Structural Behavior Investigation of Turkish Highway Bridges Considering Soil-Structure Interaction

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Abstract Highway bridges have great importance for Turkish transportation network. The starting point of bridge project is to select the most appropriate bridge form for the site. The design of the bridge starts with the analysis, followed by the design check and finally, the optimization. This sequence is repeated until a fulfilling design is achieved. With the current computer technology, nonlinear analyses also become part of this design procedure for more accurate design. There are various structural performance evaluation methods have been developed in this frame. With the development in performance analysis approaches, complex bridge parameters effecting structural behavior can be considered: such as geometry, boundary conditions, load cases, spans, bearings, abutments, bents, hinges and they are updated automatically as the bridge parameters alter. Loads, lanes and vehicles can be also defined swiftly and include width effects as well. On the other hand, assumptions made and boundary conditions considered are other critical parameters that need to be realistically defined in the analyses. Especially, soil-structure interaction may lead for unexpected structural behaviors. Therefore, site conditions should be reflected to the analysis. In the present research, soil-structure interaction effects on bridge structures are discussed and evaluated in detail. It is aimed to evaluate the structural behavior of highway bridges with different span length considering the soil-structure interaction effects. In the analysis part, representative bridges are modeled with Finite Element Analysis software SAP2000. Modeling of such an interaction is carried out with analytical model of highway bridges by considering soil effects. Finite Element based structural models are developed for representative highway bridges through SAP2000 software. Models are investigated through both nonlinear static pushover analyses and dynamic time-history analyses with selected ground motions and the performance of the highway bridges are investigated and evaluated. The results are given in tables and figures comparatively.

Keywords: Turkish Highway bridges, Soil-Structure Interaction, Static Pushover Analysis, Nonlinear Dynamic Analysis

1 Introduction

Highway bridges are very important for Turkish transportation network. The design of the bridge starts with the analysis, followed by the design check and finally, the optimization. This sequence is repeated until a fulfilling design is achieved. With the current computer technology, nonlinear static pushover analysis and the nonlinear dynamic time history analysis has become raising tools to predict the seismic demands in seismically active regions [1-7]. There are various structural performance procedures have been developed in this frame. These procedures are recommended for seismic evaluation in some design codes [8-10]. However, soil-structure interaction (SSI) effects may lead to unreliable results. Therefore, variable soil properties should be taken into account.

There are various studies. Some of them are given here. Dicleli presented results of seismic analysis of existing multi-span simply supported steel highway bridges which never designed to resist earthquakes. In this study, dynamic analysis are conducted with consideration of different bearing stiffness, span length and number of spans [11]. Chang et. al explored several major damaged bridges with typical damage modes after Chi-Chi earthquake [12]. Abeysinge et. al followed the nonlinear static analysis procedure for seismic evaluation of Greveniotikos Bridge in Greece [2]. Nicknam et. al evaluated the seismic performance of Hafez Bridge with its three-dimensional model by using nonlinear static analysis procedure, and the results showed that this bridge needs to retrofit for improving its seismic behavior [4]. Haque and Bhuiyan carried out seismic response analysis on a simple span concrete deck girder skewed bridge with using the finite element (FE) method in consideration of linear time history analysis [5]. Ciampoli and Pinto assessed the relevance of SSI effects on the dynamic response of bridge piers with using a total of 240 cases [13]. Mylonakis et. al analyzed two bridge-pier systems which are idealized versions of actual bridges in order to demonstrate actual soil profile [14]. Tongaonkar and Jangid investigated the effects of soil-structure interaction on the three-span continuous deck bridge seismically isolated by elastomeric bearings [15]. Jeremic et al investigated the influence of inelastic behavior of both the soil and the structural components during seismic response evaluation of highway bridge systems [16]. Mallick and Raychowdhury presented an investigation the effect of skew angle of a bridge-foundation system including nonlinear soil-pile interaction [17]. In regards with previous studies, SSI affects the seismic response of the bridge significantly.

