COMPARATIVE ASSESSMENT OF ADVANCED COMPUTATIONAL TOOLS FOR EMBANKMENT-ABUTMENT-BRIDGE SUPERSTRUCTURE INTERACTION

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ABSTRACT:

The scope of this paper is to investigate the range of applicability of the advanced computational tools currently available for the dynamic analysis of bridge structures accounting for embankment- foundation-abutment-superstructure interaction. Along these lines, four different analysis approaches are adopted and independently applied for the study of a real, already built overcrossing in Greece, each time making the appropriate assumptions and using purpose-specific software. Both single and multi-platform analysis is employed and the limitations and advantages of each approach are comparatively outlined and discussed. The results indicate that the last generation of computational tools available, certainly contribute towards the representation of the soil-foundation-bridge system as a whole and thus, the more accurate study of interaction problems that was not feasible to be examined in the past.

KEYWORDS: abutment–embankment system, soil-structure interaction, multi-platform analysis

1. INTRODUCTION

The importance of soil-structure-interaction for assessment of the dynamic response of bridges has been widely recognized in numerous research studies. Considering the contribution of bridge lateral boundary conditions in the overall seismic response of bridges, has illustrated the significant role played by the embankment-foundation-abutment system not only in terms of the dynamic characteristics and response of the bridge (Goel and Chopra, 1997, Mackie and Stojadinovic, 2002, Dicleli, 2005, Kotsoglou and Pantazopoulou, 2007) but also regarding the modification of the incoming seismic motion (Zhang and Makris, 2002). Earthquake damage reports and laboratory tests have also indicated that abutment failure commonly caused by rotational and/or translational outward movement of the toe or even loss of subsoil bearing capacity is fairly common, hence refined analysis of the overall system is required. However, it is a challenge to implement the computational tools and resources required to simulate the multi-parametric and complex nature of both the dynamic pier-foundation-subsoil and deck-abutment-embankment interaction as well as the shear deformation and failure of RC members (i.e. piers and piles), since coupled modeling of all these systems still requires extensive computation effort due to the model size and/or behavior complexity. As a result, it can be argued that given the above complexity and computational demand, it is rather subjective whether a single software package exists that could possibly combine all the features required for advanced simulation of the non-linear response of bridge, foundations and abutments and their supporting soil. Along these lines, this paper aims at investigating the application of distributed computational simulation as a mean to comparatively assess the limitations and challenges of the most advanced modelling approaches currently available for the study of complex SSI systems. Multi-platform simulation is one of the most promising approaches of this kind and was initially developed to accommodate multi-site hybrid simulation (Spencer et al., 2006). The dynamic response of full scale specimens that are physically separated is properly controlled with the use of purpose-specific coordination software that made feasible the incorporation of various numerical analysis platforms in the sub-structuring process. This concept has also been successfully applied (Kwon and Elnashai, 2008) for the coordination of purely numerical analysis modules (in contrast to the hybrid simulation application) for the case of real bridges in the U.S. for various soil conditions, as well as for the study of the potential impact of liquefaction susceptibility (Kwon et al., 2008). The advantage of this approach is that the appropriate selection and combination of different analysis packages, enables the concurrent use of the most sophisticated models and features of each package for each corresponding part of the system. In other words, different software can be used for different system components (i.e. abutments, superstructure and supporting pile groups) depending on the foreseen material constitutive laws and geometry.

In order to investigate the range of applicability of the advanced computational tools and methods currently available for simulating the embankment-abutment-bridge interaction, a typical, real and already built, overcrossing in Greece is chosen to serve as a benchmark and four different alternative modelling approaches are explored, namely: 1) a bridge frame model supported on complex dynamic impedance matrices that are specifically calculated for pile foundations and abutments; 2) a 3-Dimentional spring-supported frame model consisting of the bridge, its abutment and its foundation, 3) a refined 3-Dimentional solid model of the overall superstructure-abutment-embankment system and; 4) a multi-platform scheme (Kwon and Elnashai, 2008) using appropriate system sub-structuring. An overview of the bridge structure studied and the comparative assessment of the aforementioned approaches is presented in the following.

