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Simplified vs Detailed Bridge Models: A Time and Costs Decision

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Abstract

The most common question between the bridge designers is how detailed need to be the mathematical model, and how far the results obtained from simplified models are from models that are more sophisticated. This paper compares the results of different level of modeling vs. the experimental results obtained from testing a three span slab on girder bridge before and after it was retrofitted replacing the steel bearings by lead core rubber bearings. It also presents earthquake predictions using the validated models. It is expected that the results presented here will provide some modeling clues that could be used in the future for a more realistic modeling construction and parameter selection.

Keywords

Bridge, steel bearing, isolation bearings

1. Introduction

Full-scale tests of bridges have gained interest during the last 20 years. Improvements in data acquisition technology and the application of system identification concepts (Douglas1982 and 1990) have contributed to make this kind of test an important source of information. Not only conventional bridges have been tested; Lam 1990 and Kakinuma, 1994 have tested bridges with highly damped non-linear isolation devices. The advantage of having experimental data obtained from the full scale bridge tests is that this information could be used to construct reliable mathematical models that could be used later to predict the behavior of the structure under different loading conditions.

The first question that came to the mind of most of the bridge engineers is how detailed need to be the mathematical models, and how far the results obtained from a simpler models are from sophisticated models. Using the experimental results obtained from testing the South Bound Bridge carrying Route 400 over the Cazenovia Creek some 50 km southeast of Buffalo, NY., this paper intend to answer this question. The first portion of the work presented here, compares the results of different level of modeling vs. the experimental results obtained before and after the bridge was retrofitted replacing the steel bearings by lead core rubber bearings. The second portion of the paper present the earthquake predictions performed using the validated models. It is expected that the results presented here will provide some modeling clues that may be used in the future to a more realistic modeling construction and parameter selection.

2. Structural Modeling

2.1 Elastic Modeling (SAP2000)

A 3-D model using called SAP2000-3D and a 2D model called SAP2000-2D were constructed in order to compare the results obtained using different level of modeling sophistication with the experimental results. Both models are well described in reference Wendichansky (1998). The bearings properties used during the construction of these models were based on a system identification study which correlate well with the experimental results obtained from the retrieved bearings (Mander 1996). The properties of the soil were modeled using springs connected to the foundation beams. The values of these springs were extracted from the companion study done by Douglas et al. (1994).

2.2 Nonlinear Modeling (DRAIN-2DX)

If the structure does not behave elastically, the use of a complex 3D model considerably increases the computer time and is thus impractical when a parametric or approximate study need to be done or when several elements will behave in a non-linear fashion during earthquake events. A 2D FEM model for this condition was designed to be used with the program DRAIN-2DX, in which only the bearings and soil were considered to be able to reach the inelastic range. The construction of this model was conducted using basic principles of mechanics and dynamics.

Table 1 provides some information regarding to the level of complexity of the models by providing the number of degree of freedom and the type of analysis that can be performed with each model.

Table 1: Model Comparison

			Type of Analysis	
Model	**Number of Joints**	**Degree of freedom per joint**	**Linear**	**Non-linear**
SAP2000 3D	1830	$6(x, y, z, R_x, R_y, R_z)$	yes	no
DRAIN-2DX	47	$3(x, y, R_z)$	yes	yes
SAP2000 2D	21	$2(y, R_z)$	yes	no
where $x =$ translation in the X direction, $y =$ translation in the Y direction, and z = translation in the Z direction, $R_x =$ rotation around the X axis, $R_y =$ rotation around the Y axis, and $R_z =$ rotation around the Z axis.				

3. Experimental vs. Analytical Results Comparison

3.1 Pre-retrofitted Southbound Bridge

Figure 1 presents a summary of the first five transverse mode shapes and frequencies predicted by the models. It also presents the participating mass for each mode. The comparison between the 3D SAP2000 model and DRAIN-2DX model show two mode shapes that look similar at frequencies around 5.5 and 6 Hz. For these models there is a coupled condition between the longitudinal and transverse direction that does not appear in the model SAP2000-2D since the bridge in this model is restrained in the longitudinal direction (“x”). The first five mode shapes and frequencies predicted by each model are very close, with some differences in the participating mass, especially between the SAP2000-3D and the model SAP2000-2D.

