming and cannot be consistently applied in analysis and design procedures. Moreover, although some analytical, numerical and experimental methods have been applied to study the seismic behavior of pile groups, little research has been conducted to investigate the seismic behavior of pile groups located in soil slopes, other than for cases where the slope angle does not exceed 2° (Padron et al., 2008; Wilson, 1998). Consequently, a lot of complexities and unknowns have remained in this area.

The positioning of a pile within a soil slope has been considered in terms of the stabilization of unstable slopes in the absence of seismic activity (Hayward et al., 2000). Since the approach in these studies has focused primarily on the increase in safety factor of the slope through the performance of piles, the effects of piles have often not been considered. A number of studies may be found in the literature regarding the effects of inclined geometry of the ground on the lateral behavior of piles under static loading (Chen and Poulos, 2001; Mezazigh and Levacher, 1998). These studies have usually examined the effect of ground inclination on the lateral bearing capacity of piles. Also, numerous studies have been reported on the subject of seismic behavior of soil slopes (Rathje and Bray, 2000; Wartman et al., 2005). Such analytical and/or experimental studies have focused on both the stability and the seismic

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deformations of slopes, and most of them involve the use of Newmark's sliding block theory (Newmark, 1965). Pseudo-static approaches for the seismic analysis of pile foundations are attractive for practicing engineers because they are simple when compared to difficult and more complex dynamic analyses.

In the last years, several simplified approaches for analysis of single piles or pile groups have been developed that can be used with little computational effort (Abghari and Chai, 1995; Liyanaparithana and Poulos, 2005).

While a number of simplified methods for seismic evaluation and design of pile foundations are available, there are few simple methods to consider the response of pile-slope systems.

Thus, in this study, basic principles for achieving an engineering and simplified framework of seismic analysis and design of pile groups in soil slopes leading to a better understanding of the seismic behavior of pile-slope systems are established. In this regard, it is attempted to answer the following question: Is there any reasonable and practical correlation between the stability safety factor of a soil slope and seismic displacements of the pile group located in it?

The main objective of this study is to answer the above mentioned question, and if it is concluded that there exists a reasonable correlation, a simplified approach based on simple computational concepts and methods can be developed to evaluate the seismic displacements of pile groups located in soil slopes.

NUMERICAL SIMULATION

The program used in this paper is finite difference program FLAC^{3D} version 3.1 (FLAC, 1995). The calculation is based on the explicit finite difference scheme to solve the full equations of motion, using lumped grid point masses derived from the real density of surrounding zones rather than fictitious masses used for optimum convergence in the static solution scheme. Therefore, the response of slope-pile systems is analyzed by using a three-dimensional explicit-finite difference approach.

The Mohr-Coulomb model was used to simulate the nonlinear soil behavior. This model was selected from among the soil models in the library of FLAC^{3D}. The Mohr-Coulomb material model requires conventional soil parameters including unit weight (γ), friction angle (Φ), cohesion intercept (c), shear modulus (G) and bulk modulus (B). Table 1 presents the soil parameters used in the FLAC model.

Factors of safety are computed using FLAC^{3D} by means of strength reduction approach. FLAC has several options for the modeling of structural elements, including beam and pile elements, both of which were utilized for this study. It should be mentioned that in this study, the pile heads are fixed (restrained). Restrained head condition is obtained by connecting the pile heads with beam elements. The structural elements are assumed to remain elastic at all times.

Beam and pile elements are identical, except that pile elements include an interface element to model soil-structure interaction (SSI). The interface element utilizes springs to model both the shear and normal SSI behavior. The procedures used to estimate the normal spring stiffness and a validation study are outlined in the following sections.

For a dynamic analysis, FLAC^{3D} program provides several mechanical damping methods in which local damping is a simple and pragmatic method. The local damping coefficient α_{L} is defined as:

$$\alpha_{\mathrm{L}} = \pi D$$

where D is fraction of critical damping. Although the actual value given to the local damping has a profound influence on the dynamic wave transmission, if it is chosen from a certain range, it has little influence on the predicted factor of safety in seismic slope stability analysis. Hence, local damping of 0.157 (i.e., fraction of critical damping is 5% which is a typical value for geologic materials) is used in the model.