2. OVERVIEW OF THE BRIDGE STUDIED

The particular bridge adopted for study is an overpass (overcrossing) along the Egnatia highway, a large road network that has been constructed in northern Greece with more than 646 bridges built of a total of 40km length most of which are structures of relatively small dimensions (i.e. L<100m). The particular bridge studied is a three-span, symmetric structure of 70m length (span lengths are 19, 32 and 19m respectively) curved in elevation (maximum camber of 8%), that intersects the highway axis at an angle of 75.3°. The deck is 11m wide and 1.60m high. The prestressed deck has a hollow T-beam-like section and is supported on two circular piers of 1.70m diameter and 8.50m height which are monolithically connected to the superstructure and the foundation. At the abutments (which have a 10.50×1.20m wall section of 5.0m height), the deck is connected through two pot bearings that permit sliding along the two principal bridge axes and a sliding joint separates the deck from the backwall. Seismic forces are also resisted by the activation of stoppers (in the transverse direction) which are constructed at the seating of the abutments. The foundation on the other hand is deep, due to the soft clay formations characterizing the overall area. The pier foundation consists of a 2×2 pile group of 28.0 to 32.0m long piles, connected with a 1.60×5.0×5.0m pile cap, while the abutments are supported on a 1×4 pile row 27 to 35.0m long at 2.80m axial spacing, all piles having equal diameter of 1.0m. The bridge was designed for normal loads according to the German Norms (i.e. DIN 1055, 1045, 1072, 1075, 1054, 4227, 4085, 4014) while the seismic design was carried out according to the Greek Seismic Code EAK 2000 and the relevant Greek standards E39/99 for the seismic design of bridges. The bridge site is located in the Seismic Risk Zone I which is equivalent to a peak ground acceleration of ag = 0.16g. The behaviour factors of the system adopted for design according to the E39/99 document were q_x=2.50, q_y=3.50, q_z=1.00 for the response in the three principal directions, respectively. The target displacements of the bridge under study for the two directions, the two alternative soil conditions and the two earthquake levels (i.e. design earthquake and twice the design earthquake) are also depicted in Figure 2 (the complete calculation process can be found in Potikas, 2006). It is noted that for twice the design earthquake in the longitudinal direction, the joint is expected to close. Consequently, the overall bridge system stiffness in the longitudinal direction is significantly increased due to the activation of the backfill-abutment-foundation-soil subsystem. It is also noted that in the transverse direction, although damage is indeed minor for the case of soft foundation soil even for displacements corresponding to twice the level of the design earthquake, the abutment piles were found to suffer significant damage due to shear failure at their head when the supporting soil is stiff (Kappos et al., 2007). This situation is apparently detrimental because the abutments can no longer resist even their own earth pressures, hence the bridge stability is jeopardized and the high ductility of the middle piers is never utilized. Given the above observations it is clear that for the particular bridge under study, the role played by the abutment is crucial and hence the appropriate modelling of the bridge lateral boundary conditions is necessary.

