A simplified analysis of mega strip foundation on piles subjected to horizontal earthquake

Une analyse simplifiée de la bande de fondation méga sur pilotis soumis au tremblement de terre horizontal

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ABSTRACT: A simplified analysis for seismic responses of mega strip foundation on piles under the horizontal earthquake excitationis suggested in this study. Ignoring vertical, rocking and torsional motions, one dimensional wave equation for horizontal structural responses of the strip foundation is solved using the finite difference formulas. The forces resulted from the superstructure, the piles and the soils are modeled using appropriate springs. The proposed solution was found agreeable with the three dimensional finite element analysis and its computational time is much less to provide efficiency in the preliminary design stage.

RÉSUMÉ : Une analyse simplifiée pour les résponses sismiques de méga fondation filante sur pieux sous les excitations du séisme horizontal suggérées dans cette étude. En ignorant les mouvements verticaux, basculants et de torsion, une équation d'onde dimentionnelle des réponses structurales horizontales de la fondation filante est résolu en utilisant des formules de différence finie. Les forces résultent de la superstructure, les pieux et les sols sont modélisés en utilisant des ressots appropriés. Avec l'analyse de méthode des éléments finis tridimensionnels et la réduction de son temps de calcul qui fournit l'efficacité dans la phase de conception préliminaire, la solution proposée était considérée acceptable.

KEYWORDS: strip foundation, piles, seismic responses, horizontal earthquake.

1 INTRODUCTION

The methods used in design and analysis of piled raft foundation have been suggested for years (Poulos, 1991 and 2001; Clancy and Randolph, 1993; Katzenbach, 1993; Randolph, 1994; Yamashita *et al.*, 1994; Horikoshi and Randolph, 1996; Kobayashi *et al.*, 2009). They were categorized as, 1. simplified calculation methods, 2. approxima computer-based methods, and 3. rigorous computer-based methods. All these methods can provide rational solutions to different levels of design requirements.

At modern time, three dimensional (3D) FEM analysis is the most rigorous approach. The approximate numerical analysis can provide effective solutions as well. Since the computation time of such type solution is much less than the 3D FEM analysis, the approximate computer-based method could provide a useful tool to the performance based design (PBD), in which a large amount of computations can be carried out on the variability of the design parameters. A series of study (Kitiyodom and Matsumoto, 2002; Kitiyodom *et al.*, 2005) on 3D approximate computer-based methods has been suggested for static and dynamic analyses of piled raft foundation. These analyses were conducted solving the equations of motion at the nodes of the discrete raft. The piles and soils connecting to the slab were modeled by springs and dashpots. These analyses are applicable to the piled raft foundation where the loads are mounted on top of the foundation. For seismic responses of the foundation due the ground excitations, advanced solutions need to be made.

Therefore a simplified modeling on the horizontal seismic responses of piled raft foundation was suggested (Chang *et al.*, 2016^{a}). The approximate analysis was suggested solving the differential equation derived from the force equilibrium of the raft with the central difference formulas. The transmitting loads from the underneath soil-pile elements due the ground motions and the superstructure on top of the raft were considered. The suggestion and an application is presented in this paper.

2 NUMERICAL MODELLING

Figure 1 shows the schematic layout of the uncoupled motions for the spread raft of a piled raft foundation. The displacements in *x*, *y* and *z* directions are denoted as *u*, *v* and *w*. Rotations along these axes are assumed negligible. For horizontal earthquake shaking in the *x* direction, the governing differential equation for the raft can be derived based on force equilibrium conditions of the raft.

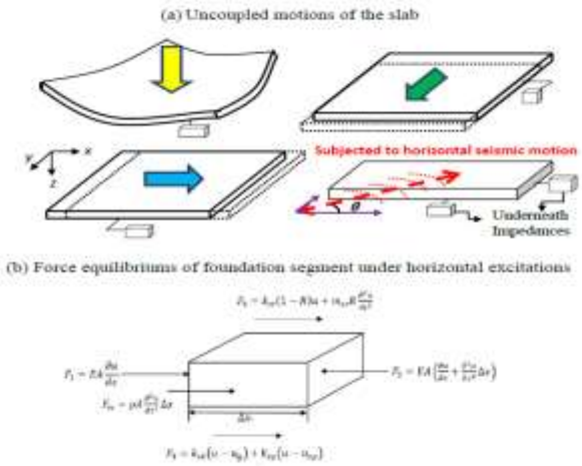

Figure 1 Layout of the uncoupled motions of a piled raft foundation, (a) uncoupled motions and horizontal impact with a bevel angle (b) force equilibrium diagram

