Performance – Based Seismic Assessment of Isolated Bridge configurations on deformable soils

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SUMMARY:
Performance-Based Earthquake Engineering (PBEE) aims to quantify the seismic performance and risk of engineered facilities using metrics that are of immediate use to both engineers and stakeholders. A recent bridge performance-based analysis framework using the PEER platform OpenSees with a three-dimensional (3D) ground-foundation graphical user interface was developed to assess repair costs for a number of seismic isolation and supporting soil profile configurations. The paper aims to exercise and develop this framework highlighting the potential beneficial effect of isolation devices in reducing the bridge repair cost and time quantities. In particular, the study is concerned with a 90 meter long, single-column, two – span bridge. Several configurations of abutments and column connections with isolation devices are presented. The beneficial contribution of the isolation technique is assessed under different supporting soil profile deformability conditions.

Keywords: PBEE, isolation devices, configurations, repair, soil deformability

1. INTRODUCTION

Performance-Based Earthquake Engineering (PBEE) is a new methodology based on the concept of design for prescribed performance rather than the more traditional prescriptive approaches, developed by the Pacific Earthquake Engineering Research (PEER) Center (http://peer.berkeley.edu). PEER contributed to theoretical development, applications in academia and industry, and also to the inclusion of precepts into the next generation of building/design codes (Cornell and Krawinkler 2000). This methodology applied to buildings has seen rapid development (FEMA-350, 2000; FEMA-356, 2000; ATC 58, 2007; ATC 63, 2007; TBI Guidelines Working Group, 2010), while relatively few attempts have been proposed in the bridge and infrastructure arena.

Recently, Mackie and co-workers have pioneered the development of a bridge performance-based analysis framework (Mackie et al., 2008; Mackie et al., 2010a) adopting the numerical PEER platform OpenSees (http://opensees.berkeley.edu). A list of performance groups (PGs) is defined based on commonly used repair methods and aggregation of decision data, mainly taken from typical pre-stressed, single-column bent, multi-span, box girder bridges in California. Damage to these PGs was tied to explicit repair procedures and repair quantities that could then be used for cost estimation and repair effort necessary to return the bridge to its original level of functionality. Using this analysis framework, other PEER researchers considered the pile-pinning effect at the abutments (Ledezma and Bray, 2008) and the increase in repair costs due to the presence of a liquefaction-susceptible soil profile (Kramer et al., 2008). Simultaneously, Elgamal and co-workers (Elgamal et al., 2003, 2008, 2009, Lu, 2006; Lu et al., 2006, Elgamal and Lu, 2009) had embarked on development of OpenSeesPL (http://cyclic.ucsd.edu/openseespl), a graphical user interface for three-dimensional (3D) ground-foundation systems applying OpenSees as the finite element (FE) analysis engine. OpenSeesPL includes pre- and post-processing capabilities to generate the mesh, define material properties and boundary conditions, allowing the execution of pushover and seismic single-pile or pile-group ground simulations.

The present work is based on a recently developed bridge PBEE user interface (Lu et al., 2010; Mackie et al., 2010b, http://peer.berkeley.edu/bridgepbee/), thanks to the recent effort born from the application of the above earlier developments. The paper aims to exercise the underlying analysis framework highlighting the beneficial effects of several configurations of abutments and pier (column) connections with isolation devices at the top of the column and at the abutment supports, in reducing the bridge repair cost/time. A study is conducted, focused on the longitudinal behaviour that might be provided by several isolation device configurations. First of all analyses are performed with fixed-base conditions (i.e., Soil-Structure-Interaction or SSI neglected). The response is assessed in terms of repair cost and time quantities such as Crew Working Days (CWD) and the total repair cost ratio (the ratio between the cost of repair and the cost of the new construction). Finally, taking into account the main bridge response parameter (column top displacement), the study is expanded to include SSI, with supporting soil profiles of different stiffness and strength configurations.

In the following sections, the employed PBEE methodology is described. The parametric study (fixed conditions) and its results are presented in sections 4 and 5. Bridge response for the three employed soil profile conditions is then presented in section 6.

2. PBEE METHODOLOGY

The methodology (Mackie et al., 2008, 2010a) is subdivided to achieve performance objectives stated in terms of the probability of exceeding threshold values of socio-economic decision variables (DVs) in the seismic hazard environment. The PEER PBEE framework is fundamentally based on the application of the total probability theorem to disaggregate the problem into several intermediate probabilistic models that involves intermediate variables, such as repair items or quantities (Qs), damage measures (DMs), engineering demand parameters (EDPs), and seismic hazard intensity measures (IMs).