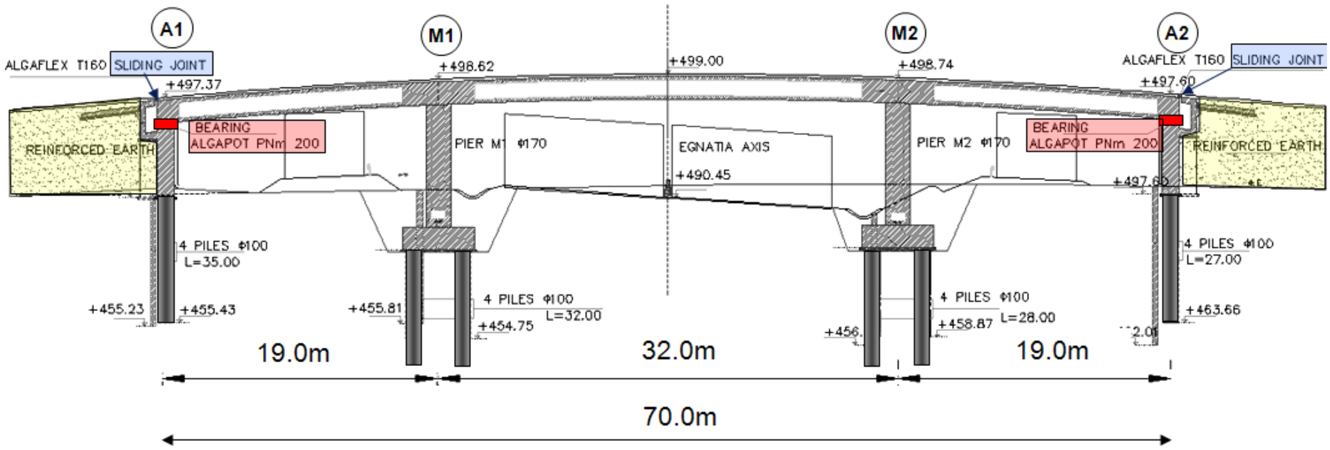

Figure 1 Longitudinal cross-section of the Egnatia highway bridge studied

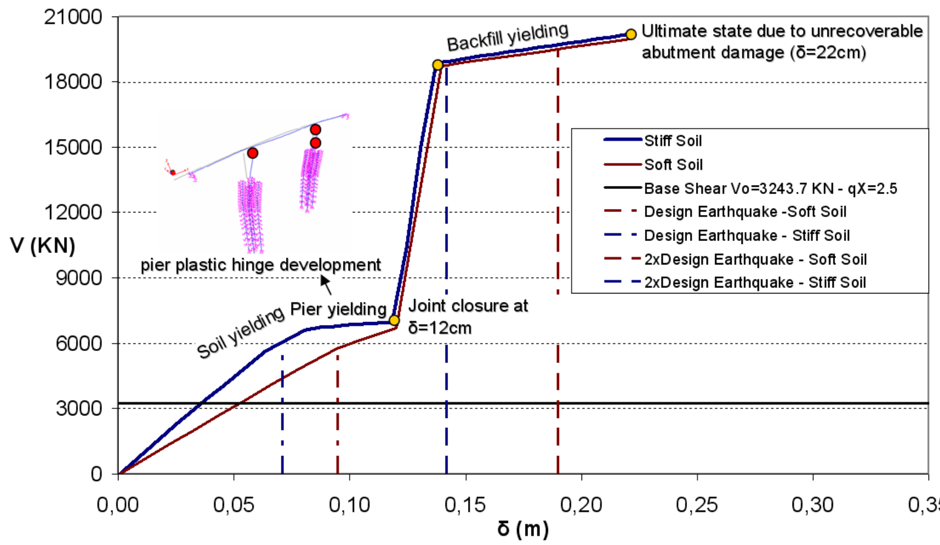

Figure 2 Pushover curve and seismic assessment of the overall system studied in the longitudinal direction for two different soil categories (after Kappos et al., 2007).

3. COMPUTATIONAL FRAMEWORK

In order to investigate and demonstrate the current capabilities of the various analysis approaches, four different models were developed. The assumptions made in each cases and the performance of all models is summarized in Table 5.1, while a brief description of the overall concept is described in the following:

3.1 Frame bridge on Spring and Dashpot systems (Model 1)

First, a bridge frame model supported on complex dynamic impedance matrices that are specifically calculated for pile foundations and abutments is developed. This consists of the superstucture (denoted as part A in Figure 3), whose pies are assumed to be connected to 6-DOF spring and dashpot systems with dynamic properties computed using the computer code ASING (Sextos et al., 2003) for coupled translational and rocking modes of vibration and given the foundation and soil properties described in section 2. Pile-to-pile interaction was accounted through the formulation of the particular computer code. The abutment dynamic stiffness and damping is computed according to Zhang and Makris (2002). Kinematic interaction was ignored. The analysis is performed using the widely used FE program Sap2000 and represents the most refined approach that can be implemented in the design practice.

