IFCEE 2021

GSP 325

From Traditional to Emerging Geotechnics

Selected Papers from the
International Foundation Congress and Equipment Expo 2021
Dallas, Texas ■ May 10–14, 2021

Edited by

Chadi El Mohtar, Ph.D.;
Stacey Kulesza, Ph.D.; Tugce Baser, Ph.D.;
and Michael D. Venezia, P.E.

ASCE

G-I GEO-INSTITUTE ASCE

GEOTECHNICAL SPECIAL PUBLICATION NO. 325

IFCEE 2021

FROM TRADITIONAL TO EMERGING GEOTECHNICS

SELECTED PAPERS FROM SESSIONS OF THE INTERNATIONAL FOUNDATIONS CONGRESS AND EQUIPMENT EXPO 2021

May 10–14, 2021
Dallas, Texas

SPONSORED BY
International Association of Foundation Drilling
Deep Foundations Institute
Pile Driving Contractors Association
The Geo-Institute of the
American Society of Civil Engineers

EDITED BY
Chadi El Mohtar, Ph.D.
Stacey Kulesza, Ph.D.
Tugce Baser, Ph.D.
Michael D. Venezia, P.E.

Published by the American Society of Civil Engineers

Published by American Society of Civil Engineers
1801 Alexander Bell Drive
Reston, Virginia, 20191-4382
www.asce.org/publications | ascelibrary.org

Any statements expressed in these materials are those of the individual authors and do not necessarily represent the views of ASCE, which takes no responsibility for any statement made herein. No reference made in this publication to any specific method, product, process, or service constitutes or implies an endorsement, recommendation, or warranty thereof by ASCE. The materials are for general information only and do not represent a standard of ASCE, nor are they intended as a reference in purchase specifications, contracts, regulations, statutes, or any other legal document. ASCE makes no representation or warranty of any kind, whether express or implied, concerning the accuracy, completeness, suitability, or utility of any information, apparatus, product, or process discussed in this publication, and assumes no liability therefor. The information contained in these materials should not be used without first securing competent advice with respect to its suitability for any general or specific application. Anyone utilizing such information assumes all liability arising from such use, including but not limited to infringement of any patent or patents.

ASCE and American Society of Civil Engineers—Registered in U.S. Patent and Trademark Office.

Photocopies and permissions. Permission to photocopy or reproduce material from ASCE publications can be requested by sending an e-mail to permissions@asce.org or by locating a title in ASCE's Civil Engineering Database (http://cedb.asce.org) or ASCE Library (http://ascelibrary.org) and using the "Permissions" link.

Errata: **Errata, if any, can be found at https://doi.org/10.1061/9780784483428**

Copyright © 2021 by the American Society of Civil Engineers.
All Rights Reserved.
ISBN 978-0-7844-8342-8 (PDF)
Manufactured in the United States of America.

Preface

This is the third volume of four Geotechnical Special Publications (GSPs) containing papers from the 2021 International Foundations Congress and Equipment Expo (IFCEE21) held in Dallas, Texas on May 5–10, 2021. This volume includes a wide variety of topics from advances in traditional geotechnical engineering to innovative approaches for characterization of soil behavior and improvement of soil properties at multiple scales. As the world moves into further into the digital and stranger times where a new normal is currently being defined, the authors contribute to the challenges in new-era educational approaches in this volume. The IFCEE conference series combines a technical conference and equipment show dedicated to the design and construction of foundation systems, using the latest geoengineering and geoconstruction technologies and practices. The IFCEE conference series is a one of a kind event that attracts attendees from around the world for the world's largest equipment exposition dedicated solely to the deep foundations industry. This Congress combined the 2021 annual meetings of ASCE's Geo-Institute, the International Association of Foundation Drilling (ADSC), the Pile Driving Contractors Association (PDCA) and the Deep Foundations Institute (DFI). This event was the fourth Congress in the IFCEE conference series, following the successful 2009, 2015, and 2018 meetings, in which these leading geotechnical and geotechnical-related organizations joined together for a single and singular annual congress. IFCEE'21 provided an international forum despite the unusual times to discuss technological advances, case histories, and present challenges and emerging topics related to geotechnical and foundation engineering. The congress was attended by a wide range of geo-professionals including engineers, contractors, academicians, equipment manufacturers, geo-technologists, researchers, and service, material, and tooling suppliers.

