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NUMERICAL STUDY OF SEISMIC EARTH PRESSURES IN CENTRIFUGE MODEL EXPERIMENTS

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ABSTRACT

A two-dimensional nonlinear finite element model was developed on the OpenSees platform to study the behavior of U-shaped cantilever retaining wall-backfill systems under seismic loading and to evaluate the magnitude and distribution of seismic earth pressures on retaining walls. The finite element model was calibrated and evaluated against a set of results from dynamic centrifuge experiments performed by the authors. The finite element model was used to assess the ability of numerical modeling in capturing the essential features of the seismic response observed in the centrifuge experiments. Results from the numerical simulations are in good agreement with centrifuge results and confirm that seismic earth pressures have a linear distribution with depth. Most importantly our results show that appropriately calibrated non-linear numerical models can capture the essential aspects of the experimentally observed seismic response of retaining structures.

Introduction

Since the pioneering work of Mononobe and Matsuo (1929) and analytical work of Okabe (1926), researchers have developed a variety of analytical models to predict the dynamic behavior of retaining walls or performed various types of experiments to study the mechanisms behind the development of seismic earth pressures on retaining structures. Numerical modeling efforts have been applied to verify the seismic design methods in practice and to provide new insights to the problem. However, successful application of numerical simulations requires adequate opportunity to calibrate the model either against well documented case history (ies) and/or experiments. Frequently, in the past, the "calibration" was obtained by comparison with so-called Mononbe-Okabe limit equilibrium solution, which does not properly reflect the actual dynamic response of the retaining structure-soil system. Alternatively, some numerical models were calibrated against results from small-scale shaking table experiments, which cannot be scaled to represent actual soil prototype behavior being a stress-dependent material. In contrast, centrifuge test results provide an excellent data base that can be used in calibrating and evaluating dynamic numerical tools, which then can be used for parametric studies and evaluation of various design alternatives. Therefore, a numerical study was conducted on a two-dimensional (2-D) finite element (FE) model using the Open System for Earthquake Engineering Simulations (OpenSees) to study the seismic behavior of retaining wall-backfill systems. The main objective of this effort was to explore how well a

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numerical model could match observed and recorded dynamic data. Specifically, the FE model was evaluated for its ability to capture the essential features of the seismic behavior of the retaining wall-backfill systems by comparing the computed responses to those measured in the centrifuge experiments performed by the authors. The FE model was calibrated against centrifuge results from three shaking events. Simulation results from one shaking event recorded during the Loma Prieta 1989 earthquake at the Santa Cruz station (Loma Prieta-SC-1) are presented in this paper.

Centrifuge Model

The FE model presented in this paper simulates dynamic centrifuge experiment LAA02 performed by the authors at the Center for Geotechnical Modeling at the University of California, Davis. The model configuration for centrifuge experiment LAA02 is shown in Fig. 1 in model units. In prototype scale, the LAA02 model consists of two retaining wall structures, stiff and flexible, of approximately 6m height spanning the width of the container. The U-shaped cantilever retaining structures were designed to represent prototype designs under consideration by the Bay Area Rapid Transit (BART). The model structures rested on approximately 12.5 m of dry medium-dense Nevada sand (Dr = 72%) and were backfilled with dry medium-dense Nevada sand (Dr = 72%). LAA02 model was constructed in a flexible shear beam container and subjected in flight to multiple shaking events covering a wide range of predominant periods and peak ground.

