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EVALUATION OF SEISMIC RESPONSE OF SOIL+BRIDGE SYSTEM USING 3D DISCRETE AND CONTINUUM SIMULATION APPROACHES

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Abstract

Soil-Structure Interaction (SSI) has a significant impact on the response of bridge structures subjected to strong earthquakes. In this study, the direct modeling method is employed to evaluate seismic response of RC bridges. Direct modeling method is the preferred approach for nonlinear analysis where the detailed behavior of soil and structure systems are represented.

Direct approach may be implemented by two different modeling methods using discrete and continuum models. In the discrete method effect of soil surrounding pile and foundations is represented by springs and dashpots. Discrete modeling approach is one of the most widely used methods to calculate response of the soil+bridge system due its relatively simple setup and low computational cost. In the continuum approach, on the other hand, continuum 2D or 3D models are used to model the soil and structural components.

Despite of popularity of the discrete modeling method in practice, it has rarely been verified against the continuum models. As a result, there is uncertainty surrounding the accuracy of the discrete methods in representing the SSI effects. The main objective of this study is to compare the response predictions of discrete and continuum models for the Meloland Road Overcrossing (MRO) located in Southern California. MRO was constructed in 1969 and has experienced multiple earthquake events. This bridge has been heavily instrumented and has been the subject of many studies [1, 2, 3, 4, 5].

To compare the results obtained from full-scale discrete and continuum modeling methods at collapse level, one 3-D discrete archetype model including SSI effects and one 3D continuum soil+bridge model are developed. The discrete models developed using SeismoStruct software. ABAQUS software is employed for the continuum analysis. Dynamic characteristics of all developed numerical models are verified against field measurement data from previous studies.

A comparison of seismic responses calculated using both methods showed significant differences in potential design parameters such as drift ratio and base shear.

Keywords: Direct Approach Analysis, Discrete Modeling Method, Continuum Modeling Method, Soil-Structure Interaction (SSI), Seismic Response.

1. Introduction and Methodology

Occurrence of severe earthquake has resulted in collapse of many pile-supported bridges globally. Interaction of soil with structure and its effect on structural response has been a major reason for collapse of bridge structures constructed on the soft soil. There is a lack of comprehensive consideration of the effect of Soil-Structure Interaction (SSI) in the seismic design of structures founded on the soft soil [6, 7]. Hanshin Expressway Bridge during the Kobe Earthquake in 1995 is one of the examples where SSI had a major contribution to collapse of the bridge. An analytical study of the Hanshin Expressway Bridge showed that soil characteristics had a significant effect on the behavior of this structure. It is concluded that elongation of the fundamental period of system (soil+structure) and modification of earthquake frequency content due to soft soil, resulted in intensifying the structural response [8].

Analytical approach to SSI is one of the most common methods to take effect of soil-structure interaction into account. In this method, soil-structure models are constructed, and seismic response of this combined system is predicted using computational methods such as nonlinear dynamic analysis. To appropriately estimate geotechnical and structural demands, detailed numerical modeling considering geotechnical and structural components are required in analyses. Accurate representation of behavior of soil as well as structural components going thorough nonlinear regime is a key factor in analytical SSI models. Detailed computer models of soil-structure systems are usually very computationally costly. In addition, there is a lack of comprehensive guidelines in code provisions regarding implementation of SSI effect in numerical models. Within the analytical framework, there are two approaches to simulate soil-structure interaction effect; namely, discrete and continuum approaches.

In discrete approach, effect of soil is represented by springs and dashpots attached to piles, abutment backwalls and abutment and pier buried foundations. Properties of these discrete elements are determined based on soil characteristics. API [9], AASHTO [10], and CALTRANS [11] offer methods to define properties of springs and dashpot for piles and abutments. Although the discrete approach offers a computationally effective solution, this approach is inherently incapable of accurately capturing the inertial and kinematic SSI effects [12]. More complex models that include lumped masses, e.g. models proposed by Wolf [13], offer an improved representation of inertial effects but the kinematic effects are still missing. Discrete models are also incapable of simulating the dynamic effects on pore-water pressure in soil which is the cause of liquefaction [12].

In continuum approach, the soil is simulated by continuum elements allowing for a more physical representation of its behavior. Soil layers are explicitly simulated in this approach using continuum elements. In this approach, development of pore-pressure (which is the cause of liquefaction) can be explicitly simulated. Although continuum approach offers more realistic representation of the soil, its complexity and computational cost compared to discrete approach makes it a less favorable choice in engineering practice. Detailed 3D continuum modeling method where soil and structure are simulated together, would capture both kinematic and inertial soil-structure interaction phenomena. Thus, the 3D continuum modeling method provides a better insight into the SSI effects compared with the discreet method. In addition, non-linear response of the soil and damage of the structural components in the model can be simulated more accurately using continuum method compared to the discrete method.