Consequently, the applications of this methodology are very general, since the possible variables that can be taken into consideration depend on the objectives that the decision makers choose to refer to. For example, probabilities of exceeding an EDP such as strain can be useful for engineers, owners may choose to refer to economically-oriented variables such as probabilities of exceeding a DV, while decision makers may be interested in repair time and cost quantities. In this regard, an important step in the damage and repair assessment is the definition of Performance Groups, based on the association of the various structural and non-structural components, using the most common repair methods.

Finally, the EDPs are computed directly from the ensemble of time history analyses performed and automatically associated with the PGs and the DVs. The data used to populate the relationships that associate EDPs to DMs and DMs to Qs is presented in Mackie et al. (2008) and the numerical implementation of the methodology inside the interface (Lu et al., 2011) is described in Mackie et al. (2010a).

3. PBEE ANALYSIS

PBEE analysis can be organized into the major components: definition of Ground Motion Input, Bridge-Ground Finite Element Model and Definition of Performance Groups and Quantities, respectively shown in the next subsections.

3.1. Ground Motion Input

The framework can employ any type of user-specified input motion. In particular, in this study all the motions are taken from the PEER NGA database (http://peer.berkeley.edu/nga/). They consist of 100 selected ground motions to be representative of seismicity in typical regions of California. They are divided into 5 bins of 20 motions each, with the two main characteristics: moment magnitude (Mw) and epicenter distance (R), for more details, see Mackie, Lu and Elgamal (2010b).

3.2. Bridge-Ground Finite Element Model

The investigate model, representative of the prevalent ordinary construction types for new California bridges, is a 90 m long, 2-span structure, supported on one circular column (1.22 m diameter) 12 m long, 6.71 m above grade (Fig. 3.1). The deck is 11.9 m wide and 1.83 m deep, and the weight is 130.30 kN/m. Each abutment is 25 m long with 30000 kN as total weight. In particular, the reinforced concrete column is modeled with nonlinear beam-column elements and fiber cross section. The deck is modeled with five separate elastic beam-column (BC) elements and the approach ramps make the connection with the longitudinal boundaries (Fig. 3.2). The interface (http://peer.berkeley.edu/bridgepbee/) allows the implementation of several support mechanism at the abutments. In this study no additional resistance of the soil (at large relative bridge-abutment displacement) is considered. For more details see also as Elgamal et al. (2011). Four isolated bridge configurations are compared. The first two consist of simple roller link connections between the deck and the abutments (MODEL 1 and MODEL 2), as illustrated in a previous study (Elgamal et al. 2012). The other two cases (MODEL 3 and MODEL 4) were developed from a modified version of the interface allowing the implementation of simple elastic springs between the deck and the top of the column (in order to simply represent presence of a base isolator).

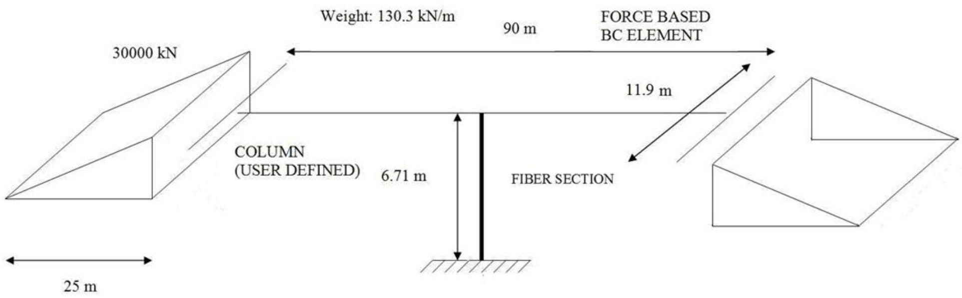

Figure 3.1. Bridge Definition for the case study

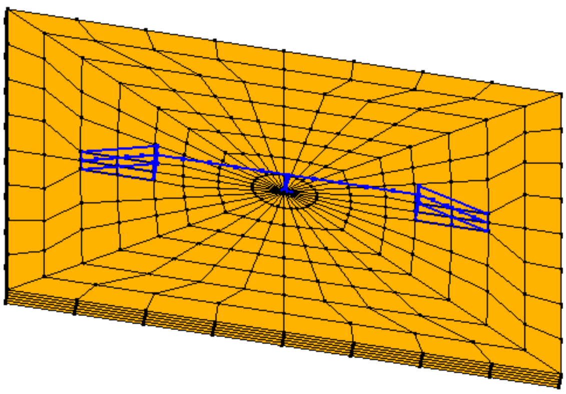

Figure 3.2. Mesh Definition (http://peer.berkeley.edu/bridgepbee/)