In the present study, it is aimed to evaluate the structural behavior of highway bridges having different span lengths considering the SSI effects. In the analysis part, representative bridges were modeled with FE Analysis software SAP2000. Modeling such an interaction was carried out with analytical model of highway bridges by considering the soil effects on the structures. Models were investigated through both nonlinear static pushover analyses and dynamic time-history analyses through selected ground motions and the performance of the highway bridges were evaluated in comparison.

2 Specification of the Bridge and Modeling

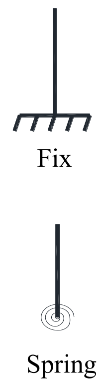
In the seismic response analyses, the base of the buildings is assumed as fixed in the common practice. This practice may lead inaccurate results in the evaluation processes. Therefore, it is critical and essential for many cases to consider SSI in the structural earthquake behavior analyses to get more accurate results. As afromentioned, many research work have been published on the effect of SSI problems to obtain more realistic assessments and several analytical modelling approaches have been proposed [13-17].

To consider the effect of the supporting soil, the SSI was simulated with vertical and rotational springs among the pier embedded foundations. The soil was characterized by its stiffness and it was idealized by Winkler spring model which is well known and the most common foundation model for SSI analysis. In this model, the spring coefficients in both bridge axis directions are calculated based on foundation geometry. In the present study, three types of soil selected for comparison; very strong soil which is assumed as fixed, strong and weak soils which are modeled with springs. The bridge models' names and their characteristics are given in Table 1.

To investigate the structural behavior of Turkish highway bridges, multispan continuous highway bridges with different characteristics were analyzed in the present study. The bridges were configured by reinforced concrete pile and pier with continuous steel girder and concrete deck. The deck width and column height of bridge were 15.0m and 4.6m, respectively. In total, nine different models were defined with 3 different span lengths as 20m, 30m, and 40m and 3 different soil conditions as very strong soil idealized without any deformation, stronger soil and weak soil as shown in Table 1. To define the soil types, different coefficients of soil reactions were used.

Table 1 Bridge Characteristics

Bridges	SSI	Soil Type	Depth (m)
M1-S1	Fix	Very Strong	20
M1-S2	Spring	Strong	20
M1-S3	Spring	Weak	20
M2-S1	Fix	Very Strong	30
M2-S2	Spring	Strong	30
M2-S3	Spring	Weak	30
M3-S1	Fix	Very Strong	40
M3-S2	Spring	Strong	40
M3-S3	Spring	Weak	40



The materials, used in columns, piers and decks, and in steel girders are as concrete with 30MPa compression strength (C30), and Steel S235, respectively. In the analyses, nonlinear material behavior was taken into consideration. For reinforced concrete columns, longitudinal steel rebar is 12 ϕ30, and stirrup is ϕ14 with 100 mm spacing. To define the nonlinear bridge behavior in SAP2000, PMM plastic hinges are defined for column element.

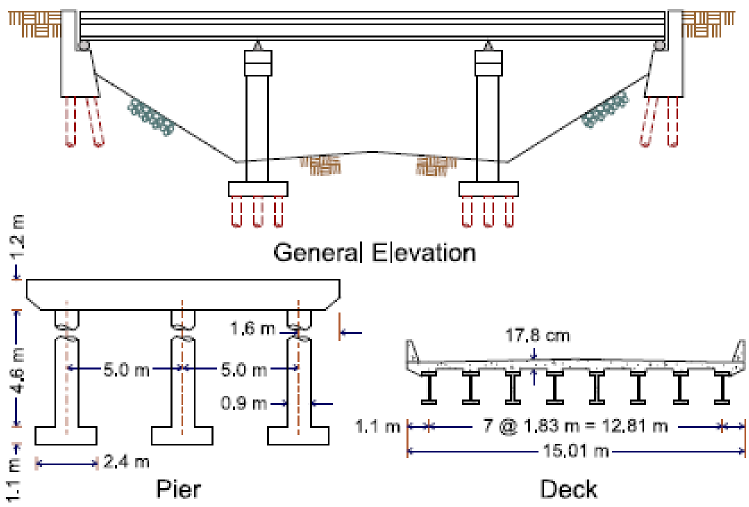


Figure 1 View of multi span continious bridges [18].

