16TH EUROPEAN CONFERENCE ON
EARTHQUAKE ENGINEERING
THESSALONIKI
18 - 21 JUNE 2018

EMPIRICAL PREDICTION MODELS FOR THE SEISMIC RESPONSE OF PILE FOUNDATIONS

Berna UNUTMAZ[1], Zeynep GÜLERCE[2], M. Abdullah SANDIKKAYA[3], N. Kartal TOKER[4]

ABSTRACT

The objective of this study is to investigate the dynamic behavior of piles and to propose an empirical relationship between selected ground motion intensity measures (IMs) and engineering demand parameters (EDPs) for seismic response of pile foundations. An intensive numerical analyses scheme, which includes three dimensional, finite-difference based dynamic analyses on generic soil-pile combinations, has been designed to select the suitable EDPs among the pile response parameters that are most significantly influenced by the characteristics of ground motion recordings. Defined soil profiles are composed of either homogeneous or variable clean sand layers with shear wave velocities (V_s) ranging between 100 to 200 m/sec. Ten near fault ground motions recorded on rock sites are selected from the PEER NGA-W1 database (Chiou et al., 2008). Analysis results showed that the variation of the selected EDP, i.e. lateral deformation at the pile head (Δx), changes linearly with ground motion IMs. The sufficiency of candidate IMs, which are selected to be the Peak Ground Acceleration (PGA), Velocity Spectrum Intensity (VSI) and Arias Intensity (I_a), is not significantly different. Prediction models for the post-cyclic Δx are developed by maximum likelihood regression using PGA and V_s as prediction parameters. These models may be used individually as design tools to determine the probability of exceeding the critical levels of post-cyclic Δx for pre-determined levels of ground shaking or may be included explicitly in probabilistic seismic hazard assessment.

Keywords: Pile head displacement; Dynamic finite-difference analyses; Engineering demand parameter; Ground motion intensity measure; Probabilistic seismic hazard analysis.

1. INTRODUCTION

Pile foundations are frequently used to transfer high structural loads through weak soils to harder strata. They are also preferred in earthquake prone areas to minimize the risk of foundation failure during seismic excitation. Dynamic response of pile groups and their interaction with surrounding soil have been studied using analytical methods (e.g. Kaynia and Kausel, 1991; El Naggar and Novak, 1996; Wang et al., 2003; Gharahi et al., 2014), using the simplified Beam-on Dynamic-Winkler-Foundation model and Green's function (e.g. Gazetas et al., 1993), and based on finite-element methods in time and frequency domains (e.g. Nogami and Konagai, 1988; Wu and Finn, 1997; Achmus et al., 2007; Giannakos et al., 2012). However, systematic studies that evaluate the dynamic behavior of piles and pile groups within a performance-based earthquake engineering (PBEE) framework that defines the engineering demand parameters (EDPs) and analyzes the effect of ground motion intensity measures (IMs) on the EDPs are limited. Bradley et al. (2009) evaluated the seismic response of single piles embedded in both liquefiable and non-liquefiable soils within the PBEE framework. They selected the peak pile head displacement as the EDP (and an approximate measure for the damage to the pile) and proposed that the Velocity Spectrum Intensity (VSI) is the most efficient IM that correlates with selected EDP.

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[1] Assoc. Prof. Dr., Civil Eng., Hacettepe University, Ankara, Turkey, berna.unutmaz@hacettepe.edu.tr
[2] Assoc. Prof. Dr., Civil Eng., Middle East Technical University, Ankara, Turkey, zyilmaz@metu.edu.tr
[3] Assist. Prof. Dr., Civil Eng., Hacettepe University, Ankara, Turkey, abdullahsandikkaya@hacettepe.edu.tr
[4] Assist. Prof. Dr., Civil Eng., Middle East Technical University, Ankara, Turkey, toker@metu.edu.tr

The objective of this study is to investigate the seismic response of pile groups within the PBEE framework and to propose an empirical relationship between selected EDPs and ground motion IMs based on the analysis results. An intensive numerical analyses scheme, which includes three dimensional, finite-difference based dynamic analyses on generic soil-pile combinations, has been designed. Defined soil profiles are composed of either homogeneous or variable clean sand layers with shear wave velocities (V_s) ranging between 100 to 200 m/sec. Ten near fault ground motions recorded on rock sites are selected from the PEER NGA-W1 database (Chiou et al., 2008) and utilized in the dynamic analyses with different pile group configurations. The post-cyclic lateral pile head deformation (Δx) is selected as the EDP, and the effects of the pile group parameters, e.g. number and the diameter of the piles, on this parameter are discussed in the next section.

Analysis results showed that the variation of the selected EDP is mostly linear with ground motion IMs and the sufficiency of candidate IMs, peak ground acceleration (PGA), VSI, and Arias intensity (I_a) is not significantly different. Therefore, prediction models for the post-cyclic Δx are developed by maximum likelihood regression using PGA, the most hazard compatible IM among the candidates. These preliminary models may be used individually as risk-based design tools to determine the probability of exceeding the critical levels of post-cyclic Δx for pre-determined levels of ground shaking or may be included explicitly in probabilistic seismic hazard assessment.

2. FINITE DIFFERENCE MODEL AND SELECTED GROUND MOTION RECORDINGS

The three-dimensional (3-D) finite difference - based simulations were performed using FLAC-3D software (2005). In the created 3-D mesh, the element size was selected to be smaller than approximately one-tenth of the wavelength associated with the highest frequency component of the input wave to prevent numerical distortion of the propagating waves in dynamic analysis. All of the soil layers were modeled as clean sands with internal friction angle of 30° and cohesion of 5 kPa. In the static analysis phase, the boundaries were fixed in both lateral directions and set free in the vertical direction. For the dynamic analysis, an equivalent linear soil model which incorporates Vucetic and Dobry (1991) modulus degradation and damping curves was utilized. The boundary conditions were selected as “free field” which accounts for the free field motion that would exist in the absence of the structure. The piles were modeled as groups of 4 (2x2) and 9 (3x3) piles (Figure 1 presents typical adopted meshes, cut for visibility – the full model includes entire pile cap and surrounding soil). The depth of the finite-difference mesh in Figure 1 is 30 m but the mesh size in x- and y- directions vary according to the pile group and diameter configurations.

