Comparative Study on EQWEAP Analysis with 2D/3D FE Solutions

Étude comparative sur l'analyse EQWEAP avec des solutions 2D/3D FE

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ABSTRACT: The seismic responses of the piles using one-dimensional wave equation analysis EQWEAP are compared to the ones from 2D and 3D finite element analyses based on PLAXIS and MIDAS GTS programs. It is found that the solutions of 1D wave equation analysis are compatible to those from finite element analyses providing that the site conditions and structural geometry are relatively simple. Moreover, pile deformations are found mainly governed by the ground motions at the same direction. The effects of ground motions at different directions are rarely important to the pile displacements. These observations suggest that the one-dimensional EQWEAP analysis is an applicable tool in estimating the seismic responses of piles under the earthquake.

RÉSUMÉ: Les réponses sismiques des pieux en utilisant une analyse EQWEAP d'onde d'équation unidimensionnelle sont comparées à celles des analyses 2D et 3D par éléments finis basés sur des programmes PLAXIS et MIDAS GTS. On retrouve que les solutions des analyses d'équations d'ondes 1D sont compatibles avec celles des analyses par éléments finis pour autant que les conditions du site et la géométrie structurelle soient relativement simples. De plus, des déformations de pieux se retrouvent principalement régies par des mouvements du sol dans la même direction. Les effets de mouvements de sol dans des directions différentes ne sont que rarement importants pour les déplacements de pieux. Ces observations suggèrent que l'analyse unidimensionnelle EQWEAP est un outil utilisable dans l'estimation des réponses sismiques des pieux sous le tremblement de terre.

KEYWORDS: seismic analysis, pile, wave equation analysis, finite element analysis

1 INTRODUCTION

One-dimensional wave equation analysis can be used to monitor the time-dependent dynamic responses of piles under earthquake. An uncoupled analysis termed as EQWEAP models the seismic ground motions from lumped mass analysis, and superimposing the ground motions to the piles via the discrete wave analysis has been proposed (Chang *et al.,* 2006, 2008, 2009a and 2012). Alternative models can be used for soils with liquefaction potential. The available ones including the use of soil parameter reduction coefficient (SPRC), the excess pore water pressure (EPWP) and the pseudo dynamic earth pressures obtained by modifying the permanent/cyclic displacement profiles (Tokimatsu and Asaka, 1998) or the maximum earth pressures (Japan Road Association, 1990). Such modeling is rather convenient for massive computations required in performance based design of piles. The authors have demonstrated a couple of case studies on bridge pile foundations using such analysis with probability analysis (Chang *et al*, 2010 2013a,b). This study intends to verify the 1D wave equation analysis with the 2D/3D FE analyses. The comparative studies were conducted using PLAXIS and MIDAS GTS programs.

2 1D WAVE EQUATION ANALYSIS EQWEAP

To model the seismic responses of the piles, the EQWEAP analysis has been suggested for years (Chang *et al*., 2001, 2008 and 2009). To obtain the solutions, free-field ground responses due to the earthquake was calculated first. A simple lumped mass analysis on horizontal layered soils was adopted to obtain the ground responses due the earthquake. The soil displacements were then applied to the discrete wave equations with the expressions of finite difference schemes. Figure 1 illustrates the discrete pile segments and the equilibrium to derive the wave equations. For large earthquake excitations whereas the ground soils are liquefiable, the so-called soil parameter reduction coefficient (JRA, 1996) could be used. Alternatively, more rigorous solutions were achieved using the excess pore water pressure (EPWP) model. The generations and dissipations of the excess pore water pressures can be simulated by using proper soil models. Once the ground responses were resolved, one could choose the *P-y* and *t-z* soil models and other types of empirical formulations to model the soil stiffness and strength parameters for the wave equation analysis. Some people use the cylindrical wave propagation theory to calculate for the elastic/inelastic soil stiffness. The model parameters must be calibrated carefully in order to obtain rational results of the simulations. In addition, a transformed radiation damping model (Chang *et al*, 2000) was used to compute time-dependent damping of the soils. In such analysis, a good control of the superstructural loads is important. The structural loads and inertia force of the pile cap as well as the lateral earth pressures on the cap were analyzed properly, and then applied to the piles. The seismic responses of a single pile can be predicted using the time-dependent ground motions. In the seismic impacts, the pile-to-pile interaction effects could be ignored (Chang *et al*., 2009b). Such analysis can serve as a fast and rational design tool for the seismic performance of piles (Chang *et al*, 2010).