In the analyses, SAP2000 FE analyses software was used for modeling of the bridges. 3D FE models were constructed for analysis of the bridges. Two types of FE were used for construction of the models: one is 2 node frame element that was used in pile, pier and deck, other was 4 node shell element that was used in the foundations. Soil conditions were taken into account with different coefficients of soil reactions and support conditions. Pile of the bridges were modelled as 0.9m diameter circular reinforced concrete column, piers of bridges are modelled as 0.75m/1.20m rectangular reinforced concrete beam, and steel girders were modelled as 0.25m/0.54m built up I sections and deck were modelled as 15.00m width and 0.18m thick concrete slab.

Modal analysis of the bridges were applied under dead load. The results of modal analysis for nine bridges were determined and listed in Table 1. For the 30m-bridge, the first two mode was found as %98 same with Nielson's bridges [18] whose first mode's period was determined as 0.44s and second mode's period was 0.31s.

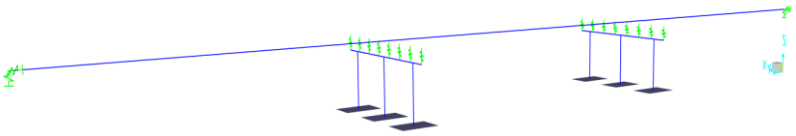


Figure 2 3D view of the bridge with 30m span length

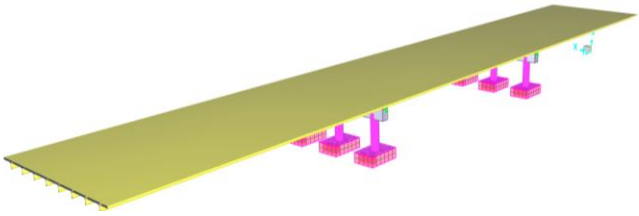


Figure 3 3D Extrude view of the bridge with 30m span length

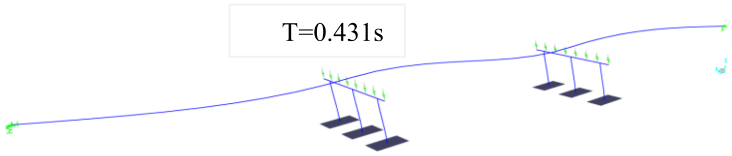


Figure 4 First mode shape of the bridge with 30m span length for soil type 3.

As given in Table 2, the increase in span lengths and the change in soil conditions from stronger to weak cause that periods of the bridges increase, thus rijidities of bridges decrease. Hence it is observed that both span length and soil conditions have important effects on the dynamic behavior of the bridges which can be seen in Table 2.

Table 2 Periods determined from modal analyses

Span Length	Mode	Soil Type		
		1	2	3
20m	1. Mode	0.163s	0.270s	0.343s
	2. Mode	0.078s	0.188s	0.204s
30m	1. Mode	0.236s	0.335s	0.431s
	2. Mode	0.129s	0.286s	0.313s
40m	1. Mode	0.288s	0.393s	0.508s
	2. Mode	0.187s	0.362s	0.403s

3 Analysis

To evaluate the seismic behavior of model highway bridges, both nonlinear static pushover analyses and dynamic time-history analyses with selected ground motions were performed and the performance of the highway bridges were investigated according to results of these analyses.

3.1 Nonlinear Static Analysis

Pushover analysis is an inelastic, incremental static analysis procedure aimed at defining the lateral force-resisting capacity of the bridges and the displacement demand on the bridges during the design-level earthquake [2].

These analyses provide a base shear vs. top displacement relationship and indicates the inelastic limit as well as lateral load capacity of the structure. The changes in slope of this curve give an indication of yielding of various structural elements. The main aim of the pushover analysis is to determine the member forces and global and local deformation capacity. The analysis is not directly predicting the actual response to an earthquake. The actual response can be obtained from the time history analyses where ground motion data are given directly implemented in the nonlinear structural analyses.