Rahmani and co-workers [5] evaluated substructuring method for analysis of soil+bridge systems. There is no significant body of work on comparing seismic response of soil+structure systems predicted using discrete and 3D continuum models (direct approach). In this study, Meloland Road Overcrossing (MRO) is used as a case study to compare calculated seismic response of the bridge using discrete and continuum approaches. MRO is a well-instrumented bridge which has been subject of multiple earthquakes in Southern California. A discrete model of soil+bridge system (D Model) is developed using the SeismoStruct software [14] and continuum models (C) is constructed using the Abaqus software. Corresponding drift and base shear of the abutment backwalls and pier column of the C and D model are calculated and compared performing nonlinear time history response analysis. Nonlinear time history response analysis is carried using a set of 10 ground motions scaled to the collapse level of the discrete archetype model (model D). Collapse scale factor of each ground motion is obtained performing IDA on the archetype model D are presented in different paper by the same authors at this conference [15].

This article is created based on doctoral dissertation of the first author. Readers are encouraged to refer to [16] for further details on modeling approach and results.

2. Model Description

2.1 Discrete Model (D Model)

A 3-D discrete finite element model (D model) of Meloland Overcrossing Road (MRO) is developed in SeismoStruct software [14] to study soil-structure effects in response of the structure. This numerical model is developed considering soil-structure interaction features. In this model, superstructure and substructure components including abutment and pier piles are represented in detail as shown in Fig. 1.

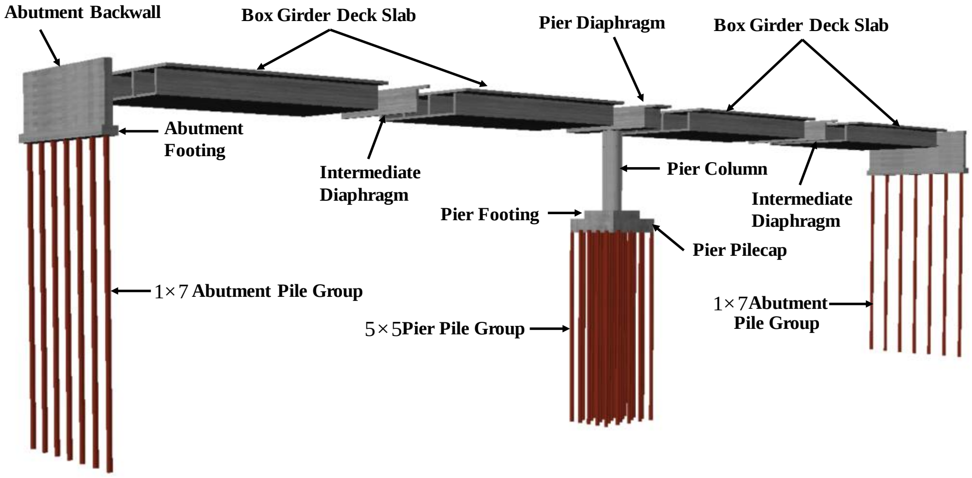


Fig. 1 – 3D view of D model constructed using SeismoStruct software [16].

2.1.1. Material Properties

Nonlinear concrete model proposed by Mander and co-workers [17] is used as the material model for the pier columns and abutment backwalls in the archetype models. The confinement effects provided by the lateral transverse reinforcement are incorporated using the methodology proposed in [17]. Material properties for the pier column and abutment backwalls are considered identical with the material properties were considered by Werner and co-workers [1] in section property computations. These values are summarized in Table 1.

Table 1– Non-linear concrete material properties for the MRO pier column and abutment backwalls [1].

Parameter	Value (unit)	Parameter	Value (unit)
$(EI)_{crack}$	3.37E+09 (Nm^2)	I_g	2.65E-01 (m^4)
$(EI)_{Uncrack}$	7.48E+09 (Nm^2)	I_{crack}	1.19E-01(m^4)
Crack % (α)	0.45(-)	Steel yield Stress (f_y)	312.3 (MP_a)
f'_c	35.6 (MP_a)	Poisson Ratio (ν_c)	0.17(-)
ε_u	0.003 (m/m)	Pier Column axial load	5,382.4 (kN)

2.1.2 SSI Features

In the discrete model (D Model), presence of the abutment embankment (or lateral response of abutment systems) is considered using the method proposed by Shamsabadi and co-workers [18]. As shown in Fig. 2 , lateral soil resistance around the abutment and pier piles are considered using lateral pile-soil support curves (p-y curves) of the API provision [9] and manual of the computer program Ensoft LPile [19].

The model parameters fitted for granular backfill using EHFD approach developed by Shamsabadi and co-workers [18] were employed here to develop the passive pressure response curve. A tri-linear curve was fitted to the data as well as shown in Fig. 3. As shown in this figure, the passive pressure response is also compared with the seismic design criteria revision 2.0 of the Caltrans [11] approach as well. As shown in Fig. 3, the initial stiffness obtained from the EHFD approach matches well with the proposed Caltrans model. The asymptotic passive force is also in a good agreement between the two models.