This publication culminates two years of effort by the technical planning committee whose focus has been to continue the success of the previous meetings in the IFCEE conference series. Many individuals are responsible for the content of this volume, all of whom served in the efforts to maintain the standard set by previous proceedings. An international call for papers and a rigorous peer review process yielded 189 accepted technical papers, that were presented in 36 sessions, in addition to invited keynote presentations. Papers were reviewed in accordance with ASCE GSP standards. Accordingly, each paper was subjected to technical review by two or more independent peer reviewers. Publication requires concurrence by at least two peer reviewers.

The year 2020 has opened a global outpouring for a change, exposing some of the most insidious elements of the health and societal regime to public examination. Despite the difficulties, the Editors worked hard with the members of the organization committee and session chairs closely. The Editors would like to express their appreciation for having been provided the opportunity to be a part of this Congress' organization, their sincere thanks to the numerous session chairs and reviewers, and they hope that these proceedings will be of use to the geotechnical engineering community for many years to come.

The Editors,
Chadi El Mohtar, Ph.D., M.ASCE, University of Texas at Austin
Stacey Kulesza, Ph.D., PE, M.ASCE, Kansas State University
Tugce Baser, Ph.D., A.M.ASCE, M.DFI, University of Illinois at Urbana-Champaign
Michael D. Venezia, P.E., M.ASCE, M.DFI, M.PDCA

© ASCE

Acknowledgments

Thanks are due to the authors, primary reviewers, session chairs, and program committee, without whom this publication would not be possible.

IFCEE 2021 Conference Program Committee

Conference Chair
Muhannad T. Suleiman, Ph.D., Lehigh University

Technical Program Committee
Tracy T. Brettmann, P.E., D.GE, M.ASCE, A.H. Beck
Les Chernauskas, P.E., M.ASCE, Geosciences Testing and Research Inc.
Peggy Hagerty-Duffy, P.E., D.GE, ADSC
Mary Ellen Bruce Large, P.E., D.GE, Deep Foundations Institute
Anne Lemnitzer, Ph.D., P.E., A.M.ASCE, University of California, Irvine
Alec Mcgillivray, Ph.D., P.E., Precast Piling Technology
Morgan Nesmith, P.E., M.ASCE, Berkel
Helen Robinson, P.E., M.ASCE, GEI Consultants
Jeff Segar, P.E., S.E., Braun intertec
Anna Sellountou, Ph.D., P.E., Pile Dynamics

Proceedings Editors
Chadi El Mohtar, Ph.D., M.ASCE, University of Texas at Austin
Stacey Kulesza, Ph.D., PE, M.ASCE, Kansas State University
Tugce Baser, Ph.D., A.M.ASCE, M.DFI, University of Illinois at Urbana-Champaign
Michael D. Venezia, P.E., M.ASCE, M.DFI, M.PDCA

© ASCE

IFCEE Draft Round Reviewers

Mehdi Abbasi
John Abdalkhani
Yasser Abdelhamid
Pramila Adhikari
Alireza Afshani
Shehab Agaiby
Sean Ahdi
Reza Ahmadi Naghadeh
Asif Ahmed
Md Ahsanuzzaman
Idil Akin
Hossein Alimohammadi
Ryan Allin
Alaa Alsharaballi
Daniel Alzamora
Zahra Amini
Joram Amir
Mohsen Amirmojahedi
Paul Andersen
Donald Anderson
Nadir Ansari
Mona Anwar
Pouyan Asem
Mohammed Ashfaq
Kamelia Atefi Monfared
Kleio Avrithi
Paul Axtell
Aditya Ayithi
Alireza Ayoubian
Britt Babcock
Hossein Bahmyari
Mohamadtaqi Baqersad
Matthew Barendse
Tugce Baser
Curt Basnett
Ryan Beemer
Brahim Benhamida
Jonathan Bennett
Duane Bents
Juan Bernal
Christine Beyzaei
Aditya Bhatt
Tejo Bheemasetti
Dale Biggers
Kedar Birid
Thomas Bjartmarz
William Black
Andrew Boeckmann
Gretchen Bohnhoff
Tommy Bounds
Reza Boushehri
Merve Gizem Bozkurt
Aaron Bradshaw
Scott Brandenberg
Tracy Brettmann
Frederick (RICK) A. Brinker
Aaron Budge
Jason Buenker
Allen Cadden
Jack Cadigan
Sean Campbell
Greg Canivan
Ziming Cao
Nina Carney
Lucas Carr
Bernardo Castellanos
Mark Champagne
Leroy Chan
Ilhan Chang
Yuyan Chen
Shi-Chieh Cheng
Les Chernauskas