The input earthquake motions were recorded as accelerograms and applied at the base of each model as horizontal acceleration time histories.

For the static solutions, the bottom boundary was fixed in the horizontal and vertical directions and the lateral boundaries were fixed in the horizontal direction. For the dynamic solutions, the lateral boundaries utilized the free-field option in FLAC that approximated a free-field condition.

Model Mesh and Boundary Conditions

The soil was modeled with continuum zones, and the structure was modeled using structural elements, as mentioned before. The mesh size and the maximum unbalanced force at the grid points (i.e., error tolerance) were selected on the basis of a series of parametric analyses to concurrently optimize accuracy and computation speed. The element sizes varied from 1m in each dimension around the structure to about 2 m far from the structure. Figure 1 shows the finite difference grid used in the FLAC model for the soil-structure system.

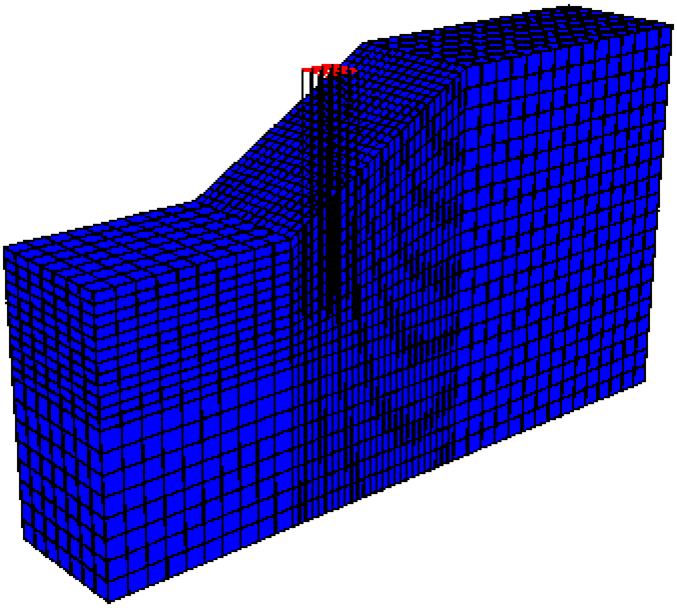

Figure (1): Model slope and finite difference mesh

PARAMETRIC STUDY

In the current study, the procedure adopted for numerical analyses consists of two main steps: the first step is to calculate safety factors of the soil slope, and the second is to calculate dynamic displacements of the pile groups. Hence, a parametric study was performed on hypothetical and comparable examples to derive practical and representative results. As shown in Figure 2 and Table 1, this study examines the effects of major factors and parameters on the response of pile-slope systems, such as configuration, number of piles in the group, soil profile (loose, medium and stiff categorized in terms of strength and stiffness) and pile spacing that is represented by the term s/d which is the ratio of spacing to diameter.

Table 1. Parameters and variables selected for parametric study

Group Configuration	s/d	Soil Properties
1x2 - 1x4 - 1x6	3	Φ=20,C^{o}=10kPa, E=20MPa
2x1 - 4x1 - 6x1	6	Φ=30,C^{o}=20kPa, E=50MPa
2x2 - 4x4 - 6x6	10	Φ=40,C^{o}=40kPa, E=80MPa

Note: it should be noted that only two ratios for s/d have been utilized in the study, and in this respect, no number has been considered for the third row of s/d column. Additionally, cohesion, friction angle and elastic modulus of soil are abbreviated as C, Φ and E, respectively.

