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EVALUATION OF SEISMIC DEMAND OF PILE FOUNDATION FOR PERFORMANCE BASED DESIGN

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ABSTRACT

Accurate prediction of seismic performance of structures is important in reducing risks from earthquakes. Within the context of emerging performance-based earthquake engineering trends, seismic performance is measured with respect to the demand of engineering systems during a seismic event as opposed to the conventional factor of safety approach. Investigation of the correlation between so-called engineering demand parameters and various intensity measures has received substantial attention in earthquake engineering, as accurate prediction of seismic demand is desired in performance based seismic design.

In this study the seismic demand of pile foundations are investigated in a performance based approach. A soil-pile-superstructure model consisting of group piles and superstructure is used in a parametric study to determine the features in the seismic response of the pile foundation. A dynamic time-step analysis is used in this research because of accurate prediction of the seismic response and estimation of the inelastic response. The seismic demand on a pile is generally related to the hysteretic energy released due to inelastic behaviors during ground shaking, so with respect to energy dissipation, various intensity measured are used to inspect their correlation with the seismic demand, which is measured in term of damage index. We use a suite of ground motion records scaled to various ranges of intensity to probabilistically investigate the full range of pile behavior from initial elastic response to failure.

INTRODUCTION

Pile foundation have been extensively used in variety of civil and geotechnical engineering purposes. One of the recent needs in practice of earthquake geotechnical engineering has been the development of performance-based design (PBD) principle, which had already been employed is seismic design of structures under strong earthquake. The rapid development of practical and reliable performance-based design in geotechnical engineering is necessary for pile foundation design as well as for superstructures resting on incompetent soils. However, PBD is still under development, and its actual applications are usually limited to evaluating seismic performance of foundation.

Collapse and/or severe damage to pile supported structures is still observed after most major earthquakes; for example, the 1995 Kobe earthquake, the 1999 Koceli earthquake, the 2001 Bhuj earthquake and the Sumatra earthquake [1,2]. This is despite the fact that a large factor of safety is apparently employed in their design. Therefore it is important that seismic performance is measured with respect to the engineering demand parameter during a seismic event, as opposed to the conventional factor of safety approach. In the context of PBEE (performance-based earthquake engineering), the seismic demands of systems need to be evaluated accurately. Due to the randomness of earthquake and the many significant uncertainties involved in evaluating a seismic performance, the whole PBD process must follow a probabilistic approach.

Contemporary performance-based earthquake engineering evaluation is typically defined based on the peer performance assessment methodology [3,4]. There are several stages to this process, consisting of quantifying the seismic ground motion hazard, structural response, damage to the building and contents, and resulting consequences. The process is also modular, allowing the stage to be studied and executed independently, and the linked back together as illustrated in Fig. 1. In the peer methodology the intermediate variables are termed intensity measure (IM), engineering demand parameter (EDP), damage measure (DM) and decision variable (DV).

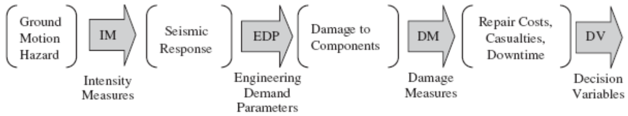

FIG. 1. Schematic illustration of performance-based earthquake engineering.

Significant research over the past decade has focused on determining such IMs for predicting structural response due to earthquake excitation. Such research has investigated the correlation between engineering demand parameters (EDPs) and IMs. For example, the peek ground acceleration (PGA) has been shown to poorly correlate with typical EDPs (e.g. maximum interstory drift, cumulative plastic rotation) in comparison with the damped spectral acceleration (Sa) at the fundamental period of the structure [5]. Alternative measures of ground motion intensity have been investigated, both of vector [6] and scalar form [7]. Recently, the correlation of various IMs with the occurrence of liquefaction in a general soil deposit [8] or optimal intensity measures for the seismic response of pile foundation are investigated [9].