To corroborate the possible differences in predictions between the models for a specific earthquake, the EL CENTRO 1940 N-S motion was used as input for the three models and the displacement time history was computed and compared. The first 15 seconds of the response are presented in Figure 2. Figures 2a and 2b show that the differences in the predictions using the 3D model and the DRAIN-2DX model were not significant in any of the directions (transverse or longitudinal) or at the pier level. In all of the cases, the DRAIN-2DX model was able to reconstruct the major peaks and in cases where there were differences, they were on the order of 9%. Figure 2c compares the results between the two SAP2000 models. From the figure is clear that a reasonable agreement was observed between both models; the differences between the predictions peaks were on the order of 12 %.

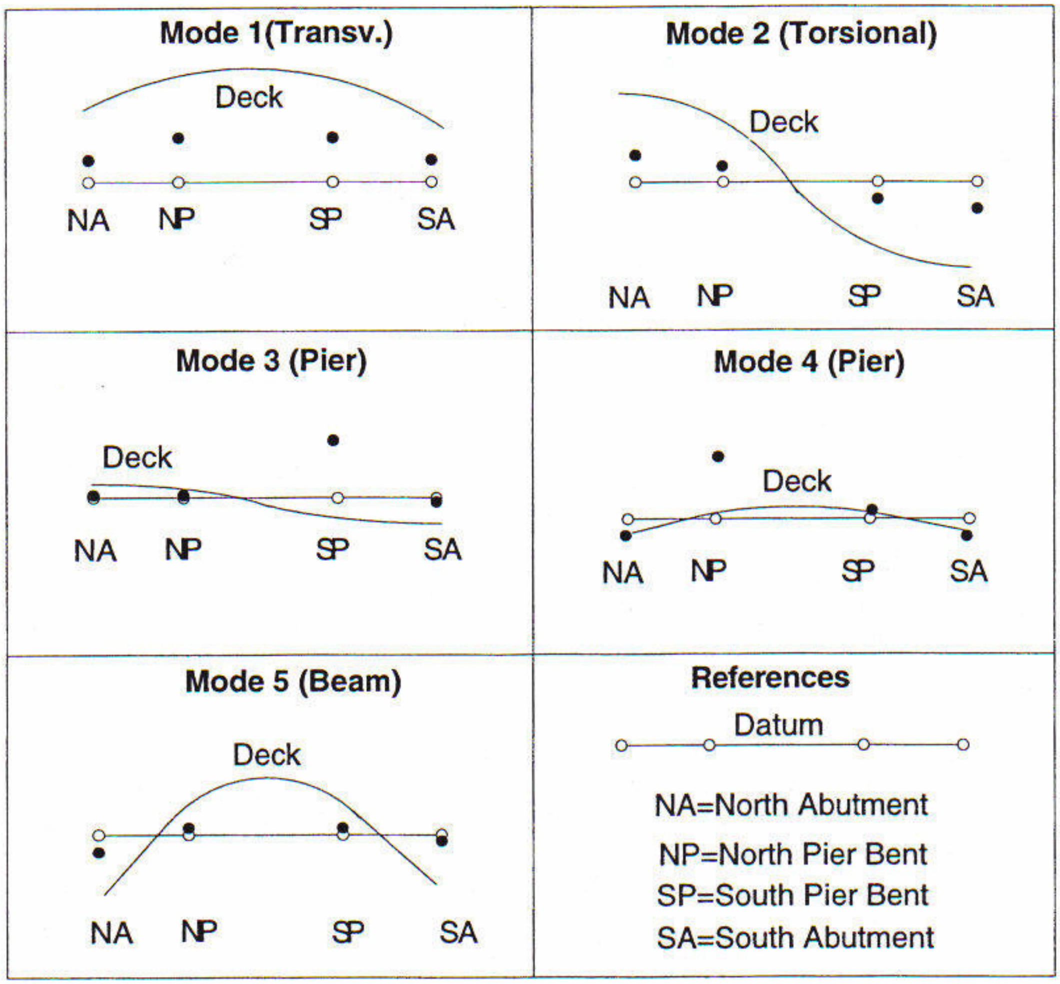
The comparison between models shows that for regular structures, if the correct parameters that govern the problem are chosen, and if these parameters are computed using logical first principles of structural mechanics and dynamics, it is possible to construct models that can predict the behavior of the structure with an average error of only around 10% compared with a much more sophisticated model. The comparison presented here was done with the intention to show that for regular slab-on-girder bridges, the simplified model can produce a good estimate. For preliminary studies, however, it is important to mention again that the reliability of this simplified model rests in a sound knowledge of the structural behavior.