3 2D AND 3D FE ANALYSES FOR COMPARISONS

Finite element (FE) analysis has been extensively used to model the dynamic pile foundation behaviors due to mechanical and seismic loads since 1960s. The seismic responses of the pile

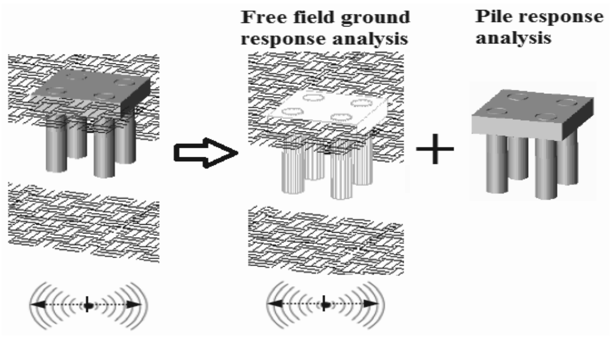

Figure 1. Schematic layout of EQWEAP analysis

foundation can be modeled closely by three-dimensional FE analysis. The geometric conditions of the site and the structure can be captured in details by a 3D FE modeling. The concerns of the loadings interfered with the shape of the structure are sometimes very important to the analysis. For example, if a torque is applied to the pile foundation where the pile cap has irregular shape and/or the piles are not in symmetric orientation, the 3D FE analysis will provide the most appropriate solution for sure. For simplicity of applications, 2D FE analysis has been frequently conducted for pile foundations. In both analyses, one needs to be cautioned about the sizes of the mesh and the elements in use. The type of element sometimes is also important, especially for nonlinear problems and time-domain analysis using explicit integration scheme. The solutions need to be checked to ensure their stability. In this study, the 2D PLAXIS program and 3D MIDAS GTS program are respectively used to simulate the pile responses. Both programs are well known civil engineering software and have been used in many studies and projects. Detailed introduction of these programs can be found in Wang (2012). One shortcoming of using these programs is that the pile nonlinearities are unable to model properly through the use of beam elements or the isoparametric plane/solid elements in the packages. Nonlinearities of the concrete structure need to be enhanced in these programs.

4 COMPARATIVE STUDIES ON NUMERICAL MODELS

A bridge pile foundation of an expressway in Hsinchuang District in New Taipei City, Taiwan was studied by EQWEAP, PLAXIS and MIDAS GTS analyses. Table 1 depicts the geological conditions and the properties and parameters of the soils at the site. Table 2 presents the soil models and model parameters used in each analysis. Acceleration time histories of 1999 Chi-Chi earthquake (M=7.3 and local intensity of IV) at a near-by seismic station TAP017 were used to simulate the seismic responses of the model piles. Studies were made for following tasks, 1. Linear analysis for piles located in elastic homogeneous layers. 2. Nonlinear analysis for piles in inelastic homogeneous layers. 3. Nonlinear analysis for piles in inelastic interlayer. 4. Effects of the seismic intensity. 5. Effects of the seismic excitations from other directions. Due the linearity of the pile elements used in PLAXIS and MIDAS GTS programs, the numerical studies were made assuming that the pile remain in linear elasticity. For homogeneous layer system, an averaged shear velocity of the soils was computed using the equivalent travel-time method. The original shear wave velocity of the soil can be obtained by empirical formulations with SPT-N values. Figure 2 and Figure 4 show the numerical models used for PLAXIS and the verifications of the solutions by varying the width of the analytical mesh. Figure 3 and Figure 5 show the numerical models used for MIDAS and the verifications of the solutions by varying the width of the analytical mesh. Figure 6 depicts the maximum pile displacements occurred along the piles at the five tasks and Figures 7~11 present the pile displacement time histories recorded at different locations. It can be seen that the maximum pile displacements and the displacement time histories from these analyses are very similar with each other. Table 3 indicates the computation time used in each analysis and their ratios via the computer in use.