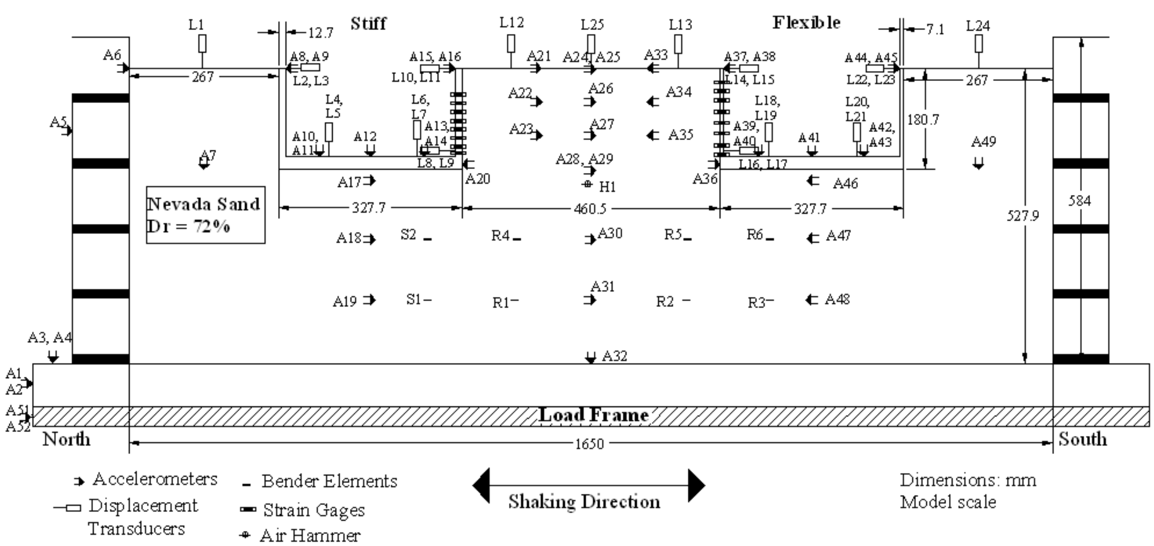

Figure 1. LAA02 model configuration, profile view.

The model structures and the soil were densely instrumented to collect accurate and reliable measurements of accelerations, displacements, shear wave velocities, strains, bending moments and earth pressures. Three different sets of instruments were used to collect accurate measurements of lateral earth pressures acting on the walls. Lateral earth pressures on the four walls were directly measured using flexible tactile pressure Flexiforce sensors manufactured by Tekscan. Lateral earth pressures were also back-calculated based on the bending moments measured by the strain gages mounted on the south stiff and north flexible walls. Finally, direct measurements of the total bending moments at the bases of the south stiff and north flexible walls were made using force-sensing bolts at the wall-foundation joints. The detailed description of the experimental work performed by the authors can be found in Alatik and Sitar (2008).

Numerical Model

Overview of Finite Element Model

The 2-D plane strain FE model of the U-shaped cantilever retaining structures and the backfill and base soil simulating centrifuge experiment LAA02 is presented in Fig. 2. The fine FE mesh consisted of a total of 6384 soil nodes, 6048 soil elements, 166 wall nodes, 164 wall elements, and 166 spring elements. The U-shaped retaining structures were modeled as linear elastic elements. A 2-D plane strain, pressure dependent, elasto-plastic material was used to model the nonlinear response of the dry Nevada sand. Nonlinear zero-length springs were used to model the interface between the retaining structures and the sand backfill.

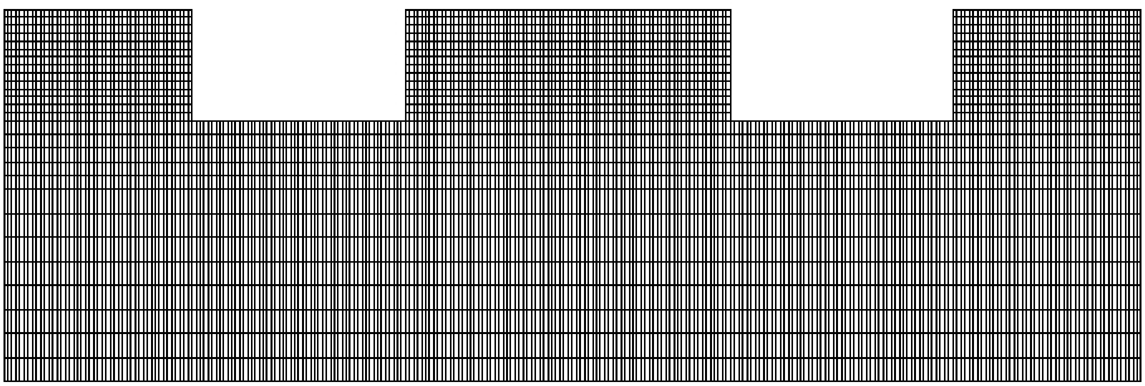

Figure 2. Two-dimensional, plane strain, FE mesh.