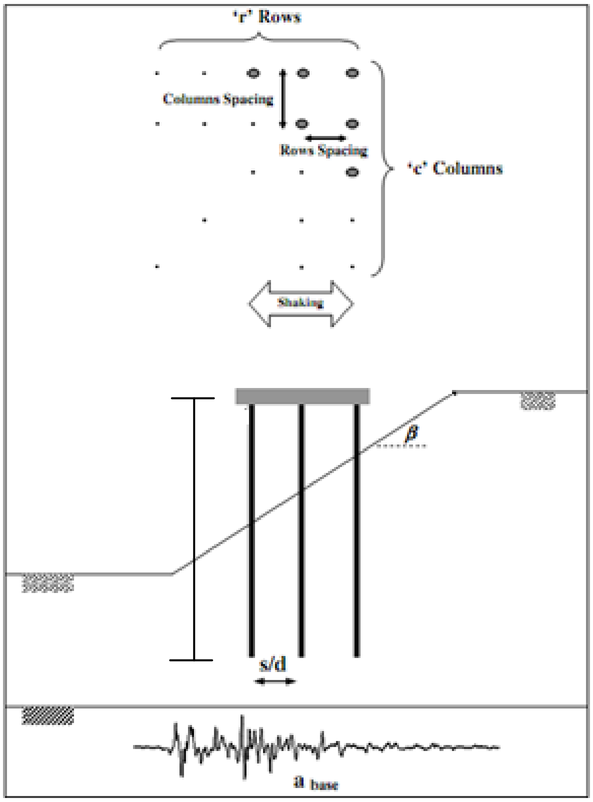

Figure (2): Parameters used in the parametric study

The properties of piles and soil slope used in the analyses are presented in Table 2.

Regarding the stability and dynamic analyses, the following points should be noted:

1. Owing to the main purpose of this study which is the investigation of seismic performance of the pile-slope system, seismic stability should be considered. In order to account for the seismic effects on slope stability, the pseudo-static approach is applied. It should be mentioned that only the horizontal component of earthquake shaking is considered and the vertical component is ignored because the effects of vertical forces tend to average out to near zero. Regarding selection of pseudo-static coefficient, it should be said that as this coefficient is a function of maximum horizontal ground acceleration, only some

fraction of peak acceleration should be selected for the coefficient. According to the studies carried out before, there are no certain rules for the selection of a pseudo-static coefficient for design but based on the recommendations cited in the literature, the most acceptable and commonly used value is one-half of the peak ground acceleration which is also used in this study (Hynes-Griffin and Franklin, 1984).

Table 2. Properties of piles and slope for parametric analysis

Case	Parameter	Value	Unit
Pile	E_p	2.00E+5	MPa
	L_p	24	m
	ν	0.3	-
	ρ	7850	kg/m^3
	t_p	1	cm
	d_p	40	cm
	I_p	2.33E-04	m^4
Soil	angle (β)	30^o	-
	H (Height of Slope)	12	m