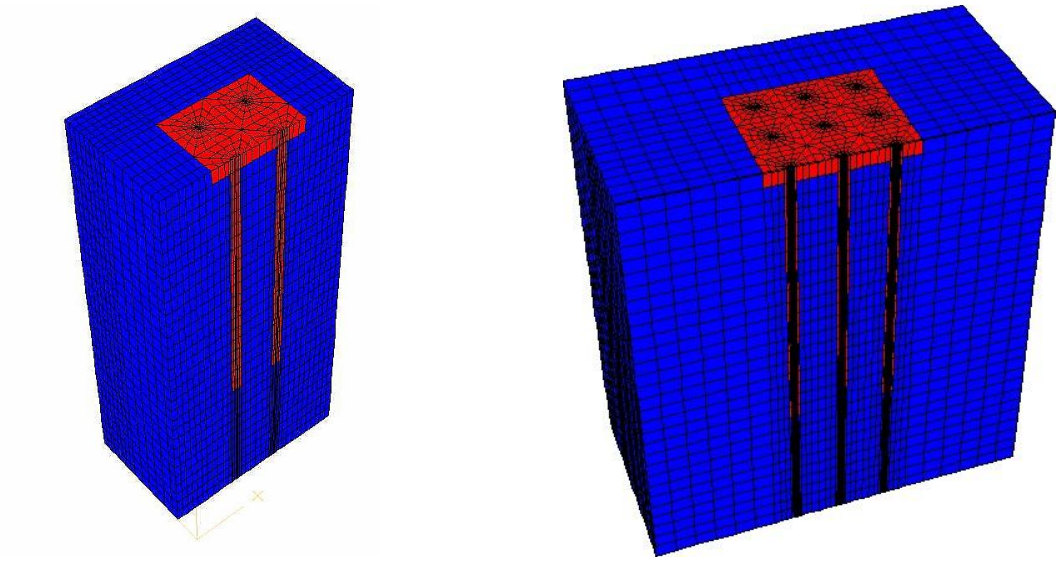

Figure 1. Typical meshes used in numerical simulations

Table 1. List of ground motions used in nonlinear simulations and regression analysis

Earthquake Name	**Year**	**Station Name**	**M_w**	**R_{rup} (km)**	**V_{s30} (m/s)**	**PGA (g)**	**Arias Intensity (I_a)**	**Velocity Spectrum Intensity**
Nahanni, Canada	1985	Site 1	6.76	9.6	660	1.0556	1.6613	20.873
Tabas, Iran	1978	Tabas	7.35	2.1	767	0.8128	1.2568	32.185
Landers	1992	Lucerne	7.28	2.2	685	0.7214	2.6198	15.517
Victoria, Mexico	1980	Cerro Prieto	6.33	14.4	660	0.5722	0.2594	11.972
Coyote Lake	1979	Gilroy Array #6	5.74	3.1	663	0.4038	0.2908	11.397
Tabas, Iran	1978	Dayhook	7.35	13.9	660	0.3505	0.1417	11.175
Hector Mine	1999	Hector	7.13	11.7	685	0.3062	0.2482	10.345
Northridge-01	1994	Santa Susana Ground	6.69	16.7	715	0.2530	0.3452	9.3795
Northridge-01	1994	Burbank - Howard Rd.	6.69	16.9	822	0.1400	0.0532	4.5604
Whittier Narrows-01	1987	Pasadena - CIT Kresge Lab	5.99	18.1	970	0.1017	0.0262	2.7823

3. EFFECT OF PILE GROUP PARAMETERS ON THE PILE GROUP RESPONSE

Simulations were run for 2x2 and 3x3 pile groups, each with 80 cm or 140 cm diameter (D), and each with 2.5D or 4D center-to-center spacing. Unutmaz and Gülerce (2016) proposed that the maximum lateral deformation at the pile head is an efficient EDP for representing the pile group response and is strongly correlated to two different ground motion IMs; PGA and I_a. A normalized form of the same parameter is employed in this study: $\Delta x/W$ (maximum lateral deformation at the pile head / pile group width in cm/m) is preferred to isolate the effects of pile group dimensions. The pile group width has been taken as center to center difference between the edge piles. $\Delta x/W$ from each analysis is plotted with respect to PGA of the input ground motion for different configurations of soil profiles and pile group parameters in Figures 2 to 7. The distribution of $\Delta x/W$ vs. PGA for different pile diameters from the same pile number and spacing configurations is compared in Figures 2, 3 and 4 for Profile 1-Vs=100 m/s, Profile 2-Vs=200 m/s and Profile 3-layered-Vs=100-200 m/s, respectively. The shear wave velocities increase linearly with depth in this last soil profile. As expected, $\Delta x/W$ decreases with increasing pile diameter for the same pile group with the same normalized spacing for each soil profile. The variation is higher for 2x2 pile groups when compared to the 3x3 groups: the scatter in the 3x3 pile groups shows that the effect of pile diameter on the distribution is negligible. This observation may be related to the improvement in the strength of the soil in 3x3 pile groups which decreases the lateral displacements.

