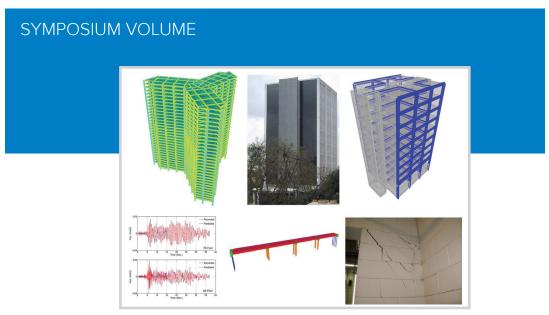
# An ACI Technical Publication



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

Editors: Yail J. Kim and Nien-Yin Chang

SP-316



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#### 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-stateof-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

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#### **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.<sup>1</sup>. 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<sup>2</sup>.

#### **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<sup>3</sup>. This building has a typical floor area of 180 m<sup>2</sup> [1937.5 ft<sup>2</sup>], 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° and longitude 118.442° 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<sup>4</sup> and Sun et. al.<sup>5</sup>. The undrained shear strength of the 4<sup>th</sup> layer is assumed to be 500 kN/m<sup>2</sup> [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<sup>1</sup> 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: