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COMPARISON OF SEISMIC RESPONSE OF NON-SEISMICALLY AND SEISMICALLY DESIGNED MULTI SPAN CONTINUOUS CONCRETE I-GIRDER BRIDGES

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ABSTRACT

Multi Span Continuous Concrete I-Girder Bridges are categorized among the most vulnerable bridge classes. Seismic response assessment for these highway bridges are essential for highway transportation networks exposed to seismic hazards. This study focuses on developing and comparing seismic response of different bridge components for seismically and non-seismically designed bridges that are common in this region. The primary differences between seismically and non-seismically designed bridges are the column details. Detailed three-dimensional (3-D) nonlinear analytical models, which account for the nonlinear behavior of the column, girders, and abutments are developed with the use of OpenSees platform. The seismic behavior of the bridge components are obtained and compared for the case of non-seismically and seismically designed bridges. The results explicitly show that the seismic behavior of the bridge components are significantly affected by seismic detailing of the reinforced concrete column. However, different components are not equally affected by this parameter.

INTRODUCTION

For at least a decade, there has been a research interest in questions of vulnerability and reliability of transport networks (Keshavarzi and Kim, 2016). Preservation and maintenance of Highways are very essential in any community, since they provide many job opportunities and billions of dollars of revenue for their communities by facilitating transportation of goods and passengers (Keshavarzi et al., 2017) and play a significant role in emergency activities planning during natural disasters such as earthquakes, fires, flood, etc.

Bridges are key nodes in any transportation network, and past earthquakes have shown that they are susceptible to damage and/or collapse during strong ground motions. Post-tensioned reinforced concrete bridges are very common among bridge designers. Kaveh et al. (2016) discussed methods for optimizing the design of post-tensioned concrete bridges using a variety of optimization techniques. They proposed a new optimization methods and compared the result with the result of other methods in the literature (Kaveh and Maniat, 2015, 2014, Farshchin et al. 2016, and Shi and Eberhart, 1998).

NLTHA technique has been exploited by several researchers (Mackie and Stojadinovic, 2001, 2005; Keshavarzi and Bakshi, 2012; Zhang and Huo, 2009; Nielson, 2005; Abbasi et al. 2015) and has proven to give reliable estimates of system performance. It serves as the foundation for even more computationally intensive techniques such as IDA. NLTHA offers the flexibility to consider analytical models with linear or nonlinear cyclic material characteristics and geometric nonlinearities such as P-Δ or full nonlinear or large deformations. The distinguishing feature of NLTHA when compared to CSM or RSA is the ability to consider a temporal dimension in addition to two or three spatial dimensions defined by the geometry.

Early seismic design provisions in the United States were developed following the historic 1906 San Francisco earthquake (FEMA, 2006). However, the first design provisions for bridges were not incorporated until 1940 principles. The 1940 design provisions involved design for a lateral seismic force equal to a certain percentage of the dead load determined by a design engineer, placed at the center of mass of the bridge. Specifications were made slightly more specific in 1941, where the dead load percentage was specified to be between 2% and 6% based on the foundation type, and subsequently found a place in the American Association of State Highway and

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Transportation Officials (AASHTO) specifications. The minimum lateral force of 2% of the dead load of the structure was still retained.

All of these aspects were included in the 1971 Caltrans Seismic Design Code (Sahs et al., 2008). The prime focus was to drive damage to the columns while the remainder of the bridge structure remained elastic (Moehle et al., 1995). Despite the modifications in design, the 1989 Loma Prieta earthquake caused spectacular damage to bridge structures.

Modern day design follows the capacity design philosophy which ensures flexural failure mode in the bridge columns (Sahs et al., 2008). This encouraged Caltrans to solicit the Applied Technology Council (ATC) to do a detailed study and obtain design and detailing suggestions, which, were not used until after the 1994 Northridge earthquake. Currently, Caltrans Seismic Design Criteria (SDC, 2010) considers all the suggestions of the ATC-32 report. In short, the 1971 San Fernando and 1989 Loma Prieta earthquakes caused considerable changes in the seismic bridge design philosophy. In order to provide reliable estimates of the risk related to the bridge classes, it is crucial to capture the design era and unique vulnerabilities associated with the bridges based on their time of construction, which is the main aim of the present study.

This paper focuses on the effect of these seismic design suggestions on the seismic response behavior of bridge structures. In order to conduct an accurate assessment, a 3-Dimensional numerical model was generated in OpenSees platform and a full nonlinear time-history analysis (NLTHA) performed for this model.

LAYOUT OF BRIDGE CLASS AND ANALYTICAL SAMPLES

This section describes an overview of the analytical models used for the components according to experimental tests in past studies. In order to carry out an accurate analysis, a three-dimensional nonlinear finite element model is developed in OpenSees (McKenna et al., 2010). The effect of pounding between the deck and the abutment is modeled using elements with a bi-linear force-deformation response based on the work done by Muthukumar and DesRoches (2006). The hyperbolic soil model suggested by Shamsabadi et al. (2010) is used in this study to model the effect of the passive soil response at the abutments. Since the deck is expected to remain elastic during seismic excitations, the composite slab and girders are modeled with linear beam-column centerline elements. The mechanical and geometric properties of the deck are then assigned to these elements.

Following Abbasi et al. (2016), piles at the abutments or bent foundations are modeled using bi-linear elastic springs. Elastic perfectly plastic elements, whose behavior is dominated by friction between the rubber and concrete, are used to model the elastomeric bearings of the girders. The shear keys are located at the abutments and are modeled based on the experimental tests conducted by Megally et al. (2001). A bilinear model is defined for the reinforcing steel. Nonlinear beam column elements with fiber-defined cross sections are used to model the columns (Abbasi and Moustafa, 2017). Based on the work done by Abbasi and Moustafa (2016), Rayleigh damping with tangent stiffness matrices was used to represent the energy dissipation in bridges.

The nonlinear hysteretic behavior of these columns is captured using a distributed plasticity element. Fiber defined cross sections enable specifying different properties for cover concrete and confined concrete. The reinforced concrete behavior is modeled using Concrete07, which is one of the available material models for concrete modeling in OpenSees. This material is provided based on the proposed model of Chang and Mander (1994). In comparison with other available concrete material models in OpenSees (e.g. Concrete01 or 03), Cocnrete07 exhibits higher initial stiffness, less softening after the peak tensile force, and it eliminates the issue of the sudden drop in the tensile concrete capacity. The reinforcing steel is modelled using the Reinforcing Steel material in OpenSees. In this material model, the fatigue and buckling behavior of steel during loading is included, which is ignored in other available material models (e.g. Steel01 or 02). The soil-structure interaction is accounted for with a set of springs, which is designated as substructure method (1985). In order to describe the behavior of the foundation at the column base, a series of translational and rotational springs are typically considered. The effective stiffness of the translation springs in this study is assumed 97.65 MN/m but the rotational stiffness is neglected considering the pinned connection nature at the base of multi column bents. Nonlinear springs are used

to model the behavior of the abutments in both the transverse and longitudinal directions. Figure 1 indicates the analytical modelling used in this study.
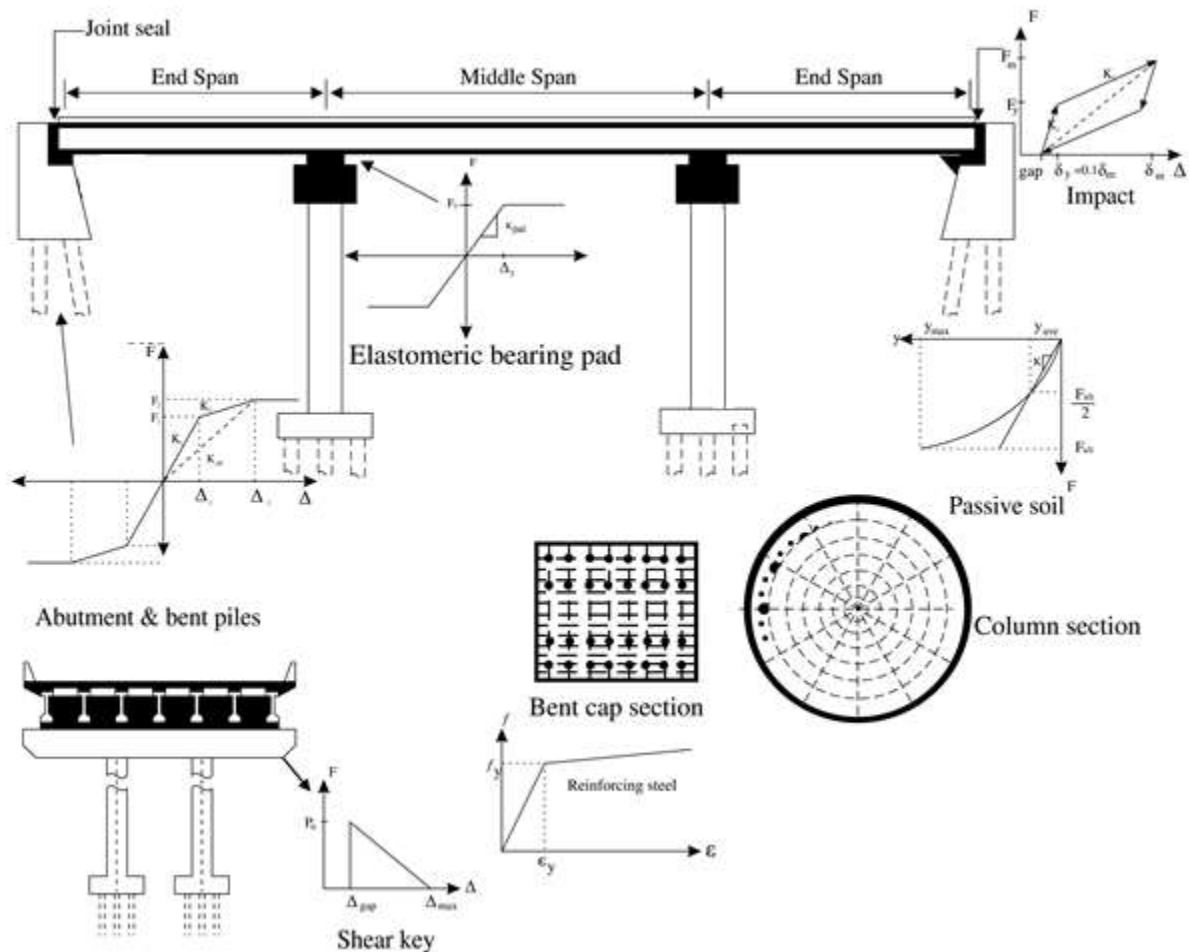

Fig. 1 A general view of the Multi Span Continuous Concrete I-Girder Bridge

The differences in the modeling of the seismically and non-seismically designed bridges are incorporated using the concrete model for the confined concrete. The effect of the closely spaced transverse reinforcement in the case of the seismically designed bridge columns is accounted for by using the confined concrete model (1988). In case of the seismically designed MSC steel bridge columns, the confined compressive strength, f_{con}, is approximately 33% larger than f'_c and the ultimate strain, ε_{cu}, is approximately 0.05. In the case of the non-seismically designed MSC steel bridge columns, f_{con} is approximately 7.1% larger than f'_c, and ε_{cu} is only about 0.012. Figure 2 illustrates typical seismic and non-seismic column cross sections.

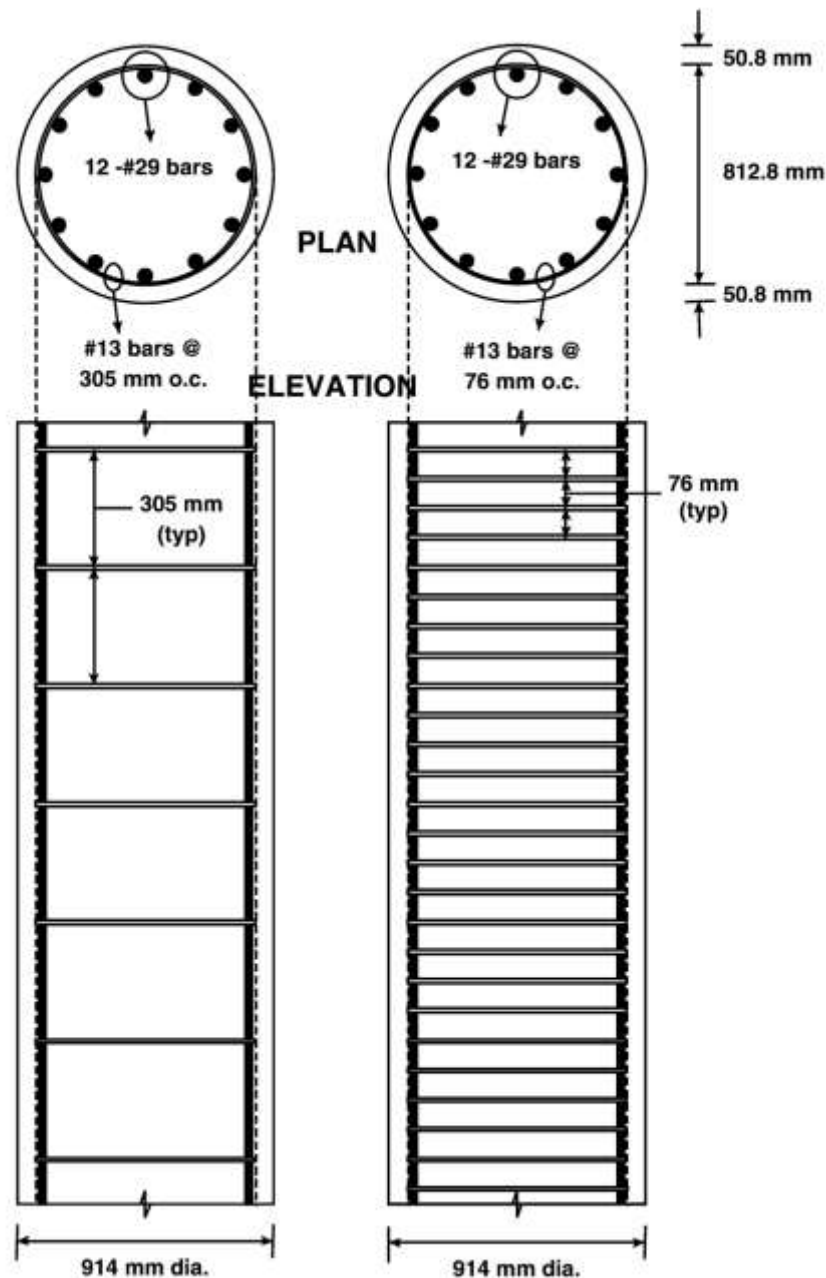Global Journal of Engineering Science and Research Management

Fig. 2 Seismic and non-seismic column cross sections

GROUND MOTION RECORDS

Nonlinear time-history analysis of the given prototype bridge is conducted to study the dynamic response of the bridge in different cases. Two orthogonal horizontal pairs of the ground motion are considered. The response spectra of the selected ground motions in the transverse and longitudinal directions are shown in Fig. 3. The record represents a near fault earthquake in California, which is selected from the suite of 20 ground motions pertinent to Los Angles developed for SAC project database (1997). This record has a peak ground acceleration of 1.018g in the longitudinal direction, and 0.98g in the transverse direction, respectively.
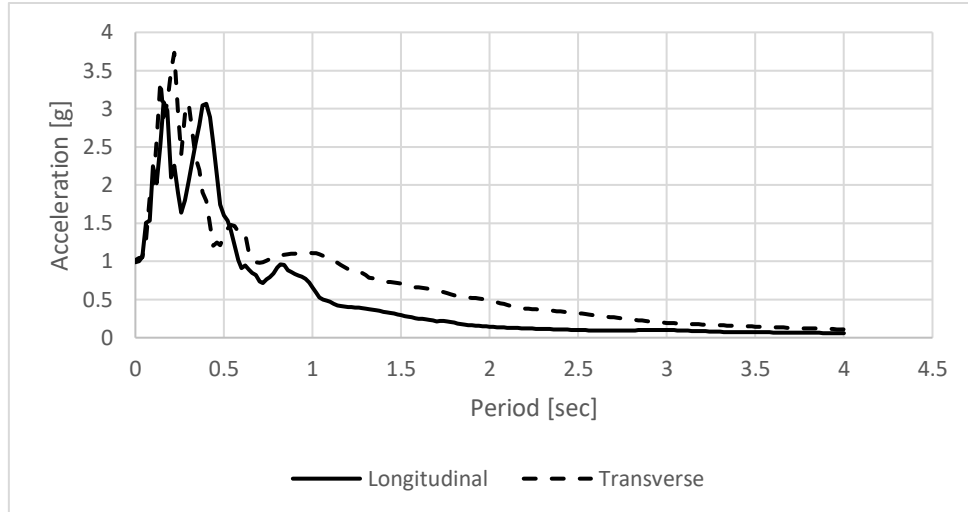
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Fig.3 Response spectrum of the ground motion selected for this study in transverse and longitudinal horizontal directions

NONLINEAR TIME-HISTORY ANALYSIS

The ground motion, previously mentioned, was used to perform nonlinear time history analysis. Selected analysis results and bridge component response are presented and discussed in this section.

The deck displacement history in the longitudinal and transverse direction is shown for non-seismically and seismically designed multi span continuous concrete I-Girder bridges in Figures 4a and b, respectively. According to the figures, the seismically designed bridges leads to a 7.94% and 11.35% increase in the deck displacement capacity along the longitudinal and transverse direction when compared to the other case, which is the non-seismically designed bridge.
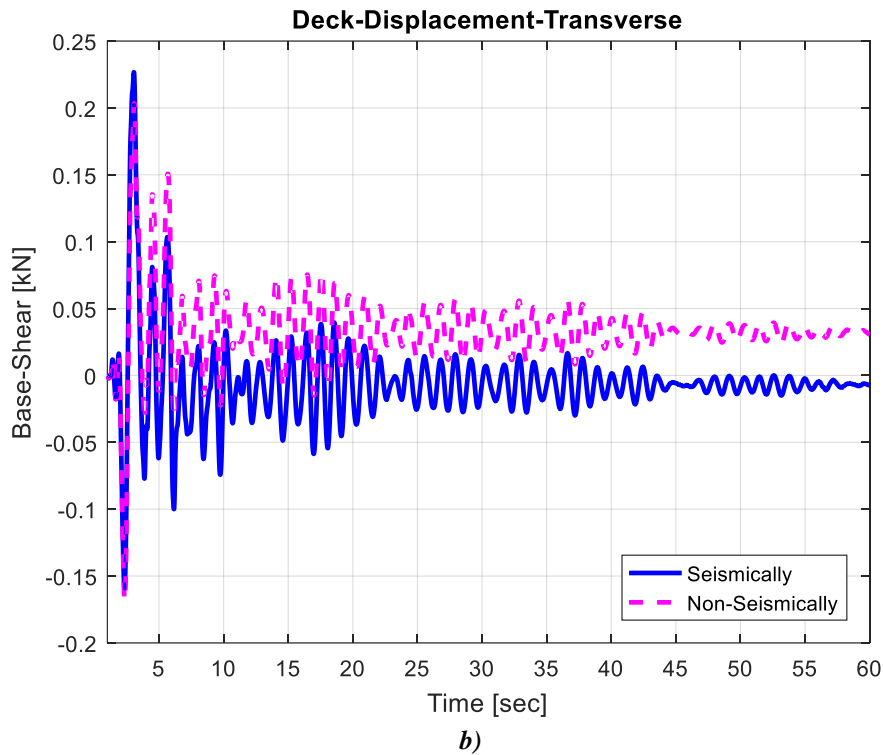

a)

b)
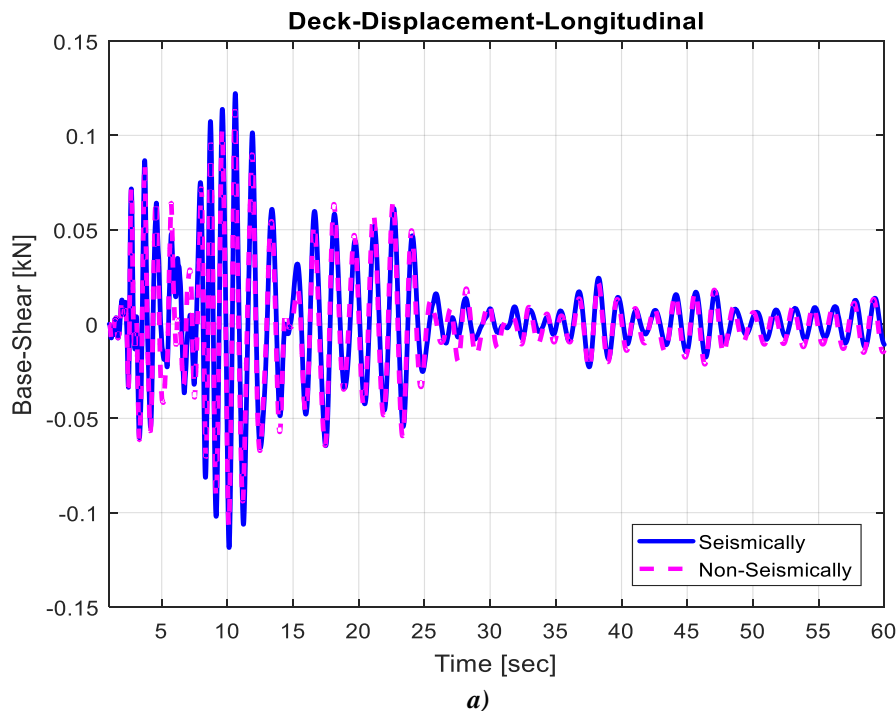
Fig. 4 The deck displacement along a) longitudinal b) transverse under the near-fault earthquake

In addition, Figure 5 shows a comparison of the deck displacement capacity in the longitudinal and transverse direction for seismically and non-seismically designed scenarios. Based on this figure, the aforementioned change can be seen for the seismically and non-seismically designed bridge.
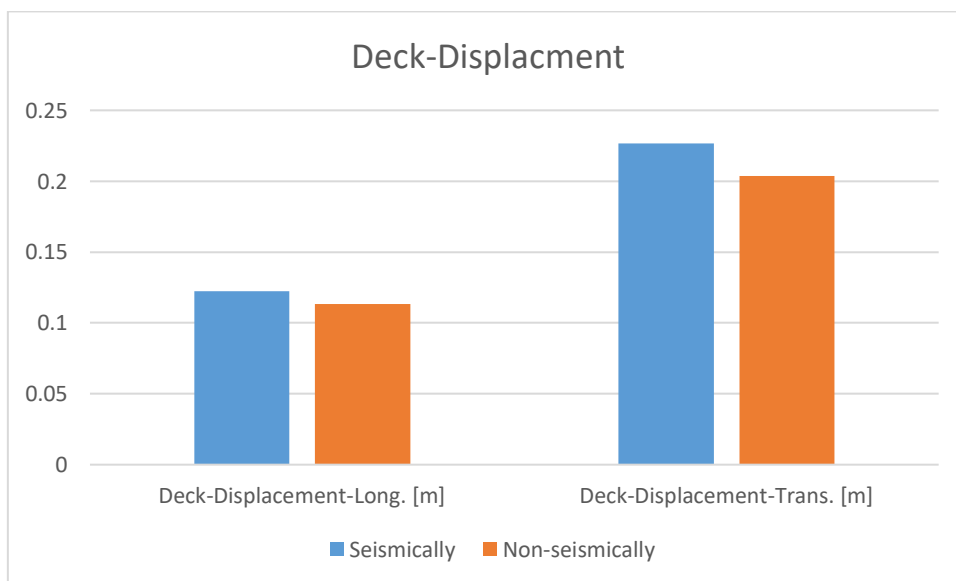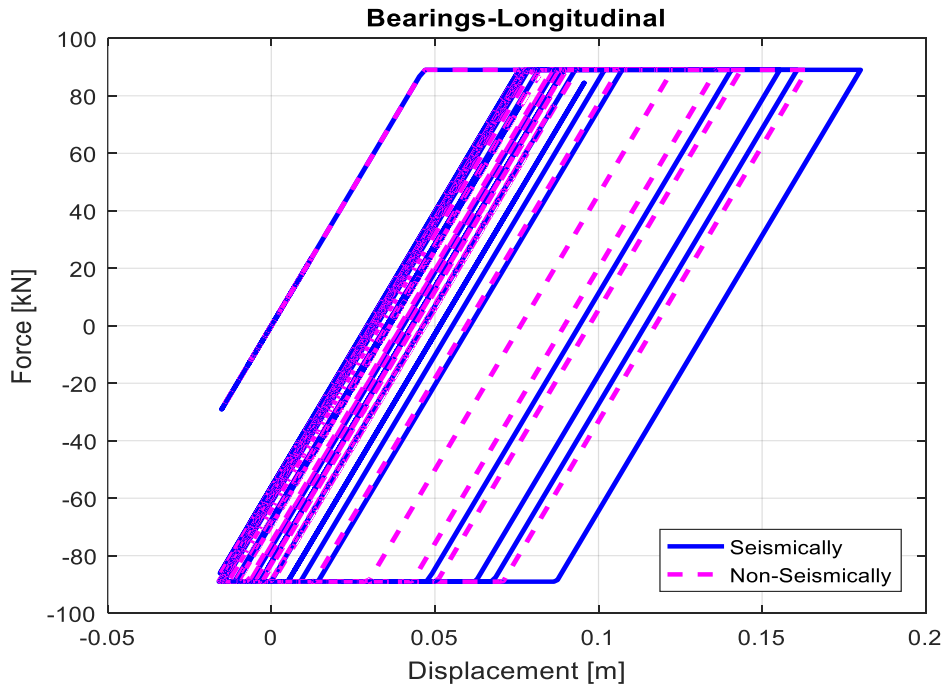

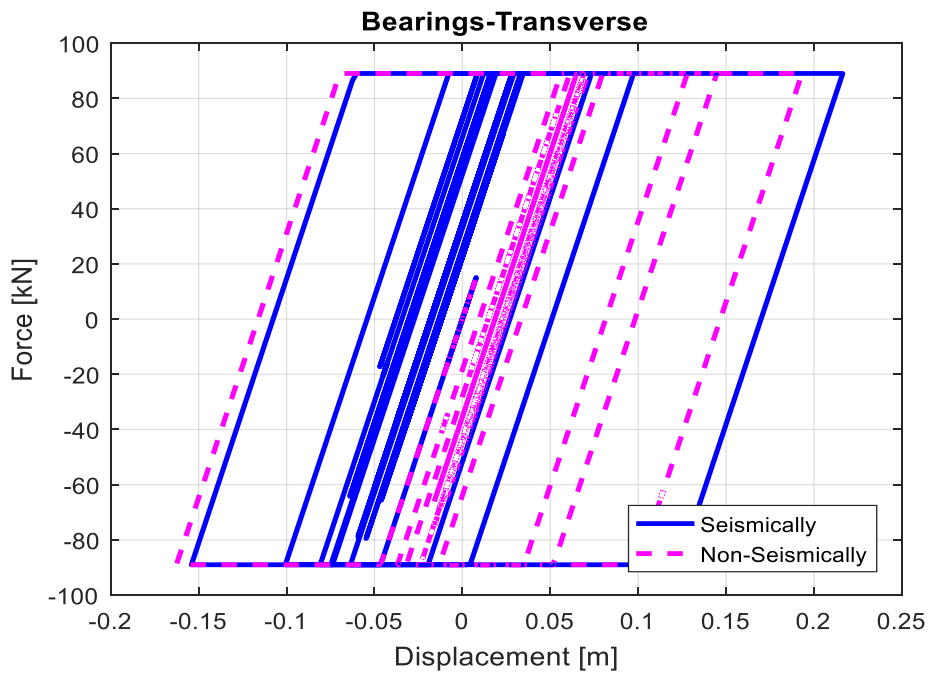***Fig. 5 Comparison of the deck displacement capacity***

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Figure 6a and b indicate a comparison of bearing capacity along the longitudinal and transverse directions, for the seismically and non-seismically designed bridges, respectively. According to these figures, considering the seismic design specifications can increase the bearing capacity along the both longitudinal and transverse directions.

a)

b)