The intensity measure approach is interesting because it allows the analysis stages shown in Fig. 1 to be performed independently. So this study focuses on the intensity measure which links the ground motion hazard with the structural response. In this paper some intensity measures for the seismic response of pile foundations embedded in soil investigated. Nonlinear dynamic analyses of soil-group piles-superstructure model are used to identify relations between engineering demand parameter and intensity measure for pile foundation.

ADOPTED SOIL-GROUP PILES-SUPERSTRUCTURE MODEL

The finite element model was consisted of a two-layer soil deposit with group piles, pile cap and superstructure as shown schematically in Fig. 2. The group piles consist of eleven concrete rounded piles with section diameter of 50 centimeters, length of 15 meters and pile spacing of 1.6 meters. The piles are entirely embedded in soil mass. A cap has been used to make eleven piles connected to each other and its thickness is assumed to be about 2.7 meters with length equal to 18.6 meters.

Considering wave transmission conditions to permit wave propagate inside soil, an optimized dimensions for soil medium around the piles is presumed. As a result, this medium has been modeled with dimensions in global x, y coordinate directions equal to 44.6, 28 meters respectively (Fig. 2).

In this paper, all numerical analyses of model under plane-strain condition are conducted by the general purpose code ABAQUS version 6.8 [10]. As shown in Fig. 2, to perform

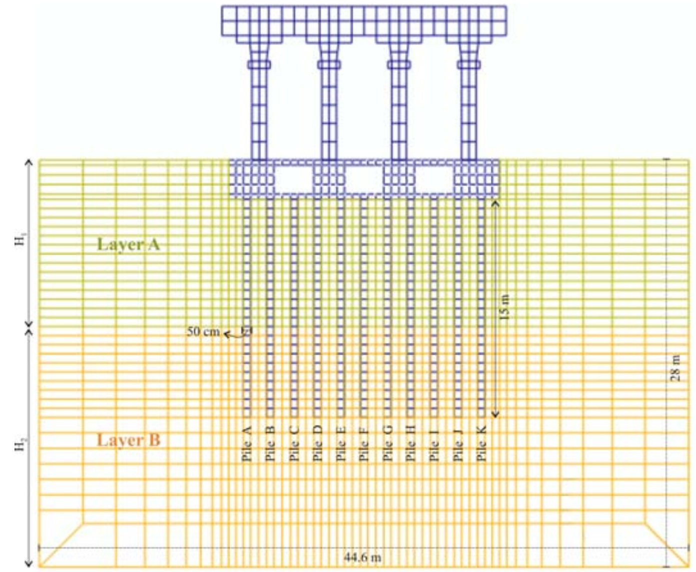

FIG. 2. Soil-group pile-superstructure.

finite element analysis and mesh the whole model, linear quadrilateral elements of type CPE4 were employed. 24, 130, 136 and 1520 elements were used to mesh piles, pile cap, superstructure and soil medium respectively. Due to intensive variations of stress and plasticity features of soil, a finer mesh was used for regions near piles.

In order to have a better prediction of soil behavior under dynamic loading, an elasto-plastic model behavior is assumed to represent both elastic and plastic behavior of soil. An isotropic elastic assumption for soil elastic behavior is considered and to predict soil plastic behavior, a Hardening Drucker-Prager model is presumed. As shown in Fig. 2, the soil profile of the model consists of 2 layers which Es of the very dense bottom layer (namely Layer B) is about 3.5Es of the adjacent upper layer (Layer A). Data obtained from the library of geotechnical software ABAQUS applications are employed [10]. These data characterized the soil stratum at various depth levels. So the essential parameters which required for analysis are presented in table 1.

Concrete damage plasticity (CDP) is one of the possible constitutive models to predict the behavior of concrete in advanced states of loadings. The behavior of concrete material used for piles depends on parameters which are presented in table 2.

Two type of interaction properly have been considered during this research. One is concerned with tangential interaction mechanism between pile circumferential surface and surrounding soil same as pile cap and surrounding soil, another is attributed as axial interaction mechanism which deals with that kind of interaction where happens between pile end and soil around.