$$EA\frac{\partial^2 u}{\partial x^2}dx = \rho A dx\frac{\partial^2 u}{\partial t^2} + k_{sb}(u-u_g) + k_{ep}(u-u_{ep}) + k_{st}(1-R)u + m_{st}R\frac{\partial^2 u}{\partial t^2} \tag{1}$$

where u = displacement of the raft; u_g = displacement of the ground soil underneath the raft; u_{ep} = displacement of the equivalent pier (pile-soil-pile system) underneath the raft; E =

Young's modulus of raft; A = cross-section area of the raft; ρ = mass density of the raft; k_{sb} = spring constant of the soils underneath the raft (units in Force/Length); k_{ep} = spring constant of pile-soil-pile system underneath the raft (units in Force/Length) which can be calculated as $k_p n + k_s A_s$, where k_p= stiffness of single pile; k_s= stiffness of the soils in equivalent pier; n = number of piles, A_s= area of the soils in equivalent pier; k_{st} = stiffness of the superstructure (units in Force/Length); R= ratio of the superstructure displacement divided by the raft displacement (*i.e.*, $R = u_{st}/u$), m_{st}= mass of the superstructure. Notice that the ratios are assumed the same for the displacements and the accelerations.

In this study, k_{sb} is simply treated as shear spring constant, *i.e.*, $G_s A_{sb}/l_s$, where G_s = shear modulus of the soil; A_{sb} = contact area of the soils outsides the pile-soil-pile elements; l_s = thickness of the soil. The stiffness parameters k_{ep} and k_{st} can be computed from shear springs too. In that case, $k_p = G_p A_p/l_p$ where G_p, A_p, and l_p are the shear modulus, cross-section area, and the length of the pile, respectively; $k_s = G_s/l_s$. $k_{st} = G_c A_c/l_c + G_m A_m/l_m$ where the subscripts c and m respectively denote for concrete structure and material inside the concrete structure. Notice that in Eq. 1, the viscous forces resulted from the superstructure and the soils underneath the raft are ignored. Using the central difference formulas, Eq. 1 can be solved easily by independent equations (Chang *et al.*, 2016^{a}). Similarly, the differential equation for the motion (displacement of v) of the slab due horizontal ground motion in y direction can be presented in the same manner differentiating the variable v with respect to y.

For lateral boundaries of the raft, free tractions were considered. Alternate equations can be achieved for the cases where no superstructure and no underneath pile and soil elements are encountered. To solve for the raft displacements, it was assumed that foundation is initially at rest. Time dependent raft displacements are thus obtained in an explicit manner. For horizontal seismic ground acceleration, *a(t)* acting to the foundation with a bevel angle of θ as shown in Figure 1(a), the analysis can be conducted independently taking into account of the acceleration's components $a(t)\cos\theta$ and $a(t)\sin\theta$ in each direction. The absolute displacements of the raft in direction of the causative ground acceleration could be calculated as $(u^2+v^2)^{0.5}$; displacement time history of the foundation can be also converted from the displacement components and averaging them to yield the solution. The above analysis was termed as EQPR (EarthQuake analysis for Piled Raft foundation) (Chang *et al.*, 2016^{a}).

2.1 Responses of pile-soil-pile elements

The time-dependent displacement functions of the pile-soil-pile elements underneath the raft due horizontal ground motions can be analyzed using the EQWEAP procedure (Chang *et al.*, 2014). In the first step, the linear and/or nonlinear free-field ground responses are able to obtain using the lumped mass analysis assuming that the ground is composed by horizontal soil layers. Secondly, the ground responses are applied to the discrete wave equations of the pile elements in order to solve for the corresponding pile displacements. Figure 2 illustrates the schematic layout of the EQWEAP procedure and the equilibriums of the pile segments used in the analysis. Notice that both the soil and pile nonlinearities can be modeled using proper material laws.