Fig. 6 The bearing capacity along a) longitudinal b) transverse directions

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Moreover, Figure 7 shows a comparison of the bearing capacity in the longitudinal and transverse direction for seismically and non-seismically designed scenarios. The bearing capacity increased by seismic detailing incorporation.
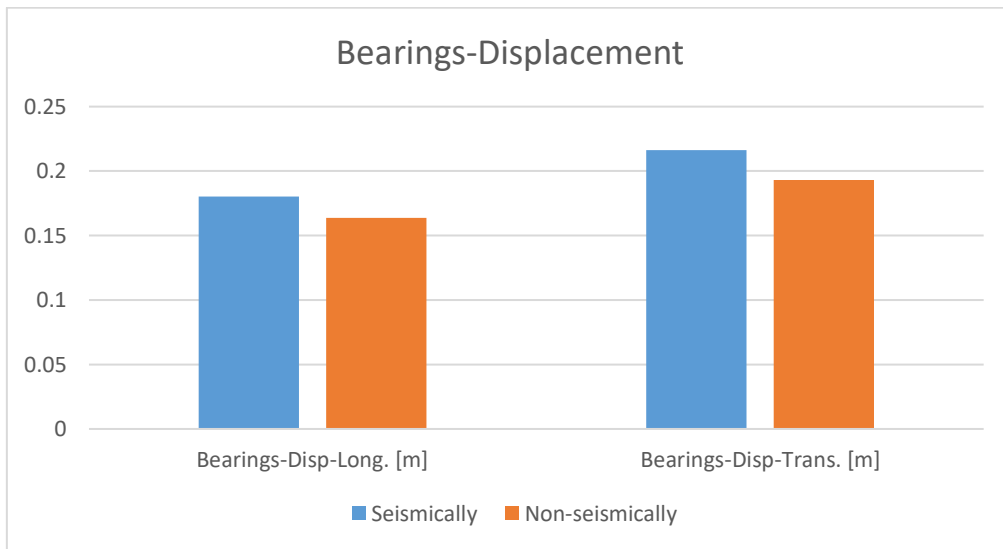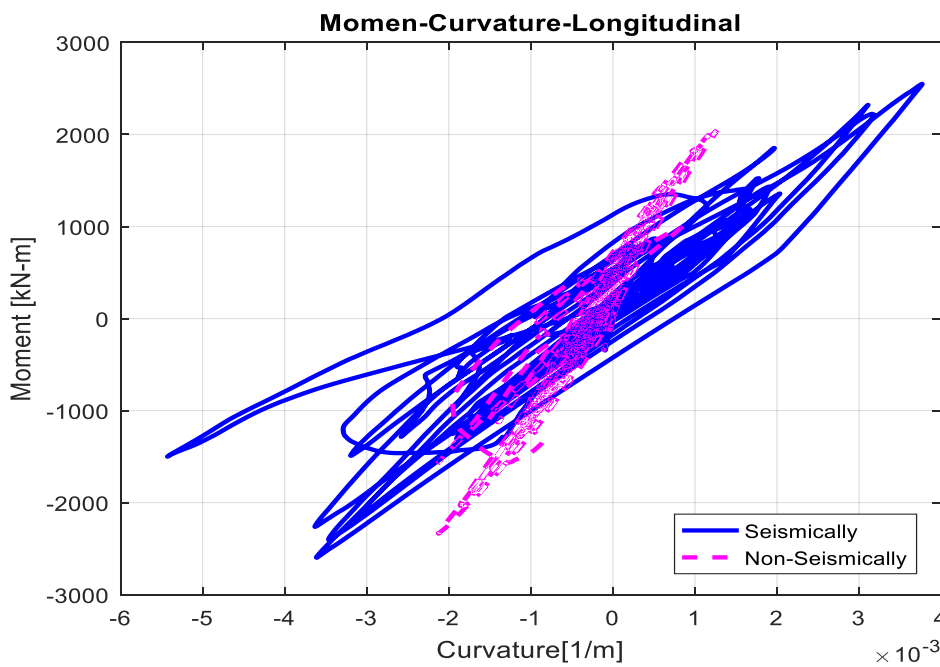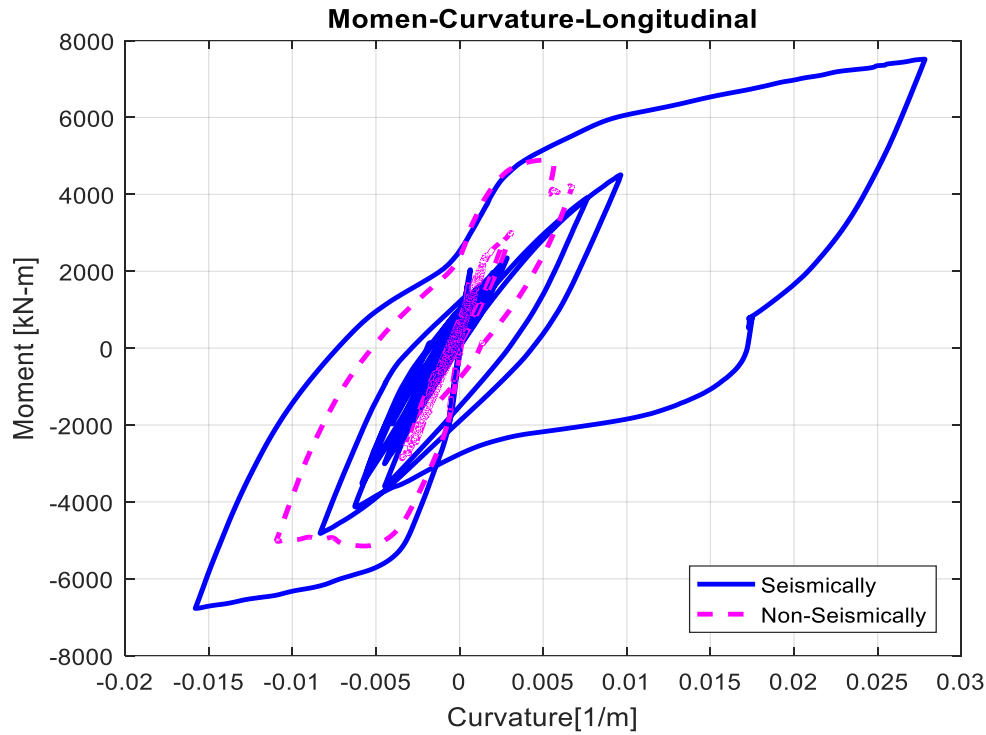

Figure 7. Comparison of the bearing capacity

A comparison of column capacity along the longitudinal and transverse directions, for the seismically and non-seismically designed bridges is illustrated in Figure 8a and b, respectively. Based on these figures, the column capacity along the both longitudinal and transverse directions increased by including the seismic design specifications.


a)

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b)