Boundary conditions of the 2-D FE mesh consisted of: 1) base nodes of the soil continuum fixed horizontally and vertically to reproduce the fixed-base conditions of the model container, 2) displacement degrees of freedom of the lateral boundary nodes of the soil continuum tied together horizontally and vertically, 3) traction free surface, and 4) dynamic excitation defined as the recorded base acceleration.

Soil Constitutive Model

The uniform density dry sand of experiment LAA02 was modeled by single-phase, four-node, quadrilateral elements. Pressure Dependent Multi-Yield (PDMY) material was used to simulate the nonlinear sand response. The PDMY soil is an elasto-plastic material that simulates the essential response characteristics of pressure sensitive soils subject to loading including shear induced nonlinearity and dialatancy. This constitutive soil model is based on the framework of multi-yield surface plasticity, in which a number of conical yield surfaces with different tangent moduli are employed to represent shear stress-strain nonlinearity and confinement dependence of shear strength. The yield surfaces are of the Drucker-Prager type. Detailed description of the PDMY soil material and its parameters can be found in Yang (2000), Yang et al. (2002, 2003, and 2008) and Elgamal et al. (2002, 2003).

Model Calibration

Table 1 presents the main modeling parameters for the dry medium-dense sand used in experiment LAA02. The initial dry soil mass density, void ratio and reference shear modulus were based on centrifuge measurements. Initial friction angle and phase transformation angle were defined based on calibration against centrifuge results and on values presented in Arulmoli et al. (1992). Poisson's ratio was defined to result in a friction angle of 35° for normally consolidated sand. The low strain bulk modulus was determined using the elastic relation with the low strain shear modulus and Poisson's ratio. Peak octahedral shear strain and contraction and dialation parameters were defined based on recommendations provided in Yang et al. (2008). Liquefaction-induced strain constants were set to zero to deactivate the liquefaction mechanism.
The yield surfaces were defined in OpenSees based on the shear modulus reduction curve specified as G/Gmax and shear strain pairs. According to the procedure outlined in Zeghal et al. (1995) and Elgamal et al. (2005), shear stress and shear strain responses at different depths along the centerline of the soil were estimated based on the one-dimensional shear beam idealization using the recorded lateral downhole accelerations for the different shaking events during centrifuge experiment LAA02. Fig. 3 presents the modulus reduction curve G/Gmax evaluated from selected shear stress-strain loops at location A27. Shear strain and G/Gmax pairs were defined in OpenSees based on Fig. 3.

Table 1. Principal modeling parameters for dry medium-dense Nevada sand (Dr = 72%).

Model Parameter	Parameter Value
Initial Mass Density (kg/m^3)	1692
Reference Shear Modulus, G_r (kPa)	5.30E+04
Poisson's Ratio	0.3
Reference Bulk Modulus, B_r (kPa)	1.15E+05
Reference Confining Stress, P'_r (kPa)	54
Peak Shear Strain	0.1
Pressure Dependent Coefficient	0.5
Shear Strain and G/Gmax pairs	Based on Fig. 4
Friction Angle (degrees)	35
Phase Transformation Angle (degrees)	27
Contraction Constant	0.05
Dilation Constants	d_1=0.6, d_2=3.0
Liquefaction Induced Strain Constants	0
Number of Yield Surfaces	11
Void Ratio	0.566

The walls and the bases of the retaining structures were modeled in OpenSees using elastic beam/column elements. Each wall consisted of 15 nodes and 14 elements, while each base consisted of 55 nodes and 54 elements. The retaining structures used in the FE model had the same prototype dimensions, mass, and properties as the aluminum structures used in the centrifuge experiments. The connections between the wall and the base of each structure were modeled as rigid moment connections in OpenSees, which means that no rotational flexibility was allowed at the connections.