3.2 Post-retrofitted Southbound Bridge

Figure 3 compares the transverse frequencies and mode shapes of the Southbound bridge, extracted from the elastic portion of the experimental results, with the predicted values using the 3D SAP2000 and 2D DRAIN-2DX models. Good agreement is evident between the experimental and analytical predictions. The modes clearly show that there no major contributions to the deck response from the piers and abutments. The results also show that the first and second modes correspond closely to rigid body translation of the deck, whereas the third transverse mode looks much like a mode corresponding to a free-free long bent beam. Similar degree of agreement was observed for the post-retrofitted north bound bridge.

Figure 4a compares the experimental acceleration and displacement histories with the predicted time histories using the 3D SAP2000 model. From the graph, it is evident that the use of the equivalent stiffness approach can predict well the maximum peak acceleration but makes a poor reproduction of the remaining portion of the time history. The same situation can be concluded from the observation of the displacement time history.

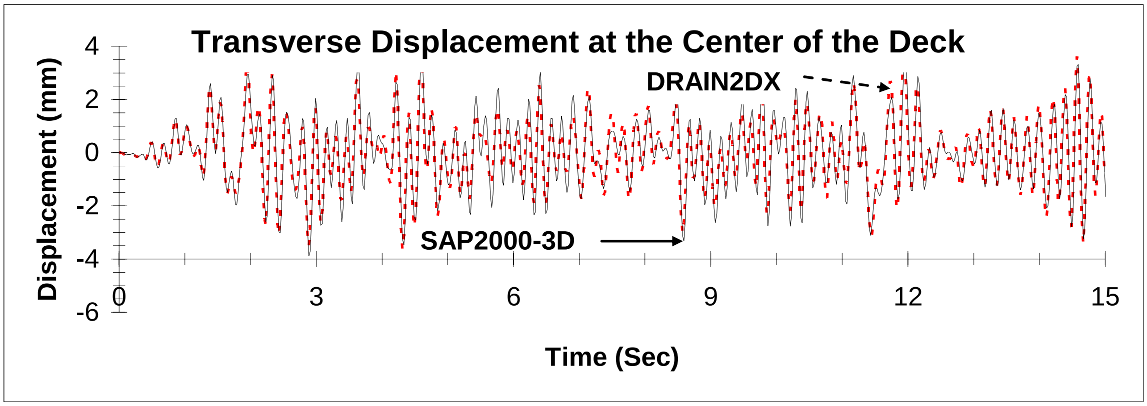
Figure 4b compares the experimental acceleration and displacement time histories of an accelerometer located in the deck of the Southbound Bridge with the analytical prediction using the nonlinear 2D model and the experimental load time history as an applied load.



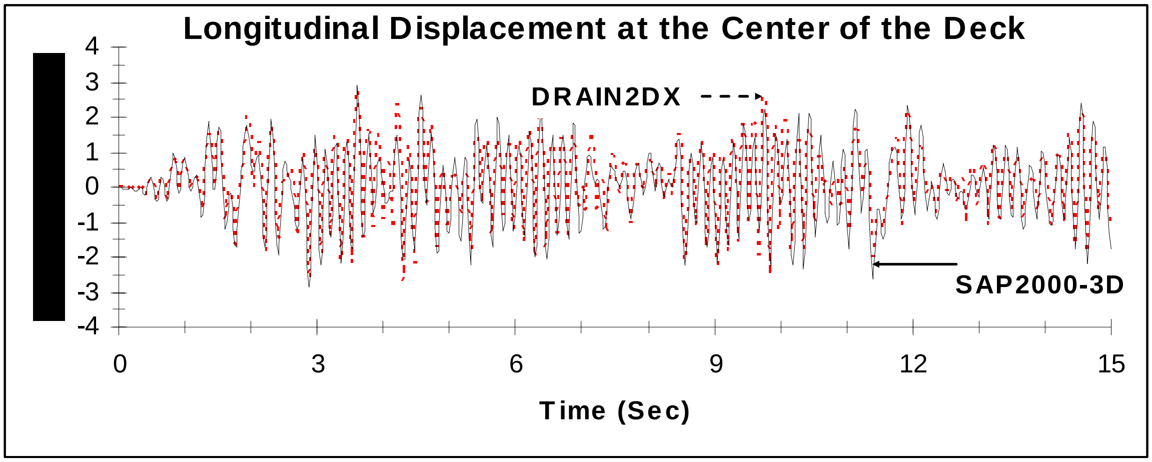
Mode	SAP2000-3D		DRAIN2DX		SAP2000-2D	
	Freq.(Hz)	P.M.(%)*	Freq.(Hz)	P.M.(%)*	Freq.(Hz)	P.M.(%)*
1	5.34 5.94	35.0 30.0	5.45 5.96	39.0 33.0	5.86	75.0
2	9.02	0.15	8.82	0.10	8.95	0.26
3	11.86	2.50	12.00	3.27	11.99	3.28
4	12.43	1.91	12.58	0.06	12.60	1.89
5	13.72	7.88	13.83	11.0	14.04	18.53
Sum=		78%		86.5%		99%

