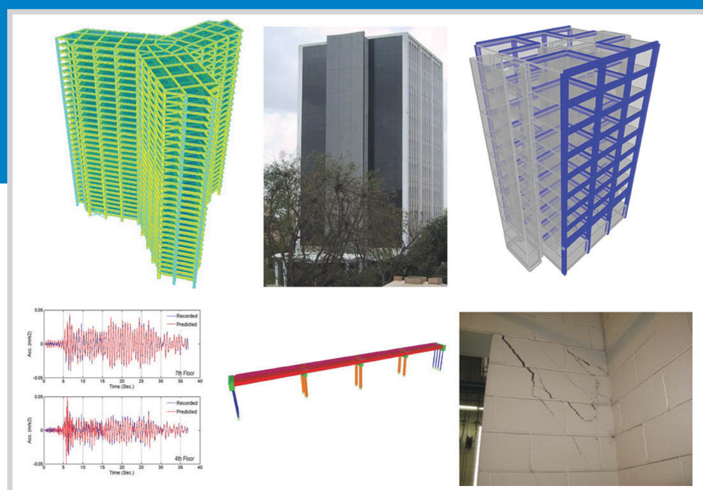
An ACI Technical Publication

SYMPOSIUM VOLUME



Design and Performance of Concrete Bridges and Buildings when Interacting with Soils and Foundations

Editors:
Yail J. Kim and Nien-Yin Chang

SP-316

American Concrete Institute
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First printing, April 2017

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Printed in the United States of America

Editorial production: Aimee Kahaian

ISBN-13: 978-1-945487-58-3

Preface

Soil-structure interaction has been of interest over several decades; however, many challenging issues remain. Because all structural systems are founded on soil strata, transient and long-term foundation displacements, particularly differential settlement, can severely influence the behavior of structural members in buildings and bridges. This is particularly important when a structure is constructed in earthquake-prone areas or unstable soil regions. Adequate subsurface investigation, design, and construction methods are required to avoid various damage types from structural and architectural perspectives. Typical research approaches include laboratory testing and numerical modeling. The results of on-site examinations are often reported. Recent advances in the-state-of-the-art of soil-structure interaction contribute to accomplishing the safe, reliable, and affordable performance of concrete structures. This Special Publication (SP) encompasses nine papers selected from two technical sessions held in the ACI Fall convention at Denver, CO, in Nov. 2015. All manuscripts submitted are reviewed by at least two experts in accordance with the ACI publication policy. The Editors wish to thank all contributing authors and anonymous reviewers for their rigorous efforts. The Editors also gratefully acknowledge Ms. Barbara Coleman at ACI for her knowledgeable guidance.

Yail J. Kim and Nien-Yin Chang
Editors
University of Colorado Denver

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Earthquake-Induced SSI Effects on High Rise Buildings

Nien-Yin Chang and Hien Manh Nghiem

Synopsis: Because of the complexity of the soil-structure interaction (SSI) effect on high-rise buildings, contemporary design codes allow the use of results from an advanced numerical analysis in the design of structures without providing further stipulation. The information on SSI effects, however, is only available for low rise buildings with simple analysis procedures. Two hypothetical 20-story buildings and one 30-story real building were subjected to seismic response analyses using SSI3D under the following conditions: rigid base, flexible base with linear foundation springs, flexible base with linear soil, flexible base with nonlinear springs, and the full SSI analysis with flexible base with nonlinear soils for two hypothetical buildings. For the real building, the calculated natural periods, base shears, and top-floor displacements were compared to the values evaluated using the recorded building motions. It was observed that the natural periods increase and the base shears decrease as the base becomes more flexible, but further study is needed to examine the top-floor side sway.