The soil-structure interaction in the FE model was simulated by zero-length nonlinear springs. Each nonlinear spring consisted of an elastic-no-tension component in parallel with a viscous component or a dashpot representing radiation damping. The properties of the nonlinear springs were generally selected based on calibration against experimental results and to be proportional to the strength and the damping of the adjacent soil elements. Horizontal springs were used to connect the backfill soil to the retaining walls while vertical springs were used to connect the base of the retaining structures to the base soil.

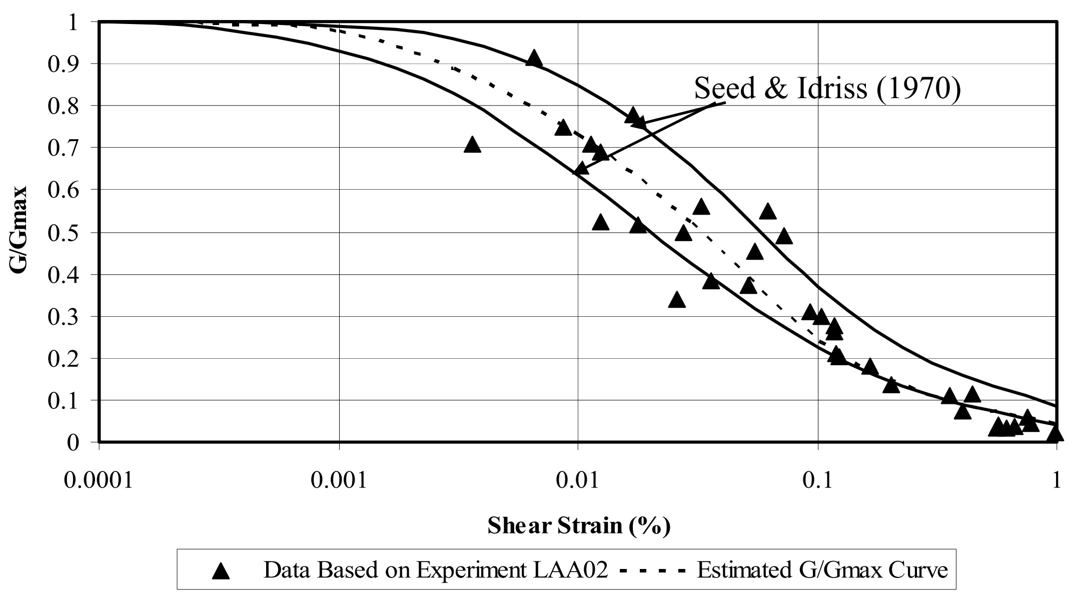

Figure 3. Modulus reduction curve estimated based on acceleration data recorded during the different shaking events of centrifuge experiment LAA02.

Simulation Results

Acceleration

Fig. 4 presents comparison of the computed and recorded horizontal acceleration time series at the top of the soil in the free field, top of the south stiff and north flexible retaining walls for the Loma Prieta-SC-1 shaking event. The input acceleration time series is also presented in Fig. 4. All acceleration time series were corrected such that horizontal acceleration is positive towards the north end of the model container. Fig. 4 shows that the computed and recorded acceleration time series at the top of the retaining structures and the soil in the free field were in excellent agreement in terms of the phase and magnitude of accelerations.