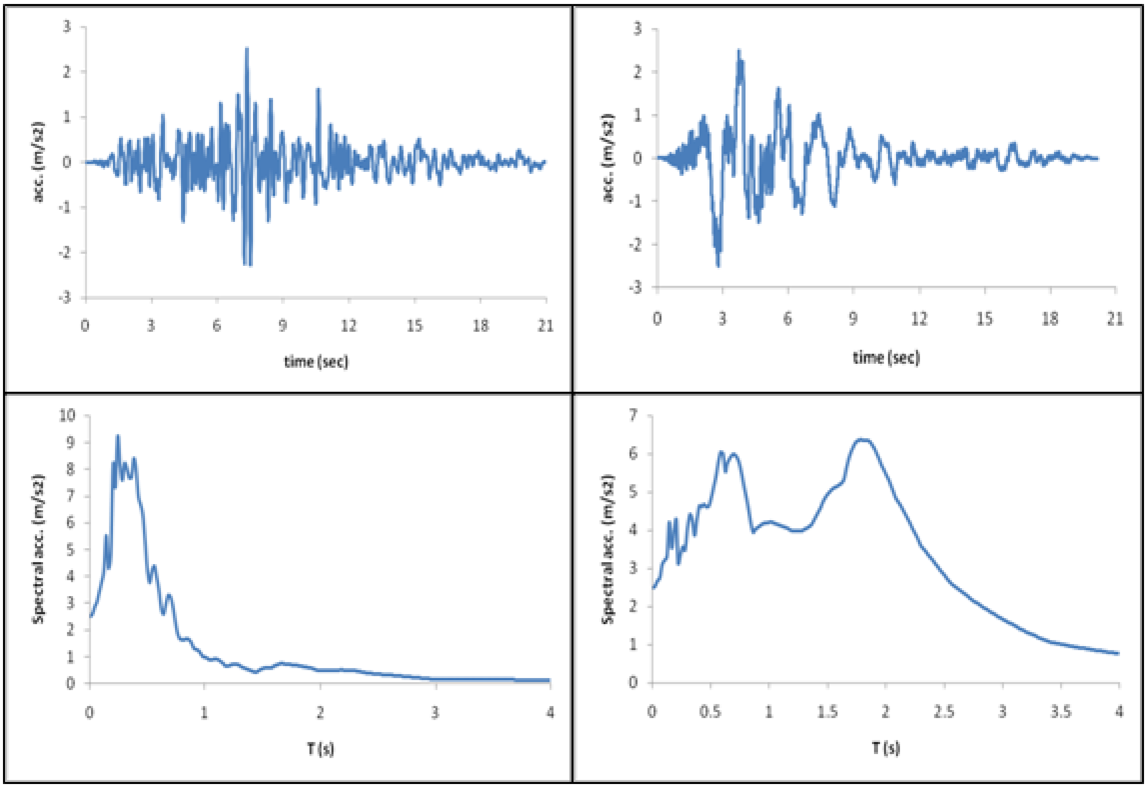

Figure (3): Time-history and acceleration response spectrum of (a) Northridge earthquake (b) North Palm Spring earthquake

2. In order to study the effects of change in frequency content of the input motion on the response

of pile-slope system, two earthquake accelerograms scaled to 0.25g with different predominant periods are selected. One of these accelerograms is the horizontal component of the North Palm Spring earthquake which has got a long predominant period (1.78s) and the other one is related to the Northridge earthquake with short predominant period (0.24s). Figure 3 shows the time-history and response acceleration spectrum of the mentioned motions.

3. Due to complexities of the effect of cap mass on group response, the effect of cap mass is ignored in the parametric study.

4. Concerning each one of the variable parameters, a value as the core is chosen that is shown in Bold-Italic. The analyses are performed with the core values; core analyses are considered as the basis for the comparison of variable parameters.

Table 3. Dimensionless parameters used in dimensional analysis

Dimensionless Parameters	
Φ_1	$\frac{E_p I_p}{E_s H_s^4}$
Φ_2	$\frac{\tan\varphi}{\tan\beta}$
Φ_3	$\frac{C}{\gamma_s H_s}$
Φ_4	$\frac{S}{d}$
Φ_5	$\frac{\delta}{d}$

DIMENSIONAL ANALYSIS

In this section, it is attempted to perform a dimensionless analysis on the results obtained in the previous section (i.e., pseudo-static safety factors and seismic pile group displacements) in order to find the most influencing and representative dimensionless parameters and produce dimensionless charts to study the correlation between the mentioned safety factors and displacements. To perform dimensional analysis, the terms involved in the mechanical properties of soil, pile and slope are combined to form independent dimensionless variable parameters. The variable parameters used in this study and their descriptions are presented in Tables 3 and 4, respectively.

In the next step, different combinations of dimensionless parameters are formed and then, related charts are drawn and dimensional analysis through a trial and error process is performed. Combined dimensionless parameters are shown in Table 5.

Table 4. Descriptions of dimensionless parameters used in dimensional analysis

Parameter	Dimension	Description
E_p	$\frac{N}{m^2}$	Pile Elastic Modulus
I_p	m^4	Moment of Inertia
E_s	$\frac{N}{m^2}$	Soil Elastic Modulus
H_s^4	m^4	Slope Height
$\tan\varphi$	-	Friction Angle of Soil
$\tan\beta$	-	Slope Inclination Angle
C	$\frac{N}{m^2}$	Soil Cohesion
γ_s	$\frac{N}{m^3}$	Soil Specific Weight
S	m	Pile Spacing
δ	m	Maximum Displacement of Pile Group
d	m	Pile Diameter