*P.M. = Participating Mass

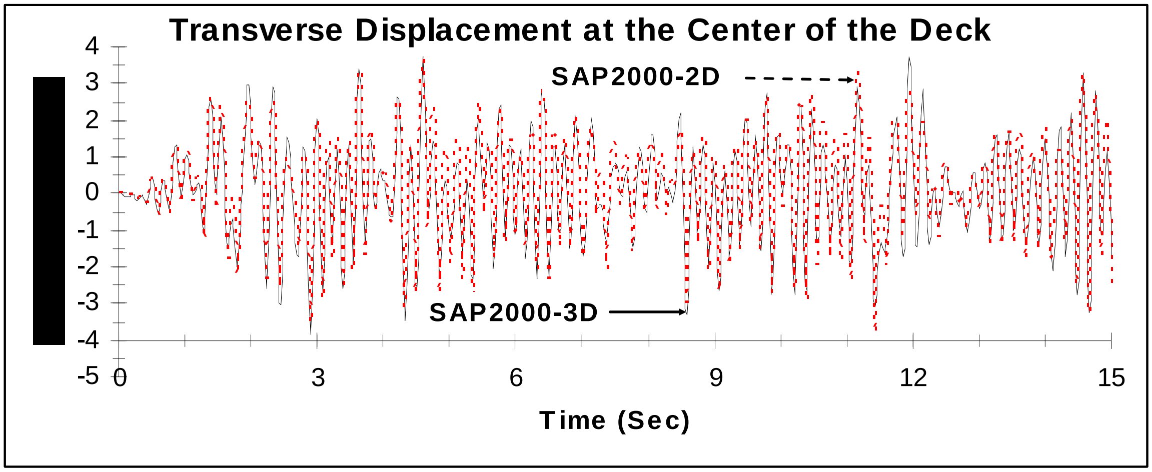
Figure 1: Results Comparison for Different Mathematical Models