Table 1. Soil data using Drucker-Prager model

Soil layer (m)	Elastic properties	Inelastic properties	Hardening behavior	
			Strain	Yield stress (MPa)
Layer A (0 – 11.45)	E = 328 (MPa)	d = 1.38 (MPa)	0.0000	2.75
			0.0200	4.14
	ν = 0.17	β = 36.9°	0.0500	5.51
			0.0900	62.00
Layer B (11.45 – 28)	E = 1121 (MPa)	d = 1.7 (MPa)	0.0000	3.44
			0.0060	4.14
	ν = 0.17	β = 58.5°	0.0120	7.58
			0.0300	67.60

E = Young's modulus, ν = Poisson's ratio,
β = Friction angle, d = Cohesion

PREDICTIONOF SEISMIC EDP AND GROUND MOTIONS

It is well known that the seismic demands on pile foundations arise due to both inertial effects from the superstructure, and kinematic effects imposed by cyclic ground displacements [2]. The vibratory motion in the vicinity of the pile foundation is complex and differs significantly from the free-field motion due to the flexural rigidity of the piles, which causes refraction and scattering of the incident seismic waves. Prediction of seismic demands considering both inertial and kinematic effects requires a rigorous dynamic analysis of a soil-group pile- superstructure system. Observations and experience from recent strong earthquakes have shown that pile foundations are subjected to very large lateral loads leading to serious damage and collapse of piles.

As with any engineering material, the seismic engineering demand parameter on a pile which shows damage measures in pile foundation is generally related to the hysteretic energy released due to inelastic behavior during ground shaking. Hence a key requirement in analysis is estimation of the inelastic response and damage to the piles. A dynamic time-step analysis is used in this research because of accurate prediction of the seismic response and estimation of the inelastic response. It allows modeling of the complex system including both inertial and kinematic effects and also soil non-linearity.

Table 2. Material parameters of CDP model for concrete

Concrete elasticity		Parameters of CDP model	
E (GPa)	26.48	β	15
		m	0.1
ν	0.17	f = fb0/fc	1.16
		γ	0.667
Concrete compression hardening		**Concrete compression damage**	
Stress (MPa)	Crushing strain	Damage C	Crushing strain
24.019	0	0	0
29.208	0.0004	0.1299	0.0004
31.709	0.0008	0.2429	0.0008
32.358	0.0012	0.3412	0.0012
31.768	0.0016	0.4267	0.0016
30.379	0.002	0.5012	0.002
28.507	0.0024	0.566	0.0024
21.907	0.0036	0.714	0.0036
14.897	0.005	0.8243	0.005
2.953	0.01	0.9691	0.01
Concrete tension stiffening		**Concrete tension damage**	
Stress (MPa)	Cracking strain	Damage C	Cracking strain
1.780	0	0	0
1.457	0.0001	0.3	0.0001
1.113	0.0003	0.55	0.0003
0.960	0.0004	0.7	0.0004
0.800	0.0005	0.8	0.0005
0.536	0.0008	0.9	0.0008
0.359	0.001	0.93	0.001
0.161	0.002	0.95	0.002
0.073	0.003	0.97	0.003
0.040	0.005	0.99	0.005

To conduct dynamic analysis, bottom of developed model was subjected to acceleration component scaled to peak ground accelerations between 0.1 to 1g in steps of 0.1g. Thus, using the 3 different ground motion records as input motions in the nonlinear time history analyses, a total of 30 analyses were performed. These records are selected from a suite of ground motion records compiled by Medina and Krawinkler [11]. This suite contains ground motions recorded on stiff soils with magnitude and distance ranges of Mw = 6.5-6.9 and R = 13.3-39.3 km, respectively. The suite is termed 'ordinary' by Medina and Krawinkler, as none of the records show effects of near-fault motions, and all of them were recorded on stiff soils.

ENGINEERING DEMAND PARAMETER INVESTIGATED

Experience from recent strong earthquakes and observations from experiments on piles have shown that pile foundations are subjected to very large lateral loads leading to serious damage and collapse of piles. Hence a key requirement in analysis is estimation of the inelastic response and damage to the pile.