Keywords: Soil-structure-interaction, pile, models, modal earthquake, stiffness, high-rise building, seismic

Nien-Yin Chang is a Professor of Civil Engineering and the Director of Center for Geotechnical Engineering Science in the Department of Civil Engineering, University of Colorado Denver. He is a licensed professional engineer in Colorado and Ohio (inactive). His research interest covers geotechnical earthquake engineering, liquefaction of soils, large-scale geotechnical model tests for GRS/MSE walls, abutments, drilled shafts, driven piles and expansive soil foundations

Hien Manh Nghiem is an Associate Professor at the Hanoi University of Architectural University (HAU) specializing in seismic soil-structure interaction software research and development for geotechnical and structural analyses and designs including deep excavations in problem soils. On leave from HAU, he serves as a visiting scholar at the Center for Geotechnical Engineering Science, University of Colorado Denver. As a Postdoctoral Research Associate he participates in GRS/MSE abutment and wall research and, as a teacher, he teaches finite element analysis and deep ground excavation in problem soils.

INTRODUCTION

A nonlinear finite element analysis computer code, SSI-3D was developed at the Center for Geotechnical Engineering Science at the University of Colorado Denver to investigate the SSI effect on structures including high rise buildings, bridges, etc.[1]. In an analysis a ground motion was imposed along the bedrock-soil interface, propagated into soil, soil-pile system and finally into the building, where beams and columns were modeled by beam elements and slabs and shear walls were modeled by shell elements. Mat foundations, piles and soil media were modeled by solid elements. Nonlinear material models were only applied to solid elements. Pile foundation and soil were represented by linear or nonlinear springs. Modal, response spectrum, and nonlinear time history analyses were performed. Nonlinear soil-pile-building interaction (SPBI) analyses were performed using different constitutive soil models, including Mohr-Coulomb (MC), modified hyperbolic model (MH) and modified Ramberg-Osgood model (MRO). Viscous damping of soils needed for SPBI analyses was determined from the damping ratio of soils using matching transfer functions from one soil layer to another. To verify viscous damping so evaluated, the recorded free-field motion was deconvoluted to find the base rock motion using soil damping and then convoluted using viscous damping to find the corresponding surface motion. Excellent agreement was found between the calculated and recorded free-field motion on ground surface. This validated the soil damping used the analysis. The validated viscous damping of soils was then used in the SPBI analysis and both kinematic and inertial interactions were included with the use of transfer function to convert a free-field motion to a corresponding basement motion, equivalent stiffness, and damping of soil-pile system. For the real building, recorded free-field ground motion was used in the analysis and the results compared to those derived from the recorded strong motion in the strong motion instrumentation program[2].

RESEARCH SIGNIFICANCE

Safe and cost effective aseismic designs of high rise buildings on piles depend on accurate soil-pile-structure interaction analyses. While rigid base analyses is prevalent, full soil-pile-structure-interaction analyses of buildings have not become a common practice because of its complexity, particularly in mathematical modeling of soil and soil-structure interface behaviors. During strong seismic shaking, a building dances with foundations and soils and produces translational, torsional and rocking motions, and proper building designs require accurate evaluation of the distribution of base shear, axial and torsional forces, torsional and bending moments and building side sways. This needs the adoption of proper constitutive models of soils and soil-foundation contact model, which need further research in development and selection of soils' constitutive models and soil-pile contact models.