3.2 Frame bridge on spring supported abutment and foundation (Model 2)

This approach involves the FE model illustrated in Figure 3 inclusive of the superstructure (part A), the abutments as modeled with 2D shell elements in 3D space (parts B and E), as well as the pile foundations modeled using beam-on-dynamic springs (parts C and D). Spring and dashpot values were computed as in Model 1 but distributed based on the area of influence of each particular spring. The analysis is performed using the widely used FE program Sap2000.

3. Frame bridge on 3D solid embankment-foundation-abutment (Model 3)

Bridge superstructure is modeled using 3D frame elements which are then connected to a 3-D (solid) abutment-foundation-embankment system at both lateral supports of the deck (Figure 4). The piers are assumed to be supported on the 6-DOF dynamic impedance matrices described above while retaining the same properties as previously. Soil is assumed as linear elastic for comparison purposes. The analysis is performed with the advanced FE software Abaqus.

3. 4 Distributed Simulation: Frame bridge on 3D solid embankment-foundation abutment (Model 4a)

In this approach, which is the most refined compared to the previously described ones, the structure is subdivided into several modules that are computationally simulated using different computer codes. The analysis of the distributed modules is coordinated with the aid of UI-SimCor (Spencer et al., 2006), an enhanced Matlab based script with its own GUI that was developed by University of Illinois in order to coordinate either software or hardware supporting NEESgrid Teleoperation Control Protocol (NTCP) as well as TCP-IP connections outside of the NEES system. The basic concept of the framework is that analytical models associated with various platforms or experimental specimens are considered as super-elements with many DOFs. The main routine enforces static equilibrium during gravity load application and conducts dynamic time integration thereafter. Each of these elements are solved on a single computer or on different computers connected through the network. Interface programs for analytical platforms have been developed for Zeus-NL (Elnashai et al. 2002), OpenSees (McKenna and Fenves 2001), FedeasLab (Filippou and Constantinides 2004), and ABAQUS. In the particular analysis of the Egnatia Highway overcrossing, two different analysis packages were coordinated by UI-Simcor, corresponding to three distributed modules, namely: (a) the bridge sub-system, which was modeled using the verified inelastic dynamic analysis matlab program FedeasLab (Filippou and Konstantinides, 2004), the left (b) and right (c), pile-supported, abutment-embankment system that was modeled using 3D solid elements and the commercial FE package Abaqus (Model 4a in Figure 5). In order to minimize computational time, a relatively simpler 3D abutment-embankment system was adopted after appropriate calibration of stiffness (along the overall height) and damping with the refined 3-Dimentional soil Model 3.

4. VALIDATION

4.1 Benchmark model: Frame bridge on Spring and Dashpot systems with comparable properties (Model 4b)

To validate the accuracy of multi-platform analysis, a firth frame model (Model 4b) was developed in addition to the aforementioned four, using comparable geometrical and material properties with those assumed in Model 4a. In particular, the deck cumber was ignored and a point mass was assumed at both lateral boundaries equal to the total abutment-embankment was that was considered at the edge control points during the multi-platform analysis. Figure 6 illustrates that when compatible assumptions are made, the agreement between the single-platform (integral bridge model in Sap2000) and the multi-platform analysis (coordinating the response of Abaqus 3D volumes and FedeasLab bridge molules) was indeed very satisfactory.