© ASCE

Bhaskar Chittoori
Gye-Chun Cho
Alek Chongris
Liang Chern Chow
Andrew Ciancia
Jose Clemente
Travis Coleman
Brady Cox
Sheng Dai
Domenic D'Argenzio
Biswajit Dasgupta
Tayler Day
Ricardo de Abreu
Nariman Dehghani
Berk Demir
Aditya Deshmukh
Darren Diehm
Jinung Do
Wenjun Dong
John Edens
Chadi El Mohtar
Hesham El Naggar
Usama El Shamy
Kirk Ellison
Alexander Erb
Alan Esser

Jongwan Eun
Matt Evans
Fawzy Ezzein
Zahra Faeli
Zachary Fallert
Ray Fassett
Sixto Fernandez
Michael Flanagan
Keyvan Fotoohi
Kevin Foye
Rudolph Frizzi
Andrew Fuggle
Aaron Gallant
Paolo Gazzarrini
Hande Gerkus
Ismaail Ghaaowd
Pegah Ghasemi
Omid Ghasemifare
Majid Ghayoomi
Shahin Ghazizadeh
Avishek Ghosh
Matt Glisson
Aaron Goldberg
Michael G. Gomez
David Graham
Mattias Grävare

Jared Green
Garry Gregory
John Grillo
Donald Hagerty
Peggy Hagerty-Duffy
Jim Hambleton
Seth Hamblin
Nasser Hamdan
Jie Han
Pat Hannigan
Jim Hansen
Md Haque
Mahsa Hedayati
Bernard Hertlein
Shaun Hevey
Chu Ho
Amanda Hohner
A S M Fahad Hossain
Laureano Hoyos
Feng Huang
Jonathan Hubler
Nick Hudyma
Erin Hunter
Mohamad Hussein
Nejan Huvaj
Hannah Iezzoni

© ASCE

Ritesh Ingale
Amin Iraji
Kazi Moinul Islam
Md Aminul Islam
Md Azijul Islam
Karam Jaradat
Ningjun Jiang
Allen Jones
Mohammad Joshaghani
Bhargav Kumar K P
Raviteja K V N S
James Kaklamanos
Peter Kandaris
Thierno Kane
Pourya Kargar
Andrew Keene
Amaneh Kenarsari
Siva Kesavan
Majid Khabbazian
Taha Khalaff
Yazen Khasawneh
Hamed Khodadadi
Sara Khoshnevisan
Mohammad Khosravi
Ali Khosravi
Mahsa Khosrojerdi
Tony Kiefer
Hyunki Kim
Meeok Kim
Eric Kline
Dimitrios Konstantakos
Alireza Kordjazi
Alexander Kormanos
Andy Kositsky
Tim Kovacs
Tim Kovaks
Mayooran Krishnathasan
Hanumanth Kulkarni
Prem Kumar
Wing Shun Kwan
Debra Laefer
Rakam LamaTamang
Junghwoon Lee
Gang Lei
Anne Lemnitzer
Aaron Leopold
Christopher Lewis
Kun Li
Marina Li
Jiliang LI
Robert Liang
Willie Liew
Garland Likins
William Likos
Hai Lin
Guoming Lin
Jiaojun Liu
Erik Loehr
Scott Mackiewicz
Ashley MacMillan
Sai Anudeep Reddy Maddi
Nariman Mahabadi
Masrur Mahedi
Wael Mahmood
Michael Malusis
Kalehiwot Manahiloh
Shahed Manzur
Alejandro Martinez
Mario Mauro
Paul Mayne
Alec McGillivray
Michael McGuire
Naveen Meena
Marc Miller
Richard Millet
Kim Mingu
Mohammadreza Mir Tamizdoust