This solution was suggested in the past years and it was found reliable in comparison with the FEM analysis and pseudo static solution in matching the field observations (Chang *et al.*, 2014; Chang *et al.*, 2016^{b}). Although the EQWEAP analysis is suggested for single piles, with proper calculations of the load distributions while the effects of pile-to-pile interactions were included (Chang *et al.*, 2009), this analysis can be used to monitor any single pile response within a pile group. In general, the piles were found moving accordingly with the ground motions. The differences between them are able to neglect. In applying the EQWEAP analysis into the piled raft foundation problem, it is suggested to obtain the response of the pile-soil-pile elements (or the equivalent pier), u_{eq} in connection with the raft as $u_{eq} = (u_p\sum A_p + u_{fd}\sum A_s) / (\sum A_p + \sum A_s)$.

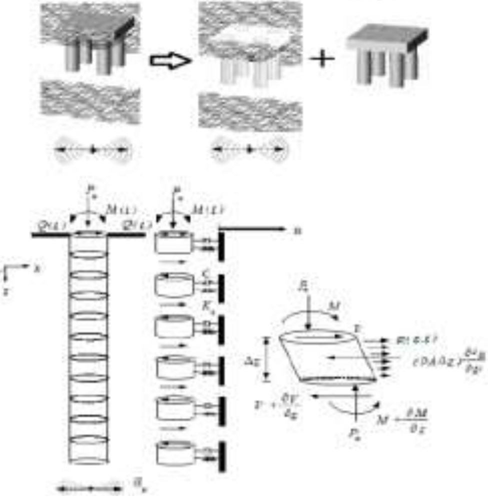

Figure 2 Schematic layout of the EQWEAP analysis and equilibriums of pile elements (from Chang *et al.*, 2014)

In the above equation, u_p=time-dependent displacement function of the single piles; u_{fd}= free-field response function of the surface ground soil; $\sum A_p$ is the total cross-section area of the piles and $\sum A_s$ is the total area of surface soils in the pile-soil-pile elements. This would help to calculate the seismic ground force.

2.2 Responses of superstructures

The loads from the superstructure acting on top of the piled raft can be simulated as a single degree of freedom system (SDOF) and/or multiple degrees of freedom system (MDOF) represented by a set of mass-spring-dashpot elements. The formulation is presented for the forces transmitting only through a spring-mass system. A displacement ratio R, defined as the ratio of superstructure displacement u_{st} divided by foundation displacement u, will make the computations much easier. The same quantity of R is also assumed for the ratios of accelerations. The analysts may change the values of R in a rational range to see how the foundation is affected by the characteristics of the superstructure.

3 EXAMPLE AND VALIDATION

Assuming that a strip concrete slab with dimensions L×B×H=300m×60m×2m is allocated at the surface of a ground site consisting of soft soils whose thickness is 13m and underlain by gravels. Five massive superstructures are evenly mounted on the slab. For each one of them, 81 concrete piles with pile diameter of 2m and pile length of 28m, oriented in a ring shape with radial distance at 7, 14, 21 and 26 meters from the central pile (see Figure 3) are installed under the slab of 60m×60m to support the superstructures. In addition at each corner of the slab, three piles were seating in a triangular shape.

As a result, each superstructure is supported by 93 concrete piles under the slab. Total number of the piles would be 465. Material properties and model parameters used in the proposed analysis and the 3D FEM modeling using Midas-GTS program

(Midas, 2012) are tabulated in Table 1.

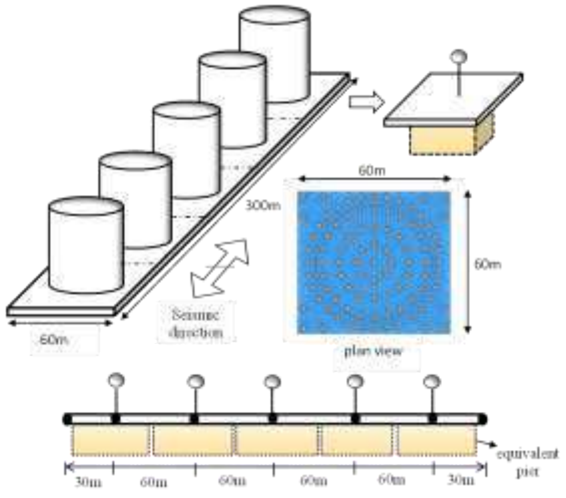

Figure 3 Numerical model for strip raft foundation on piles.