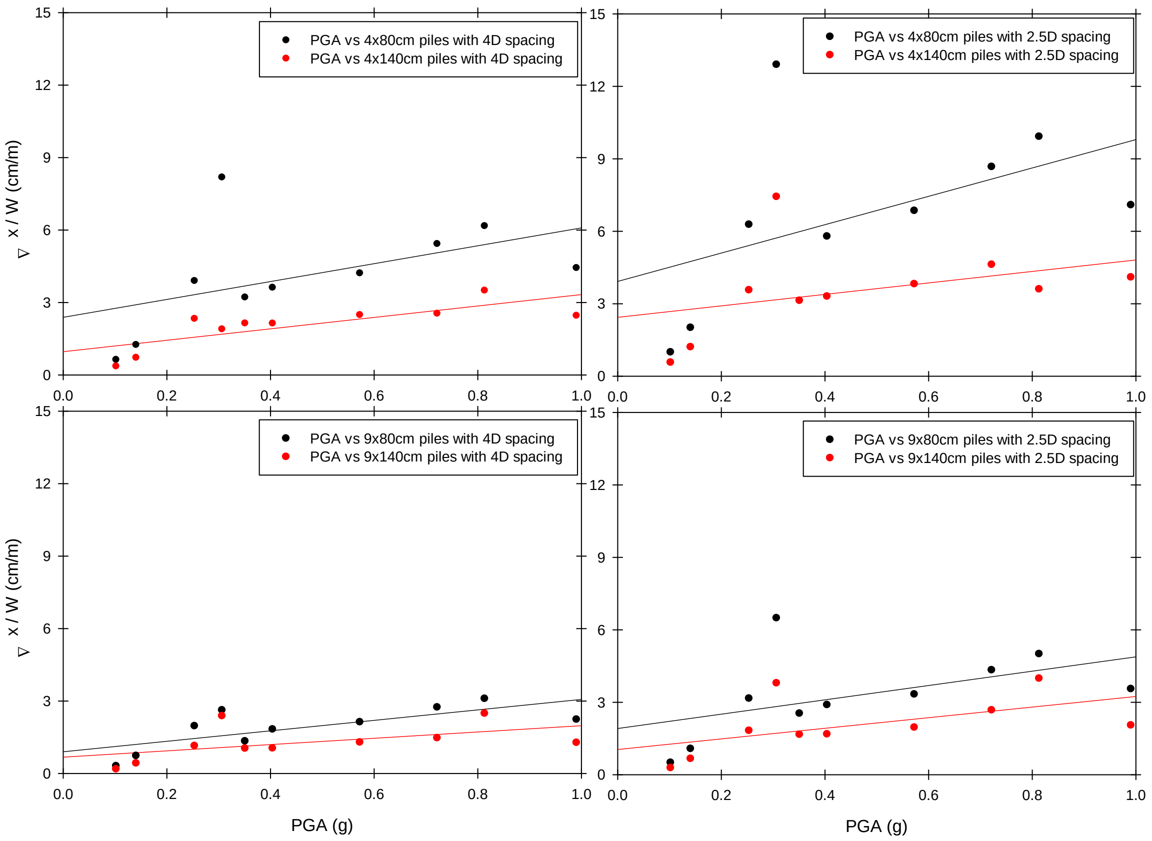

Figure 2. The variation of normalized post-cyclic Δx with pile diameter for Profile 1, Vs=100 m/s

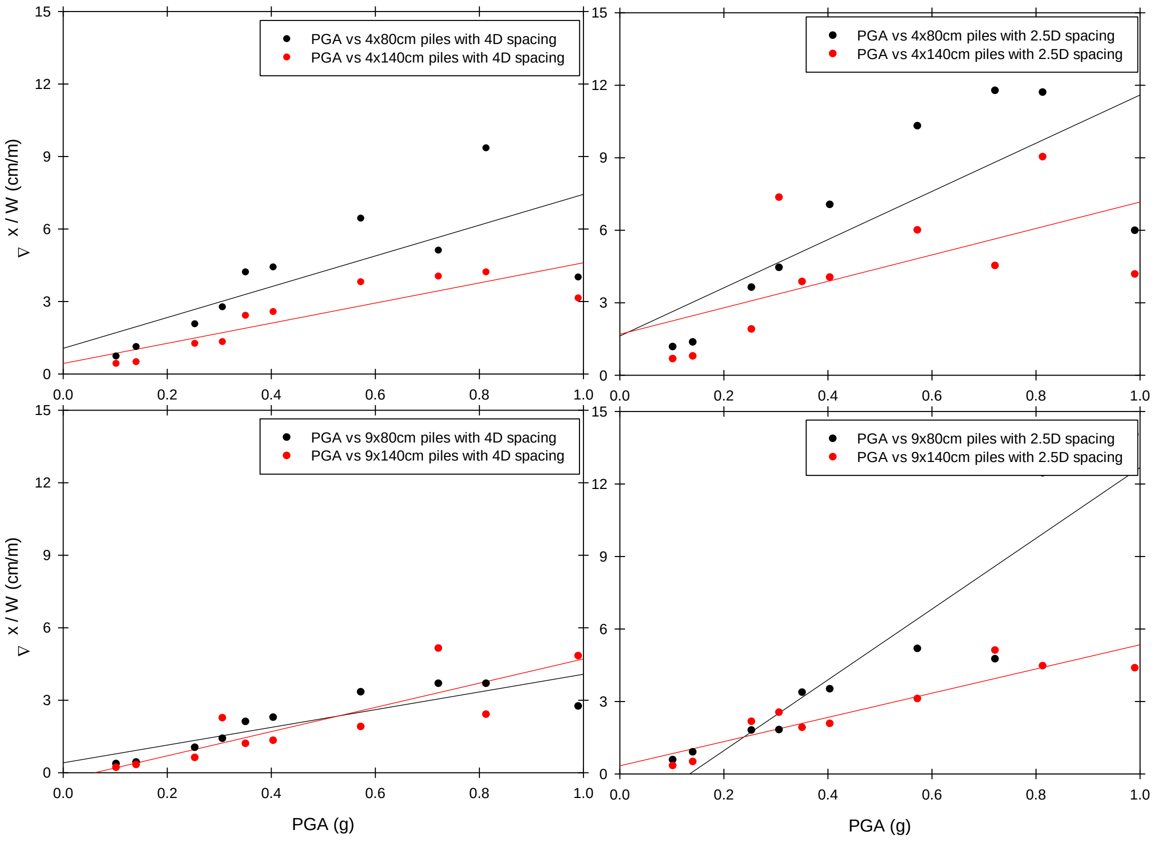

Figure 3. The variation of normalized post-cyclic Δx with pile diameter for Profile 2, Vs=200 m/s