© ASCE

Rozbeh Moghaddam
Aly Mohammad
Ahmed Mohammed
Ali Morovatdar
Sarah Morton
Ramin Motamed
Diane Moug
Gray Mullins
Ryan Murphy
Boohyun Nam
Ali Nazari Tileki
Saeedeh Naziri
Morgan NeSmith
Thang Nguyen
Thai Nguyen
Silas Nichols
Masoud Nobahar
Ozgun Numanoglu
Ebuka Nweke
William Oder
Hyunjun Oh
Kyle O'Hara
Guney Olgun
Kimball Olsen
Scott Olson
Michael Owens

Ayse Ozdogan Dolcek
Srisothinathan Pakeetharan
Dimitrios Palantzas
Miguel Pando
Walter Paniagua
Arun Parihar
Jorge Parra
Amanda Parry
Veniecy Pearman-Green
Tom Pennington
James Pergues
James Phipps
George Piscsalko
Mihail Popescu
Amir Poshnejad
Mehran Pourakbar
Avinash Prasad
James Racine
Parishad Rahbari
Salman Rahimi
Saidur Rahman
Saman Rashidyan
Stephanie Robat
Shane Robat
Don Robertson
Seth Robertson

Helen Robinson
Brent Robinson
Kyle Rollins
Wenyong Rong
Shahrzad Roshankhah
Aaron Sacks
Shahin Safavizadeh
Rajni Saggu
Rodrigo Salgado
Kwestan Salimi
Duraisamy Saravanathiiban
Paul Sauco
Robert Saunders
Joseph Scalia
Montgomery Schultz
Jeff Segar
Ahmed Senhaji
Ali Shafiee
Maryam Shahbazi
Mahesh Sharma
Xianda Shen
John Shoucair
Shweta Shrestha
Nayyar Siddiki
Damian Siebert
Tim Siegel

© ASCE

John Siekmeier
Samuel Singer
Joanna Smith
Ashish Solanki
Moataz Soliman
Hoda Soltani
Nina Stark
Daniel Stevenson
Eric Steward
Jeremy Stone
Jewels Stover
C. K. Su
Robert Swan
Sonia Swift
Konstantinos Syngros
Steve Szabo
Gilbert Tallard
Nagasreenivasu Talluri
Chia tan
Hui Tao
Julian Tao
Masi Tavakol
Ed Theinat
Amanda Toye
Adeleine Tran
Leon van Paassen
Michael Venezia
Gerald Verbeek
Osvaldo Vitali
Antonios Vytiniotis
Scott Walker
Bill Walton
Corrie Walton-Macaulay
Jintai Wang
Mark Wayne
Gillian Williams
Brian Wilson
Katherine Winters
Daniel Woeste
Mike Wongkaew
Chris Woods
Ruoyang Wu
Mike Wysockey
Shangzhi Xiao
Yang Xiao
Guangchao Xing
Thamer Yacoub
Davood Yazdani Cherati
Adam Yoda
Luis Zambrano Cruzatty
Siavash Zamiran
Shahabeddin Zaregarizi
Justin Zarella
Yida Zhang
Yang Zhang
Bo Zhang
Yao Zhang
Yan Zhang
Benchen Zhang
Yewei Zheng
Cheng Zhu
Katerina Ziotopoulou

© ASCE

Contents

Earthquake Engineering

Study of Period Lengthening Effects in Soil–Structure Interaction Systems 1
Jaime A. Mercado, Luis G. Arboleda-Monsalve, and Kevin Mackie

Comparison of Different Methods Used to Account for Shear Wave Velocity Variability in 1D Ground Response Analyses 11
Mohamad M. Hallal and Brady R. Cox

Runout Modeling of Earthquake-Triggered Landslides with the Material Point Method 21
Abdelrahman Alsardi and Alba Yerro

Numerical Modeling of Higher Mode Effects of Adjacent Tall Buildings on Seismic Response of a Tunnel 32
Yuamar I. Basarah, Ozgun A. Numanoglu, and Youssef M. A. Hashash

HVSRweb: An Open-Source, Web-Based Application for Horizontal-to-Vertical Spectral Ratio Processing.....42
Joseph P. Vantassel, Brady R. Cox, and Dana M. Brannon

