On Seismic Performance and Load Capacities for Pile Design

A propos des performances sismiques et les capacités de charge pour la conception de pieux

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ABSTRACT: This paper suggests alternative seismic design procedures using probability analysis and wave equation solutions. The assessments of an existing pile foundation and a new design is suggested by checking up the maximum moment of the pile with the moment capacities for the seismicity of interest. The pile displacements correspondent to the moment capacities can be found and used as the allowable pile displacements. For a preliminary investigation on seismic design of the pile foundations in an engineering project, one can establish a monographic procedure considering both load capacities and seismic performance of the piles. The design could be carefully verified through a good use of the monographs.

RÉSUMÉ: Cet article suggère des procédures alternatives de conceptions sismiques utilisant l'analyse de probabilité et des solutions d'équations d'ondes. Les évaluations d'une fondation sur pieux existante et une nouvelle conception sont proposées en vérifiant le moment maximum du pieu avec la capacité de moment pour la sismicité d'intérêt. Les déplacements de pieux correspondants aux capacités de moment peuvent être trouvés et utilisés comme les déplacements de pieux admissibles. Pour une enquête préliminaire sur la conception sismique de fondations sur pieux dans un projet d'ingénierie, on peut établir une procédure monographique en tenant compte et des capacités de charge et des performances sismiques des pieux. La conception pourrait être soigneusement vérifiée par une bonne utilisation des monographies.

KEYWORDS: seismic performance, load capacity, pile design

1. INTRODUCTION

Performance Based Design (PBD) has received considerable attentions from geotechnical society in the past decade. For pile foundations, the design procedure needs statistical investigations on bearing resistances and deformations of the piles. Possible changing of the loads and the material parameters are often considered. In addition, the uncertainties of the methods for calculations, laboratory and/or in-situ measurements, and the type of construction may also be included. For piles susceptible to the earthquake impacts, seismic performance of the piles ought to be analyzed carefully. Since the dynamic strength parameters of the soils were often found large than the static ones, the study on seismic effects to pile capacities are generally fucusing on soil liquefaction. For example, the soil parameter reduction coefficient, DE (JRA, 1996) can be used to reduce the soil strength and/or the soil stiffness for liquefaction occurred due earthquake excitations. In general, pseudo-static superstructural loads are carried in the seismic design for pile capacities. According to the suggestion of Honjo *et al.* (2002), PBD analysis can be made by LRFD method and reliability analysis as well as probability analysis. While the first two methods were used by many investigators in studying the static performances of pile foundations, a probability method named as PBEE (Performance Based Earthquake Engineering) analysis, suggested by US Pacific Earthquake Engineering Research Center, has been adopted by Kramer (2008), Bradley *et al.* (2008) and Chang *et al.* (2009, 2010) to investigate the seismic performance of bridge pile foundations. For design practice, the seismic performance of piles can be monitored using pseudo-static or dynamic analysis. While the former is easier to conduct, the latter requires much longer time of computations, especially for FEM analysis. Therefore an effective but rather fast solution is desired. Such analysis is now available by Chang *et al* (2006, 2008) as EQWEAP solving the free-field ground responses (w/ the lumped mass analysis) and using them to obtain the corresponding pile displacements out of the discrete wave equations. In this paper, the possible connections between the seismic performance and the calculated bearing capacities of the piles are discussed based on the simplified modeling.

2. PERFORMANCE BASED EARTHQUAKE ENGINEERING ANALYSIS

An excellent overview of the PBEE analysis can be found in Kramer (2008). The so called Framing equation declares that the annual rate of exceednace (λ) of a decision variable (DV) for any engineering project can be analyzed as a triple-integral based on those consequent probabilities from the intensity measured (IM), the engineering demand parameter (EDP) and the damage measure (DM). The integral can be decomposed to solve for the rate of exceednace for IM, EDP and DM, respectively. Based on rational simplifications, analytical equations were suggested to compute the corresponding probabilities of these indices at different seismic levels. For instance, the seismic design code in Taiwan requires that the structures need to be analyzed at moderate earthquake, design earthquake and the maximum consideration earthquake, which implies that within a 50 yrs design life, the corresponding probabilities of occurrence of these quakes are 80%, 10% and 2%, and the return periods are 30, 475 and 2500 years, respectively. With the local hazard curves (λ vs PGA, see Figure 1) suggested by Cheng (2002), one can find the corresponding PGAs at different seismic levels, ex, the ones in Taipei are found to be 0.12g, 0.29g and 0.51g, respectively.