(a) SAP2000-3D vs DRAIN 2DX



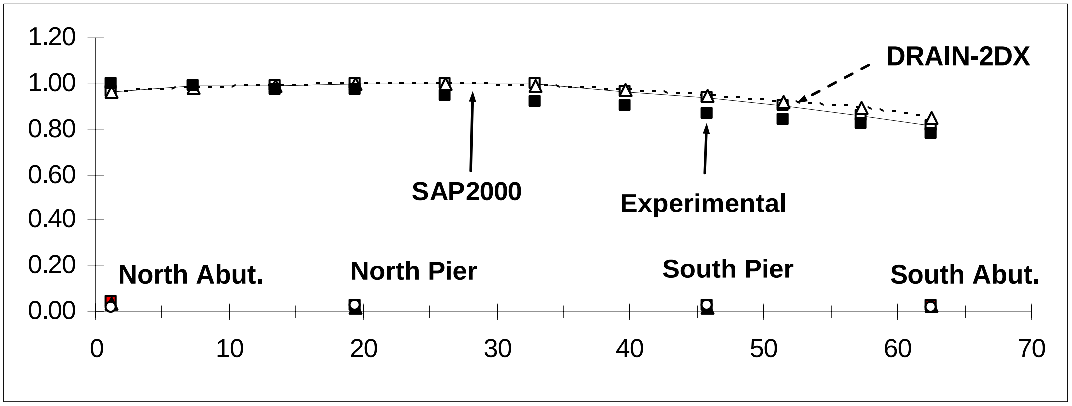
(b) SAP2000-3D vs DRAIN2DX



(c) SAP2000-3D vs SAP2000-2D

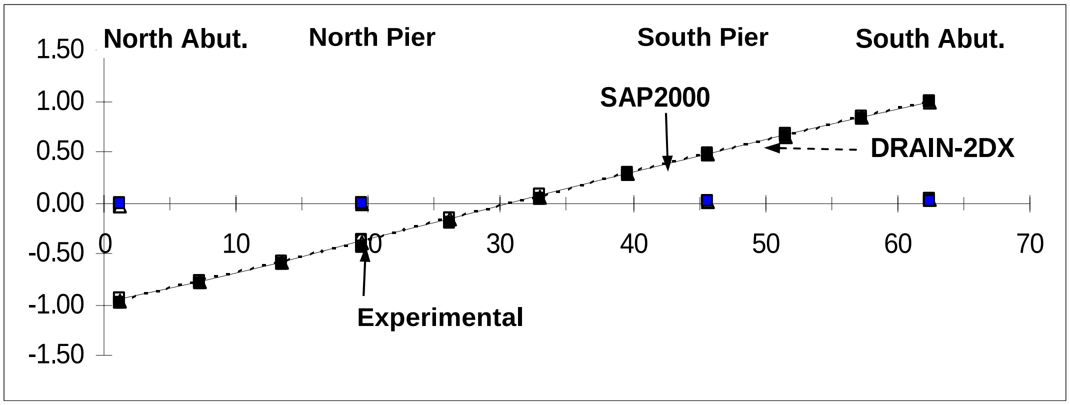
Figure 2: Comparison of the Southbound Models for El CENTRO Earthquake