Engineering demand parameters (EDPs) are structural response quantities that can be used to estimate damage to structural and nonstructural components and systems. In the performance-based assessment of structural systems, typically cumulative plastic rotation and peak interstory drift are used as the engineering demand parameters [5,12]. For example, peak response measures such as peak floor acceleration and peak interstory drift have been commonly adopted as the EDP for use in the fragility curve development of structural components [6,7].

Various EDPs can be considered for pile foundation such as peak pile curvature or peak lateral displacement of the pile head [9]. The peak pile curvature would seem the most obvious candidate to use for pile demand, as it directly relates to the peak strains at the critical section of the pile and hence the extent of damage and/or the peak foundation displacement can be used as a proxy for damage to connections and post-earthquake serviceability of relevant lifelines (e.g., electricity and water piping).

It is known that the dissipation energy is directly related to extent of damage. In other word, the higher level of damage results in the higher amount of energy which dissipated during the process of damage. In this regard, maximum damage dissipation energy magnitude (DDEM) was considered as an engineering demand parameter in addition to another EDP (namely peak strain) in this study.

OPTIMAL INTENSITY MEASURES FOR PILE RESPONSE

Significant research over the past decade has focused on determining optimal IMs for peredicting structural response due to earthquake excitation [5,6,7,13]. Since pile foundations involve both kinemaric and inertial effects due to soil and superstructure response, respectively, it is necessary to examine potential IMs and identify the optimal IM for prediction of the pile response. The determination of an optimal IM for prediction of a level of seismic engineering demand parameter is guided by the concepts of 'efficiency' and 'sufficiency' as defined by Shome and Cornell [5].

The term 'Efficiency' gives a measure of correlation of IM with EDP, and is typically measured via the standard deviation of the logarithm of the residuals, $\beta_{\ln EDP \backslash IM}$. The residuals represent the error between the raw data and some trend line from regression. The better efficiency of the IM, the smaller the value of β, which consequently reduces the number of analyses required to estimate the mean demand with a certain level of confidence.

The assumption that structural response depends only upon the IM parameter have been termed as the condition "sufficiency". The term 'Sufficiency' refers to the independence of the residuals, ε, with respect to typical ground motion parameters such as magnitude, source distance and scaling. Therefore, if an IM is sufficient with respect to a given ground motion parameter, there should be no trend in the residual as a function of the ground motion parameter. Such independence is typically quantified by determining the ρ-value which corresponds to the probability that the slope of the regression line through the residual-ground motion parameter is equal to zero [14]. Generally a ρ-value of less than 0.05 indicates that there is evidence that the slope is non-zero and a ρ-value less than 0.01 indicates strong evidence. For example, if an IM is sufficient with respect to magnitude and distance, then consideration of magnitude and distance when predicting EDP will not reduce the uncertainty in prediction of EDP. Sufficiency of an IM with respect to scaling is important since in contemporary PBEE, a suite of ground motion records is typically scaled to a predetermined IM level to assess performance. If an IM is not sufficient to scaling then this indicates that the EDP induced by records scaled to a certain level IM = im, will be biased compared to the EDP induced by un-scaled records with IM = im [15].

It is well known that the destructive potential of a ground motion is dependent on its intensity, frequency content and duration. Different IMs include acceleration-, velocity-, and displacement-based ground motion intensity measures, both of peak and cumulative nature which can be found in Riddell [16]. Thus different ground motion IMs quantifies some or all of these characteristics of the ground motion. For example, peak quantities such as PGA and PGV which are investigated in this study, account for the ground motion intensity only. We used the PGV and PGA as IMs in the analysis because the PGV is a predictable IM (i.e. small scatter in the attenuation relation) due to availability of numerous attenuation equations [8] and the PGA is a conventional intensity measures which used for the most analysis.