3.3. Definition of Performance Groups and Quantities

PBEE methodology assesses the damage and repair, grouping the various structural and non structural components into PGs. Each group contains a collection of components that reflect global-level indicators of structural performance that contribute significantly to repair-level decisions. The interface is built with 11 PGs (Mackie, Lu and Elgamal, 2010b), representative of typical bridge schemes and used in this study. For each performance group, discrete damage states (DS) are defined, and each of these has a subset of different repair quantities (Qs), associated for a given scenario. The interface is built with 29 Qs (Mackie, Lu and Elgamal, 2010b) and they were applied to the present study. In particular, the total repair cost can be generated through a unit cost function that is based on the Qs. Finally, for each Q, an estimate of the repair effort can be obtained through a production rate. More information on the derivation of the default DSs, Qs, unit costs, and production rates can be found in Mackie et al. (2008).

4. PARAMETRIC STUDY

A parametric study with various longitudinal stiffness values was performed in order to evaluate the longitudinal resistance that might be provided by four different configurations. The employed simple elastic models to represent seismic isolation are roughly representative of real high damping rubber bearing response commonly used in professional bridge engineering applications. In particular, the LRN500X130 isolator (ζ=4%, G=0.9 MPa, D = 500 mm) from ALGA (http://www.alga.it) is considered in this study. The four structural configurations (MODELs) consist of:

MODEL 1. Bridge with no Isolation devices: the column and the deck are rigidly tied together and the abutments give no resistance to the bridge deck displacement (roller support at the abutment locations);

MODEL 2. Isolated Abutments: the abutments are connected to the deck with one elastic longitudinal spring (KLA= 4000 kN/m) to model the presence of two isolation devices (LRN500X130);

MODEL 3. Isolated Column: 5 isolation devices (LRN500X130) on the top of the column (KLC = 10000 kN/m) and no resistance between the abutment and the deck (as in Model 1);

MODEL 4. Double Isolation: 5 isolation devices (LRN500X130) on the top of the column (KLC = 10000 kN/m) and one elastic longitudinal spring (KLA= 4000 kN/m) to account for the presence of two isolation devices (LRN500X130) at the abutment locations.

Fig. 4.1. And Table 4.1 present the four configurations adopted in the study. In particular, the fundamental shape modes and frequencies are shown in Fig. 4.2, Fig. 4.3 and Table 4.2.

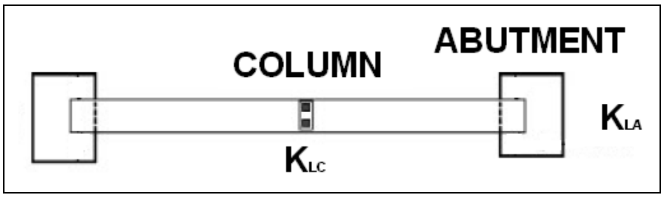

Figure 4.1. Schematic of the model with elastic springs

Table 4.1. Data for MODEL Stiffness

	KLA [kN/m]	KLC [kN/m]	ISOLATION
MODEL 1	0	fixed	No isolation
MODEL 2	4000	fixed	On abutment
MODEL 3	0	10000	On column
MODEL 4	4000	10000	On abutment & On column

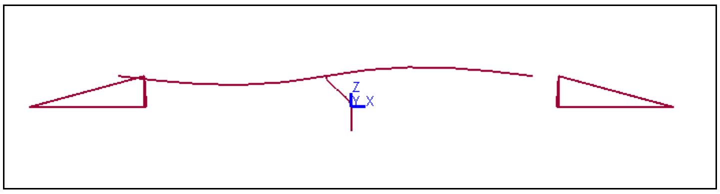

Figure 4.2. 1st Shape Mode, MODEL1 (scale: 200)