SEISMIC RESPONSE OF HYPOTHETICAL BUILDINGS

Description of Two Hypothetical Buildings

The first building is a 20-story reinforced concrete office building 75.6 m [248 ft] tall with rectangular base footprint, shear walls and concrete moment frames, four frames in the X direction and nine frames in the Z direction. The 0.15 m [5.8 in.] thick concrete slab is pre-stressed. The beam section dimensions depend on span length and do not change between floors. The column section dimensions remain the same for several floors and are decreased every few floors per design requirement from the bottom to the top of the building. The shear wall has a uniform thickness of 0.25 m [9.84 in.] throughout the full building height. All stories have the same height of 3.6 m [11.8 ft]. The length of each span in the Z direction is 4.8 m [15.75 ft]; in the X direction, the middle span is 2.4 m [7.87 ft] long and the others are 7.5 m [24.6 ft] long. The building is supported on 126 drilled shafts of 0.8 m [31.5 in.] in diameter, which are connected at top with a 1.5 m [4.92 in.] thick pile cap. The plan, elevation and isotropic views of the building are given in Fig. 1. The second building is a 20-story office tower 82.2 m [269.69 ft] tall. It is modified from the building analyzed by Krishnan[3]. This building has a typical floor area of 180 m^2 [1937.5 ft^2], and story height of 4.0 m [13.12 ft]. The lateral systems are steel moment frames along the perimeter of the building and diaphragms are assumed to be rigid. The 0.14 m [5.5 in.] thick concrete slabs rest on metal decks with 0.0254 m [1 in.] topping supported on interior steel beams supported by gravity and moment frame columns. All interior steel beams are assumed to have no contribution to the lateral system and are not considered in the building model. The building is supported by 80 1.0 m-diameter [3.28 ft-diameter] drilled shafts with 1.5 m [4.92 ft] thick pile cap. Plan, elevation and isotropic views of the building are given in Fig. 2.

Site Selection and Soil Properties

The site is located at latitude 34.069^0 and longitude 118.442^0 with a soil profile represented by weathered bed-rock underlying 19.8 m [64.96 ft] of surficial clayey silts and sands. Table 1 gives site name, sensor number, site class and peak ground acceleration for parametric studies. For the detailed descriptions of these sites below, refer to Stewart and Stewart (1997). The dynamic properties of soils including shear modulus, shear wave velocity and damping are summarized in Tables 2 and 3 for the subsoil of the site shown in Table 1. The properties of soil model are calculated from curves given by Seed and Idriss[4] and Sun et. al.[5]. The undrained shear strength of the 4^{th} layer is assumed to be 500 kN/m^2 [72.5 psi]. The MRO parameters are calculated by using shear strength at middle of soil layers. Properties for equivalent linear analysis of deconvolution are shown in Table 4. Natural site periods are shown in Table 5.

Analysis Assumptions and Procedures

The following assumptions are made in these analyses:

- Beams, columns and slab are elastic in all analyses
- 100 percent of dead load and live load are used in modal and time history analyses
- 5 percent model damping is used to determine the Rayleigh damping of beams, columns, shear walls and slabs.

The analyses of both buildings include: 1) Modal analysis, and 2) Time history analysis. In modal analysis, the periods, mode shapes, modal participation factors are determined. For time history analyses, the Rayleigh damping of beams, columns, slabs, walls and foundations are determined from 5 percent modal damping for all modes by matching two first natural frequencies in the X direction.

Dead Load and Live Load

The dead load and live load for buildings are based on the occupancy of floor according to Table 4-1 of ASCE 7-10. Dead load and live load applied on the floor are assigned on plate elements as vertical uniform loads. The self-weight of structural system is calculated internally using the program. The dead load and live load are input separately as two load cases. Dead load and live load are used to determine the consistent mass of structure.

Time History Functions

In seismic soil-structure interaction analysis, the ground motion is imposed on the bedrock below the pile tip. Thus, the recorded surface ground motion is deconvoluted through the soil layers to establish the associated bedrock motion. Input motion must be located deeper than pile tip or the bedrock-soil boundary. The deconvoluted motions at the bedrock level are shown in Fig. 3.

Foundation Properties

Foundation properties of the two buildings include the stiffness, damping values of pile and pile group that were used in modal, response spectrum, and time history analyses for flexible base cases. The real and imaginary parts of impedance functions of single pile and pile group are calculated by the method presented by Nghiem[1] and shown in Tables 6 to 9. Tables 6 through 8 show the soil model effect is not significant for the same building, however, the initial stiffness (both real and imaginary parts), is significantly different between the concrete and steel structures. The pile arrangements for Buildings 1 and 2 are shown in Figs. 4a and b, with dimensionless pile spacing S/D=3. All piles are connected by a 1.5 m [4.92 ft] thick reinforced concrete pile cap. Lateral load-displacement functions of pile head for single piles fixed at the pile top are from stand-alone SSI3D analyses. The soil-single pile system can be modeled by six equivalent springs (three translations and three rotations) at the top of the pile. The equilibrium equation is written as follows:

$$[K]\{U\} = \{P\} \tag{1}$$

where $[K]$ 6 x 6 is the stiffness matrix; $\{U\}$ is the displacement vector; and $\{P\}$ is the load vector. The stiffness matrix, displacement vector and load vector for a pile are given in Eqs. (2) and (3) and shown in Fig. 5.