Fig. 8 The column capacity along a) longitudinal b) transverse directions

Furthermore, Figure 9a and b indicate a comparison of the moment and curvature of the column capacity in the longitudinal and transverse direction for seismically and non-seismically designed scenarios. The column capacity increased by considering the seismic specifications for the substructures. Based on these figures, a significant change of the column capacity can be seen in comparison of the seismically and non-seismically designed bridge.
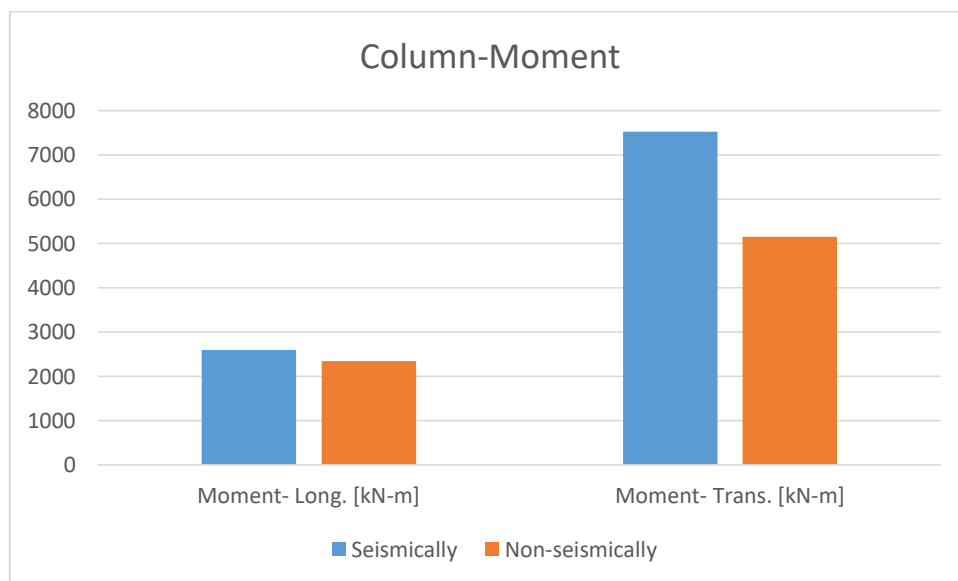
a)
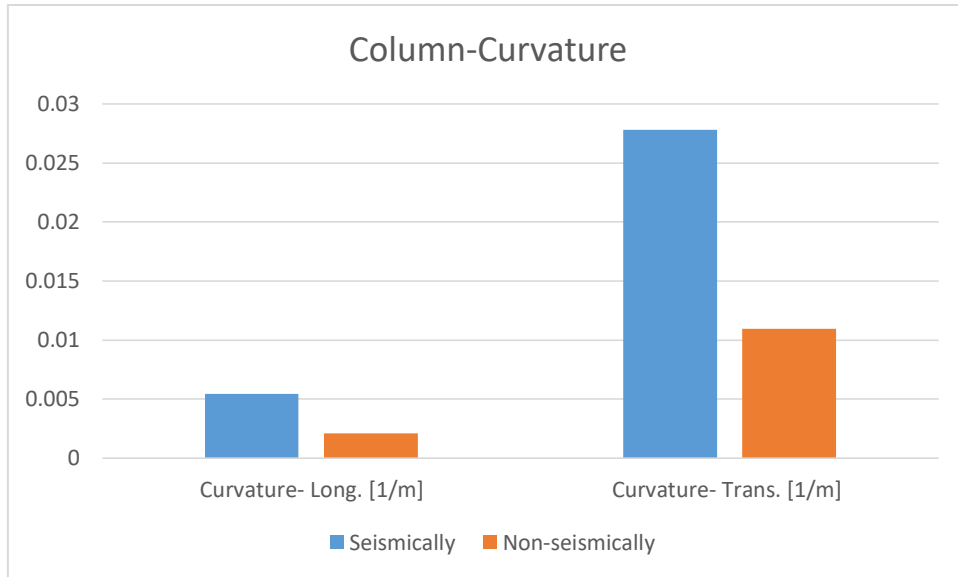
b)

Fig. 9 Comparison of the column capacity in case of a) moment, and b) curvature

The seismic capacity of the backfill soil and piles are shown in cases non-seismically and seismically designed multi span continuous concrete I-Girder bridges in Figures 10a and b, respectively. According to the figures, the seismically designed bridges leads to a 13% increase in the capacity of the bridge foundation compared with the other case, which is the non-seismically designed bridge.
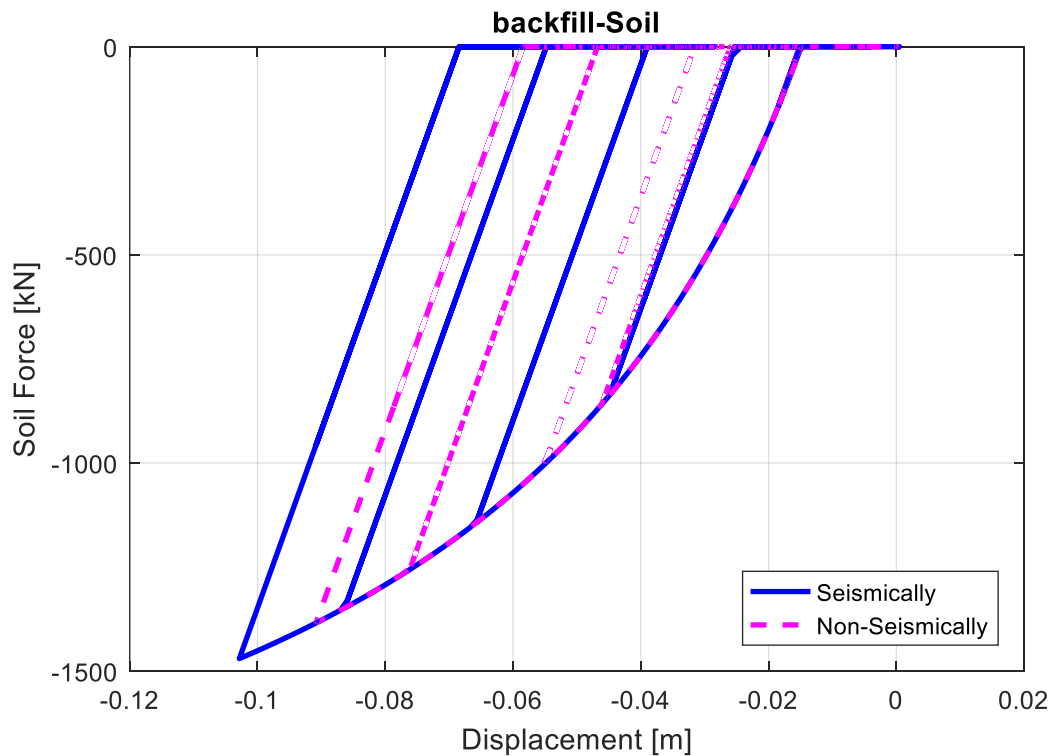
a)
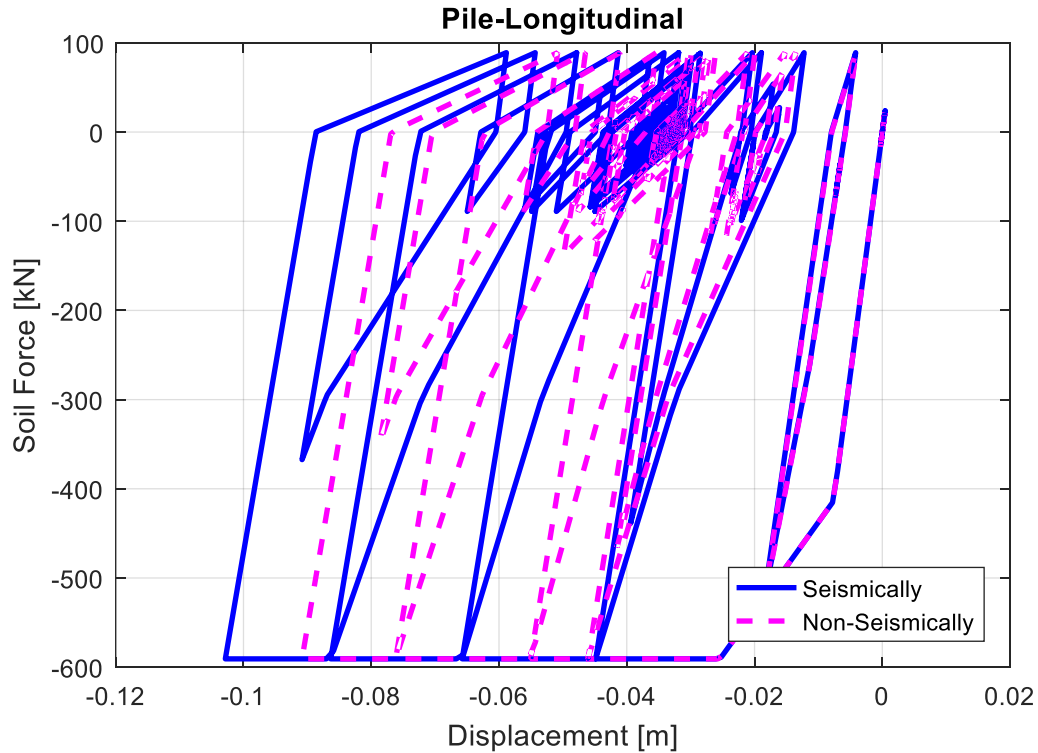
b)