RESULTS

Figure 3 illustrates the observed peak strain from the 30 nonlinear analyses for two intensity measures (PGA and PGV). The plots indicate the efficiency of the candidate IMs with the numerical values of β given in Fig. 3. It is apparent that there is a reduced scatter in the relationship between PE and PGV (β = 0.76) as compared to that of PE and PGA (β = 0.83) for pile C as shown in Fig. 3a and 3b. Inspection of the results for pile H shows similar trends as those for pile C. It becomes apparent that PGV has good efficiency (smallest β value) with respect to predicting the Peak strain for some piles. Although this trend was not observed for all piles, but It indicates that it's not enough just using conventional peak ground acceleration as an IM in the analysis for predicting better the seismic performance of pile foundations.

Figure 4 depicts the damage dissipation energy magnitude from all analyses for PGV and PGA. Figures 4a and 4b show the EDP-IM correlation in pile C for two intensity measures. A difference in the scatter between these plots is clearly evident. As illustrated in Fig. 4c and 4d, there is a significantly reduced scatter in the relationship between DDEM and PGV (β = 0.63) as compared to that of DDEM and PGA (β = 0.75). Figures 4a-f all show the efficiency of the acceleration based IM is noticeably less than the velocity based IM. It was found that the PGV is also sufficient with respect to magnitude and source distance.