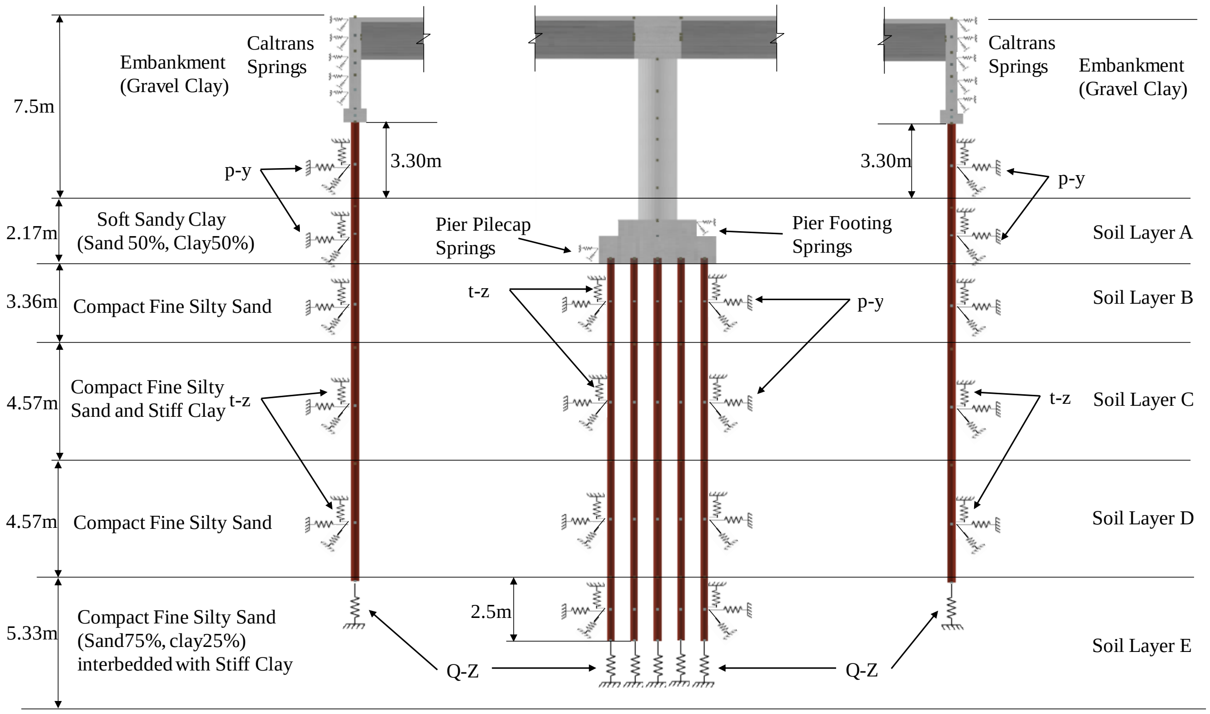


Fig. 2 – Abutment backwalls' springs and API springs arrangement are considered in the discrete model to simulate Abutment-backfill soil interaction and soil-pile interaction, respectively [16].

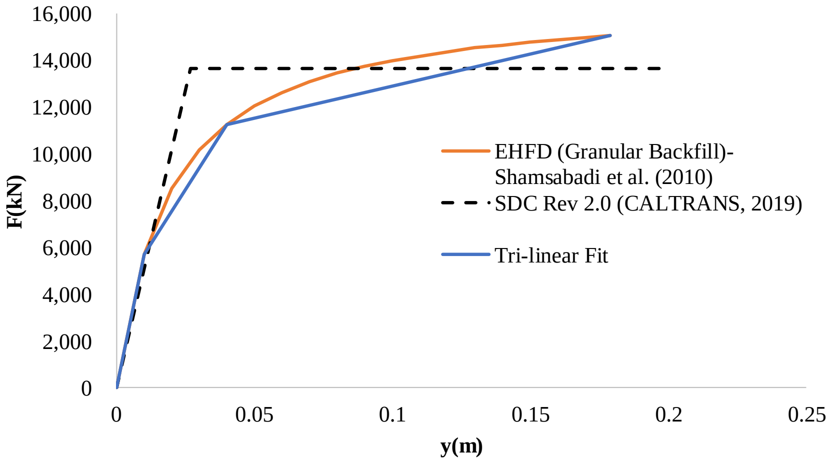


Fig. 3 – Non-linear abutment response in longitudinal direction of the Meloland Road Overcrossing (MRO)

Using the relevant API p-y, t-z, and Q-z equations [9], force-deflection curves for abutment and pier piles are calculated and defined in the discrete model.

2.2 Continuum Model (C Model)

A 3D nonlinear continuum model (C Models) is developed in ABAQUS and used in nonlinear analyses as Meloland Road Overcrossing (MRO) reference model. This model includes a detailed representation of the structure, soil layers and the embankment soil. In this model, Infinite Boundary Elements (IBEs) are used as Absorbing Boundary Conditions (ABCs) in the model's boundary walls to simulate unbounded domain. IBEs ensure that energy is dissipated at the model edges rather than reflecting into the system. It serves to represent the far-field regions and provide "quiet" boundaries to the FE model in dynamic analyses [20]. Discretized continuum model is shown in Fig. 4.

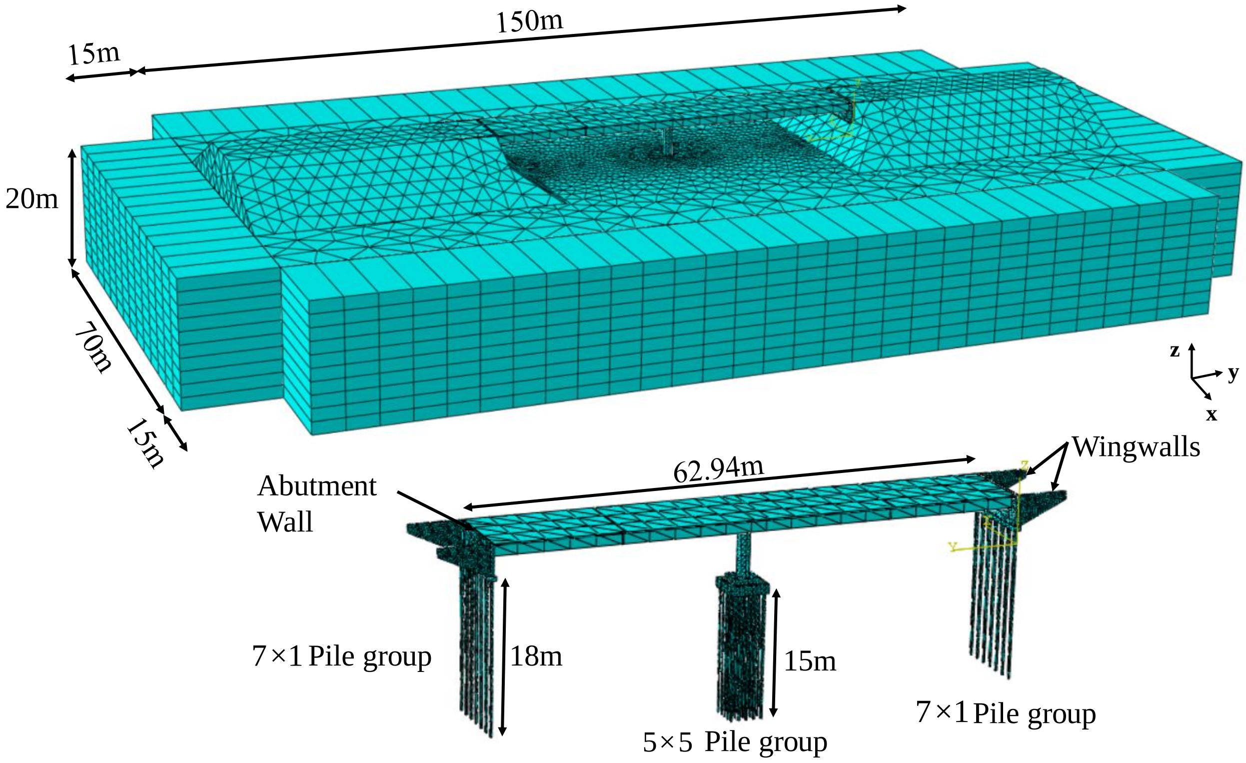


Fig. 4 – Developed 3D nonlinear continuum model (C) using ABAQUS software as Meloland Road Overcrossing (MRO) reference model [16].

Similar to the discrete model, section and material properties are considered based on Werner and co-workers [1] as specified in Table 1. In addition, an elastic-perfectly plastic model is used to define the axial behavior of the steel rebars in the 3D continuum model based on steel yield stress considered by Werner and co-workers [1] and listed in Table 1. Concrete damage plasticity model characterizing compressive and tensile response of concrete in ABAQUS is used in the C model to simulate the concrete damages in abutment backwalls and pier column.

Density, bulk and shear modulus of the soil layers are adopted from the previous studies conducted by Kwon and Elnashai [3]. Modulus of elasticity, shear wave velocity and poison ratio of the soil layers are calculated using the adopted values. Mohr-Coulomb (M-C) plasticity model is used in C model for the continuum analyses as failure or strength criterion. In Mohr-Coulomb (M-C) plasticity model, it is assumed that failure is controlled by the maximum shear stress and that this failure shear stress depends on normal stress. M-C model simulates elastic-perfectly plastic behavior. The elastic behavior is linear and when soil yields, the behavior becomes perfectly plastic [20].

2.3 Damping

In D model, modal damping ratio for the first transvers mode is identified 18.7% by Zhang and Makris [2] and between 19%-26% by Werner [21]. For the discrete models in this study, a Rayleigh damping with a damping ratio of 4% as suggested by Kwon and Elnashai [3] is applied to structural components on modes 1 and 10 as global damping. In addition, a damping ratio of 25% is applied to abutment backwalls, foundations and piles to capture the damping effect of embankment and surrounding soil.

In continuum model C, damping ratio 4% and 12.5% are considered for structural components and soil layers, respectively. Accordingly, Rayleigh damping coefficients (α and β) for bridge and soil components of the continuum model (C model) are calculated and defined in the model. It should be noted that unlike the discrete models, in continuum models, radiation damping effects are explicitly simulated using infinite boundary walls discussed earlier.