Fig. 10 The seismic capacity of a) backfill soil and b) pile

Figure 10a and b illustrate a comparison of the soil and pile seismic capacity for seismically and non-seismically designed cases. The displacement capacity of the soil and pile is significantly changed by including the seismic specifications, while there is a negligible change in comparison of the forces these bridge components.

a)

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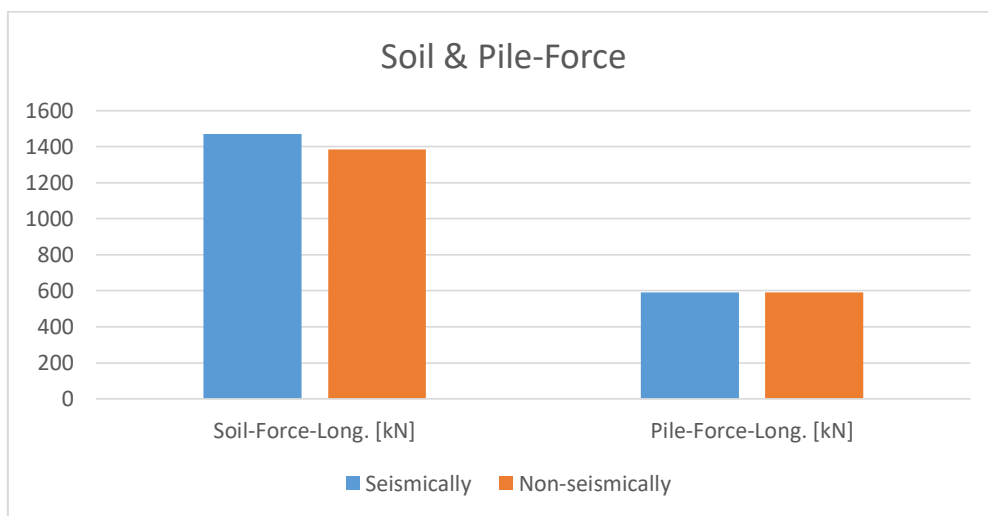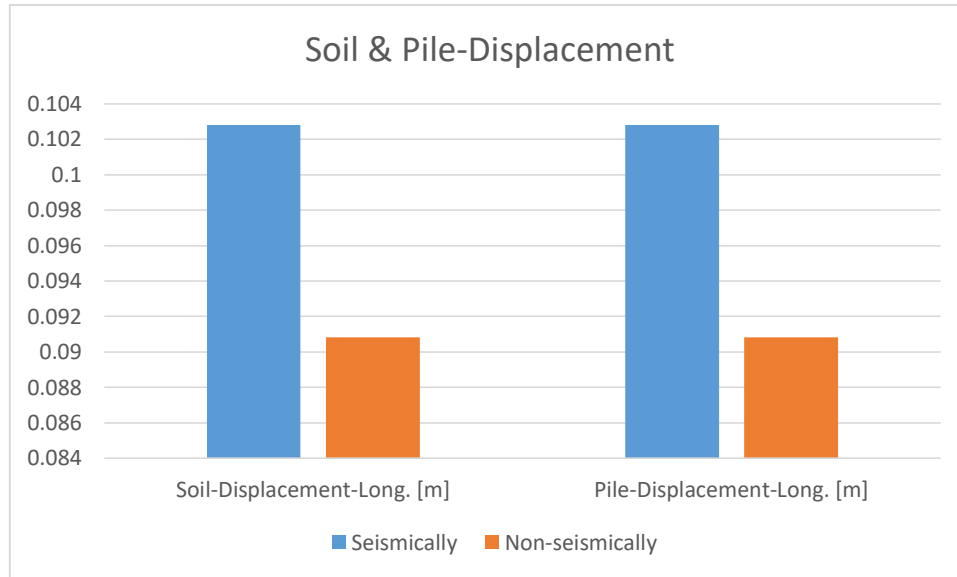
b)

Fig. 11 Comparison of seismic capacity of a) backfill soil and b) pile

In order to provide more convenience for readers, the summary of the capacity of all the bridge components are obtained and compared for the seismically and non-seismically designed scenarios in Table1.

Table 1. Summary of the capacity of all the bridge components

	Seismically	Non-seismically	Difference [%]
Moment- Long. [kN-m]	2599	2338	**11.16**
Moment- Trans. [kN-m]	7518	5148	**46.04**
Curvature- Long. [1/m]	0.005429	0.002127	**155.24**
Curvature- Trans. [1/m]	0.02783	0.01096	**153.92**
Soil-Force-Long. [kN]	1470	1384	**6.21**
Soil-Displacement-Long. [m]	0.1028	0.09083	**13.18**
Pile-Force-Long. [kN]	591	591	**0.00**
Pile-Displacement-Long. [m]	0.1028	0.09083	**13.18**
Bearings-Force-Long. [kN]	89	89	**0.00**
Bearings-Disp-Long. [m]	0.1801	0.1638	**9.95**
Bearings-Force-Trans. [kN]	89	89	**0.00**
Bearings-Disp-Trans. [m]	0.2163	0.1932	**11.96**
Deck-Displacement-Long. [m]	0.1223	0.1133	**7.94**
Deck-Displacement-Trans. [m]	0.2267	0.2036	**11.35**

SUMMARY AND CONCLUSIONS

In this paper a 3D analytical model for a multi span continuous concrete I-girder bridges has been developed using OpenSees platform. In order to study the effect of the seismic design specifications on the bridge seismic behavior, nonlinear time history analysis has been conducted for different bridge cases. The bridge is modeled with and without seismic detailing. One pair of orthogonal horizontal earthquake records from previous California events with strong (near-fault) intensity have been utilized in the analysis. The seismic response of all different bridge components, e.g. columns, deck displacement, bearings, backfill soil, pile, and foundation have been compared in different cases.