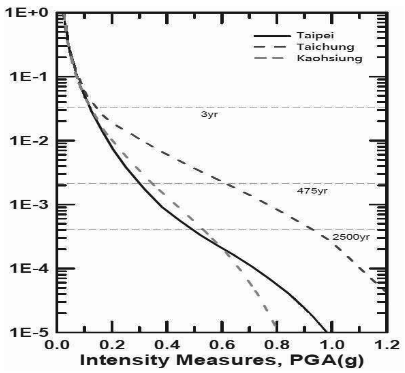

Figure 1. Seismic hazard curves in Taiwan (after Cheng, 2002)

These PGAs are the design target PGA (PGAt), one can use these PGAs to calibrate the possible seismic records in hand. The calibrated seismic records can be regarded as scenarios for numerical studies. For any specific pile foundation located in Taipei metropolitan, the vertical load (V), horizontal load (H), pile diameter (D), pile length (L) and the area ratio of steer bar (Ar) are known from the regular design. The site conditions are also acknowledged from the previous work of site investigation. A simplified ground conditions can be thus assumed. Notwithstanding, the soil parameters in use must be calibrated carefully. For example, the solution of EQWEAP adopts empirical formulations suggested for soils in Taipei. The shear wave velocities (Vs) of the soils can be correlated to the in-situ SPT-N values. Moreover, all the model parameters used in the stress analysis must be calibrated with cautions. The nonlinear soil model used in EQWEAP are those suggested by Finn et al. (1977), Seed and Idriss (1982) and Skempton (1986). One can use such analysis to compute the pile responses under the scenarios. The maximum pile displacement occurred during the quake will be taken as the EDP index, and the maximum internal bending moments occurred along the pile will be used as the DM index. Using the schemes suggested by Kramer (2008), one can find the annual rates of exceedance to both EDPs and DMs under different PGAt. Nonlinearities of the piles can be modeled through a tri-linear relationship of the bending moment and curvature of the pile (see Figure 2). An approximate Bouc-Wen model suggested by Kunnath and Reinhorn (1989) was considered. The model parameters α and Z were solved easily by interpreting the moment capacities and the associated curvatures obtained from LPILE analysis (Sung, 2012).

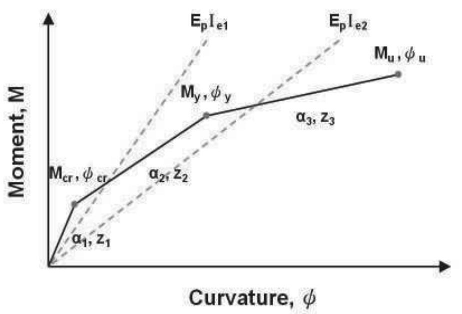

Figure 2. Approximation of the tri-linear moment-curvature relationships for concrete pile

Table 1 presents the information and model parameters of a numerical study using EQWEAP for bridge pile foundations of an expressway in Hsinchuang District, New Taipei City. Figures 3a,b shows the results of the maximum pile displacements versus PGAt and the corresponding annual rates of exceedance versus maximum pile displacements. Figures 4a,b shows the ones of the maximum pile bending moments versus the maximum pile displacements and the corresponding annual rates of exceedance versus maximum bending moments. It can found that the maximum pile displacements of the numerical model under the seismic levels are 19, 45 and 79 cm, respectively. The corresponding maximum pile moments found at the pile head are 7347, 22148 and 28679 kN-m. Comparing to the moment capacities (i.e., Mcr, My and Mult) obtained from the LPILE analysis, the numerical piles will have concrete cracks occurred under the moderate earthquakes (however most of the pile shaft still remains elastic). For design earthquake, the piles are found to be within the yield limit of the bar. As to the maximum consideration earthquake, the plastic hinge will not be generated in this case. A corresponding design scheme is suggested in Figure 5 whereas the zone of the dash lines is an option in which one can determine the allowable pile displacements according to the moment capacities for different seismic concerns.