Table 5. Combined dimensionless parameters

Combined dimensionless parameters including displacement and safety factor used in the analysis	
Parameters including safety factor (FS)	Parameters including displacement (δ)
$FS.\frac{C}{\gamma_s H_s}$	$\frac{\delta}{d}.\frac{E_p I_p}{E_s H_s^4}, \frac{\delta}{d}.\frac{E_s H_s^4}{E_p I_p}$

$FS.\frac{\tan\varphi}{\tan\beta}$	$\frac{\delta}{d}.\frac{\tan\varphi}{\tan\beta}$
$FS.\frac{C}{\gamma_s H_s}/\frac{S}{d}$	$\frac{\delta}{d}.\frac{C}{\gamma_s H_s}$
$FS/\frac{S}{d}$	$\frac{\delta}{d}.\frac{\tan\varphi}{\tan\beta}.\frac{E_p I_p}{E_s H_s^4}$
FS	$\frac{\delta}{d}.\frac{\tan\varphi/\tan\beta}{C/\gamma_s H_s}.\frac{E_s H_s^4}{E_p I_p}$
-	$\frac{\delta}{d}.\frac{\tan\varphi}{\tan\beta}.\frac{E_s H_s^4}{E_p I_p}$
-	$\frac{\delta}{d}.\frac{\tan\varphi}{\tan\beta}.\frac{E_s H_s^4}{E_p I_p}/\frac{S}{d}$

DIMENSIONLESS CHARTS

After determining different combinations of dimensionless parameters, the primary dimensionless parameter representing the relation between psuodo-static safety factor and maximum seismic displacements of pile group is attempted to be found. For this reason, the dimensionless parameters were drawn *versus* each other in various charts, and after comparing and investigating the charts, it was observed that in many cases either there is not adequate correlation between the selected parameters or these parameters do not demonstrate meaningful behavioral difference. Eventually, the parameter

$$\Psi = \frac{\delta}{d}.\frac{\tan\varphi}{\tan\beta}.\frac{E_s H_s^4}{E_p I_p}/\frac{S}{d}$$

was found the most appropriate and versatile involving all of the natural and geometrical properties of the pile-slope system and selected as the primary dimensionless parameter. Dimensionless charts illustrating the correlation under this parameter are shown in Figure 4.

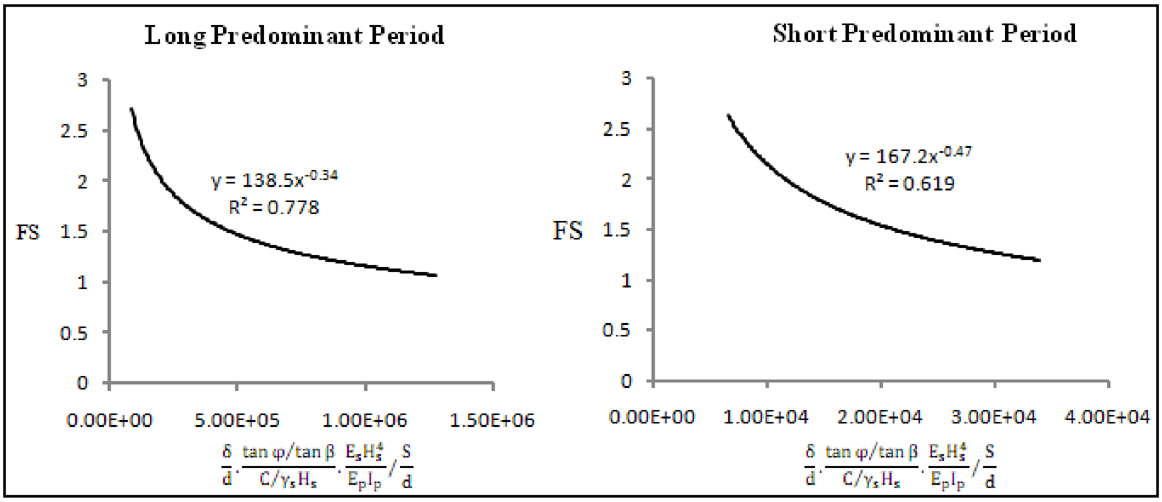

Figure (4): Correlation between safety factor and seismic displacement of pile group under the primary dimensionless parameter