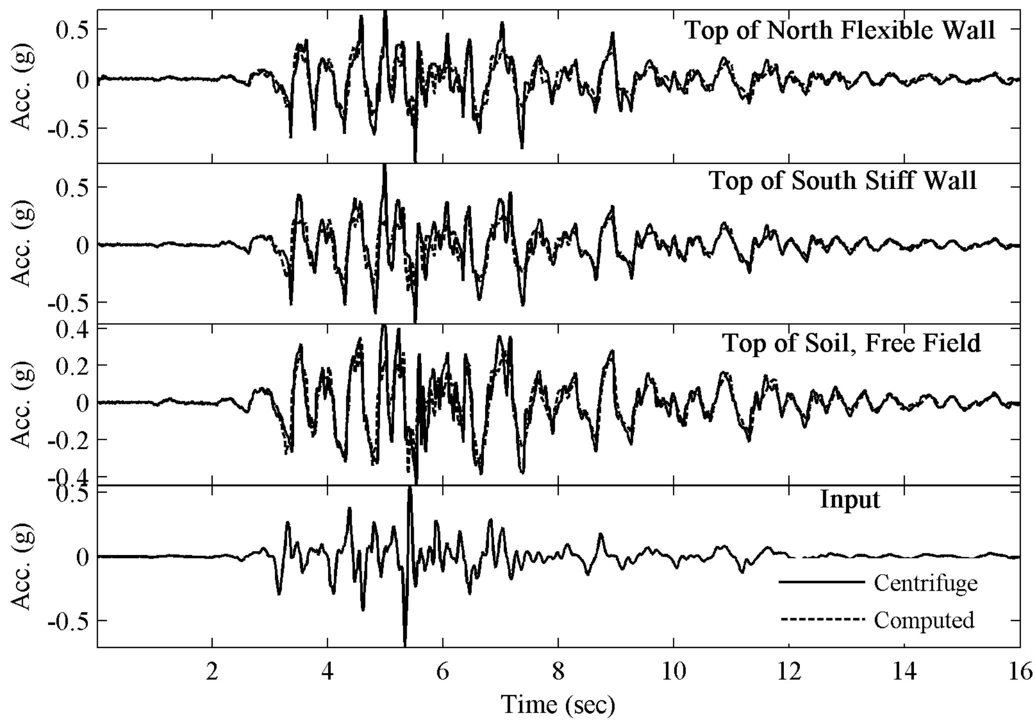

Figure 4. Comparison of recorded and computed accelerations at the top of the soil in the free field and at the top of the south stiff and north flexible walls during Loma Prieta-SC-1.

Bending Moments

Fig. 5 presents recorded and computed total wall moment time series on the south stiff and north flexible retaining walls during the Loma-Prieta-SC-1 shaking scenario. Total wall moments represent the moment on the retaining walls due to the combined effects of earth pressures (static and dynamic) and wall inertia. Recorded total wall moment time series are interpreted from the strain gage measurements while computed total wall moment time series are obtained in OpenSees using the wall element recorder. Moments presented in Fig. 5 were corrected such that positive moment corresponds to wall rotation away from the soil for both stiff and flexible walls.

Fig. 5 shows that the computed and recorded total wall moments are in good agreement. The computed moments well reproduced the phase and magnitude of the moment responses of the stiff and flexible walls. Moreover, the FE model successfully simulated the gradual increase in static moment as a result of shaking and soil densification and the cubic distribution of static and total moments along the depth of the walls.

Lateral Earth Pressure

Fig. 6 presents a comparison of the computed and recorded total (static plus dynamic) lateral earth pressures at various locations on the south stiff and north flexible walls during the

Loma Prieta-SC-1 shaking event. Recorded earth pressures in Fig. 6 were measured using the Flexiforce sensors while computed earth pressures were obtained in OpenSees using spring force recorders. Lateral earth pressures in Fig. 6 were corrected such that positive earth pressure corresponds to a force acting on the wall in the direction away from the backfill.