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According to the results, it can be seen that the bridge seismic behavior is favorably affected by including the seismic detailing of the columns into bridge design considerations. The seismically designed bridges in general increases the capacity and hence, reduce the seismic vulnerability of the different bridge components particularly under severe earthquakes. This is attributed to the fact that more transverse reinforcement can provide more confinement for the core concrete of columns, which leads to an acceptable seismic behavior of bridges under strong seismic motions. Thus, less demands and lower displacements can be expected. As a result, the seismic detailing should necessarily be considered especially for bridges located in seismic zones. In the other words, ignoring the seismic provisions can lead to some irreparable consequences.

REFERENCES

1. Keshavarzi, B., Y.R. Kim. A Viscoelastic-based Model for Predicting the Strength of Asphalt Concrete in Direct Tension. Journal of Construction and Building Materials, 2016, 122, 721-727.
2. Keshavarzi, B., Y.R. Kim, M.N. Guddati. Investigation into Fatigue Damage Growth Direction in Asphalt Concrete Pavement Sections Based on simplified Viscoelastic Continuum Damage (S-VECD) Theory. Submitted to the Journal of Mechanics and Materials.
3. Kaveh, A., M. Maniat, and M. Arab Naeini. "Cost optimum design of post-tensioned concrete bridges using a modified colliding bodies optimization algorithm." Advances in Engineering Software 98 (2016): 12-22.
4. Kaveh, Ali, and Mohsen Maniat. "Damage detection based on MCSS and PSO using modal data." Smart Struct Syst 15.5 (2015): 1253-70.
5. Kaveh, Ali, and Mohsen Maniat. "Damage detection in skeletal structures based on charged system search optimization using incomplete modal data." Int J Civil Eng IUST 12.2 (2014): 291-298.
6. Farshchin, Mohammad, Charles V. Camp, and Mohsen Maniat. "Optimal design of truss structures for size and shape with frequency constraints using a collaborative optimization strategy." Expert Systems with Applications 66 (2016): 203-218.
7. Shi, Yuhui, and Russell Eberhart. "A modified particle swarm optimizer." The 1998 IEEE International Conference on Computational Intelligence, 1998.
8. Mackie, K., Stojadinovic, B. Probabilistic seismic demand model for California bridges, Journal of Bridge Engineering, 6, 2001, pp: 468-480.
9. Mackie, K., and Stojadinovic, B.. Fragility Basis for California Highway Overpass Bridge Seismic Decision Making, PEER Report 2005/02, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA, 2005.
10. Keshavarzi, B., A. Bakshi. A New Approach for Consideration of Earthquake Low Cycle Fatigue Phenomena on Reinforced Concrete Frames. Proceedings of the 15th World Conference on Earthquake Engineering, Lisbon, Portugal, 24-28 September, 2012.
11. Zhang, J., Huo, Y. Evaluating effectiveness and optimum design of isolation devices for highway bridges using the fragility function method, Engineering Structures, 31, 2009, pp: 1648-1660.
12. Nielson, B. G. Analytical Fragility Curves for Highway Bridges in Moderate Seismic Zones, Ph.D. Dissertation, Georgia Institute of Technology, Atlanta, GA, 2005.
13. Abbasi M, Zakeri B, Amiri GG. Probabilistic seismic assessment of multiframe concrete box-girder bridges with unequal-height piers. Journal of Performance of Constructed Facilities. 2015 Mar 3;30(2):04015016.
14. FEMA. FEMA 454: Designing for Earthquakes: A Manual for Architects, Federal Emergency Management Agency, U.S. Department of Homeland Security, Washington, DC, 2006.
15. Sahs, S., Veletzos, M., Panagiutou, M., Restrepo, J. Visual Inspection and Capacity Assessment of Earthquake Damaged Reinforced Concrete Bridge Elements: Integrate Research and Deployment Final Report, California Department of Transportation, Sacramento, CA, 2008.
16. Moehle, J., Fenves, G., Mayes, R., Priestley, N., Seible, F., Uang, C.-M., Werner, S., Aschheim, M. Highway Bridges and Traffic Management, Earthquake Spectra, 11, 1995, pp: 287-372.
17. SDC. Seismic Design Criteria, Version 1.6, California Department of Transportation, Sacramento, CA, 2010.
18. McKenna, F., Scott, M., Fenves, G. L. Nonlinear Finite-Element Analysis Software Architecture Using Object Composition, Journal of Computing in Civil Engineering, Vol. 24, No. 1, 2010, pp. 95-107.

Global Journal of Engineering Science and Research Management

19. Muthukumar, S. and DesRoches, R. A. "Hertz contact model with non-linear damping for pounding simulation," Journal of Earthquake Engineering and Structural Dynamics 35, 2006, 811–828.
20. Shamsabadi, A., Khalili-Tehrani, P., Stewart, J. P., and Taciroglu, E. "Validated simulation models for lateral response of bridge abutments with typical backfills," Journal of Bridge Engineering, ASCE 15(3), 2010, 302–311.
21. Abbasi M, Abedini MJ, Zakeri B, Ghodrati Amiri G. Seismic vulnerability assessment of a Californian multi-frame curved concrete box girder viaduct using fragility curves. Structure and Infrastructure Engineering. 2016 Dec 1;12(12):1585-601.
22. Abbasi M, Moustafa MA. SEISMIC FRAGILITY CURVES FOR SYSTEM AND INDIVIDUAL COMPONENTS OF MULTI-FRAME CONCRETE BOX-GIRDER BRIDGES 2. 2017.
23. Megally, S. H., Silva, P. F., and Seible, F. "Seismic response of sacrificial shearkeys in bridge abutments," Report No. SSRP-200l/23, Department of Structural Engineering, University of California, San Diego, 2001.
24. Abbasi, M., and M.A. Moustafa. Effect of viscous damping modeling characteristics on seismic response of bridges. Proceedings of Istanbul Bridge Conference, Istanbul, Turkey, 8-10 August, 2016.
25. Chang G, Mander J Seismic energy based fatigue damage analysis of bridge columns: part 1 – evaluation of seismic capacity. (Technical Report No. NCEER-94-0006) Buffalo, NY: State University of New York, 1994.
26. Wolf J (1985) Dynamic soil-structure interaction. Englewood Cliffs, NJ: Prentice-Hall Inc.
27. Mander, J. B., M. J. N. Priestley, and R. Park. Theoretical Stress-Strain Model for Confined Concrete. Journal of Structural Engineering, Vol. 114, No. 8, 1988, pp. 1804–1826.
28. SAC. Joint Venture Steel Project Phase 2 - Project Task: 5.4.1: Suites of earthquake ground motions for analysis of steel moment frame structures, SAC Steel Project, Richmond, CA, 1997.