3. Analysis

3.1 Eigenvalue Analysis

Eigenvalue analysis is performed on the developed models to validate the fundamental periods of the structure and their corresponding mode shapes against measured ambient testing reported by Ventura and co-workers [4]. The calculated periods and mode shapes for discrete (D) and continuum (C) models are summarized in Table 2 and compared with corresponding measured value from the ambient test reported in [4].

Table 2 – Modal periods and frequencies of the models C and D along with corresponding measured modal period [frequency] from Ambient Vibration Test (AVT) [4] for the MRO

Mode	**Period (Frequency) T_i (s)[f_i (Hz)]**			**Mode Description**
	C	**D**	**AVT**	
1	0.28[3.57]	0.3[3.36]	0.297[3.37]	Vertical anti-symmetric mode
2	0.25[4.00]	0.28[3.57]	0.275[3.63]	Transverse mode
3	0.23[4.35]	0.22[4.61]	0.224[4.47]	Vertical symmetric mode

3.2 Hazard Analysis

A set of ten ground motions with strike-slip mechanism are chosen from the NGA-West 2 ground motion database of the Pacific Earthquake Engineering Research Center (PEER) [22] to perform non-linear response history analysis. These ground motions were scaled to collapse level corresponding to the discrete archetype model D. The selected input motions are summarized in Table 3.

Table 3 – Collapse level ground motions used in non-linear analyses of the MRO continuum model

Event Number	**Earthquake Name**	**PEER RSN No.**	**Year**	**Collapse Scale Factor (SF)**	**M**	**Predominant Period(s) / Unscaled PGA (g)**
1	Imperial Valley-06	184	1979	1.6	6.53	0.40/0.48
2	El Mayor-Cucapah-Mexico	5836	2010	3.6	7.2	0.18/0.23
3	Hector Mine	1787	1999	1.6	7.13	0.50/0.33
4	Landers	879	1992	1.4	7.28	0.08/0.79
5	Parkfield	30	1966	1.6	6.19	0.36 / 0.44
6	Superstition Hills-02	723	1987	1.4	6.54	0.64/0.43
7	Bam-Iran	4040	2003	1.2	6.6	0.20/0.81
8	Kobe-Japan	1119	1995	1.2	6.9	0.46/0.70
9	Duzce-Turkey	1602	1999	0.8	7.14	0.4/0.81
10	Kocaeli-Turkey	1158	1999	1.6	7.51	0.38/0.36

3.3 Non-linear Time History Analysis (C, and D Models)

Non-linear Time History Analysis (THA) is used in SeismoStruct on the D model and ABAQUS on the C model to assess performance of a soil+bridge system with the discrete and continuum representation of soil. In the performed time history analysis, excitation is applied in the longitudinal and transvers directions to the end of springs and dashpots of the discrete model using a set of 10 ground motions summarized in Table 3 Whereas, the bottom of the 3D continuum model is subjected to the same set of the ground motions in the longitudinal and transvers directions. To optimize the analysis runtime, a significant duration of the ground motions between 5% and 95% of Arias Intensity (I_A) is considered in performing time history analysis with 0.02s input time step. It is shown in Ashkani Zadeh [16], this simplification does not result in missing the peak response comparing to the case that entire duration of a ground motion record is used in analysis.

4. Results

4.1 Drifts, Base Shears, and Spectra Comparison

Calculated seismic response using discrete and continuum approaches to capture different soil-structure interaction effects for the 3D MRO models are compared. Calculated maximum drifts of the pier column and abutment backwalls are listed in Table 4.

Table 4 – Comparison of the maximum drift of the discrete and continuum models at the collapse level for all the earthquakes.

Model	**Pier Column Drift (%)**		**Abutment Backwall Drift (%)**	
	Transverse Direction	Longitudinal Direction	Transverse Direction	Longitudinal Direction
C Model	1.4	1.58	0.6	0.95
D Model	1.03	0.82	0.25	0.87

The continuum model has predicted higher drift values in both pier column and abutment backwalls when compared to the discrete model. In the pier column, the discrete model predicts a drift of up to 1% whereas the continuum model predicts up to about 1.6% of drift. In the longitudinal direction in abutment backwalls, both models have about 1% drift. One of the major differences between the continuum and discrete models, is the absence of representation of the kinematic SSI including depth effect in the discrete model since the same ground motion time histories are applied to all the soil springs and dashpots.

Result of maximum base shear of the continuum model C and discrete model D for the abutment backwalls and pier column are compared at the collapse level for all the ground motions and presented in Fig. 5. Except for the abutment backwalls in the longitudinal direction where the continuum model consistently shows higher base shear values, in other cases the differences between the base shear responses of continuum and discrete models are ground motion-specific. Characteristics of each ground motion play a key role in predicted base shear response.