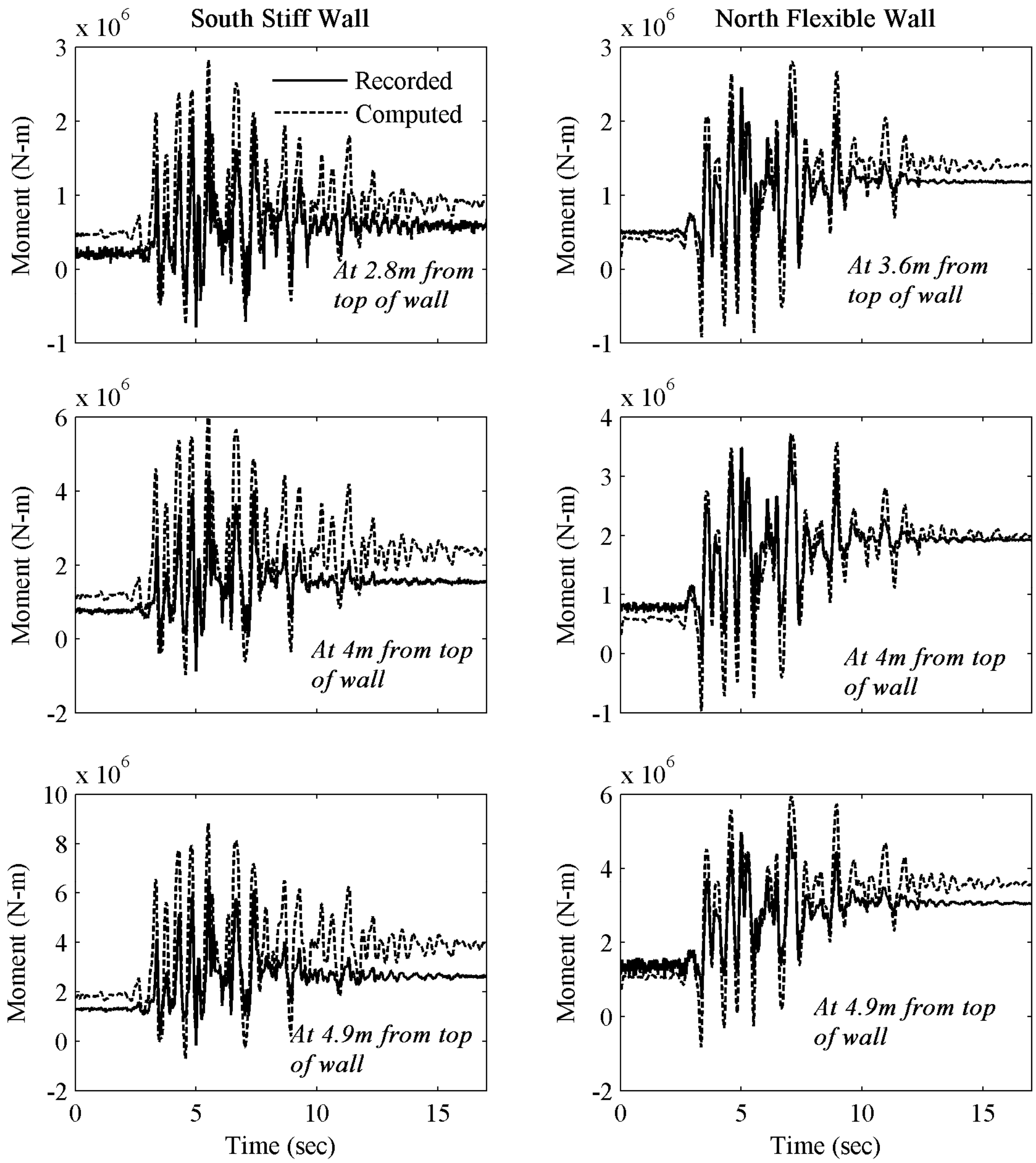

Figure 5. Comparison of computed and recorded total wall moment time series at different locations on the south stiff and north flexible wall during Loma Prieta-SC-1.