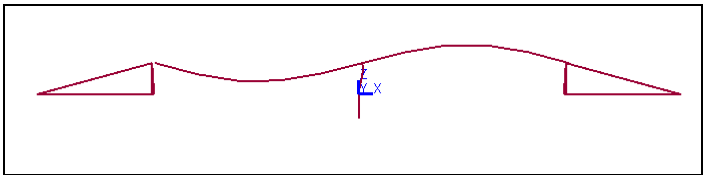

Figure 4.3. 2nd Shape Mode, MODEL1 (scale: 100)

Table 4.2. Data for MODEL Natural Periods (First and Second)

	T1 [s]	T2 [s]
MODEL1	0.80	0.50
MODEL2	0.75	0.38
MODEL3	2.32	0.53
MODEL4	1.67	0.38

5. PBEE RESULTS FOR FIXED BASE CONDITION (NO SSI)

This section illustrates the results in terms of Total Repair Cost Ratio and Time considering fixed-base conditions, neglecting soil structure interaction as a first reference study. Due to the assembly-based (vector) nature of the method applied, and according to the total probability theorem, it is possible to disaggregate the results (repair costs and time) into individual contributions. The developed user interface (Lu et al. 2010, 2011, Mackie et al. 2010b) can compute directly several figures that summarize the different disaggregated quantities. In particular, the main contribution to Total Repair Cost and Time is shown to be the longitudinal column displacement and the relative longitudinal deck-abutment motion (Fig. 5.1 and Fig. 5.2). These two values contribute to the Total Repair Cost Ratio and Time results represented in Fig. 5.3 and 5.4 where the beneficial effect of the isolator devices are shown to be expected for low values of Peak Ground Acceleration (PGA).

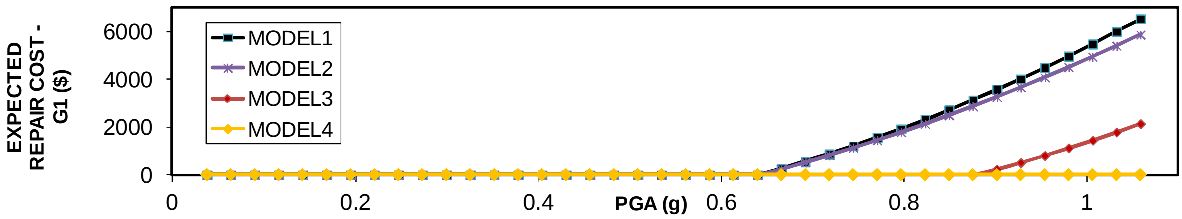

Figure 5.1. Expected repair cost – G1: Max Long. Drift Ratio (Column)

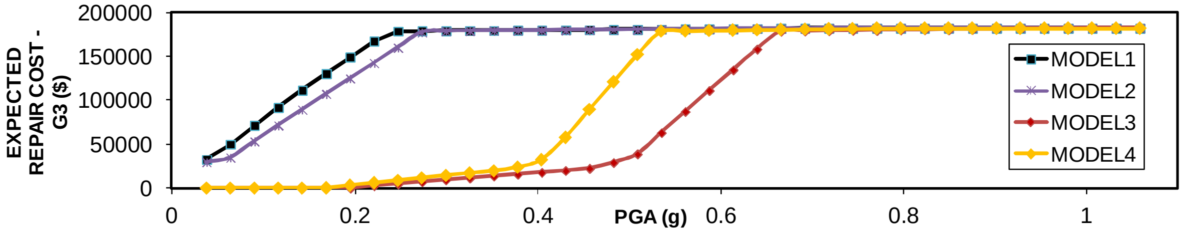

Figure 5.2. Expected repair cost – G3: Max Long. rel. Deck end/ Abut. displacement

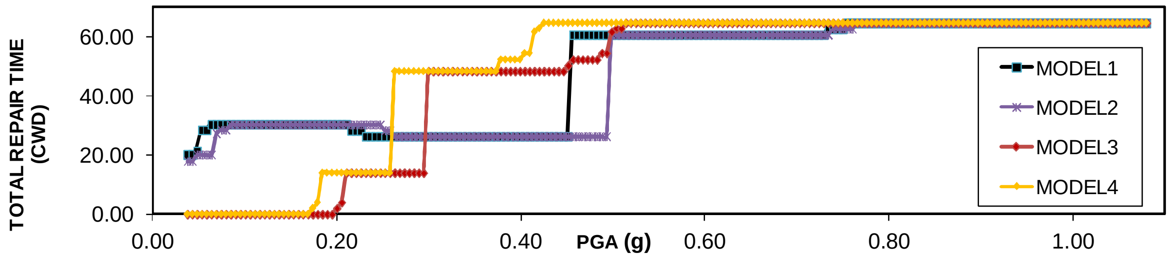

Figure 5.3. Total Repair Time (Crew working Days, CWD)