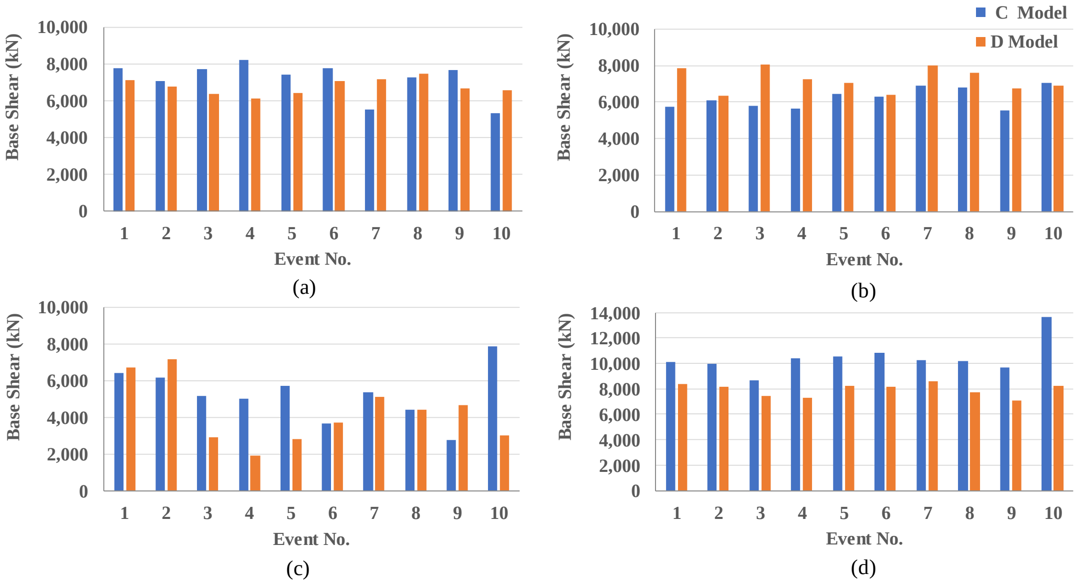


Fig. 5 – Comparison maximum base shear results at the collapse level (a) pier column shear in transverse direction (b) pier column shear in longitudinal direction (c) abutment backwall shear in transverse direction (d) abutment backwall shear in longitudinal direction

Pseudo acceleration response spectrum (for 5% damping) of the Imperial Valley-06 and El Mayor ground motions at the collapse level computed using C and D model at the center of bottom of the pier pilecap in the transverse direction are compared in Fig. 6.

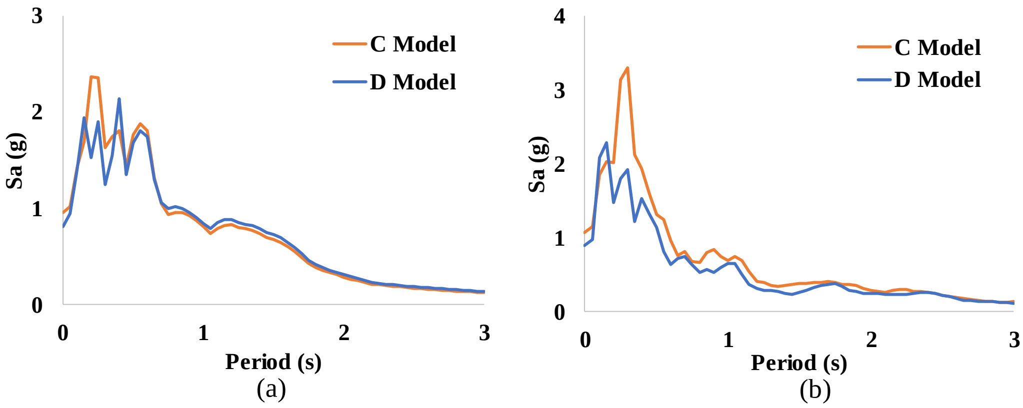
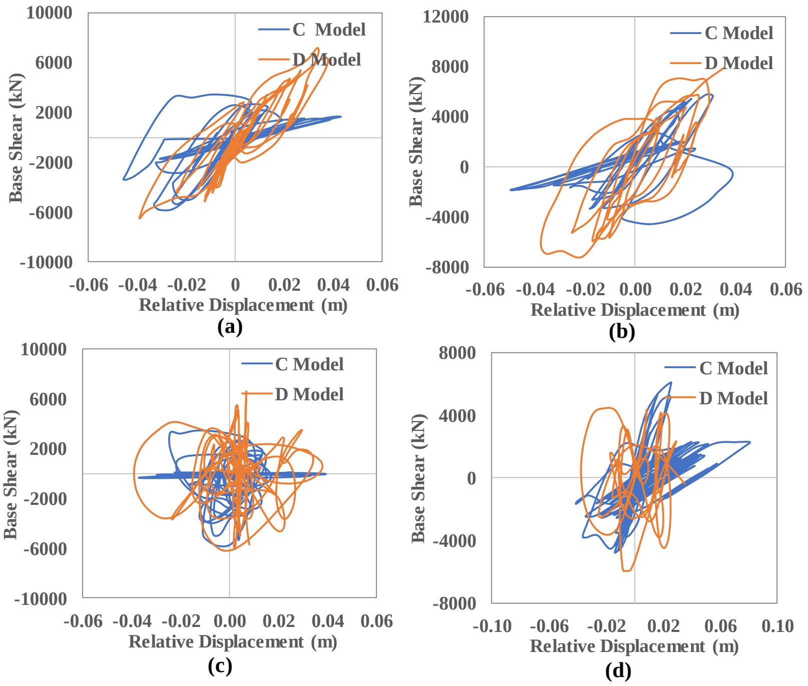


Fig. 6 – Spectra with 5% damping of the bottom pier pilecap using the collapsed level ground motions in transverse direction (a) Imperial Valley-06 with SF=1.6, (b) El Mayor with SF=3.6

As it can be seen, there is significant difference between the calculated pseudo spectral acceleration at the center of the bottom of pier pilecap using the discrete and continuum models specially in short period range where the first few modes of the soil+bridge system are residing. Lack of representation of the kinematic SSI effects, including the depth effect, in the discrete model is a major contributor to this observed difference.