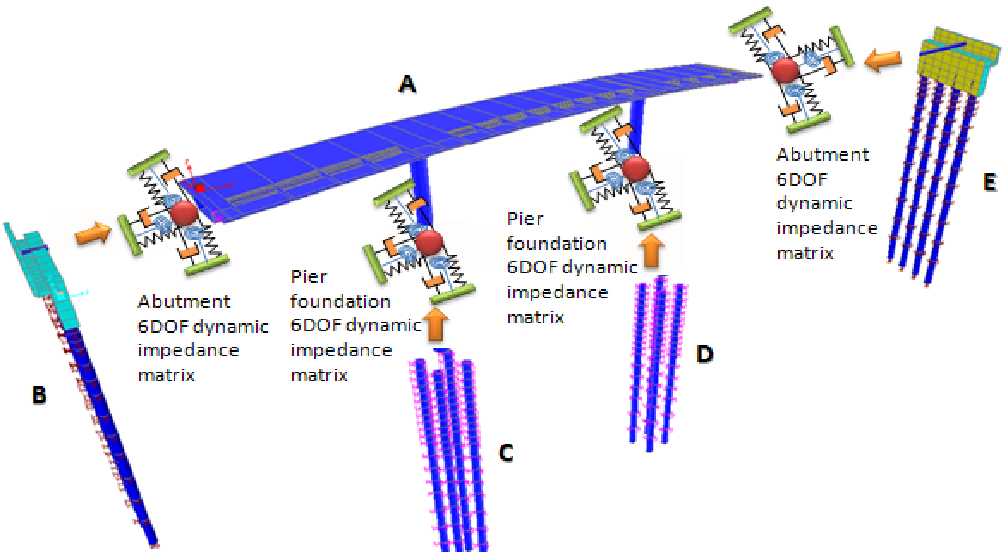

Figure 3 Overview of dynamic spring-supported Model 1 and Model 2

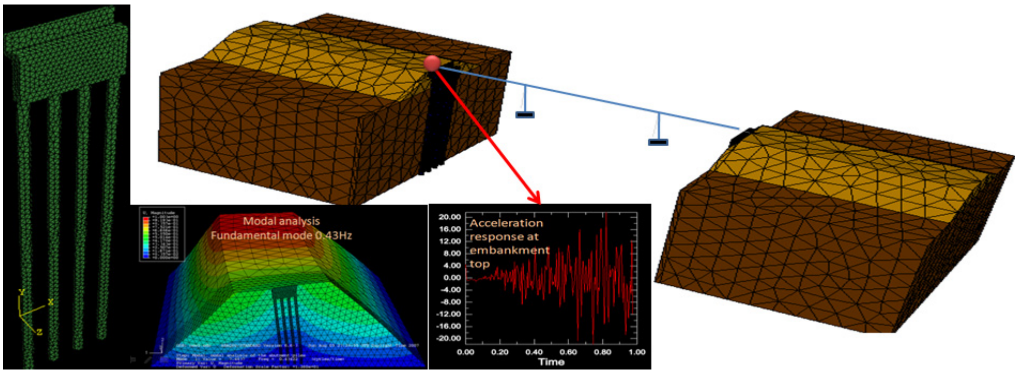

Figure 4 Overview and sample results of 3-Dimentional Model 3

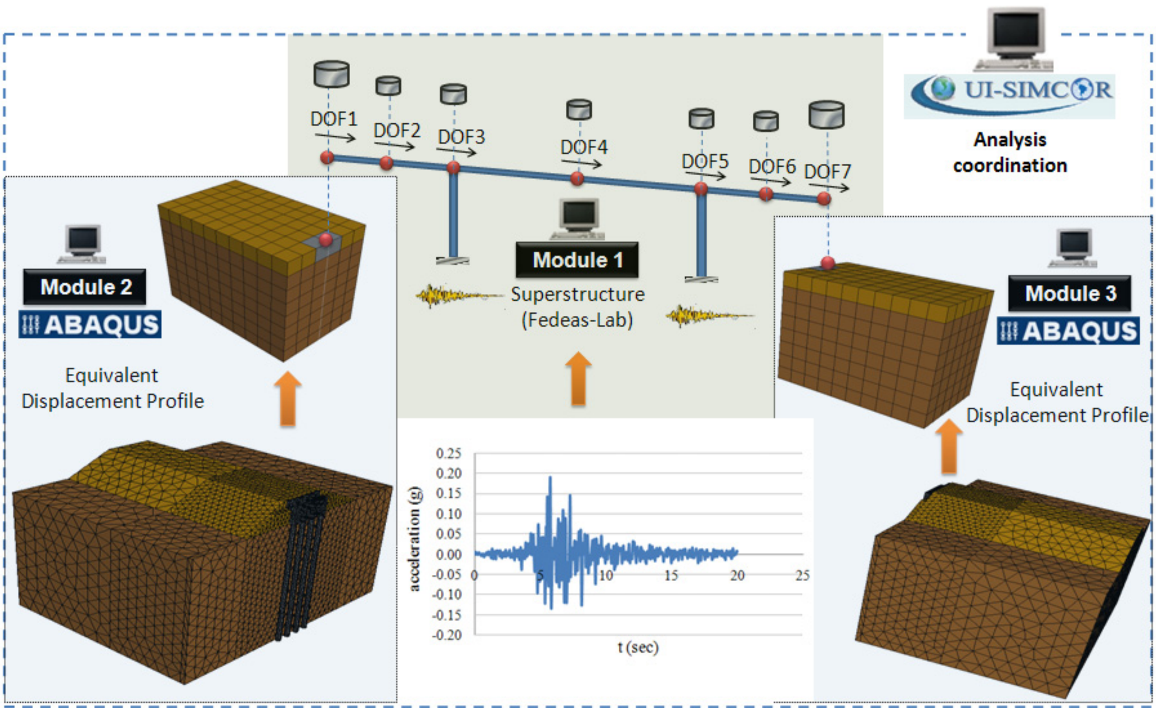