Table 1 Geotechnical information of numerical model in this study

Depth (m)	Layers	Soil	γ (kN/m^3)	SPT -N	C (kN/m^2)	ϕ (°)	Vs (m/s)
0~4	Surface fill	Sand	18	3	9.8	30	115
4~10	SS form. VI	CM	19	5	9.8	28	171
10~20	SS form. V	SM	20	14	0	33	192
20~40	SS form. IV	CM	20	11	20	28	222
40~50	SS form. III	SM	20	21	0	34	221
50~60	SS form. II	CM	20	14	20	35	241
60~70	SS form. I	SM	20	30	0	30	248

Table 2 Material parameters and structural dimensions in use

Parameters and dimensions of piles		
Bridge pile foundation 3×3 piles Pile diameter: 2m, Pile length: 60m Design vertical loads: Ordinary 9000 kN, Seismic 18000 kN, Horizontal load = 10~15% vertical load、Maximum steel bar Ar = 2% E=30 MN/m^2、ν= 0.15、γ=24 kN/m^3		
Model parameters used for soils		
Approach	Method/model parameter	Spring and damper
EPWP	Finn's EPWP model where C_1=0.8, C_2=0.79, C_3=0.45, C_4=0.73; R = 0.00031(100-Dr)^2 + 0.0062; m=0.43, n = 0.62, k_2 = 0.0028; Seed and Idriss's model of G/G_{max} where $K_{2,max}$ = f(Dr); and Skempton's equation where Dr (%) = $f(N_{1,60})$	Spring: $K_s = n_h x$; empirical relationships of SPT-N and n_h could be found in Johnson and Kavanagh (1968) Damper: Transformed damping (Chang and Yeh, 1999)

NOTE: V_s=80N^1/3 for sand, V_s=100N^1/3 for clayey soils.