Frequency: SAP2000 = 1.88 Hz - DRAIN2DX = 1.85 Hz - Exp Average = 1.96 Hz



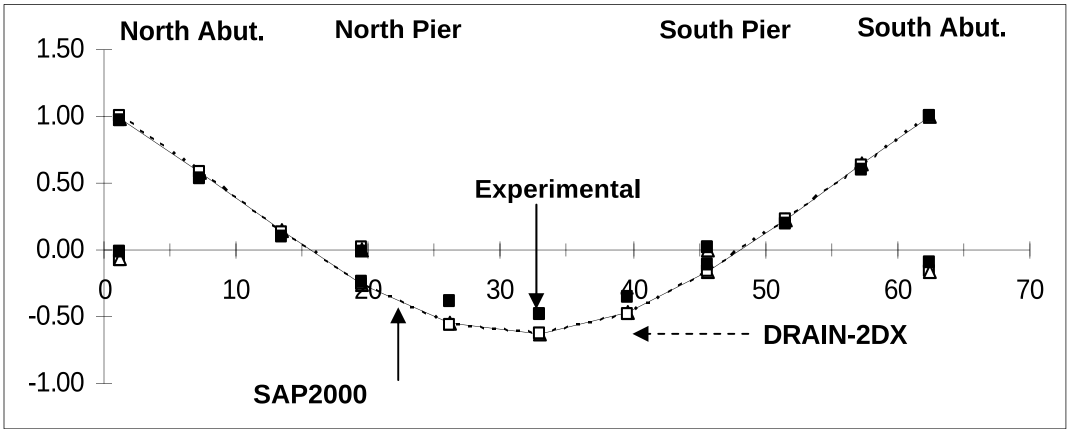
(a) First Transverse Mode

Frequency: SAP2000 = 3.12 Hz - DRAIN2DX = 3.09 Hz - Exp Average = 3.13 Hz



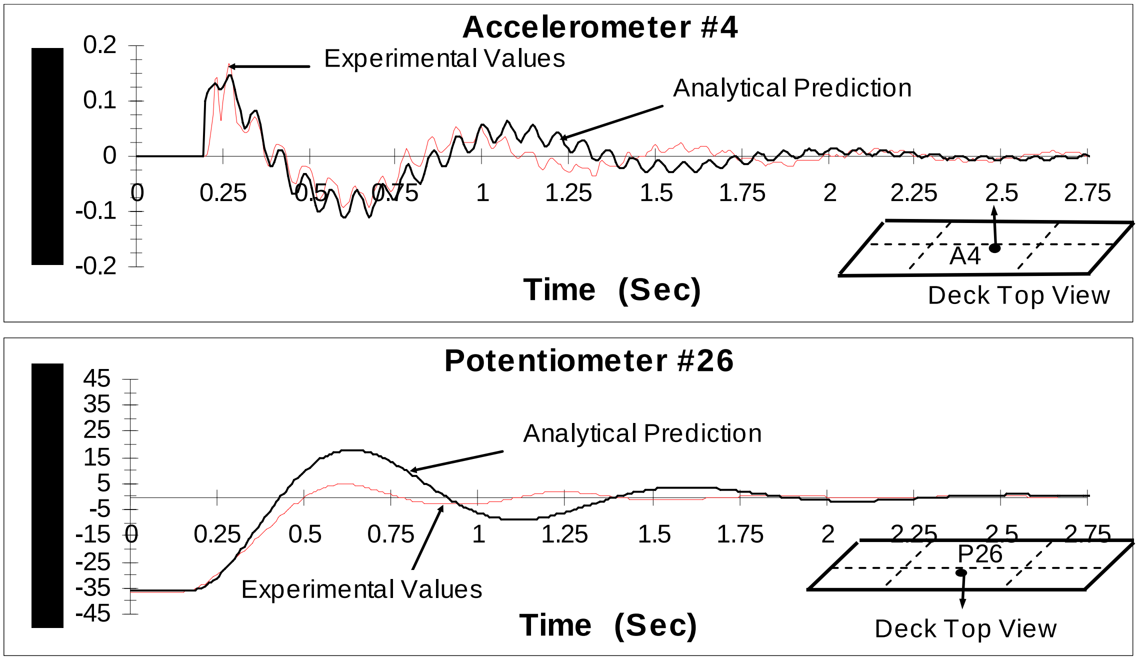
(b) Second Transverse Mode

Frequency: SAP2000 = 14.16 Hz - DRAIN2DX = 14.59 Hz - Exp Average = 14.05 Hz

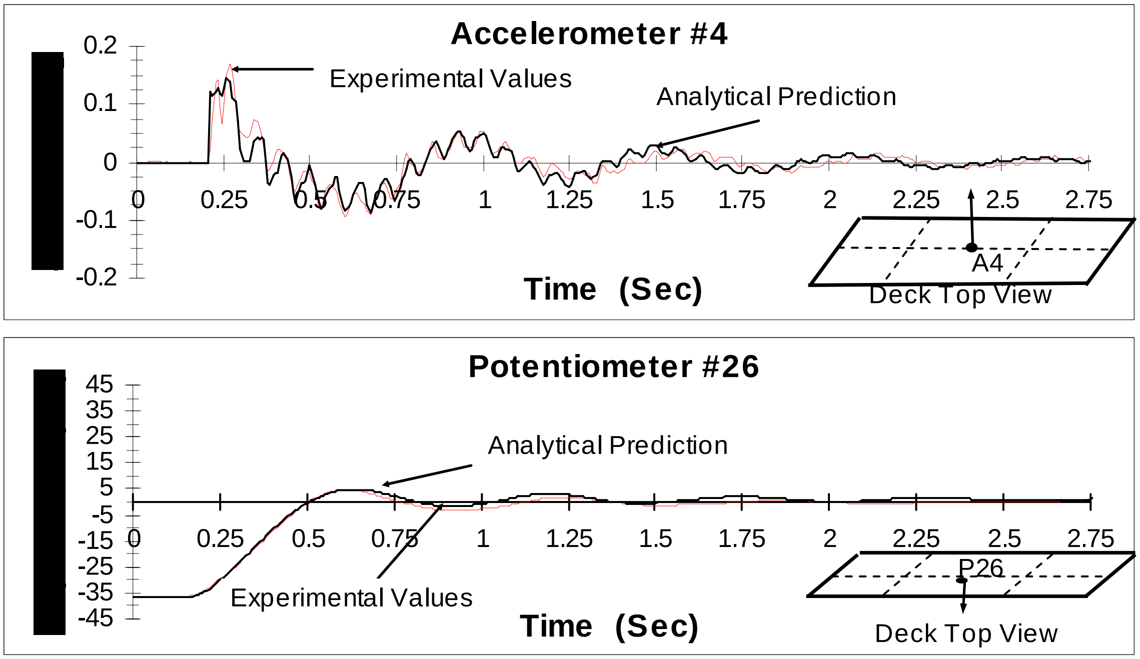


(c) Third Transverse Mode

Figure 3: Experimental vs Analytical Transverse Modes of Post-retrofitted Southbound Bridge



(a) SAP2000-3D Model



(b) DRAIN2DX Model

Figure 4: Experimental vs Analytical Results of Post-retrofitted Southbound Bridge

The comparison shows a good agreement between the experimental and analytical predictions. The model is also able to predict quite well the displacement time history. From these predictions, it is clear that the behavior of the bridge is controlled by the nonlinear properties of the bearings.