Figure 5 Distributed computational simulation (Model 4a)

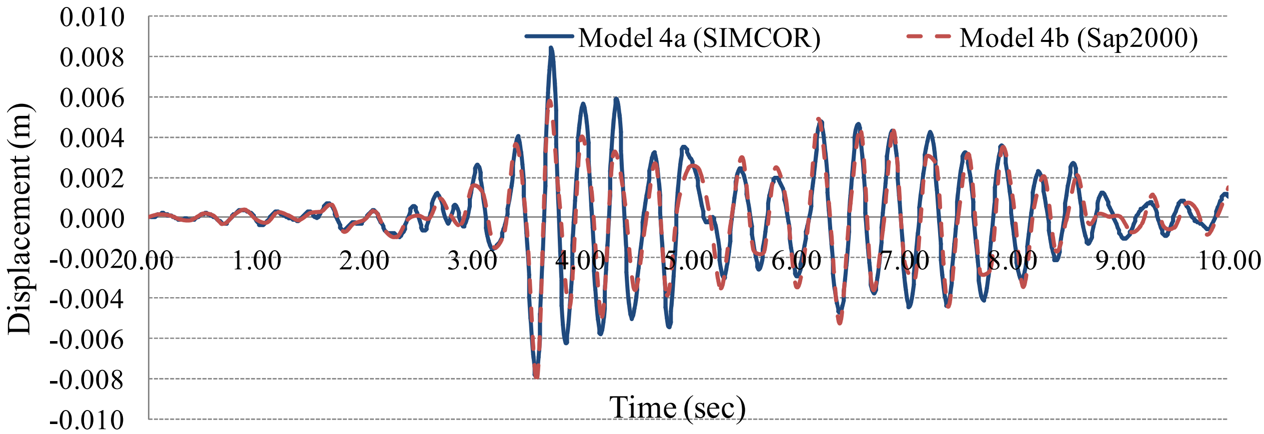

Figure 6 Dynamic response of the deck using multi-platform and single-platform approaches of Models 4a and 4b for compatible material and geometry assumptions.