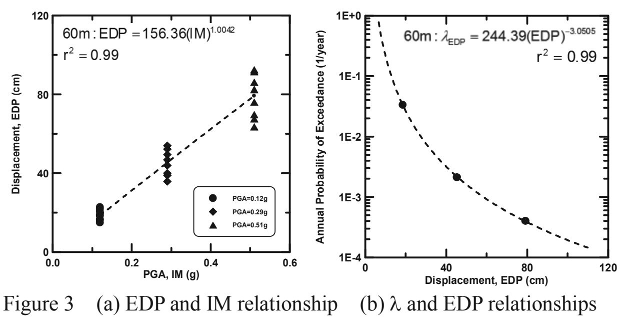

Figure 3 (a) EDP and IM relationship (b) λ and EDP relationships

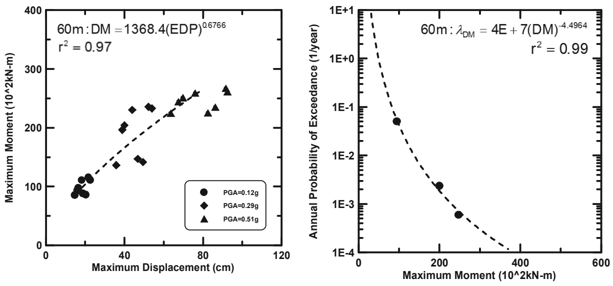

Figure 4 (a) DM and EDP relationship (b) λ and DM relationships

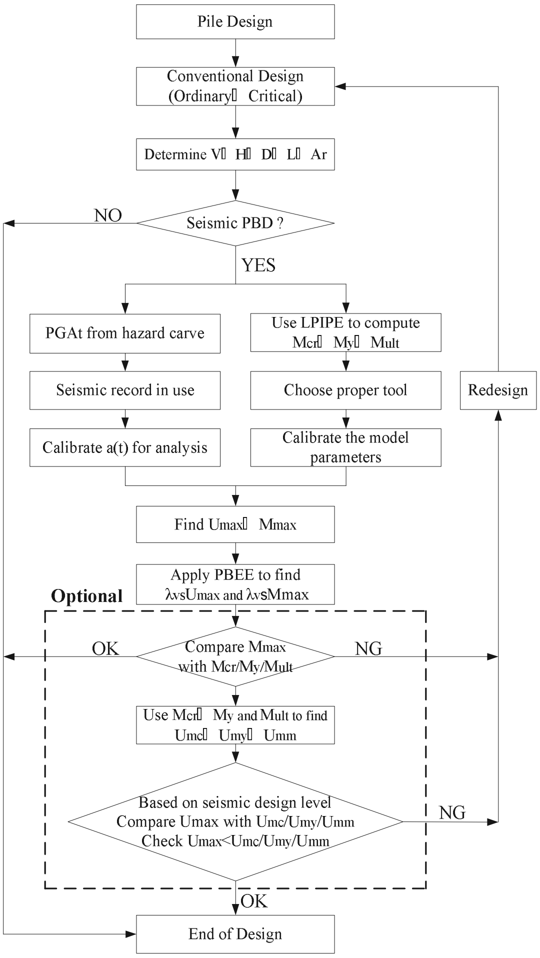

Figure 5 Scheme of seismic PBD for piles suggested

3. LOAD CAPACITIES FROM APILE AND LPILE ANALYSIS

In order to find out the capacities of the numerical piles, APILE and LPILE programs (Ensoft, Inc.) were adopted in this study. The axial and lateral capacities of the piles were analyzed respectively. With the presumed soil parameters and appropriate soil models of *t-z*, *Q-z* and *P-y* relationships (see Table 1, the monotonic load-displacement curves of the piles were computed. A variety of methods can be used to interpret the axial and lateral capacities of the pile. Based on the local experiences, the vertical pile capacity was interpreted using the methods suggested by AASHTO (2002), Fuller and Hoy (1970) and Chin (1970), whereas the lateral pile capacity was interpreted by the methods of McNulty (1956), Pyke (1984) and Manoliu et al. (1985). Table 3 summarizes the results obtained from the study. It can be seen for the axial capacity, the order of predictions is such that Chin>F&H>AASHTO. For the lateral capacity, the order is Manoliu>Pyke>McNulty. One must know that these predictions are only used for preliminary design investigations. To ensure that the calculations are appropriate compared to the real conditions, pile load tests and/or other types of in-situ testing techniques for pile capacities must be performed. As mentioned in above paragraph, LPILE can be used to reveal the moment capacity of the pile. Figure 6 depict the moments for a concrete pile to crack (Mcr) and the corresponding curvatures of the pile under the influences of pile diameter and axial load, presuming that the area ratio of the steel bar Ar is 2%. One can find similar results for My and Mult. The pile diameter and the area ratio of the steel bar will significantly affect the moment capacities. One can find the observations in Figure 7. Moreover by changing the pile diameters and fixing other design parameters, the maximum pile bending moments exerted on the piles can be found at different seismic PGAt. Figure 8 shows the result obtained from EQWEAP using the record at one of the seismic stations. This calculation can be expanded by using many seismic records as well. In that case, the final results would be more representative to the seismic design for piles. With a series of calculations on piles of a certain length, the engineer can establish a set of monographs for design purpose. Figure 9 suggests the procedures to be taken. A satisfactory design requires that any mobilized maximum bending moment of the pile to be less than the moment capacities at the seismic levels of interest. In the monographs, the stop of the arrow lines must in the shaded regions to satisfy the design requirements.

Table 3 Pile capacities from various interpretations

Vertical capacities (kN)							
Method\D	0.5m	0.75m	1m	1.25m	1.5m	1.75m	2m
AASHTO	1500	3000	4800	6650	8550	10800	13350
Fuller and Hoy	5200	9400	14000	17600	23950	29500	35400
Chin	6501	9867	15078	20509	28692	34550	43546
Lateral capacities (kN)							
Method\D	0.5m	0.75m	1m	1.25m	1.5m	1.75m	2m
McNulty	140	220	340	500	680	880	1140
Pyke	250	500	900	1600	2750	3800	5200
Manoliu, *et al.*	340	785	1399	2228	3306	4800	6598