A Comparison between Coupled SPH-DEM and LBM-DEM Approaches for Soil Liquefaction 53
Saman Farzi Sizkow and Usama El Shamy

DEM Simulations of the Effect of Desaturation on Liquefaction Hazard Mitigation.....61
Usama El Shamy and Ataollah Nateghi

Emerging Topics in Geotechnical Engineering

Thermo-Poroelastic Behavior of a Confined Porous Layer under a Combined Heat-Fluid Source 69
X. Zhai and K. Atefi-Monfared

Quasi-Static State of Thermally Induced Pore Water Pressure.....80
Seyed Morteza Zeinali and Sherif L. Abdelaziz

A Temperature-Dependent Model for Thermal Conductivity Function of Unsaturated Soils.....89
Toan Duc Cao, Sannith Kumar Thota, Farshid Vahedifard, and Amin Amirlatifi

© ASCE

Assessment of Thermo-Osmosis Effect on Thermal Pressurization in Saturated Porous Media.....99
Mohammadreza Mir Tamizdoust and Omid Ghasemi-Fare

Numerical Study and Experimental Validation of the Thermal Performance of a U-Tube Borehole Heat Exchanger for a Geothermal De-Icing System.....109
Omid Habibzadeh-Bigdarvish, Teng Li, Gang Lei, Anand J. Puppala, and Xinbao Yu

Load Transfer Anisotropy at Snakeskin-Inspired Clay-Structure Interfaces.....119
Lin Huang and Alejandro Martinez

Studying the Relationship between Indigenous Microbial Communities, Urease Activity, and Calcite Precipitation in Artificial Mixes of Clay and Sand.....130
Somaye Asghari, Bhaskar C. S. Chittoori, Malcolm Burbank, and Nick Hudyma

Bio-Inspired Underground Communication Using Seismic Waves.....139
Yi Zhong, Yunqi Gao, and Julian Tao

Effect of Rotation on Penetration: Toward a Seed Awn-Inspired Self-Burrowing Probe.....149
Yong Tang and Junliang Julian Tao

Application of EICP for Coastal Erosion Mitigation.....160
Vinay Krishnan, Hamed Khodadadi Tirkolaei, and Edward Kavazanjian Jr.

A Mixed-Reality Pedagogical Innovation in the Reality of a New Normal.....170
Victoria G. Bennett, Casper Harteveld, Yevgeniya V. Zastavker, Tarek Abdoun, Mohsen Hossein, Mehdi Omidvar, Kejun Wen, and Xenia Wirth

Exploring Contemporary Themes in Geotechnical and Geoenvironmental Engineering Education.....179
James L. Hanson, Nazlı Yeşiller, Amr El Badawy, and Marie Yeung

Geostructures

Probabilistic Stability Assessment of Earthen Levees Subjected to Earthquake Loads.....189
Lei Wang, Sandae Tait, Sara Khoshnevisan, Farhad Barati, and C. Hsein Juang

Slope Failures in North Dakota: Influence of Geology, Topography, and Salt Concentration in Pore Fluid.....197
Beena Ajmera, Kamal Raj Upadhaya, and Aaron Lee M. Daigh

Effect of Rainfall Intensity and Duration on the Highway Slopes Reinforced with Recycled Plastic Pin.....206
Md. Aminul Islam and Md. Sahadat Hossain

© ASCE

Analysis of Failure Mode on Tunnel-Type Anchorage by Model Tests and Numerical Analyses 217
Hyunsung Lim, Seunghwan Seo, Young-Hun Ko, Sungjune Lee, and P. Moonkyung Chung

Failure Heights and Failure Modes of Eight Column-Supported Embankments via 3D Numerical Analyses 227
Zhanyu Huang, Katerina Ziotopoulou, and George M. Filz

Effect of Rainfall Infiltration on Stability of a Tropical Slope from Western Pacific..... 237
Ujwalkumar D. Patil, Giordan Kho, Victoria Lopez, John Jenson, Mark Lander, and Shahram Khosrowpanah

Limit Equilibrium Probabilistic Analysis of Three-Dimensional Open Pit Using the Stochastic Response Surface Method..... 247
Brigid Cami, Sina Javankhoshdel, and Thamer Yacoub