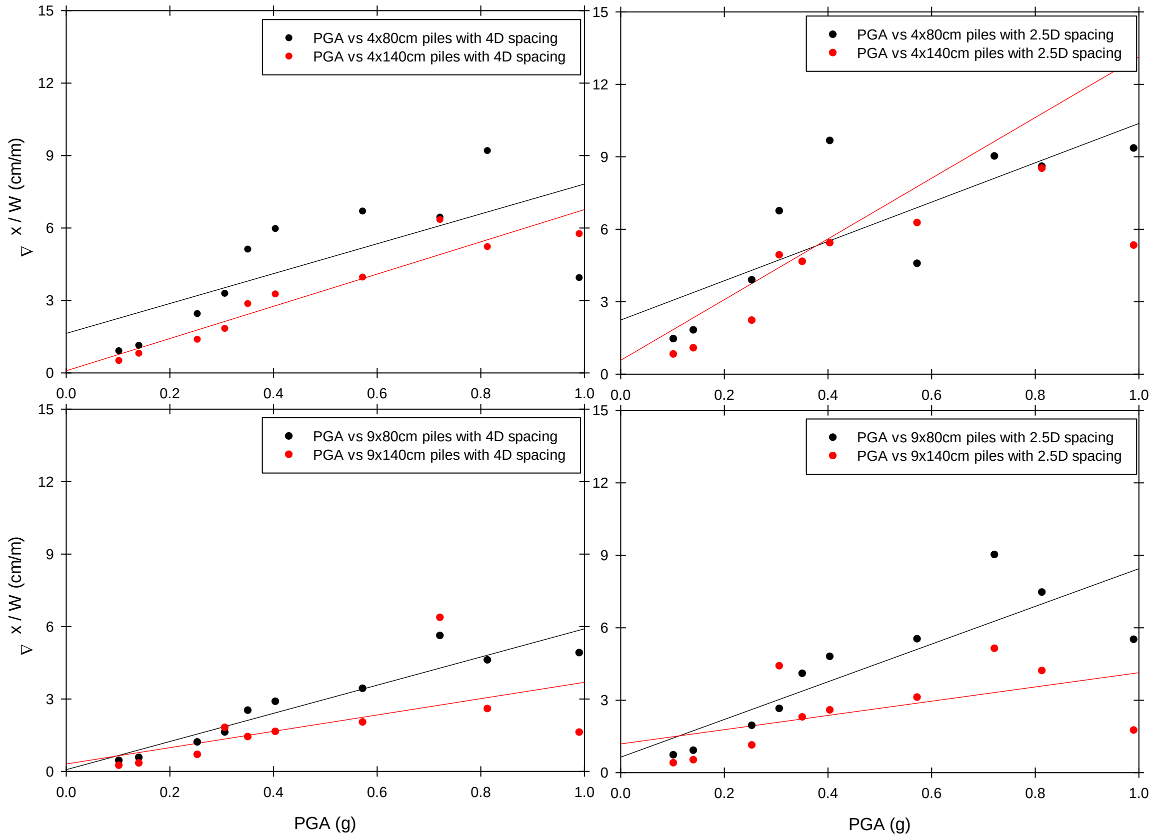

Figure 4. The variation of normalized post-cyclic Δx with pile diameter for Profile 3 - layered, Vs=100-200 m/s

The effect of pile spacing was found to have a very limited effect on the maximum lateral deformation of the pile head by Unutmaz and Gülerce (2016). Figures 5 to 7 show that if the other pile group parameters are the same, the effect of pile spacing is negligible for each soil profile, except for 2x2 pile group with D=80 cm. It is notable that the lateral displacements presented in these figures are normalized with group width, a parameter increases with increasing spacing. Therefore, Δx/W decreases even if the maximum lateral deformation at the pile head is increasing with increasing pile spacing. The number of piles in the group is an important parameter that affects the dynamic response of piles.

Overall trends in Figures 2 to 7 indicate that the lateral top displacement of the piles decreases as the number of piles increases. Effect of the number of piles on the post cyclic Δx/W is comparable with the effect of pile diameter (Figures 2 to 4), especially for the cases with 2.5D spacing. Therefore, number of piles and pile diameter might be included as a predictive parameter in the final model.