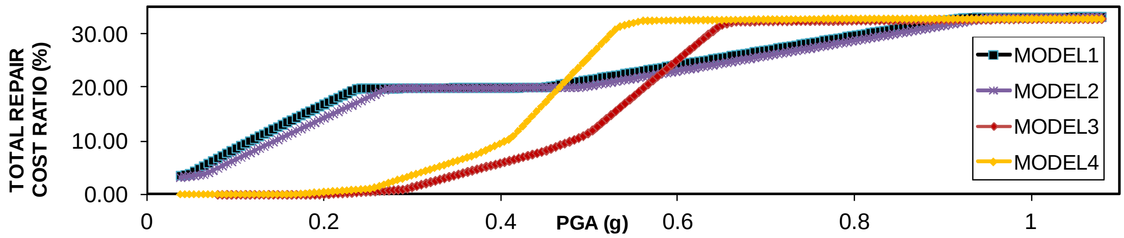

Figure 5.4. Total Repair Cost (%)

6. SOIL DEFORMABILITY EFFECTS

In this section, the column maximum displacement for 3 soil profile conditions with increasing deformability (Table 6.1) are reproduced, corresponding to three representative input motions (Table 6.2 and Fig. 6.1-6.3) defined along the soil mesh base in the longitudinal direction (x-axis). The main modelling parameters include standard clay-soil (Von-Mises, multi-yield surface plasticity model) properties such as shear, bulk modulus and cohesion. The soil mesh base boundaries were modeled using the penalty method in order to ensure fixed conditions. Shear beam assumptions were considered along the vertical soil mesh boundaries in the longitudinal direction (along the 10m soil profile depth).

Figures 6.4-6.6 show model response for the three soil conditions with the three input motions. The results are compared with the previous fixed-base case (with no Soil Structure Interaction). In this regards, it is possible to assess how the soil deformability modifies the column deformation profile considerably. In particular, the soil flexibility causes the column displacement to increase. Generally, this displacement assessment is a basis for verifying the positive effect of isolation on column deformability and on the entire system performance, as presented in section 5. For illustration, Fig. 6.7 and 6.8 show MODEL1 (soft clay) 3D mesh deformation (plan and 3D view) for CAP motion at t = 6.50 sec.

Table 6.1. Employed soil properties (hyperbolic shear stress-strain curve, with hysteretic response)

	Soft Clay	Medium Clay	Stiff Clay
Mass density (t/ m^3)	1.3	1.5	1.8
Reference shear modulus (kPa)	$1.3 \cdot 10^4$	$6.0 \cdot 10^4$	$1.5 \cdot 10^5$
Reference bulk modulus (kPa)	$6.5 \cdot 10^4$	$3.0 \cdot 10^5$	$7.5 \cdot 10^5$
Cohesion (kPa)	18	37	75
Strain at peak shear strength	0.1	0.1	0.1

Table 6.2. Input motions

	A-KOD	CAP	RRS
PGA (g)	0.154	0.511	0.852
PGV (cm/s)	18.76	34.76	160.055
PGD (cm)	6.09	9.088	29.613