Table 1 Geotechnical information of numerical model in this study

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

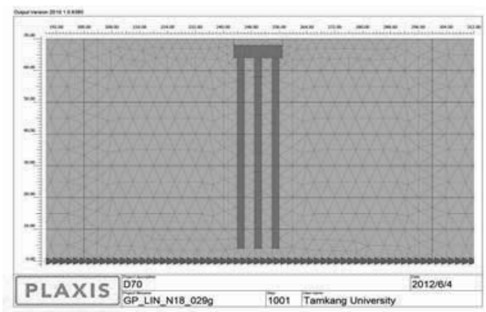

Figure 2. Discrete mesh used in 2D PLAXIS analysis

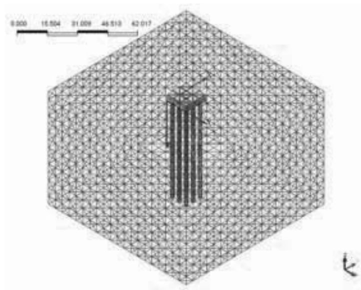

Figure 3. Discrete mesh used for 3D MIDAS GTS analysis

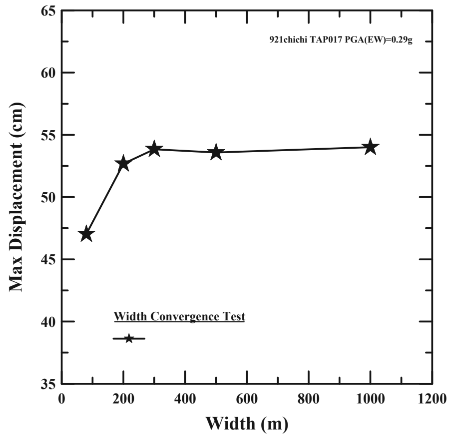

Figure 4. Influences of the analytical mesh used in PLAXIS

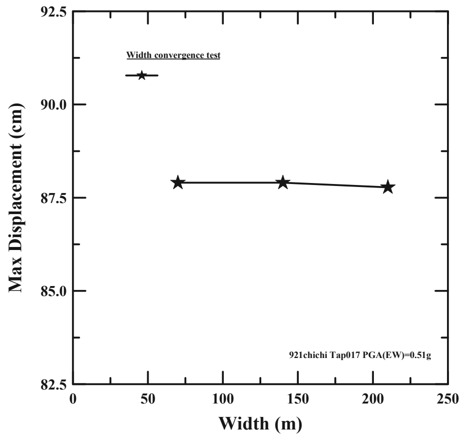

Figure 5. Influences of the analytical mesh used in PLAXIS

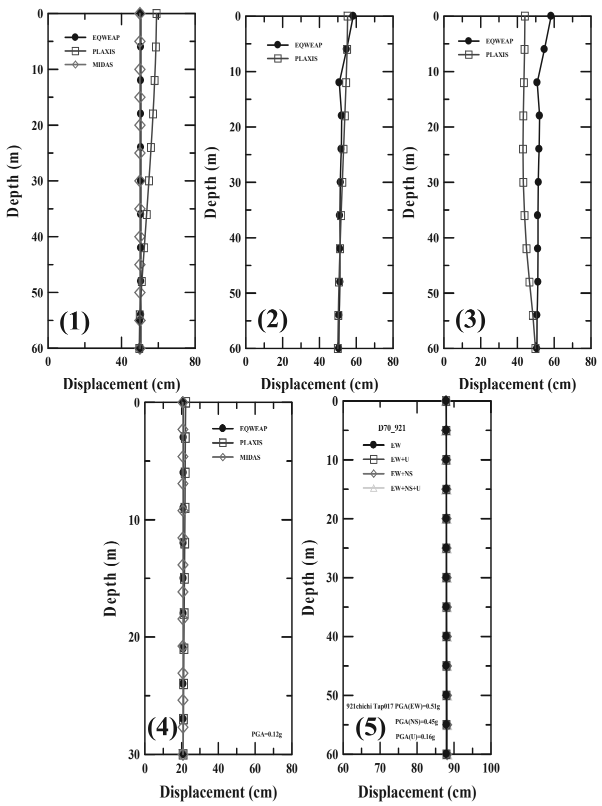

Figure 6. Maximum pile displacements obtained from the analyses for tasks No.1~No.5