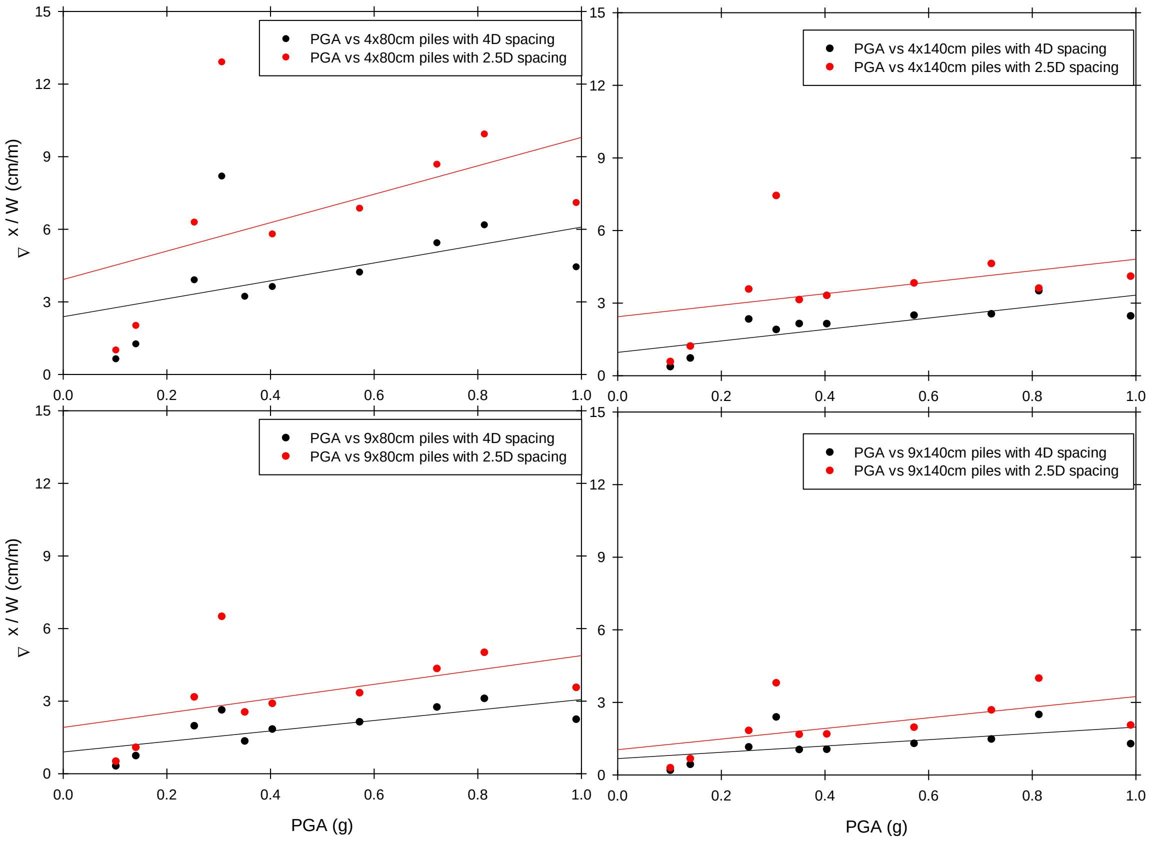

Figure 5. The variation of normalized post-cyclic ∆x with pile spacing for Profile 1, Vs=100 m/s.

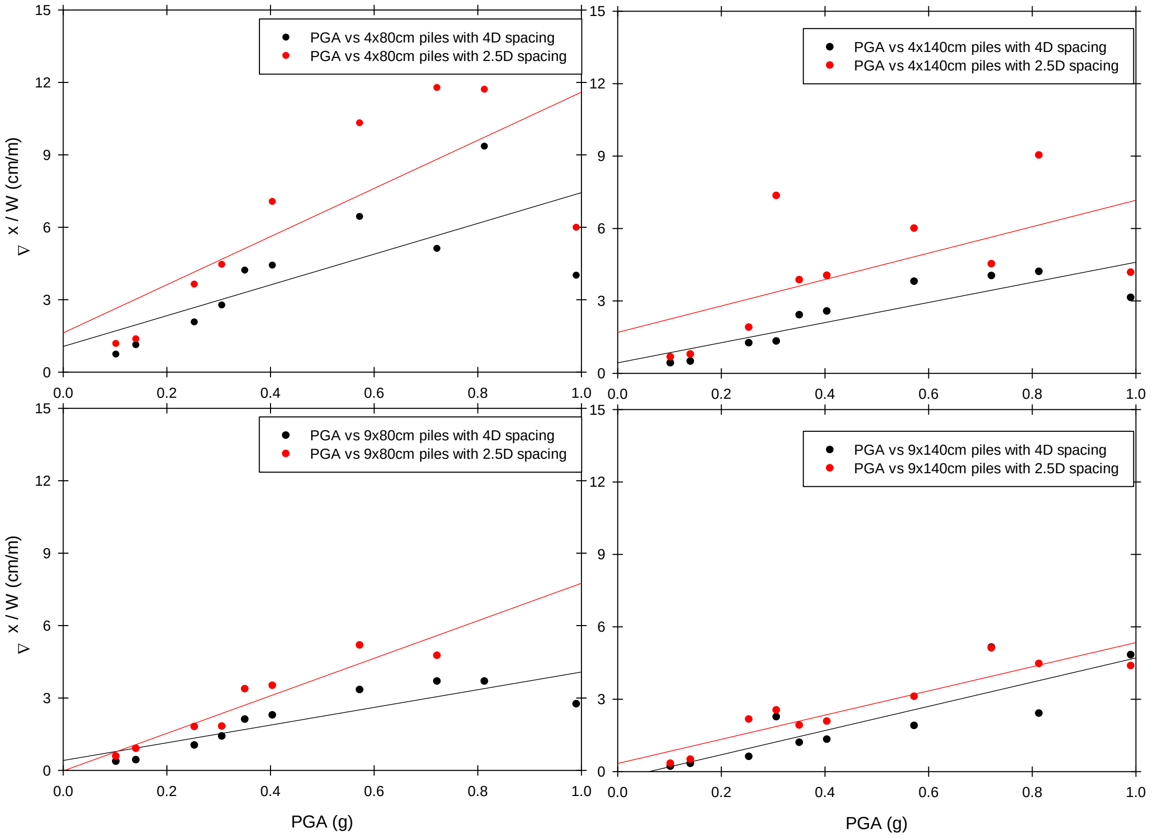

Figure 6. The variation of normalized post-cyclic ∆x with pile spacing for Profile 2, Vs=200 m/s.