According to this Figure, a good and acceptable correlation between pseudo-static safety factor and the displacement under the primary dimensionless parameter, is found. As seen in this Figure, a reasonable and correct behavior of the system is illustrated under the primary dimensionless parameter which includes all of the factors and parameters involved in the problem. To further elucidate, it should be said that if this parameter is kept constant, a decrease in stiffness and strength of the system, on the one hand decreases the safety factor and on the other hand leads to an increase in the displacements. In other words, safety factor and displacement, that are two behavioral parameters, are correlated to each other by the obtained dimensionless parameter which is a natural-geometrical parameter.

RESULTS AND INTERPRETATION

According to Figures 5 and 6, as the safety factor of the slope decreases, the pile group displacements increase. This result can be interpreted through two geotechnical and seismic viewpoints. Regarding the geotechnical viewpoint, as seen in Figure 5, while the dimensionless parameter is kept constant, a decrease in the safety factor results in an increase in the induced pile group displacements.

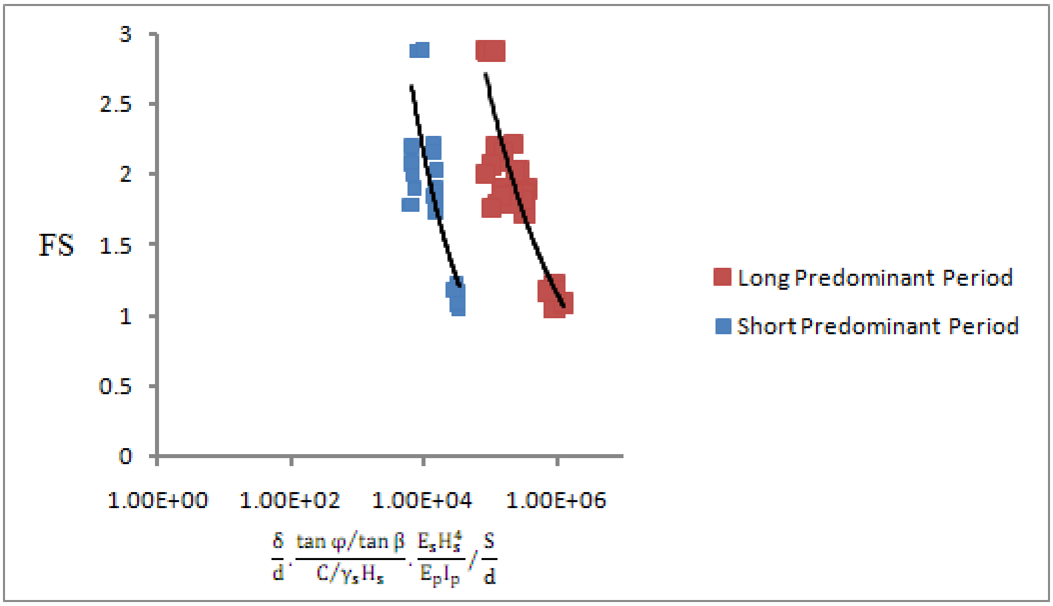

Figure (5): Pile group displacements increase as a result of a decrease in the safety factor (geotechnical viewpoint)

Figure 6 illustrates that the rates of increase in displacements induced by the short and long predominant periods are different. As shown in this Figure, following the decrease in the safety factor of the system, when the predominant period of input motion is long, pile groups have experienced much greater displacements compared to short predominant period input motion. This finding is interpreted through a seismic viewpoint, and it should be said that as the safety factor decreases, natural frequency of the system also decreases and due to the proximity of this frequency to the frequency of input motion, amplification phenomenon occurs whereas, in case of short predominant input motion, frequency of the motion is long, and this difference between the period of input motion and the natural period of the system makes the rate of increase in displacements insignificant. Thus, the difference in increase in the amount of displacements is attributed to the amplification phenomenon.