Effect of Future Extreme Precipitation on Expansive Soil Embankments 255
Prince Kumar, Aritra Banerjee, Surya Sarat Chandra Congress, and Anand J. Puppala

A Reliability-Based Design Optimization of Cantilever Reinforced Concrete Retaining Walls 267
Humam Mhd. Al Sebai, Samer Barakat, and Mohamed Arab

Applications of Statistical Design of Experiments to Study the Factor of Safety of Unreinforced Slopes..... 278
Yuderka Trinidad González, Vernon R. Schaefer, and Derrick K. Rollins

Site Characterization

Introducing a Novel Technique for Rectifying Tilted Structures Using Microtunneling Boring Machines..... 287
Rouzbeh Vakili, Alexander Herzog, Sotirios Vardakos, and Matteo Montesi

An Empirically Developed CPT-Based Assessment Method for Characterization of Sinkhole Vulnerability in Florida Karst..... 297
Ryan Shamet, Boo Hyun Nam, and Heejung Yoon

SPT-Seismic Full Waveform Inversion for Deep Site Characterization 308
Majid Mirzanejad, Khiem T. Tran, Michael McVay, David Horhota, and Scott J. Wasman

Bench-Scale Testing of Grouts for Geo-Slice Peels..... 318
Kaleigh M. Yost, Russell A. Green, Eric Herwitz, and Liam Wotherspoon

Behavior of Unsaturated Hydraulic Conductivity of Water Balance Cover Measured through Field Instrumentation..... 330
Md. Jobair Bin Alam, Naima Rahman, Prabesh Bhandari, and Md. Sahadat Hossain

© ASCE

Application of Shear Wave Velocity to Rock Rippability Estimates Based on Poisson's Ratios Determined from Laboratory and Field Measurements 339
Salman Rahimi, Clinton M. Wood, Rendon Rieth, and Ashraf Kamal Himel

Freeze-Thaw Electrical Resistivity Hysteresis Response of Frost Susceptible Clayey Sands 350
Rui Liu, Daniel Offenbacker, Cheng Zhu, John Schmalzel, Yusuf Mehta, Benjamin Barrowes, Danney Glaser, and Wade Lein

Ability of the Multichannel Analysis of Surface Waves Method to Resolve Subsurface Anomalies 360
U. Arslan, J. A. Crocker, J. P. Vantassel, and B. R. Cox

Robust Climate-Adaptive Shallow Foundation Design Optimization Subjected to Hydrological Loads.....372
Vahidreza Mahmoudabadi and Nadarajah Ravichandran

Wind Turbine Intermediate Foundation Performance through Frequency Analysis 384
Yazen Khasawneh, Mohammad Nasim, Ashkan Nafisis, Sadra Javadi, and Linna Duan

Evaluation of Pinnacle Bedrock Topography Using Surface Waves: A Numerical Simulation of Full Waveform Tomography 394
Siavash Mahvelati, Alireza Kordjazi, and Joseph T. Coe

© ASCE

Study of Period Lengthening Effects in Soil–Structure Interaction Systems

Jaime A. Mercado, S.M.ASCE[1]; Luis G. Arboleda-Monsalve, M.ASCE[2]; and Kevin Mackie, F.ASCE[3]

[1]Research Assistant, Dept. of Civil, Environmental, and Construction Engineering, Univ. of Central Florida, Orlando, FL. Email: jamercado@knights.ucf.edu
[2]Assistant Professor, Dept. of Civil, Environmental, and Construction Engineering, Univ. of Central Florida, Orlando, FL. Email: luis.arboleda@ucf.edu
[3]Professor, Dept. of Civil, Environmental, and Construction Engineering, Univ. of Central Florida, Orlando, FL. Email: kevin.Mackie@ucf.edu

ABSTRACT

Natural period of structures can be elongated by the inclusion of a flexible foundation system. Period lengthening arising from the inclusion of soil–structure interaction (SSI) changes seismic design of structural and geotechnical systems, since period elongation may lead to larger demands in the structure. This paper parametrically studies the main variables that influence period lengthening characteristics of tall buildings. Variables such as the fixed-base natural period of buildings, structural aspect ratios, and effective soil shear wave velocity of supporting soils were included in the analysis using a direct approach. Three-dimensional (3D) numerical simulations including SSI effects were included to show the effects of period lengthening of tall buildings when compared to more common fixed-base 3D analyses. The analyses were performed using OpenSees by applying ground motions in two directions. Supporting soils are modeled by means of a direct approach in a fully coupled continuum soil-structure system formulation to represent in a more realistic manner the SSI effects. It is concluded that period lengthening of the first natural period of the structure arising from including SSI effects in the numerical framework produced more flexible structures. SSI generally increases the engineering demand parameters when compared to fixed-base models.