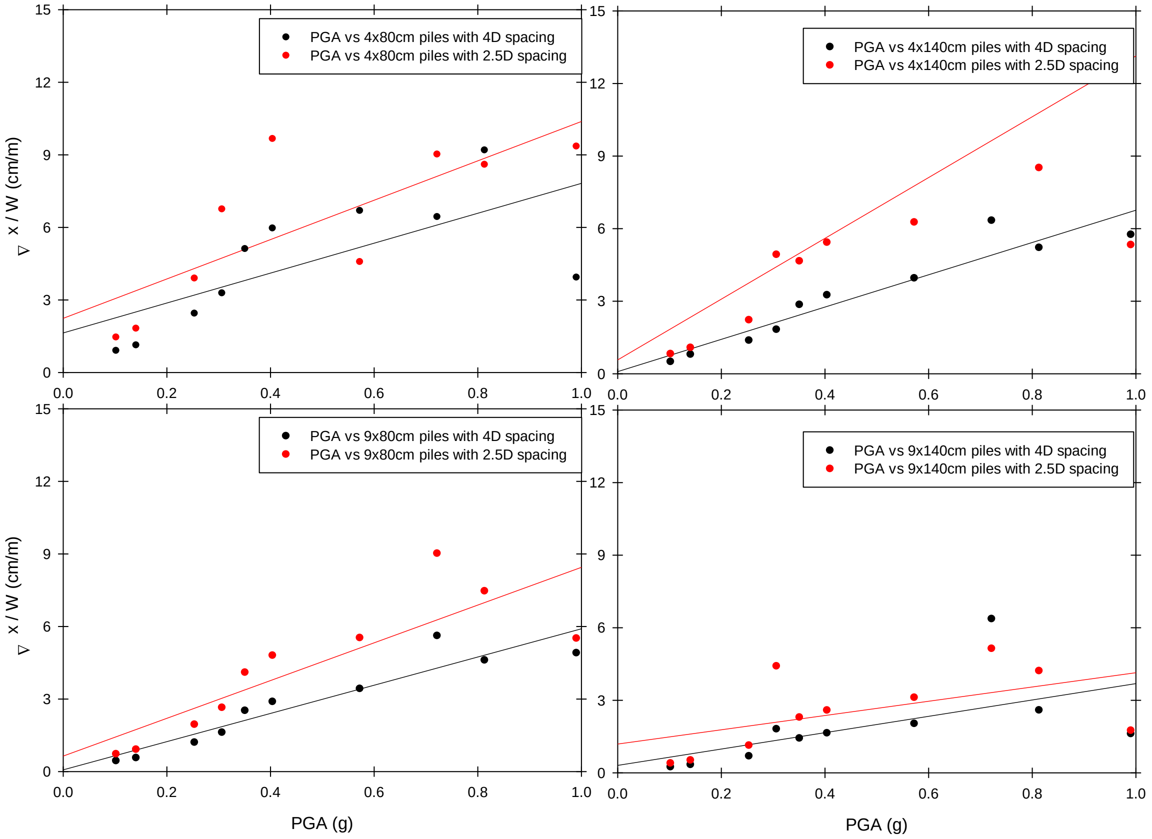

Figure 7. The variation of normalized post-cyclic Δx with pile spacing for Profile 3 - layered, Vs=100-200 m/s.