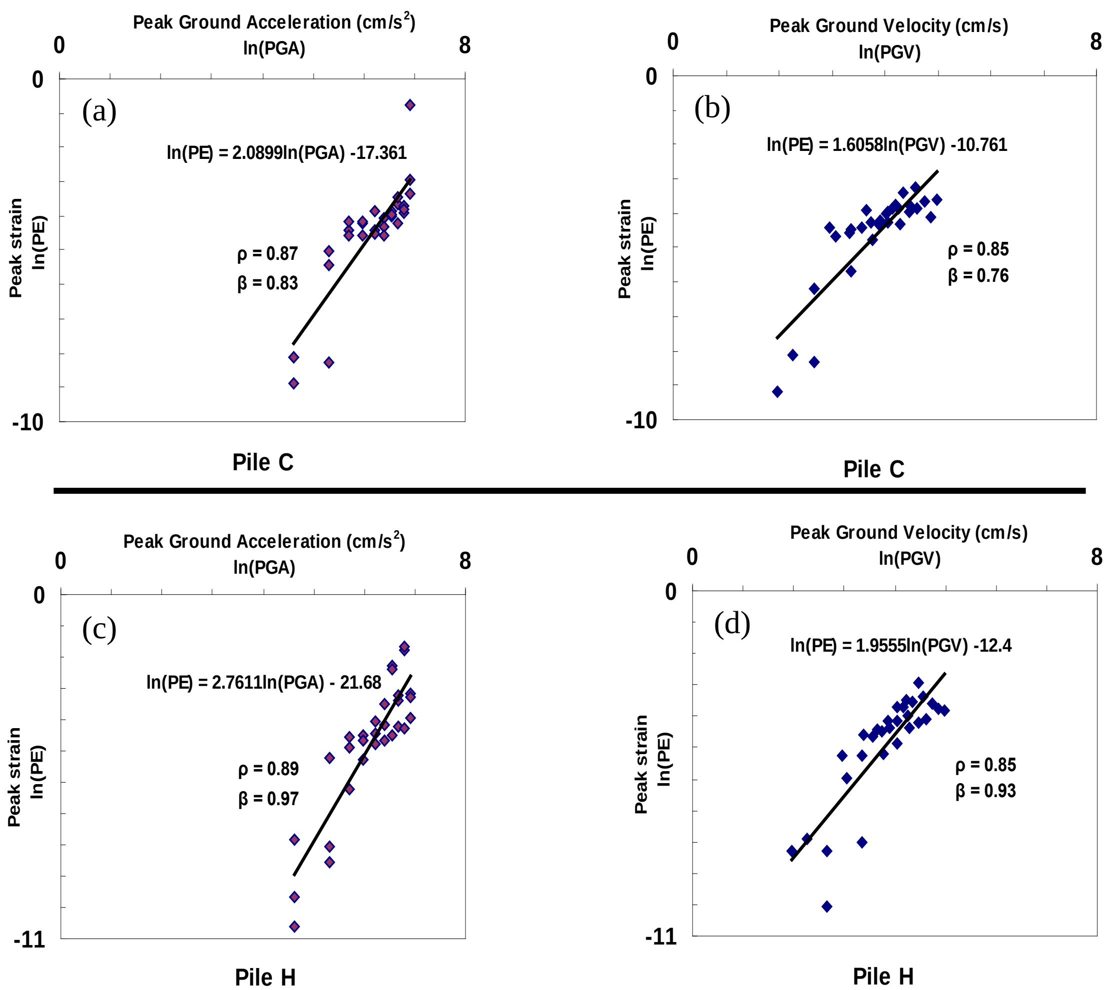

FIG. 3. Comparison of PE-IM scatter plots for: (a)&(b) scatter plot for PGA and PGV for pile C, respectively; (c)&(d) scatter plot for PGA and PGV for pile H, respectively.