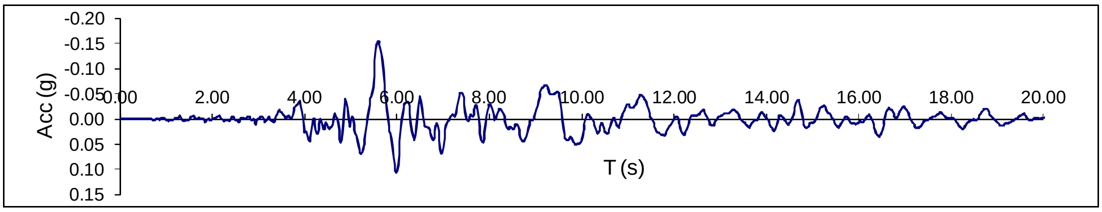

Figure 6.1. A-KOD input motion

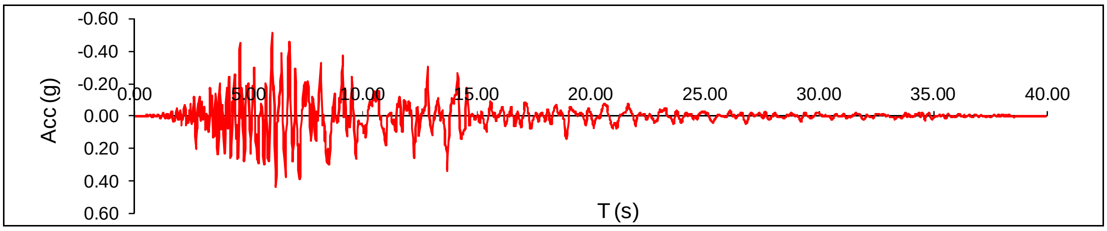

Figure 6.2 CAP input motion

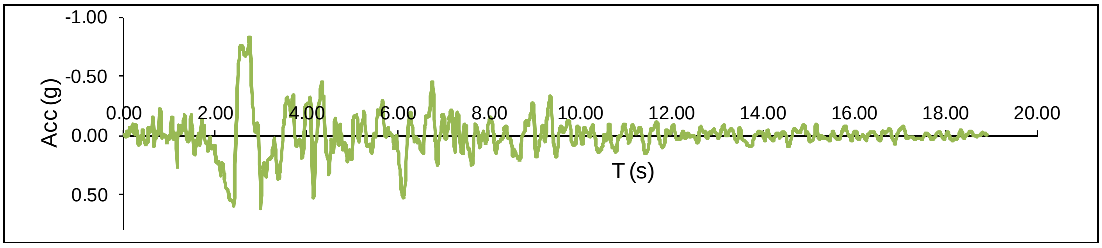

Figure 6.3 RRS input motion

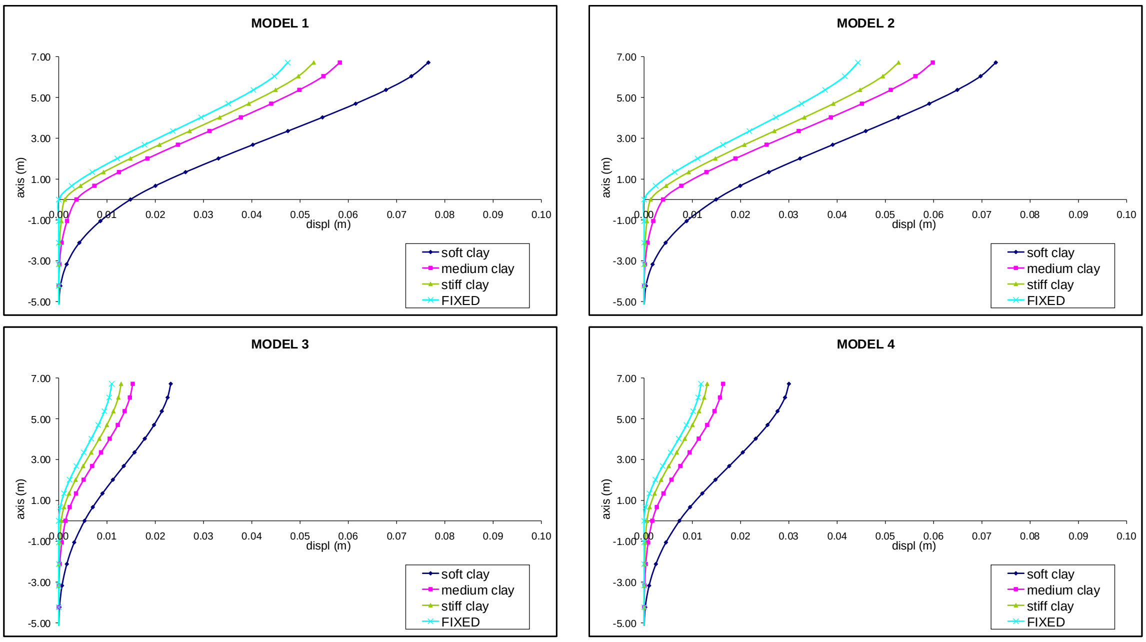

Figure 6.4. Column maximum deformation for different soil conditions (motion: A-KOD)