Table 5.1 Summary of available features and performance of the four approaches under study.

Model Features and Performance	Model 1	Model 2	Model 3	Model 4
Middle piers pile group foundation stiffness	Point Spring	Spring supported Frame	Point Spring	Fixed**
Middle piers pile group damping	✓	✓	✗**	✗ **
Abutment stiffness	Spring	3D on shell	3D	3D
Embankment stiffness	Spring	Spring	3D	3D
Abutment foundation stiffness	✗	3D on shell	3D ✓	3D ✓
Embankment mass	Point mass	Point mass	3D ✓	3D ✓
Embankment soil stresses	✗	✗	✓	✓
Backfill soil stresses	✗	✗	✓	✓
Soil nonlinearity potential	Spring (p-y)	Spring (p-y)	Abaqus built-in models (Mohr-Coulomb Drucker-Prager, Cam-Clay)	Multiple software choices (Opensees, Abaqus)
R/C nonlinearity potential	Lamped plasticity	Lamped plasticity	Abaqus Built-in constitutive law	Multiple software choices (Opensees Zeus, FedeasLab)
Computational time*	2min	4min	2 ½ hours	2 ¼ hours

* Integration time refers to 10sec duration of uniform ground excitation at 0.01sec step executed on a Core 2 Duo processor, 2GB RAM.
** Refers to particular FE modeling scheme; more refined models are also feasible but where not adopted herein.

5. COMPARATIVE ASSESSMENT AND CONCLUDING REMARKS

Given the detailed data available for the particular case-study, an effort was made to use common assumptions regarding earthquake excitations and solution algorithms. Along these lines, the Kozani, Greece earthquake (PGA=0.19g) was uniformly applied in all cases, while the Hilbert-Hughes-Taylor integration method was used, with time step Δt=0.01s and a total of 1000 steps (10s of input). A uniform damping value of 5% was assumed for the first and second modes of vibration, defined through the Rayleigh alpha and beta corresponding factors. Gaps and stoppers that have been designed for the particular structure were ignored to ensure maximum possible activation of the embankment-abutment system. Backfill and foundation soil properties were also taken identical between models 3 and 4 based on the actual soil properties described in section 2. All analyses were conducted in the elastic range and the excitation was performed in the longitudinal direction. Parametric analysis was also performed to investigate the relative influence of various assumptions that inevitably varied between the four approaches i.e. spring and dashpot constants of Models 1 and 2 in contrast to Poisson's ratio and modulus of elasticity for soils in Models 3 and 4, embankment finite element mesh dimensions and size, among many others. It was concluded that the parameter related to the maximum level of uncertainty was the critical embankment mass that was expected to be activated during the particular earthquake excitation and most importantly, the means to simulate its effect in the framework of the four different analysis strategies adopted. In contrast to the validation case (section 4) the value of the single point mass that was used for Models 1 and 2 at the lateral boundaries of the bridge to represent the 'active' embankment-abutment system, was predicted independently (blindly) based on the concept of critical embankment length (Zhang and Makris, 2002) and without any calibration to 3-D solid Models 3 and 4, where the activated embankment mass was inherently considered. Next, the dispersion in the dynamic response of the bridge due to the assumptions and modeling approach adopted was assessed, as illustrated in Figure 7. In particular, it is seen that following four different approaches to consider the effect of embankment-abutment-superstructure interaction, the maximum longitudinal displacement of the deck lies in the range of 0.6-1.0cm whereas the fundamental period of the overall system may also differ by more than 100% despite the effort to use compatible properties where available. Further response measures (i.e. middle pier stresses) are not presented herein due to lack of available space; however, it is noted that the dispersion is of the same order. It is also seen (Table 5.1) that multi-platform analysis is a very promising concept since it provides stable results within the envelope of the response produced by the other three approaches while enabling the consideration of 3-Dimentional geometry without exceeding the computational time required for a conventional single-platform 3-D modelling of the entire embankment-abutment-bridge system. Moreover, it noted that the multi-platform simulation coordinated by UI-Simcor, may also offer significantly improved flexibility towards the consideration of the inelastic response of the R/C members, as it can combine a number of specialised models and software currently available.