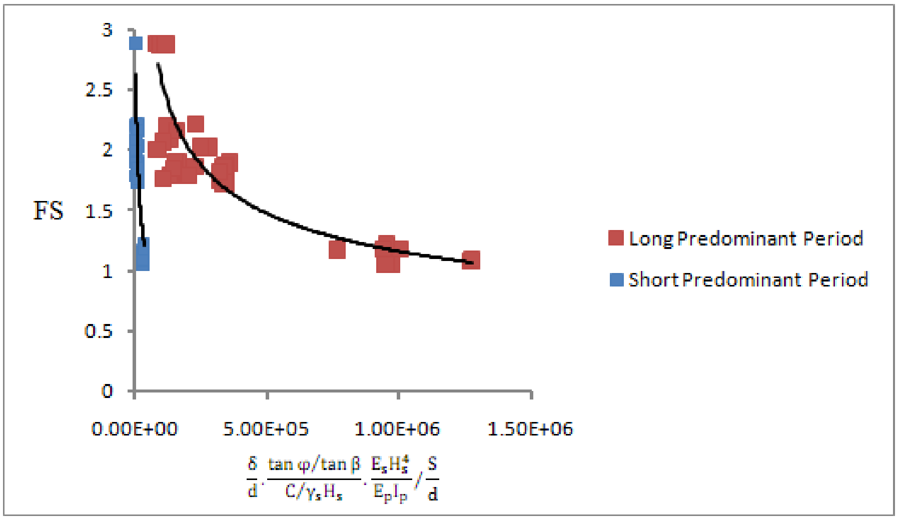

Figure (6): Significant difference in the rate of displacement increase due to amplification (seismic viewpoint)

In general, the above mentioned results are summarized in Figure 7. According to this Figure, decrease in stiffness and strength of the system and/or generally weakening the system decreases the safety factors, and on the other hand as the predominant period of input motion increases, displacements become more sensitive to the increase.

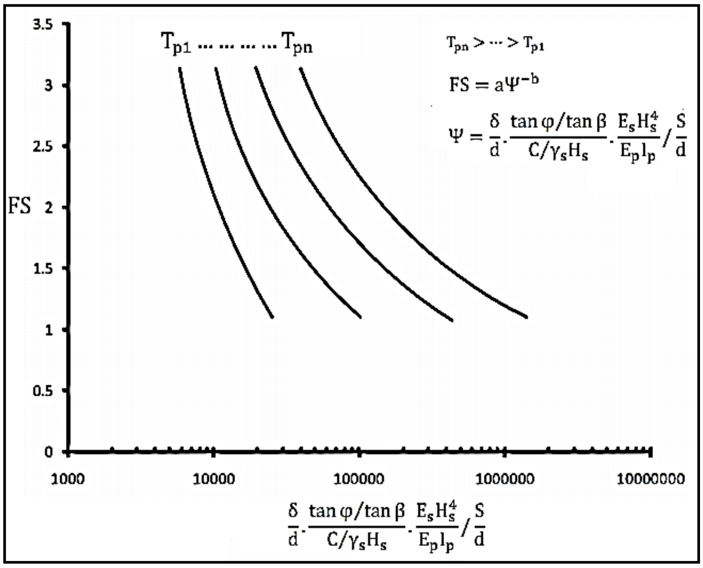

Figure (7): Response of pile-slope system to the change in predominant period of input motion

CONCLUSIONS

With regard to the results obtained from the analyses, the major conclusions drawn from this study are as follows:

1. The correlation between two behavioral parameters; safety factor and displacement through a dimensionless parameter including all of the natural and geometrical parameters of pile-slope system was obtained.

2. Decrease in strength and stiffness of soil decreases safety factor of the system and as a result of this decrease, pile group displacements increase. In addition, as the soil stiffness decreases, its natural frequency decreases as well. Thus, if predominant frequency of the input motion is short, natural frequency of the system becomes proximate to the frequency of the input motion and leads to greater displacement increase compared to the case when the predominant frequency of the input motion is short.

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