INTRODUCTION

Modeling soil-structure interaction when analyzing the dynamic response of tall buildings, largely affects the dynamic characteristics of supporting soils and structure since the system is placed on a flexible support system that causes variations in the engineering demands parameters (EDPs) in relation to conventional fixed-base building models. Soil-structure interaction should be considered when analyzing the dynamic response of buildings to avoid unrealistic computation of engineering demand parameters that affect seismic designs. Mylonakis and Gazetas (2000) found that the period lengthening of a structure due to SSI did not necessarily produce a conservative response and may lead to larger ductility demands in the structure. SSI generally increases the natural period of the structures by the inclusion of a flexible base soil-foundation system. This is usually referred to as period lengthening. This period lengthening may modify the seismic performance of a building by increasing translation and rotation due to the flexibility of the soil. SSI effects are properly accounted for in seismic response analyses when soil strength and stiffness reduction (i.e., strength-stress-strain soil response), soil damping evolution characteristics, and soil-foundation-structure responses are modeled as a fully coupled system. NIST (2012) and Givens (2013) summarized several methods to account for SSI effects,

© ASCE

in the tall buildings due to the modeling assumptions. Time histories analyses showed how the phasing of the responses is elongated when SSI effects are included. Also, the results showed that fixed-base conditions are not always conservative and the inclusion of SSI effects in tall buildings affects the computed distribution of engineering demands along the structure height. SSI generally increased the engineering demand parameters when compared to fixed-base assumptions, which can lead to more realistic computation of seismic demands in current structural or geotechnical practice. Inclusion of SSI effects and the use of advanced 3D structural models is strongly recommended by the authors when evaluating the seismic response of tall buildings to avoid underestimation of earthquake-induced demands in seismic project designs.

ACKNOWLEDGEMENTS

Financial support for this work was provided by the National Science Foundation Grant No. CMMI-1563428. The support of Dr. Joy Pauschke, program director at the National Science Foundation, is greatly appreciated.

REFERENCES

AMEC. (2013). Final Geotechnical Data Report. Regional Connector Transit Corridor Project. Contract No. E0119. Prepared for Metro. Los Angeles, California.

Arboleda-Monsalve, L. G., Mercado, J. A., Terzic, V., and Mackie, K. R. (2020). "Soil–Structure Interaction Effects on Seismic Performance and Earthquake-Induced Losses in Tall Buildings." *Journal of Geotechnical and Geoenvironmental Engineering*, 146(5),

ASCE. (2017). *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*. American Society of Civil Engineers, Reston, VA,

Biot, M. A. (1962). "Generalized Theory of Acoustic Propagation in Porous Dissipative Media." *The Journal of the Acoustical Society of America*, 34(9A), 1254–1264,

Blume, J. A. (1968). "Dynamic Characteristics of Multistory Buildings." *Journal of the Structural Division*, 94(2), 377–402.

Filippou, F. C., Popov, E. P., and Bertero, V. V. (1983). "Effects of Bond Deterioration on Hysteretic Behaviour of Reinforced Concrete Joints. Report to the National Science Foundation." Earthquake Engineering Research Center, (August), 1–212.

Givens, M. J. (2013). *Dynamic Soil-Structure Interaction of Instrumented Buildings and Test Structures.* Ph.D. Dissertation, Universtity of California, Los Angeles.

Lysmer, J., and Kuhlemeyer, R. L. (1969). "Finite Dynamic Model for Infinite Media." *Engineering Mechanics Division*, 95(1882), 167–188.