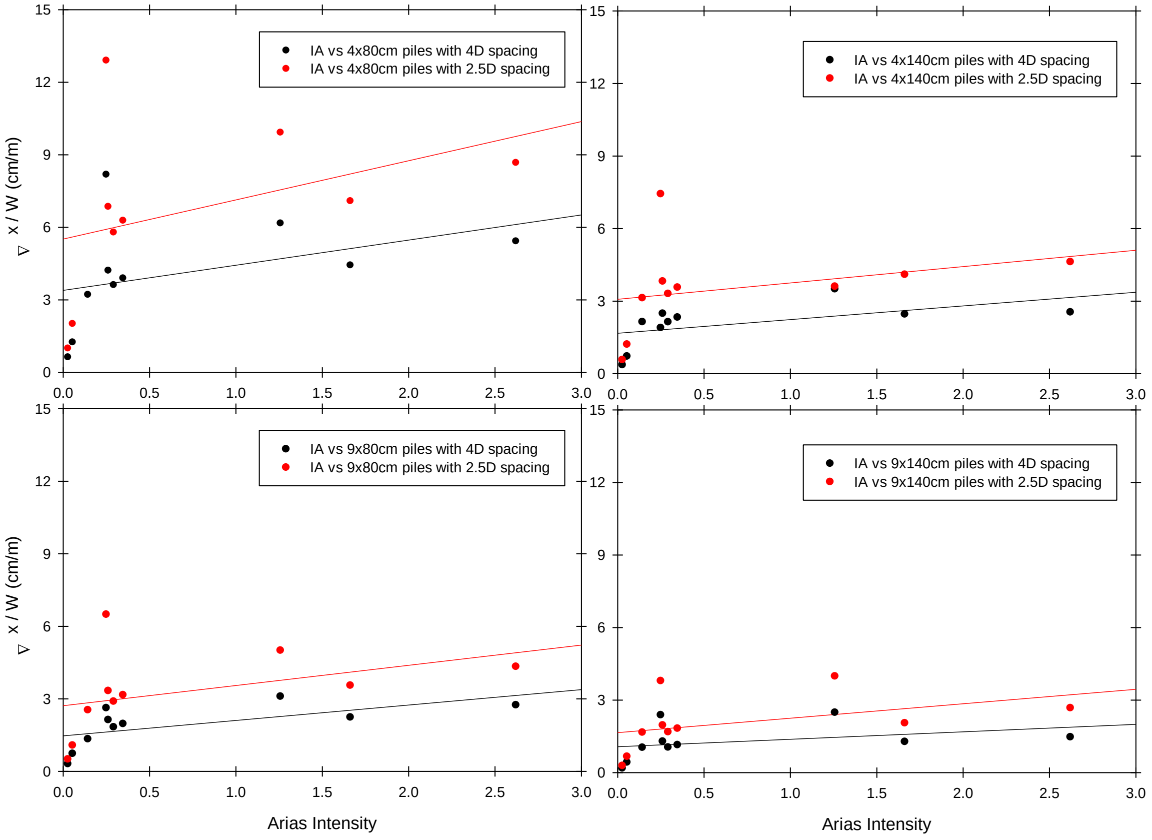

Figure 8. The variation of normalized displacement with respect to I_a

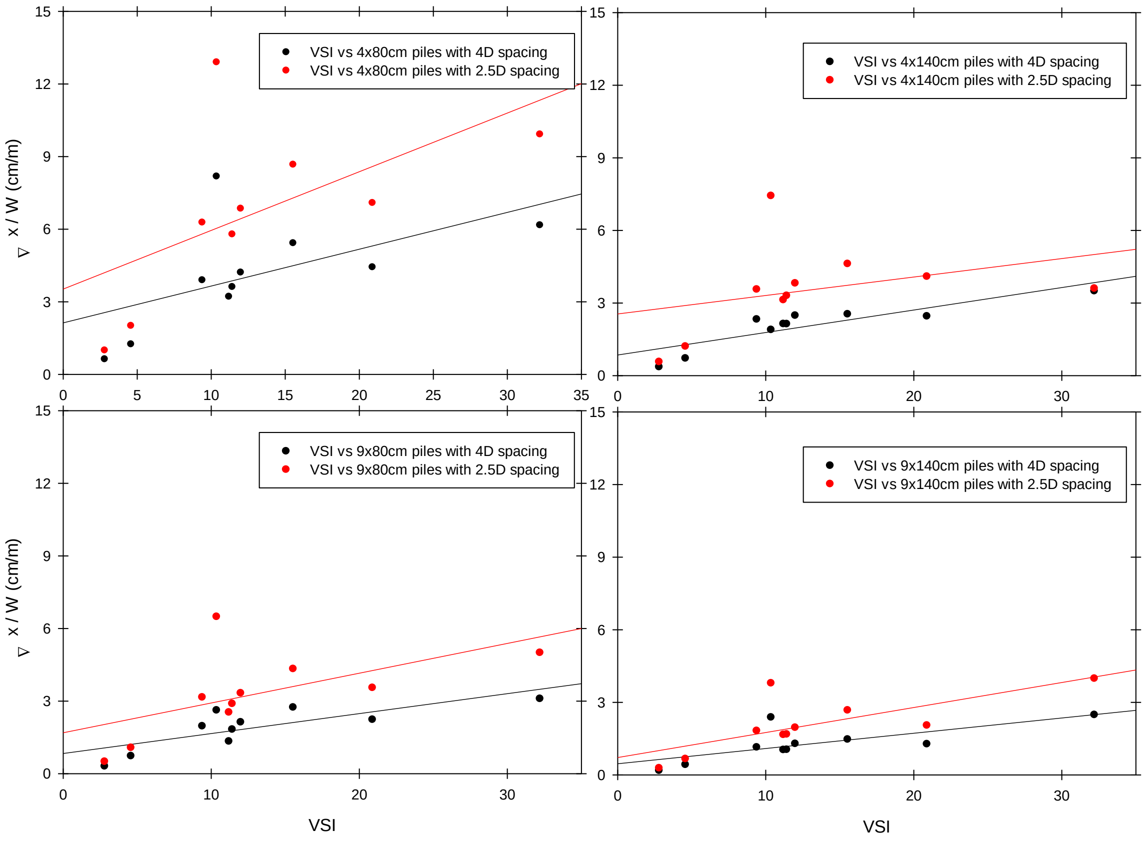

Figure 9. The variation of normalized displacement with respect to VSI

4. EFFECT OF GROUND MOTION IM ON THE PILE GROUP RESPONSE

The variation of maximum pile head displacement with respect to PGA is given in Figures 2 to 7: in general terms, post-cyclic Δx/W increases with PGA within a large scatter. The variations of the post-cyclic Δx/W with respect to I_a and VSI for Profile 1 are given in Figures 8 and 9, respectively. Comparison of Figures 2, 8 and, 9 clearly shows that: i) the scatter of the data is not improved by employing I_a instead of PGA, ii) scatter with respect to PGA is compatible with the scatter with VSI, and iii) the distribution of Δx/W with I_a is non-linear as proposed by Unutmaz and Gülerce (2016). Therefore, a linear relationship with PGA or VSI can be utilized in the preliminary model.

5. PRELIMINARY SEISMIC DEMAND MODELS FOR POST CYCLIC DISPLACEMENT

Based on the observations presented in the previous sections, a preliminary model form is selected with two predictive parameters, PGA and V_s. The pile group parameters (number, diameter, and spacing) are currently excluded from the model since the effect of the pile diameter on the response is negligible at this pile-soil relative rigidity and the configurations of pile number and pile diameter are currently limited. A quantitative analysis for the efficiency of the ground motion IMs was not performed as given in Bradley et al. (2009); however, PGA is preferred in the preliminary model due to its hazard compatibility even if the prediction performance is similar to VSI. After many trials, the best fit for the prediction of post cyclic lateral displacement is achieved with simple form as given in Equation 1. The constants (θ values) in this equation are estimated using maximum likelihood regression and presented in Table 2.

$$\Delta x = \theta 1 \cdot V_s^{\theta 2} + \theta 3 \cdot PGA + \theta 4 \qquad (1)$$

Table 2. Parameters of the prediction model for post cyclic lateral displacement of pile head.

Constant	Value
θ1	0.350
θ2	0.565
θ3	18.378
θ4	0.215

The standard deviation of the proposed equation is 6.625. The adjusted R^2 value is 0.36. Predicted and the calculated values of lateral displacement are compared in Figure 10. In this figure, the solid line is the 1:1 line which means that the values of displacements calculated from the finite difference analysis and estimated by Equation 1 are exactly the same. The dashed lines have slopes of 1:2 and 2:1. While calculating these values, the average of shear wave velocity over the top 30 m is used as the input parameter for the heterogeneous (layered) soil profile.