It is thus evident that a model that cannot replicate bearing behavior may produce only approximate predictions, independent of the complexity of the overall computational model itself. On the other hand, due to the large differences in stiffness between the bearings and the other components of the structure, a simpler model that can replicate the bearing behavior well may be able to produce better agreement between the observed and predicted behavior. It is also important to observe the existence of a higher mode in the acceleration time histories. The frequency of this made (which is around 14 Hz) is not related to the bearing properties but rather to the deck-structure characteristics and resembles the bending of a free-ended beam.

4. Implication of using simplified mathematical model in design

Undertaking non-linear transient analyses that lead to accurate results is a painstaking time-consuming task. Such definitive analyses go well beyond routine design office procedures that are commonly used by bridge engineers for either (i) seismic design of new bearing systems; or (ii) the seismic analysis and evaluation of existing bridges with bearing systems that exhibit highly non-linear behavior. Procedures for the seismic design of new elastomeric bearing systems (including the effects of the non-linear behavior of lead-rubber bearings, whenever present) are currently based on linearized elastic methods of analysis where effective secant stiffness is used instead of non-linear material behavior.

Figure 5 shows the comparison of the transient response made between the equivalent linear and non-linear analysis. It is evident that both the non-linear time history analysis as well as the linearized approach provides good agreement with the displacement amplitudes. This indicates that the assumptions inherent in the linearization process appear to be satisfactory. However, from figure 5 it is also evident that the linearization may not provide a good agreement with the overall response behavior in terms of frequency content or displacement amplitudes that are smaller than the maximum displacement.

5. Conclusions

The present work compares the results obtained from different level of modeling details. All of the mathematical models used, were validate against full-scale field test performed over a three span slab on girder bridge. The comparison was performed before and after it was retrofitted with elastomeric lead core bearings. The principal findings can be summarized as its follows:

1) The use of simplified models can produce good estimates if the correct geometry is chosen. For this study, it was found that the transformed section approach to model the entire deck-girder system worked well. When the bridges were seated on steel bearings making the structure very stiff, the inclusion of diaphragms' and bearings' flexibility in the model were essential to adequately capture the transverse behavior of the superstructure of the bridge.
2) The experimental results of the full scale bridge tests, and the companion component tests, showed that bridge behavior is highly dependent of the level of displacement. Therefore, special care should be taken when modeling the boundary conditions.
3) When initially modeling a bridge structure, there is a temptation to assume that the foundation system is strong and stiff thereby assuming full fixity at the pile cap (column base) level. However, the inclusion of equivalent soil springs and masses in order to model soil-structure the interaction is highly recommended. The inclusion of these springs allows one to consider the flexibility of the structure at the foundation level. The use of a fixed-base system not only ignores such flexibility, but also requires an artificial decrease in other structural stiffness properties in order to fit the results. This may end up being an unrealistic representation.