$$[K] = \begin{bmatrix} K_{11} & 0 & 0 & 0 & K_{15} & 0 \\ 0 & K_{22} & 0 & K_{24} & 0 & 0 \\ 0 & 0 & K_{33} & 0 & 0 & 0 \\ 0 & K_{42} & 0 & K_{44} & 0 & 0 \\ K_{51} & 0 & 0 & 0 & K_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & K_{66} \end{bmatrix} \tag{2}$$

$$\begin{aligned} \{U\} &= \begin{bmatrix} u_x & u_y & u_z & \theta_x & \theta_y & \theta_z \end{bmatrix} \\ \{P\} &= \begin{bmatrix} P_x & P_y & P_z & M_x & M_y & M_z \end{bmatrix} \end{aligned} \tag{3}$$

where K_{11}, K_{22}, and K_{33} are the translational stiffness components; u_x, u_y, u_z are the translations; and P_x, P_y, P_z are the loads along the axis x, y, and z, respectively; K_{44}, K_{55}, and K_{66} are the rotational stiffness components, θ_x, θ_y, θ_z are the rotations and M_x, M_y, M_z are the moments about axis x, y, and z, respectively; and $K_{51} = K_{15}$ and $K_{24} = K_{42}$ are coupling stiffness. The coupling effects between vertical stiffness, torsional stiffness and others, and between stiffness in the directions x and y are ignored. Single piles are symmetric in the x-z and y-z planes in their local coordinates and soil and pile isotropic in the x and y directions. Under these conditions, some stiffness components are equal, $K_{11} = K_{22}$ and $K_{15} = K_{51} = K_{24} = K_{42}$.

Kinematic Analyses

Kinematic interaction results from the occurrence of stiff foundation elements on the surface of or embedded in a soil deposit causes foundation deformations to differ from those in free field. The kinematic interaction will occur whenever the stiffness of foundation obstructs development of the free-field motion. Kinematic analyses need to be performed to determine ground floor motions from far field motions.

Modal Analyses

In modal analyses, a total of 12 modes are calculated for fixed base, full soil-pile-building interaction (SPBI) and spring model of soil-foundation system. The natural periods and directions of vibrations of the first three modes are given in Tables 10 and 11. The SSI effects are represented by the comparison between the flexible base analysis and fixed base analysis. It was found the influence on natural period is not significant, and the natural period for Building 1 in the flexible base analysis is about 5 percent higher than that in the fixed base analysis, for Building 2 it is 2 percent higher, and the difference is affected by the stiffness of the soil-pile system. The natural periods computed using the spring model of soil-pile system are in good agreement to those of soil-structure interaction system with 1 percent maximum differences for first three modes. This shows that the initial spring stiffness given in Tables 6 and 7 are good approximations for stiffness of soil-pile system.

Time History Analyses

Time history analyses are performed for full soil-pile-structure interaction and simple model of soil-pile system. In analyses, the free field motion duration is shortened to 25 seconds and used in calculating the corresponding bedrock motions through deconvolution and then used in the time history analyses. For the full soil-pile-structure interaction analyses, three soil models: Mohr-Coulomb (MC), modified hyperbolic (MH) and modified Ramberg-Osgood (MRO) are used to evaluate the effect of soil models. The story shears for full soil-pile models are shown in Figs. 6 for Building 1 and Fig. 7 for Building 2, the maximum base shears and the total displacements at the 20th floor level are given in Table 12. There are no significant differences between results of analyses using the three soil models in analyses in terms of story shear as shown in Figs. 6 and 7. The total displacements in full soil-pile model analyses are compared to those from fixed-base analyses in Table 12. For the flexible base using linear and nonlinear springs,