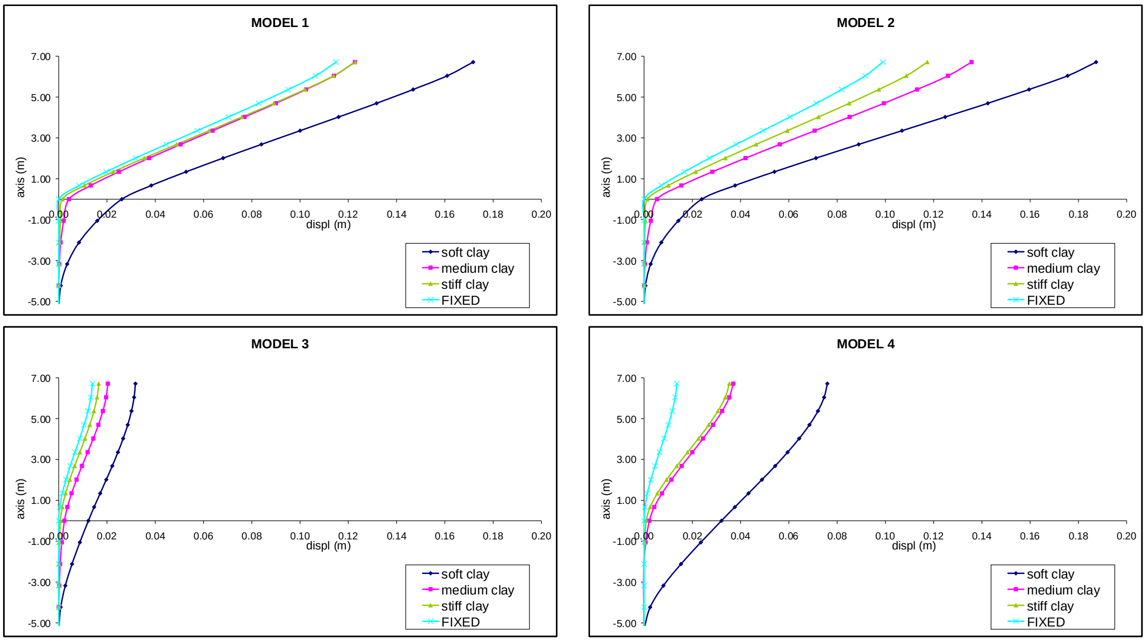

Figure 6.5. Column maximum deformation for different soil conditions (motion: CAP)