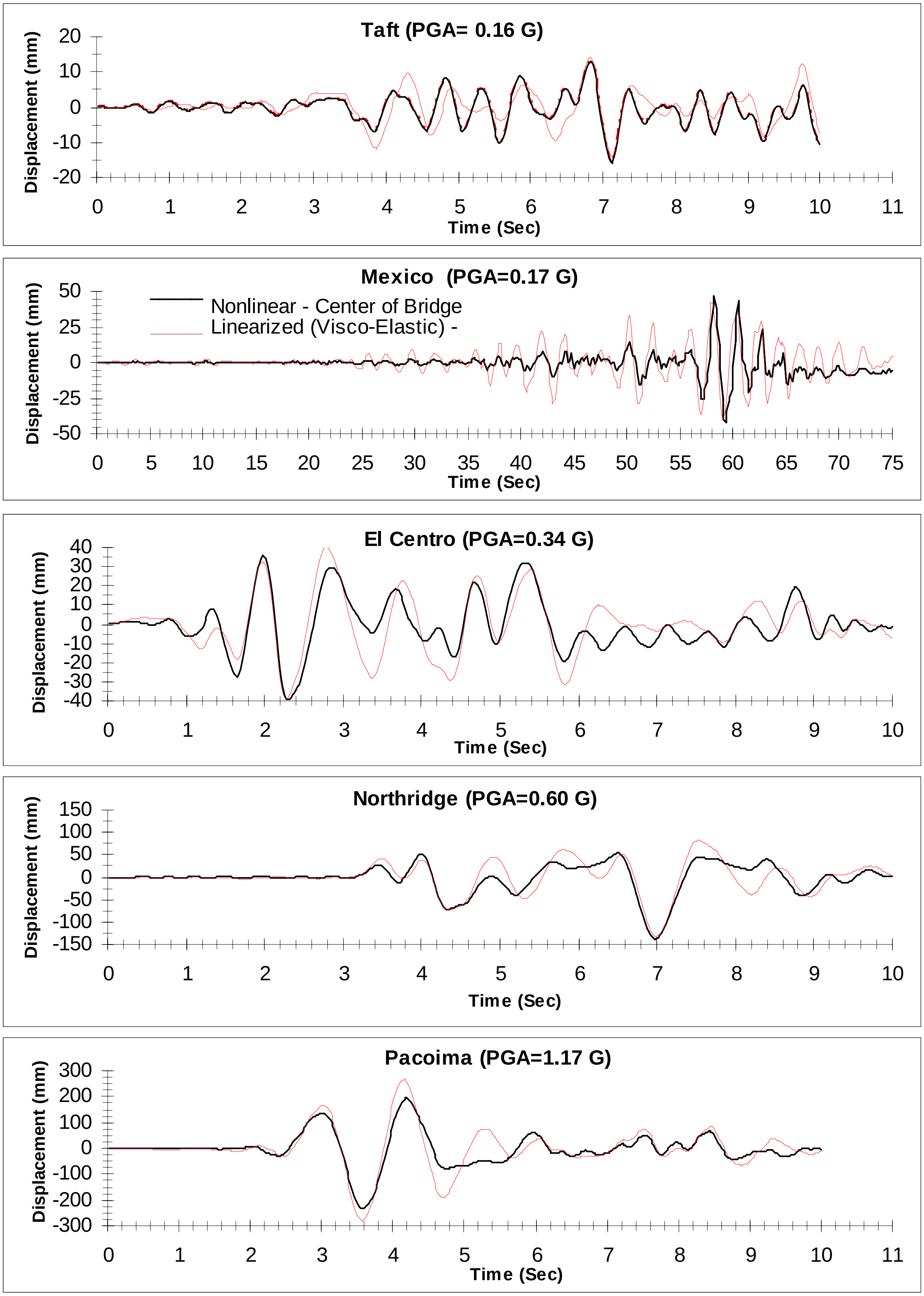


Figure 5: Southbound Bridge-Model Comparisons for Isolation Bearings

4) There is also a temptation to assume that steel expansion bearings do indeed expand. Thus an analyst will commonly modal such bearings as a roller support. Based on this and companion field and laboratory studies (Mander et al., 1996) this is clearly a faulty assumption. Steel bearings possess a significant amount of frictional resistance that until broken (at high force levels) should be modeled by assuming fully fixed supports with only a release of longitudinal moments that is a pin support. Thus some form of non-linear structural modeling is essential in studying the limits of bridge behavior when seated on steel bearings.
5) From the above points it is clear that for the construction of a reliable simplified elastic model of a slab-on-girder bridge, special emphasis should be given to the determination of the contribution of the diaphragm, bearings (especially the degree of bearing fixity), and soil-structure interaction. The analytical models proposed for this project were constructed following this approach and in each case were able to predict with reasonable agreement the experimental dynamic response.
6) For bridges with flexible seismic isolation bearings, the overall response is governed by the bearings themselves. Therefore, the major focus in modeling should be a reliable mechanical model of bearing behavior based on large deformation laboratory tests.
7) The experimental results of the retrofitted Southbound bridge seated on the seismic isolation bearings showed that an adequate prediction can be made of the initial displacement and peak response acceleration using linearized elastic modeling in which an equivalent stiffness and damping approach is used to model the lead rubber bearings. However, the overall time history was poorly modeled. On the other hand, a non-linear model using the laboratory-identified properties of the bearings was able to reconstruct with a good agreement the experimental results.

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