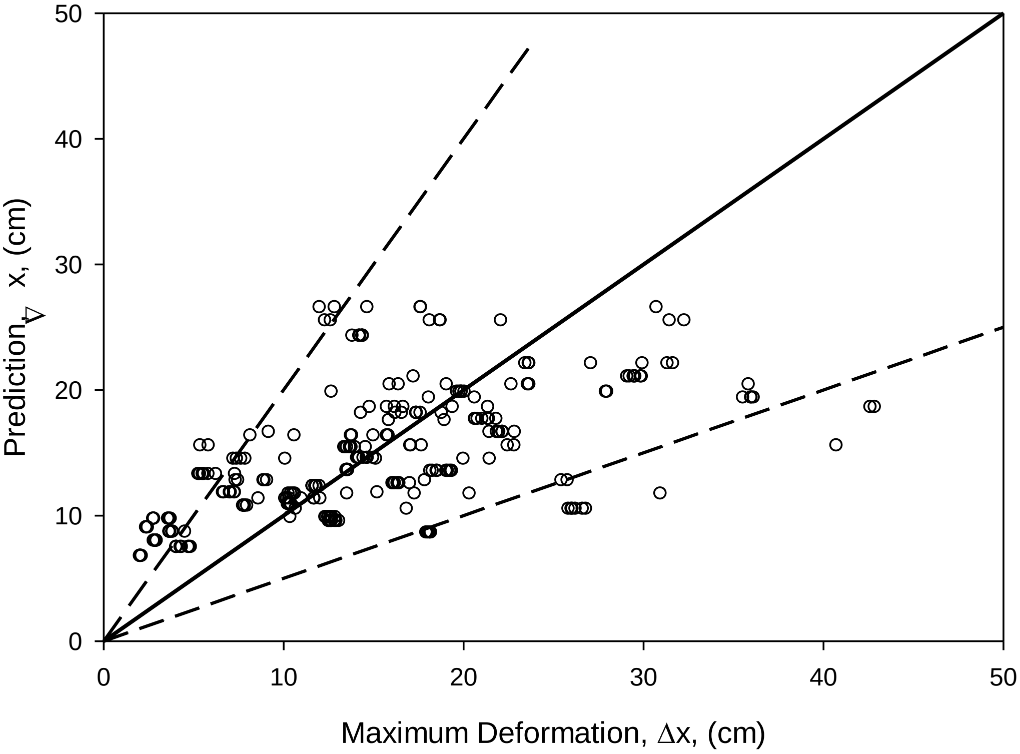

Figure 10. The comparison of predicted vs. calculated post cyclic lateral displacement values.

The normalized model residual (δX) is calculated as shown in Equation 2. The developed model is also tested for this parameter (δX). For both PSDMs, normalized residuals are plotted against the ground motion IMs employed in the model as shown in Figure 11. According to this figure, the normalized residuals are equally distributed along the zero line; therefore, a systematic bias is not included in the models. However, for small shaking levels, especially when the PGA<0.2g, the normalized residuals are all negative, indicating that the proposed correlation between the maximum lateral displacement and ground motion IMs is not very effective in small strain levels. Further analysis with ground motions of small amplitudes should be carried out to understand the underlying reason for this inconsistency

$$\delta X = \Delta x(\text{actual}) - \Delta x(\text{predicted}) / \Delta x(\text{actual}) \qquad (2)$$

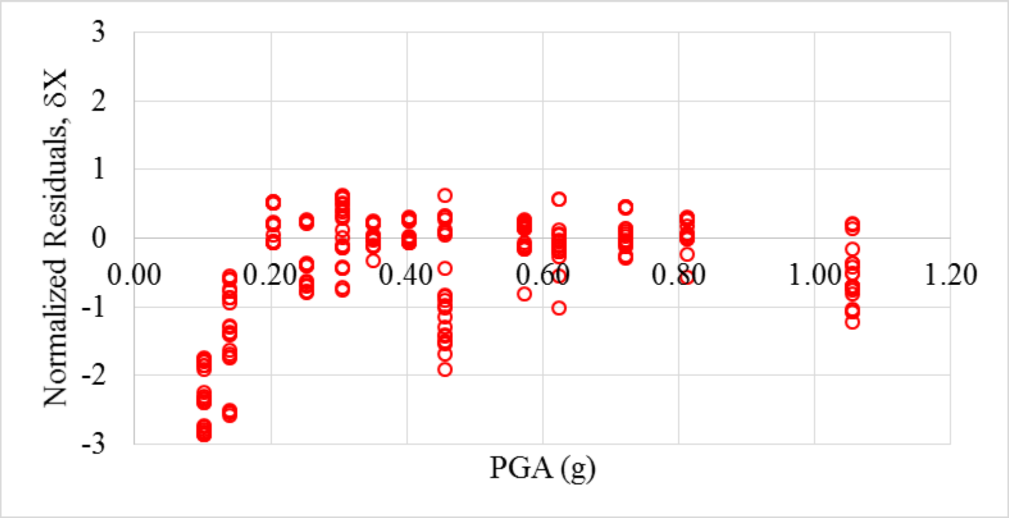

Figure 11. Normalized residuals (δX) vs. PGA

6. CONCLUSIONS

The objective of this study is to develop a simplified equation for predicting the post-cyclic lateral pile head deformation (Δx) for pile groups, using ground-motion IMs, soil properties, and pile group configuration variables. To compile the dataset used in the regression, finite difference analysis were performed to calculate Δx for different pile configurations (number of piles in groups, diameter of piles and pile spacing) for three different soil profiles with ten near fault input motions recorded on rock sites. The input motions are not scaled, however, they are selected to reflect a large range of ground shaking levels (PGA=0.1g-1g). As a result of these analysis, it was found that post-cyclic Δx/W increases with PGA as expected. The variations of the post-cyclic Δx/W with respect to I_a and VSI shows that I_a is not a better parameter for estimating pile head displacement. Similarly, PGA and VSI show a similar trend with each other and the distribution of Δx/W with I_a is non-linear. Preliminary form of the prediction model includes PGA and the average V_s of the soil profile; nevertheless, this preliminary form will be improved by adding another parameter to represent the strength of the pile group (such as the replacement ratio, relative rigidity or relative stiffness) when the database is extended with further analyses. A quantitative analysis for the efficiency and the dispersion of the ground motion IMs are not conducted; therefore, the ground motion IM used in the regression may be re-evaluated in the final form of the model. It should be emphasized that these analyses only include limited ground-motion, soil profile, and pile group configurations and do not reflect a generalized solution that covers full ranges of these parameters. To find a more generalized solution for predicting the lateral pile head displacements during seismic excitations, the number of finite difference analysis should be increased with different soil and pile configurations (with also different pile stiffness values). Enlarging the dataset with increasing the number of records can be important to change the pattern of results before proposing the final form of the model.

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