McKenna, F., Fenves, G. L., Scott, M. H., and Jeremic, B. (2000). "Open System for Earthquake Engineering Simulation (OpenSees)." Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

Mercado, J. A., Arboleda-Monsalve, L. G., and Terzic, V. (2019). "Seismic Soil-Structure Interaction Response of Tall Buildings." *Geo-Congress 2019*, American Society of Civil Engineers, Philadelphia, PA, 118–128,

Mercado, J. A., Mackie, K. R., and Arboleda-Monsalve, L. G. (2020). "Modeling Nonlinear-Inelastic Seismic Response of Tall Buildings with Soil-Structure Interaction." *Journal of Structural Engineering*, Under Peer Review.

© ASCE

Mylonakis, G., and Gazetas, G. (2000). "Seismic Soil-Structure Interaction: Beneficial or Detrimental?" *Journal of Earthquake Engineering*, 4(3), 277–301,

National Institute of Standards and Technology NIST. (2012). Soil-Structure Interaction for Building Structures, Report NIST/GCR 12-917-21.

Stewart, J. P., Fenves, G. L., and Seed, R. B. (1999). "Seismic Soil-Structure Interaction in Buildings. I: Analytical Methods." *Journal of Geotechnical and Geoenvironmental Engineering*, 125(1), 26–37.

© ASCE

Comparison of Different Methods Used to Account for Shear Wave Velocity Variability in 1D Ground Response Analyses

Mohamad M. Hallal, S.M.ASCE[1]; and Brady R. Cox, Ph.D., P.E., A.M.ASCE[2]

[1]Graduate Research Assistant, Dept. of Civil, Architectural and Environmental Engineering, Univ. of Texas, Austin, TX. Email: mhallal@utexas.edu
[2]Professor, Dept. of Civil, Architectural and Environmental Engineering, Univ. of Texas, Austin, TX. Email: brcox@utexas.edu

ABSTRACT

One-dimensional (1D) ground response analyses (GRAs) have generally been found to yield site response predictions that are different than recorded ground motions at many downhole array sites, presumably due to their laterally variable subsurface conditions. While there is no doubt that some sites are indeed too variable to be modeled using 1D GRAs, it is also possible that simple 1D analyses could still be effectively used if spatial variability is accounted for via a rational, site-specific approach. In this study, we test three approaches that can be used to account for spatial variability in 1D GRAs: (1) randomization of shear wave velocity (Vs) profiles; (2) increasing the small-strain damping ratio; and (3) an H/V geostatistical approach for generating site-specific spatially variable Vs profiles. We test these approaches at two downhole array sites so that the 1D GRA results can be compared with recorded ground motions. Of the investigated approaches, we find that the H/V geostatistical approach produces superior results and reproduces phenomena observed in the recorded site response at both downhole array sites. In regard to each of these approaches, we discuss issues that should be resolved to enable their adoption in practice.

INTRODUCTION

Many recent studies (e.g., Afshari and Stewart 2019; Kaklamanos et al. 2013, 2020; Tao and Rathje 2019; Teague et al. 2018; Thompson et al. 2009, 2012) have illustrated that one-dimensional (1D) ground response analyses (GRAs) are generally unable to accurately replicate recorded ground motions at many borehole array sites. This is generally attributed to the laterally variable subsurface conditions at most sites, which causes complex phenomena not captured by 1D GRAs. Several methods have therefore been proposed to better model the variability of subsurface conditions. For example, stochastic randomization of shear wave velocity (Vs) (e.g., Toro 1995), utilizing suites of Vs profiles from surface wave testing (e.g., Teague et al. 2018), and increasing the small-strain damping ratio (D_{min}) (e.g., Tao and Rathje 2019) are all simplified methods that attempt to incorporate complex 3D variability through modifications to 1D analyses. Recently, Hallal and Cox (2020a) proposed a new geostatistical approach for building pseudo-3D Vs models using a single measured Vs profile and spatially distributed estimates of fundamental site frequency (f_0) from horizontal-to-vertical spectral ratio (H/V) noise measurements ($f_{0,H/V}$) recorded using broadband seismometers across the site.

In this paper, we investigate three approaches that incorporate spatial variability into 1D GRAs. We test these approaches at two downhole array sites so the 1D GRA results can be compared with recorded ground motions. The investigated approaches include: (1)

© ASCE