Predicted hysteresis curves calculated at the pier-column base in the continuum and discrete models are presented in Fig. 7. There is a major difference observed between the discrete and continuum models. It should be noted that the applied ground motions were scaled to collapse level, leading to extreme hysteresis behavior shown in this figure.

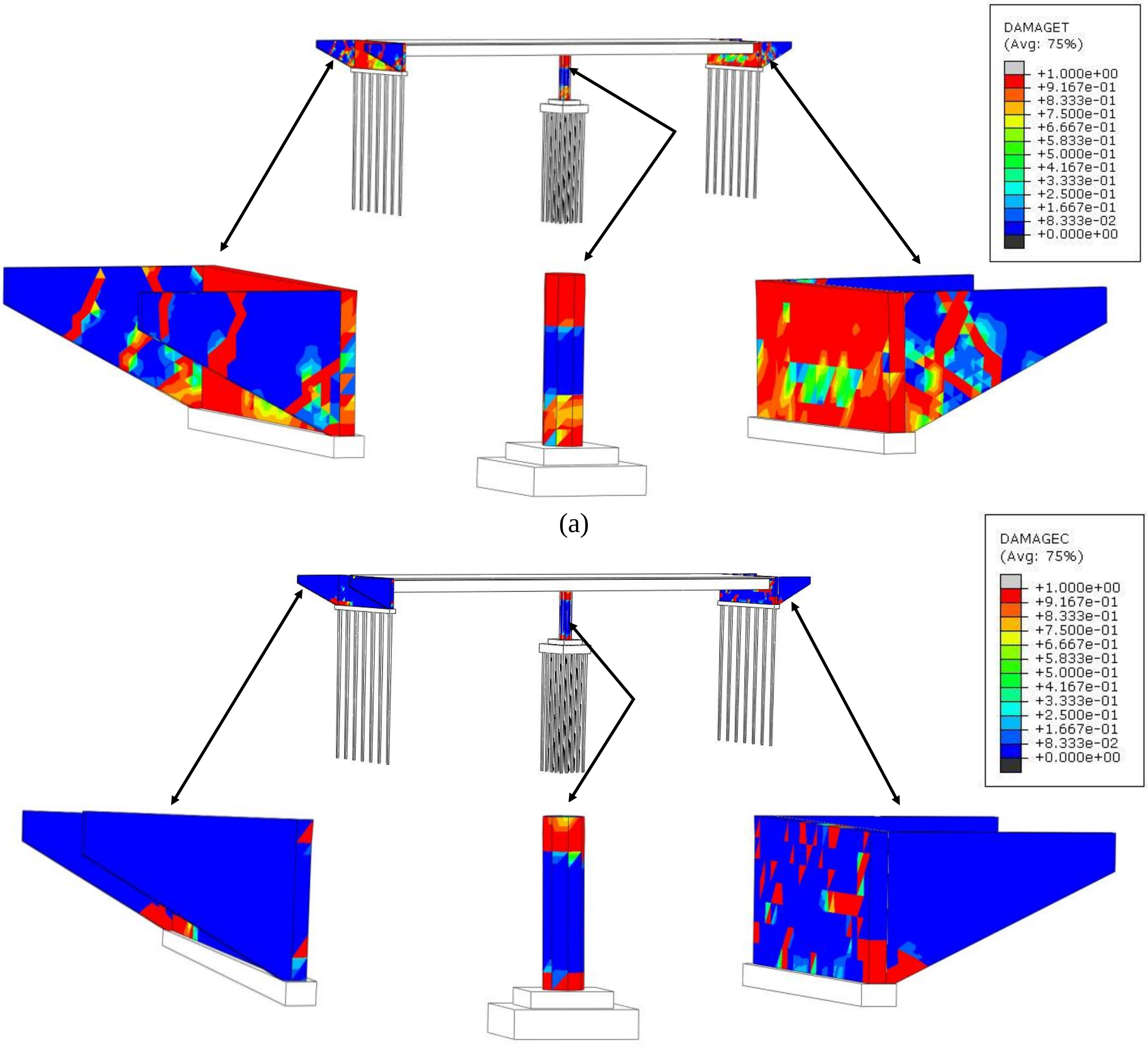


(a) (b) (c) (d)

Fig. 7 – Calculated hysteresis curves of the pier column using the C and D model (a) Imperial Valley-06 with SF=1.6 in Transverse direction (b) Imperial Valley-06 with SF=1.6 in Longitudinal direction (c) El Mayor with SF=3.6 in Transverse direction (d) El Mayor with SF=3.6 in Longitudinal direction

4.2 Concrete Tensile and Comprehensive Damage and Yielding of Soil Layers (C Model)

The continuum model allows for investigating the detail of concrete and reinforcement failure in structural components. In concrete damage plasticity model employed here, degradation of the elastic stiffness is characterized by two damage variables which are functions of plastic strain. Concrete tensile and compressive damage of the abutment backwall and pier column predicted for scaled Imperial Valley-06 (SF=1.6) earthquake ground motion are shown in Fig. 8. Formation of plastic hinges at the top and bottom of the pier column can be observed in this figure.