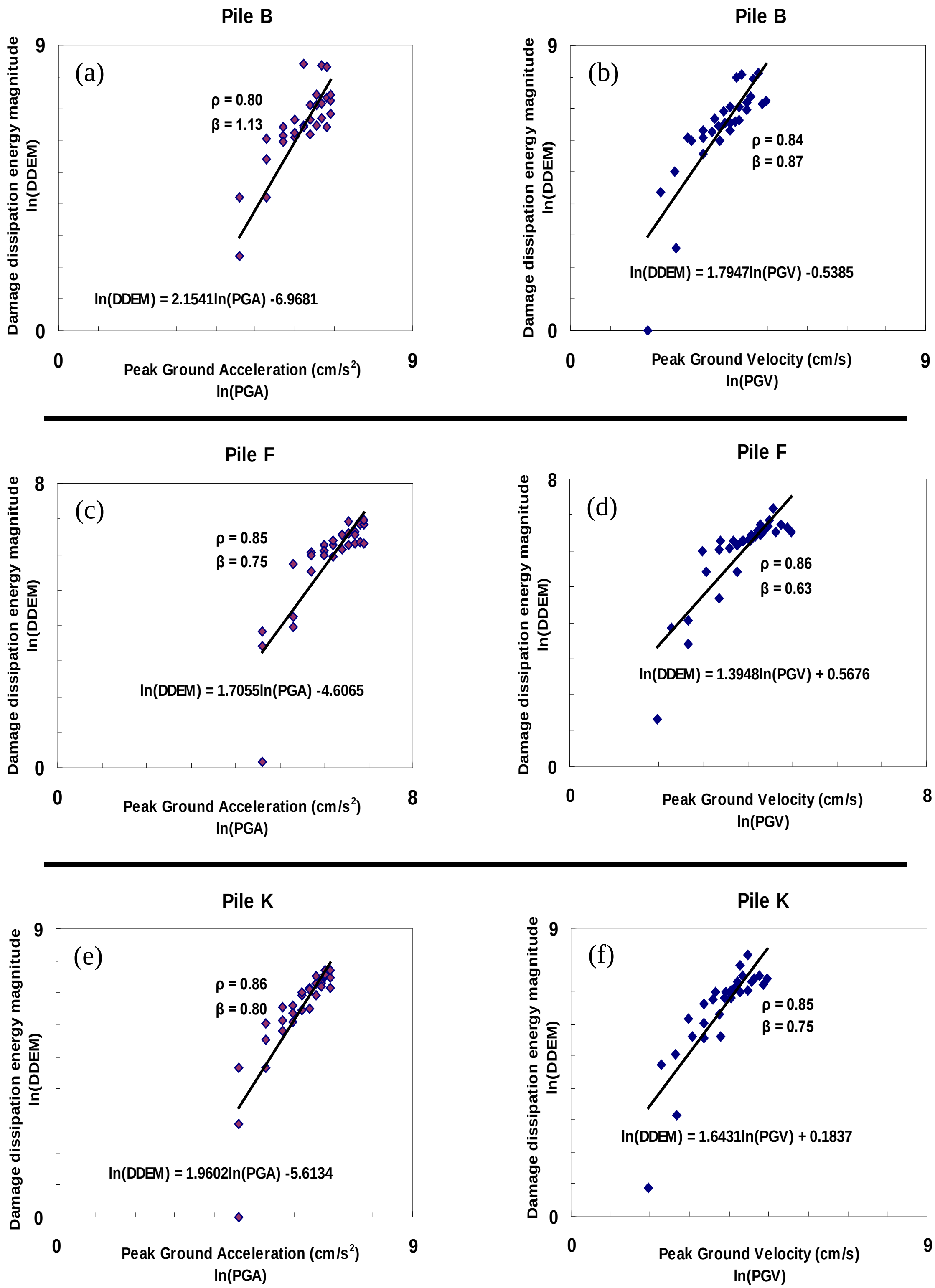

FIG. 4. Comparison of DDEM-IM scatter plots for: (a)&(b) scatter plot for PGA and PGV for pile B, respectively; (C)&(d) scatter plot for PGA and PGV for pile F, respectively; (e)&(f) scatter plot for PGA and PGV for pile K, respectively.

Figure 5 depicts the dispersion values in the prediction of the damage dissipation energy magnitude for the all piles. As shown in this figure, The PGV has good efficiency with respect to predicting the damage dissipation energy magnitude in most of piles. As a result, this intensity measure evaluates better the level of damage to the piles.

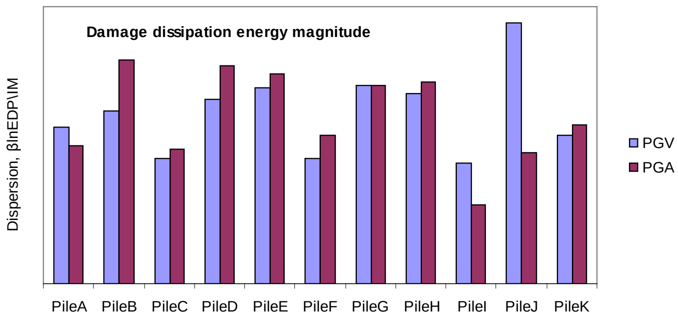

FIG. 5. Efficiency of IMs (PGV and PGA) for DDEM for all piles.

CONCLUSIONS

In this paper, the evaluation of the seismic performance of pile foundation within the Pacific Earthquake Engineering Research (PEER) center framework has been investigated. We have investigated the correlation of ground motion intensity measures (PGV, PGA) with the seismic engineering demand parameter on pile foundation. IMs considered were scalar form. A key requirement in analysis is estimation of the inelastic response and damage to the piles.

The concrete damaged plasticity model (CDP) is primarily intended to provide a general capability for the analysis of concrete structures under cyclic and/or dynamic loading. Damage associated with the failure mechanisms of the concrete (cracking and crushing) results in a reduction in the elastic stiffness. So by using this model, we enable predict the real behavior of concrete piles to study the measure of damage in regard with the failure mechanisms.

Three ground motion records were scaled to peak accelerations ranging from 0.1 to 1.0g resulting in 30 seismic analyses for a given adopted soil-group piles-superstructure model. The rigorous dynamic analysis for the adopted model captures both kinematic and inertial effects from the imposed soil displacement and the vibration of the superstructure respectively. It also considers pile group effects which typically result in significant transient tension and compression effects on piles.

By considering the model it was found that velocity based measures of intensity (PGV) in some piles correlate better with the peak strain as compared to acceleration based measures of intensity (PGA). It indicates that it's not proper just using conventional peak ground acceleration as an IM in the analysis for estimation of damage to the piles. So further research are necessary to study separate quantification on the effects of inertial, kinematic, pile group and foundation rocking to better predict the seismic performance of pile foundation.

It was found that in most of piles, PGV predicted the damage dissipation energy magnitude (DDEM) with the lowest uncertainty (highest efficiency) as compared to PGA. In addition to PGV being efficient, it was found that it is also sufficient with respect to magnitude and source distance. As a result, the peak ground velocity as a proper IM could predict the seismic performance and inelastic response of piles and also better estimate damage to the piles. Further studies to investigate the effectiveness of the different IMs and EDPs for pile groups and capture cross-interaction effects on the response on the whole system are necessary.

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