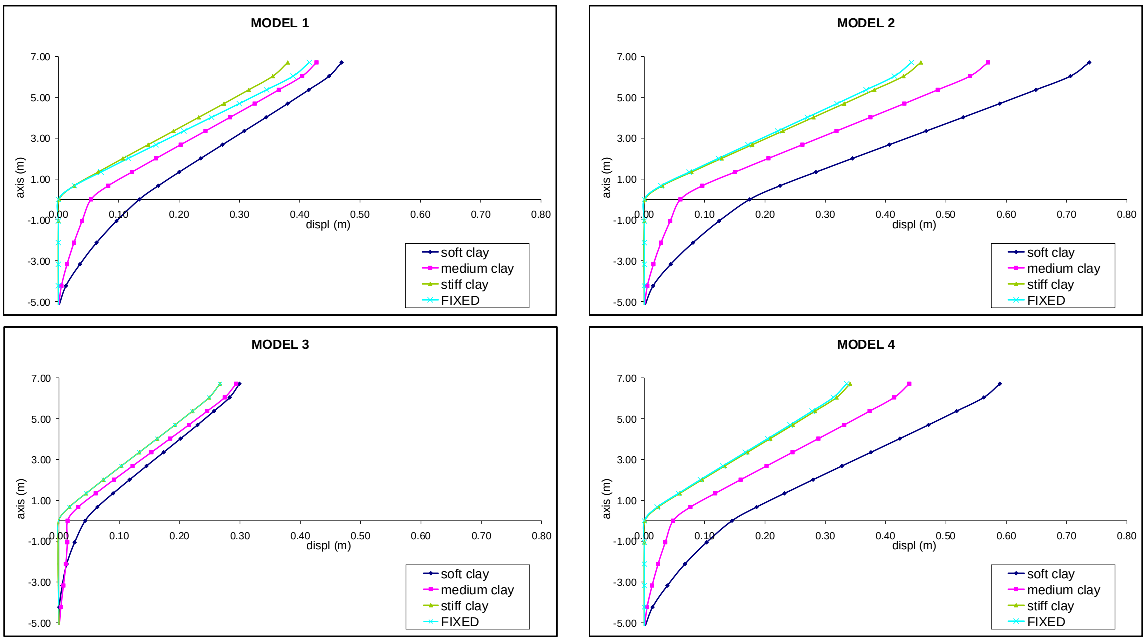

Figure 6.6. Column maximum deformation for different soil conditions (motion: RRS)

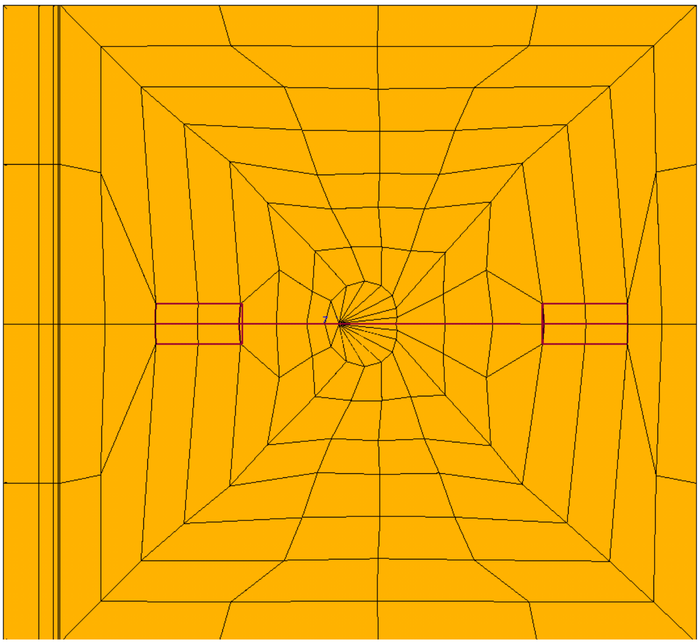

Figure 6.7. MODEL1 (soft clay) - PLAN view (3D mesh) - SCALE 1:500

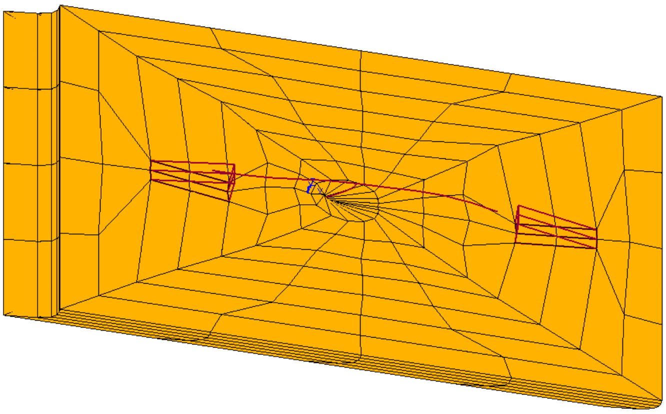

Figure 6.8. MODEL 1 (soft clay) 3D view (3D mesh) - SCALE 1:500

8. CONCLUSION

The study conducted in this paper may be viewed as a pilot investigation to present an overall PBEE analysis framework for a simple single-column bridge-abutment with several idealized seismically-isolated configurations. The first part of this study highlighted the main parameters that contribute to Total Repair Cost and Time as the column and abutment displacements. Thereafter, three representative motions were applied to illustrate the impact of three ground profile configurations with increasing deformability in order to assess the soil contribution to the overall system response.

The investigations demonstrate the potential of this numerical formulation in assessing the beneficial effects of an implemented base isolation technique. The results offer insights to improve bridge seismic reliability assessment in the presence of deformable soil conditions, thus providing a basis for future analysis, management of computational resources, and investment in more refined models. In this regards, two main aspects may be investigated further. First, the effect of transversal response has to be taken into account in order to analyse and investigate a more realistic scenario. Second, further applications would focus on further elaborate descriptions of the soil domain and the structure itself. In particular, an important step lies in the implementation of non-linear behaviour models including the rotational components for the isolation devices. Finally, analysis with soil-structure interaction for liquefaction-induced response situations may be also of value.

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