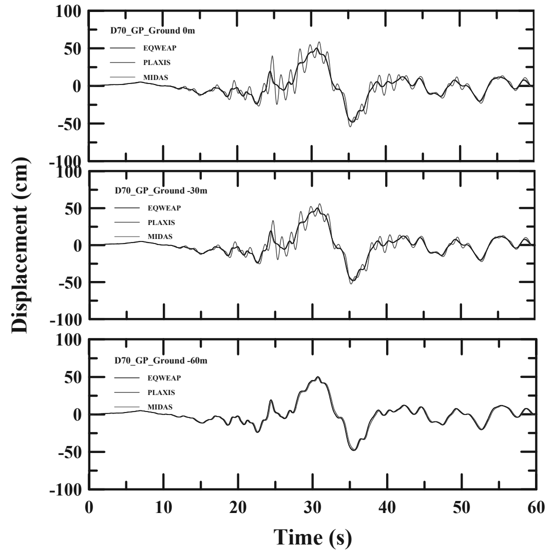

Figure 7. Pile displacement time- history for No.1 case study

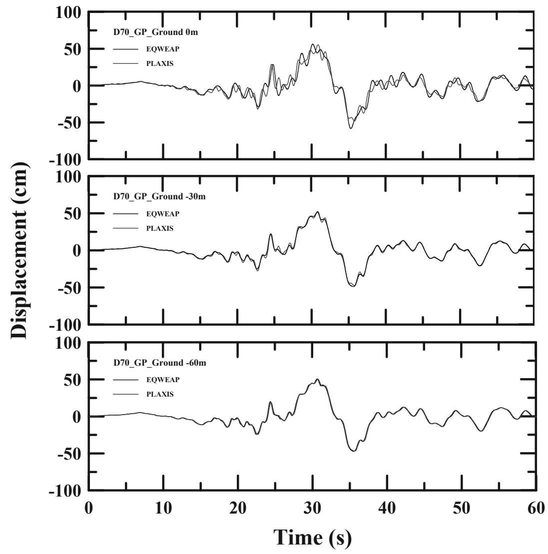

Figure 8. Pile displacement time-history for No.2 case study

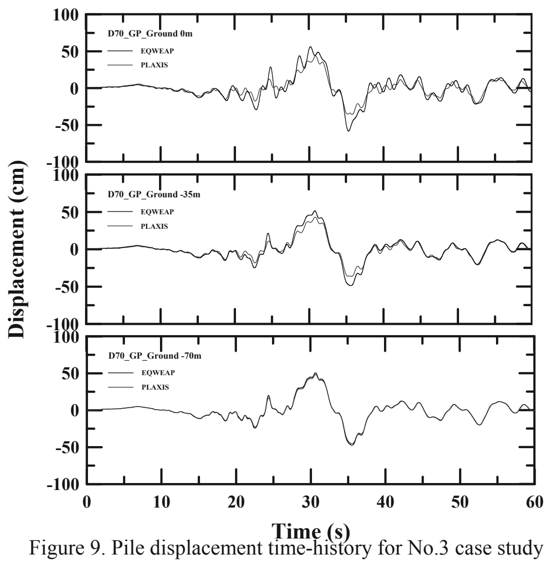

Figure 9. Pile displacement time-history for No.3 case study

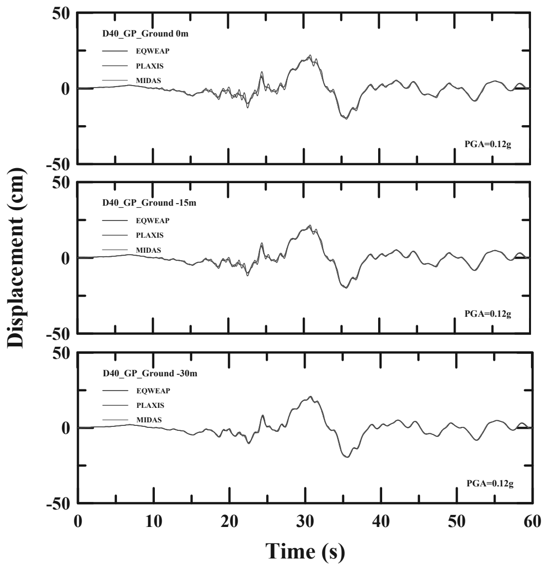

Figure 10. Pile displacement time-history for No.4 case study

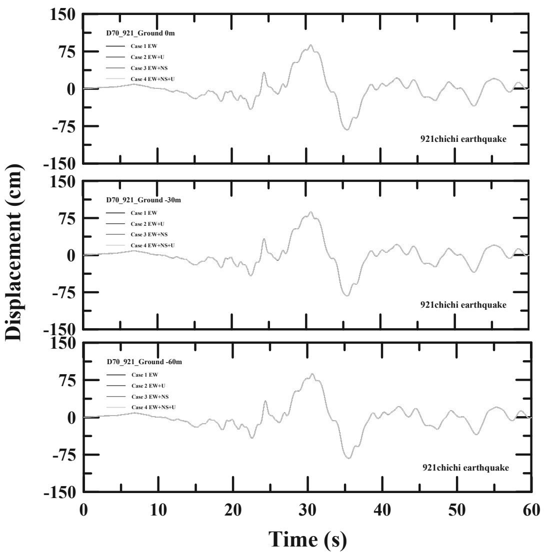

Figure 11. Pile displacement time-history for No.5 case study

Table 3 Comparisons on time required in various analyses

	EQWEAP	PLAXIS	MIDAS/GTS
case	free field		
node numbers	14	≒1600	≒2000
time	≒3 min	≒15 min	≒60 min
time ratio	≒1 : 5 : 12		
case	piles		
node numbers	11	≒6000	≒5500
time	≒5 min	≒45 min	≒150 min
time ratio	≒1 : 9 : 30		
platform	CPU	RAM	OS
	AMD X2 250 3.00 GHz	4.00GB	Windows 7

5 CONCLUDING REMARKS

This paper discusses the numerical solutions for seismic responses of the piles from one-dimensional wave equation analysis EQWEAP with those from two- and three-dimensional finite element analyses using PLAXIS and MIDAS GTS programs. Linear and nonlinear solutions were both checked for a homogeneous soil system, whereas the nonlinear solutions were verified for the interlayer system. It was concluded that the solutions from these analyses are agreeable at a variety of seismic intensities. In addition, the pile displacements were found nearly independent with the seismic excitations at other directions. Therefore it is concluded that the one-dimensional analysis can provide rational solutions to the seismic responses of the piles while it requires much less time for computations.

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