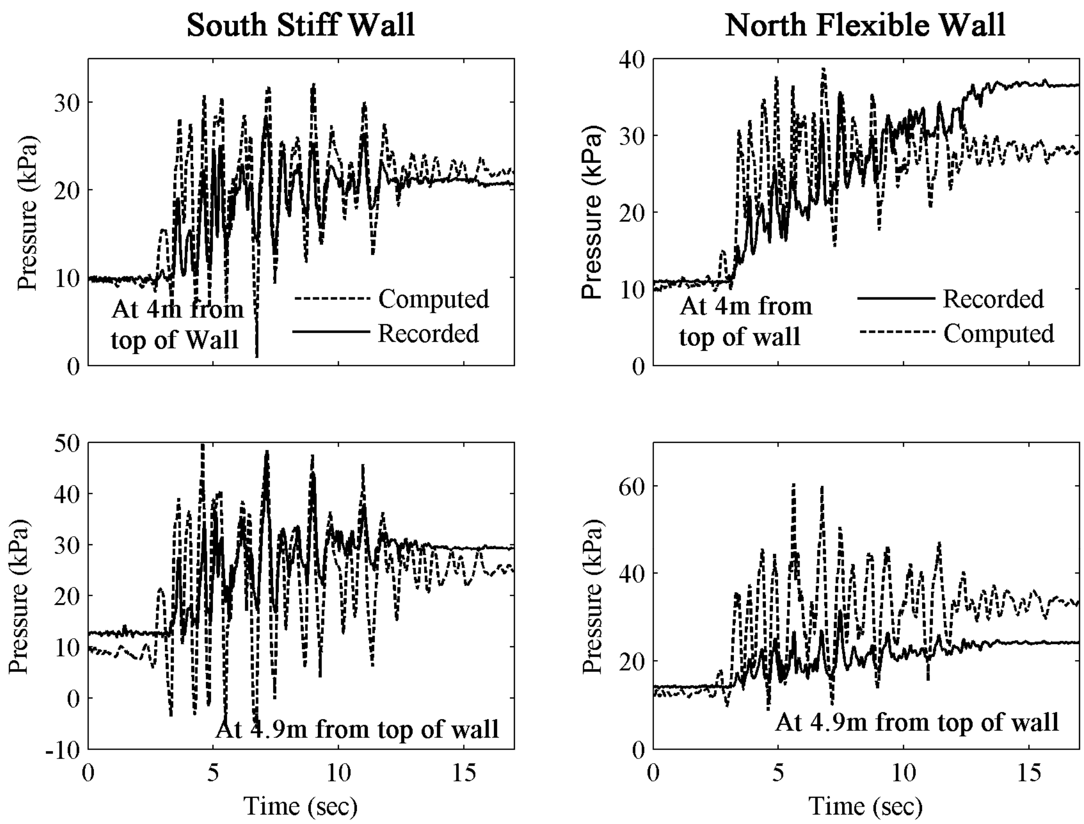

Figure 6. Comparison of computed and recorded total earth pressure time series at different locations on the south stiff and north flexible walls during Loma Prieta-SC-1.

As shown in Fig. 6, a poor to reasonable agreement is observed between the computed and recorded total earth pressures on the stiff and the flexible walls. Despite the reasonable phase agreement between the recorded and computed total earth pressure time series, computed values usually overestimated the magnitude of the recorded total earth pressures. It should be noted that the accuracy of the earth pressure magnitudes measured by the Flexiforce sensors is limited due to drift and conditioning problems encountered with these sensors during the centrifuge experiments. Moreover, the computed earth pressures in OpenSees were sensitive to small variations in the properties of the wall-soil springs and the type of soil-structure interaction. While the soil-wall spring properties were carefully selected to obtain a good overall agreement in the computed and recorded moment and pressure responses, a more elaborate modeling of the soil-structure interaction could possibly produce better results. Overall and despite the mentioned limitations, the main characteristics of the static and total earth pressures acting on the stiff and the flexible retaining walls observed in the centrifuge experiment were adequately simulated by the FE model.

Soil Shear Stress and Strain Responses

Fig. 7 presents a comparison of interpreted and computed shear stress (τxy) and shear strain (εxy) time series in the middle of the backfill in the free field for the Loma Prieta-SC-1 shaking scenario. Interpreted shear stress time series was evaluated based on the one-dimensional shear beam idealization. Interpreted shear strain time series was evaluated based on the displacement time series obtained by double-integrating the acceleration records. This method of estimating the shear strain time series eliminates any residual static shear strain after shaking because of the high pass filtering and double integration of the acceleration records. It should be noted that shear stress and shear strain estimates based on the centrifuge recorded accelerations are of second order accuracy. As shown in Fig. 7, the computed and interpreted shear stress strain time series are in very good agreement.