(a)

(b)

Fig. 8 – MRO continuum model's concrete damage at the collapsed level Imperial Valley-06 Earthquake (SF=1.6) (a) tensile damage (b) compressive damage

4.3 Yielding of Soil Layers (C Model)

Yielding of soil layers are monitored using the flag variable AC YIELD (actively yielding) available for built-in material models in ABAQUS [20]. This identifier provides a yes/no flag whether the material is currently in yielding state [20]. Yield state of soil layers in the continuum model are shown in Fig. 9 where the model was subjected to scaled-up El mayor ground motion (SF=3.6). As shown in this figure, there is a significant yielding taking place around the piles specially in the Soil Layer A.

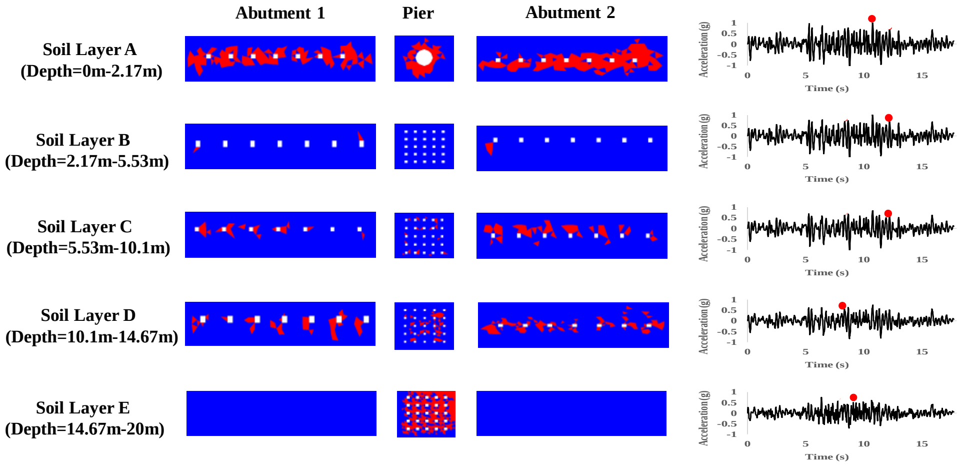


Fig. 9 – Yielding state of various soil layers around the piles subjected to collapse level El Mayor ground motion (SF=3.6). Red color is an indicator of yielding state.

5. Concluding Remarks

In this study direct method was used to evaluate seismic performance of a soil+bridge system. Discrete and continuum representation of soil and bridge system were employed. Discrete method has been more commonly used in simulation of SSI features compared to continuum approach. This is due to existence of more established modeling techniques and computational feasibility of discrete models. In contrast, continuum method has been not often used due to complexity of model set-up, material response assignment and its computational cost. The purpose of this study was to offer a comprehensive comparison between the commonly used discrete modeling approach and the more detailed continuum representation. Nonlinear time history analysis was performed using a set of 10 ground motions chosen from NGA-West2 database scaled to the collapse level.

Comparing the seismic response calculated using the nonlinear analysis for the abutment backwall and pier column of the MRO, it was observed that there is a significant difference between the results obtained using the continuum and discrete approach. The continuum model consistently showed higher drift envelopes for both pier column and abutment backwall when compared to the discrete model. The continuum model also showed higher pseudo spectral acceleration specially in the higher frequency region where the natural frequency of soil+structure resides. Absence of representation of the kinematic effect in the discrete model is a major contributor to the difference observed between the two models. Specifically, depth effect is not captured in the discrete model where the same ground motion excitation is applied along the depth to all soil springs and dashpots. A comparison of the base shear of the two models for all ground motions was also presented. It was shown that in most of the cases, the differences between the base shear responses of continuum and discrete models are ground motion-specific where characteristics of ground motions play a key role in the predicted base shears.

It was shown that despite of complexity and computational cost of the continuum method, this method has a greater capability to predict SSI features that either can't be directly or accurately simulated in the discrete models (including kinematic SSI effect). Detailed simulation of non-linear behavior of soil and formation and propagation of damage in structural components are among the benefits of the continuum modeling approach.

Advancements in computational modeling and development of powerful computer clusters have made the use of continuum models feasible. Analytical SSI modeling requires accurate representation of behavior of soil and structural components going thorough nonlinear regime. Successful modeling requires high fidelity constitutive models that can predict response of soil layers and structural components undergoing extreme nonlinear conditions such as damage and collapse.

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