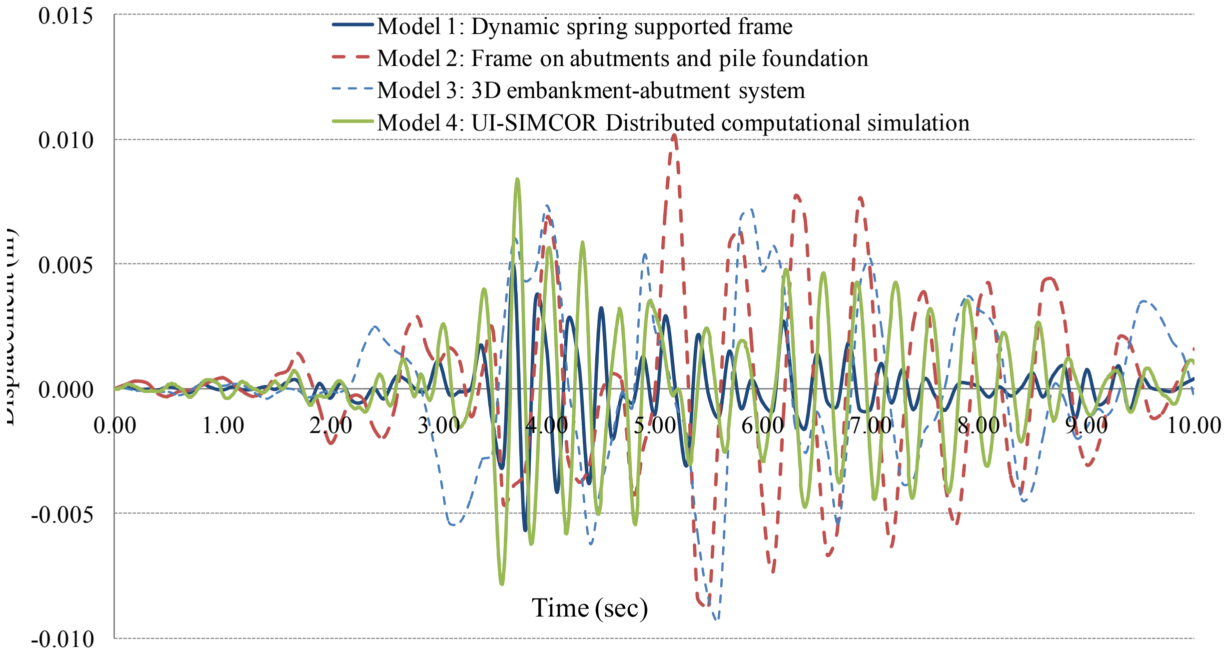

Figure 7 Dynamic response of the deck for various embankment-abutment-foundation-superstructure interaction modeling approaches

CONCLUSSIONS

Four different analysis approaches to simulate the dynamic interaction between the embankment, the abutment, its foundation and the bridge were adopted and comparatively assessed for the study of a real overcrossing in Greece using a wide variety of software that involve both single and multi-platform analysis. It is concluded that the last generation computational tools available, provide a number of new capabilities, however, given the dispersion of the results observed through alternative analysis strategies, it is deemed that still, careful consideration of the various modeling aspects is the major reliability factor independently of the complexity of the analysis approach followed. Moreover, it was shown that multi-platform analysis is a promising alternative which combines rigor and complexity at acceptable computational cost, while it provides additional flexibility in case the inelastic dynamic response of the superstructure and/or the supporting soil is sought.

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