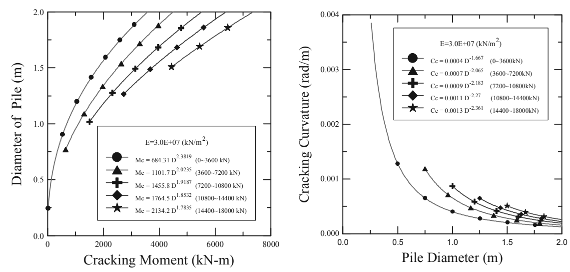

Figure 6 Effects of pile diameter and vertical load on Mcr

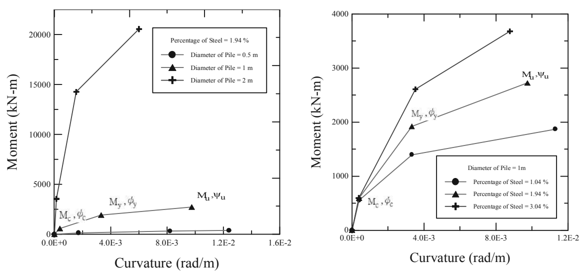

Figure 7 Effects of pile diameter and Ar on moment capacities

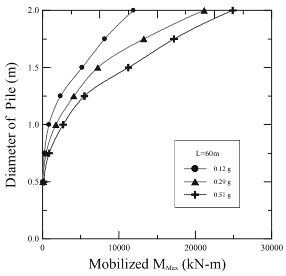

Figure 8 Maximum moments of piles varying pile diameter and PGAt

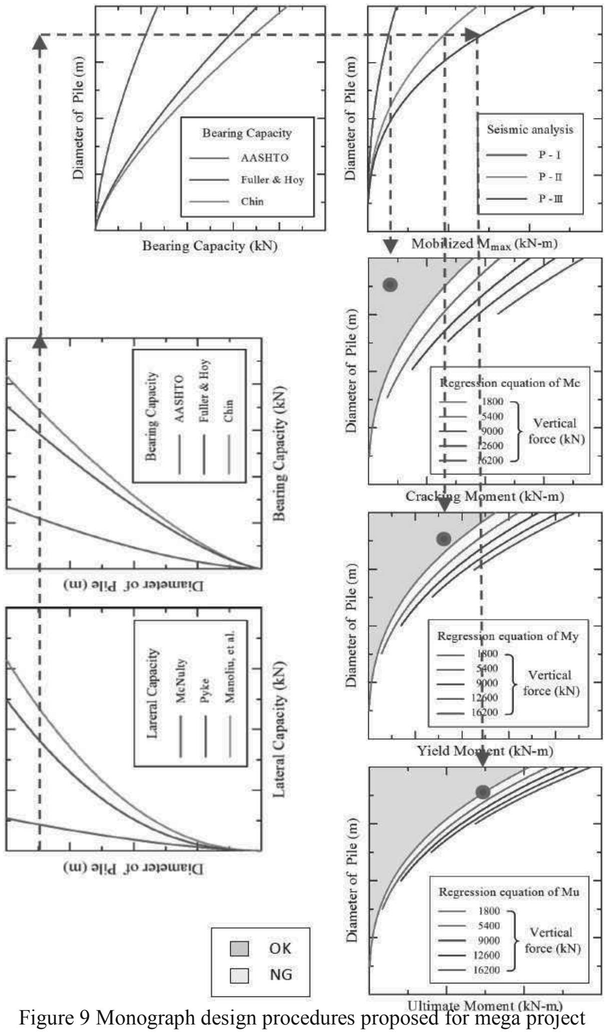

Figure 9 Monograph design procedures proposed for mega project

4. CONCLUDING REMARKS

Seismic performances of the piles on numerical models were studied in this paper using probability analysis and solutions from discrete wave equations. For the assessments on existing pile foundations and/or a new design case, rational procedure is suggested based on the regular design. The maximum bending moments of the piles occurred during the quakes can be compared to the moment capacities in order to validate the design. The pile displacements associated with the moment capacities can be treated as the allowable displacements. If a preliminary design investigation is desired, the engineers can establish a series of monographs beforehand for piles with required length. The pile diameter, the area ratio of steer bar and the axial loads are the variables. The possible influences of these design variables on both axial and lateral load capacities and the moment capacities of the pile can be found, and the monographs showing their influences can be later on used to pick up the pile diameter. Such monographs can be simply used to fulfill the design with concerns on seismic performance and load capacities of the piles.

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