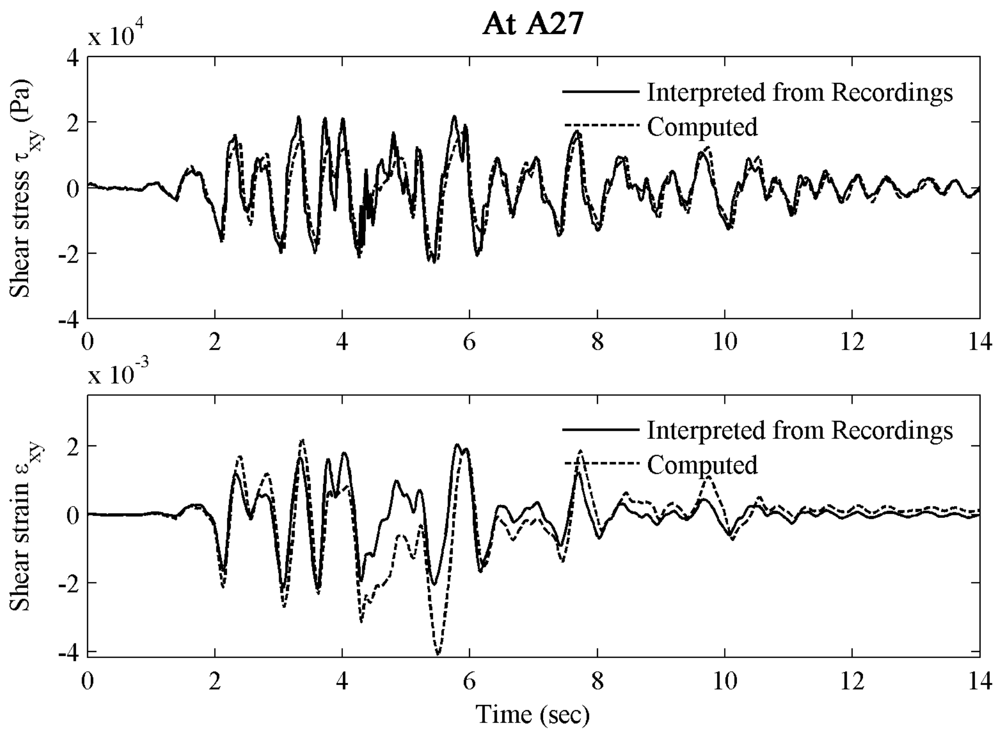

Figure 7. Comparison of computed and recorded shear stress and strain time series in the middle of the soil backfill during Loma Prieta-SC-1.

Conclusions

Centrifuge experiments and numerical simulations were carried out to study the behavior of cantilever retaining wall-backfill systems under seismic loading and to evaluate the magnitude and distribution of dynamic earth pressures on the walls. Numerical simulations were performed on a 2-D plane strain FE model developed on the OpenSees platform and calibrated and evaluated against a set of centrifuge model results for three shaking events. Computed and recorded results consisting of acceleration, bending moments, earth pressures and shear stress and strain time series were compared. Despite the simplifications and inherent limitations in the FE model, as well as the uncertainties in the input parameters, computed results show that the FE analysis is able to capture reasonably well the essential system responses observed in the centrifuge experiments. Based on the results of this study, we conclude that numerical simulations and centrifuge testing, paired together, provide an effective tool for understanding the complex soil-structure interaction problem in the design of retaining structures. The ultimate goal, of course, is to be able to use numerical models with confidence in order to make reliable prediction of expected behavior of retaining structures under seismic loading. At this point, further experimental and analytical work is needed to reach the requisite level of confidence for use in design.

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