Table 1 Material properties and parameters used in the analyses

Method	Material Properties	Model Parameters
EQPR analysis	Piles and raft : E= 3× 10^4 MPa; γ = 24kN/m^3; ξ = 0.02; ν = 0.1;	Pile, raft, soft soils and gravel: linearly elasticity
3D Midas-GTS analysis	Soft soils: E= 137.4 MPa; Vs= 180 m/sec, γ = 14 kN/m^3; γ_{sat} = 16 kN/m^3; ξ = 0.05; ν= 0.3 Gravel: E=1582.4 MPa; Vs=560m/sec; γ =20kN/m^3; γ_{sat}=22kN/m^3; ξ = 0.05; ν = 0.25	Piles and raft : Linearly elasticity Soft soils: Modified Cam Clay model c= 2 kg/cm^2; ϕ = 35°; OCR =1.0; λ= 0.087; κ= 0.0073; e_0 = 1.042; M = 1.24; k_0 = 0.48 Gravel: Mohr Coulomb model c = 0 kPa; ϕ = 36°; k_0 =0.41

Seismic accelerations recorded at the TAP052 station in EW direction during the 1999 Chi-Chi earthquake was taken as the input of ground motion. Figure 4 shows the acceleration records obtained by a calibrated one based upon the designed Peak Ground Acceleration (PGA) at 0.24g and the alternative one fitting acceleration record with the designed spectrum under the same level of PGA. It can be seen that although the time-dependent accelerations are in similar forms, the resulting response spectra are very different. The formation of an artificial earthquake is very important. Figure 4(b) and 4(c) were obtained after baseline corrections.

The analysis is then conducted with the input seismic motions using the first method. Horizontal seismic motion is assumed independently in the longitudinal and transverse directions of the foundation whereas the bevel angle is kept as 0° and 90°. For analysis in *x* direction, seven nodes along the raft are analyzed. For analysis in *y* direction, three nodes are computed. Notice that time increment used in the proposed analysis is 0.0005 sec to ensure stability of the solutions (the original data has time increment of 0.005 sec). The discrete model used in 3D FEM modeling is shown in Figure 5. Convergence and stability of the FEM solutions were ensured varying the types of elements, discrete mesh, and boundary conditions.

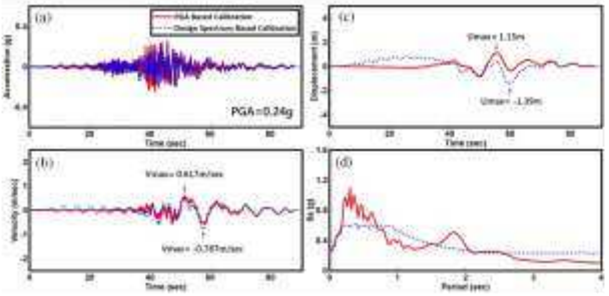

Figure 4 Seismic Inputs for the analyses

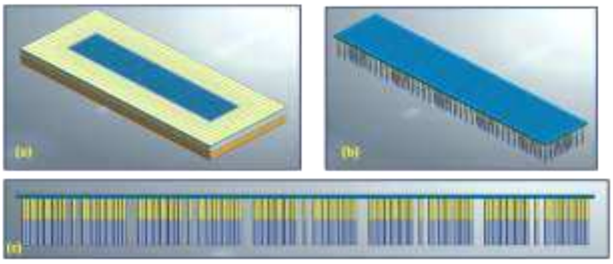

Figure 5 3D DEM model for the validation of the simplified analysis

Figure 6 depicts the results from the EQPR analysis and the solutions from 3D Midas-GTS analysis assuming that there is no superstructure on top of the foundation. It can be found that the solutions are rationally compatible providing that the stability of solutions is ensured. The time increment used in Midas analysis is 0.02 sec.

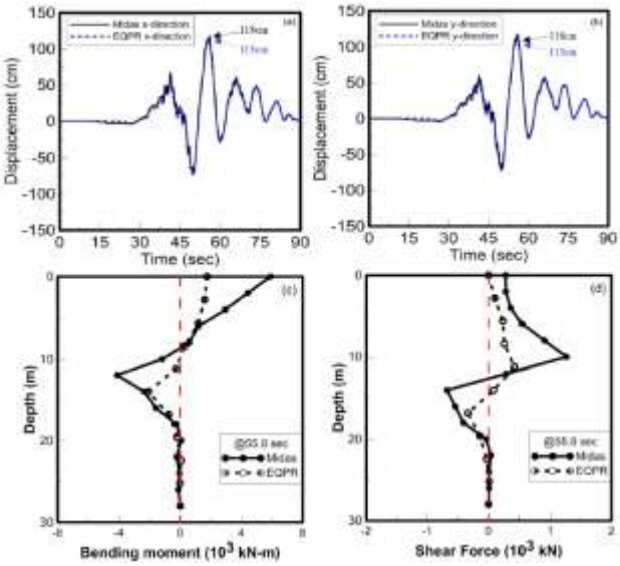

Figure 6 Seismic responses of strip raft foundation on piles obtained from Midas and EQPR analysis, horizontal ground motions at (a) *x* direction (b) *y* direction (c) bending moment (d) shear force

It is interesting to learn that the ground motions acting in *x* direction (longitudinal direction of the slab) will yield very small difference than those acting in *y* direction. Figure 6(c) and 6(d) depicted the internal bending moments and shear forces at the time (55.8 sec) when the maximum displacements occurred. The FEM and simplified solutions have some disagreements since the nonlinearities of the structure were captured by different material models. Various stress conditions at the pile heads will also affect the results. More comparisons on the internal stresses of the piles from different numerical modeling can be found in Hong (2016). Parametric studies on the influence factors have been reported (Chang *et al.*, 2016[a]).

To reveal the influence of displacement factor *R*, the superstructure was taken as a single degree of freedom (SDOF) system mounting on the raft. The resolved foundation time-dependent accelerations can be treated as the base motions to solve for the associated motions of the superstructure. Time histories of the relative displacements and the absolute displacements as well as the time-dependent ratio *R* can be shown in Figure 7(a), 7(b), and 7(c). *R* was found oscillating with time in between 0.5~1.2.

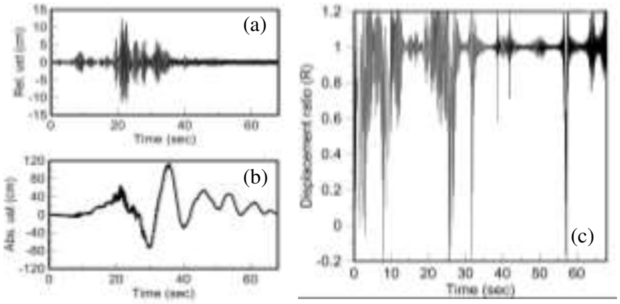

Figure 7 SDOF motions of the superstructure subjected to the foundation shaking (a) relative displacement time-history (b) absolute displacements time-history (c) displacement ratio *R* calculated as a time-dependent function

Referring to the response of a single pile solution under the earthquake obtained earlier by Chang *et al.* (2016[b]), it seems that the responses of piles and raft of the foundation will be governed by the ground motions. From the 3D FEM modelling, the pile responses were found also dominated by the ground motions. Table 2 shows the required time for computations, the EQPR analysis seems to be a very efficient solution to the preliminary design. It will make the Performance Based Seismic Design (PBSD) much easier for the piled raft foundations.

Table 2 Computation time of the numerical analyses

Method	Computer features	Computation time (sec)
EQPR analysis	CPU: Intel Xeon E3-1231v3 RAM: 16GB	60 sec based on Δt of 0.0005sec (computations required for EQWEAP analysis is included)
3D Midas-GTS analysis		9hr 25min 10sec for 174780 elements based on Δt of 0.02 sec

4 CONCLUSIONS

A simplified analysis called EQPR was suggested to monitor the seismic responses of a strip foundation on piles subjected to horizontal earthquake motions. Finite difference formulas were used to discretize the governing differential equation of the strip foundation. The simplified analysis is validated with 3D finite element analysis based on Midas-GTS program. Numerical model was given for strip foundation on piles at a site with relatively shallow soft soils underlain with gravels. The piles are seating in the layer of gravels. The conclusions of this study were drawn as follows.

1. The simplified analysis can provide rational solutions to the seismic responses of rectangular foundation on piles in a very efficient manner.
2. The effect of superstructure is significant to the foundation displacement. The existence of the superstructure will reduce the foundation displacement. The more rigid the superstructure is (displacement ratio *R* becomes smaller), the less the foundation displacement will be. In reality, the displacement ratio *R* between the superstructure and the foundation is time dependent, and it can be in a range of 0.5~1.2.
3. The observations have limitations based on the usage of shear springs. Seismic design of the piled raft foundation needs to check carefully the internal stresses of the piles. The foundation displacements should be used only for explicit comparisons.

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