In the present study, after modeling the bridges with and without consideration of SSI effects, a nonlinear pushover analysis is carried out for evaluating the seismic response of the bridges. Pushover analysis are carried out for lateral direction of the bridges. The graphical results of the pushover analyses are presented in Figure 5. The pushover curves are depicted for each case and drawn for each bridge model.

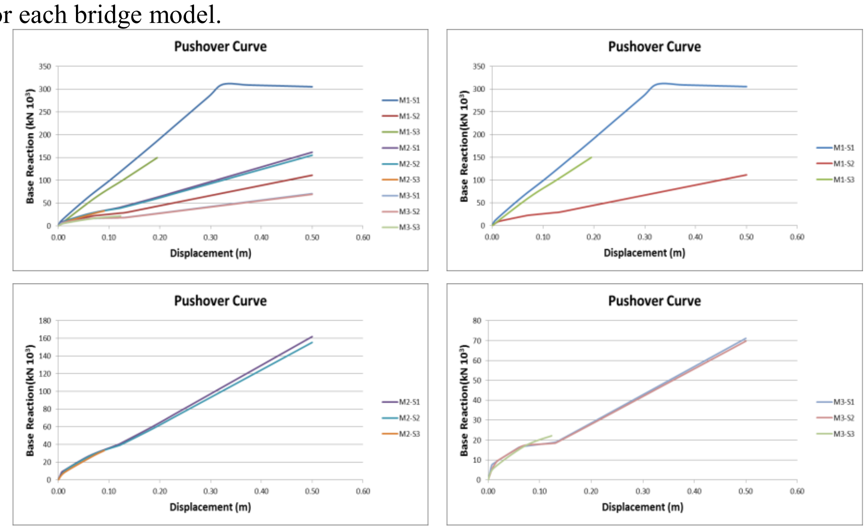


Figure 5 Pushover Curves for lateral directions of the bridges

3.2 Nonlinear Dynamic Analysis

In the nonlinear dynamic analyses procedure, dynamic loads are applied on the structures directly to get the structural displacements. Therefore, this method becomes universal tool in the seismic evaluation of most kind of structures [5-7,11]. Thus, presented study involves nonlinear dynamic analyses on the bridges. The FE models of bridges has been subjected to 9 earthquake ground motions which were selected as 3 ground motion records from each site class. The selected ground motion data have different strong motion durations, frequency contents and peak ground accelerations. Selected ground motions are recorded during Imperial Valley (1940), Coalinga (1983), N. Palm Springs (1986), Loma Prieta (1989), Lander (1992), Northridge (1994), Kobe (1995) and Kocaeli (1999) earthquakes. Ground motion data used in the time history analyses are given in Table 3. The ground motion data were chosen from different destructive earthquakes around the world. Earthquake names, date of earthquakes, magnitudes (Mw), peak ground velocities (PGV), peak ground accelerations (PGA) for the components and site classes for selected ground motion data are presented in Table 3, respectively. Peak ground accelerations are in the range of 0.01290 to 0.5683g, where g is acceleration due to gravity. The results of the time history analyses are presented in Figure 6. A comparison for all models is given in Figure 7.

Table 3 Ground motion datas

No	Earthquake	Date	(Mw)	PGV (cm/s)	PGA (g)	Site Class
1	Landers	28/06/1992	7.3	20.0	0.1460	A
2	Loma Prieta	18/10/1989	6.9	33.9	0.4730	A
3	N. Palm Springs	08/07/1986	6.0	3.40	0.1290	A
4	Kocaeli	17/08/1999	7.4	17.7	0.2188	B
5	Northridge	17/01/1994	6.7	52.1	0.5683	B
6	Whittier Narrows	10/01/1987	6.0	22.0	0.3330	B
7	Imperial Valley	15/10/1979	7.0	29.8	0.3130	C
8	Loma Prieta	18/10/1989	6.9	38.5	0.2470	C
9	Coalinga	02/05/1983	6.4	8.60	0.0980	C

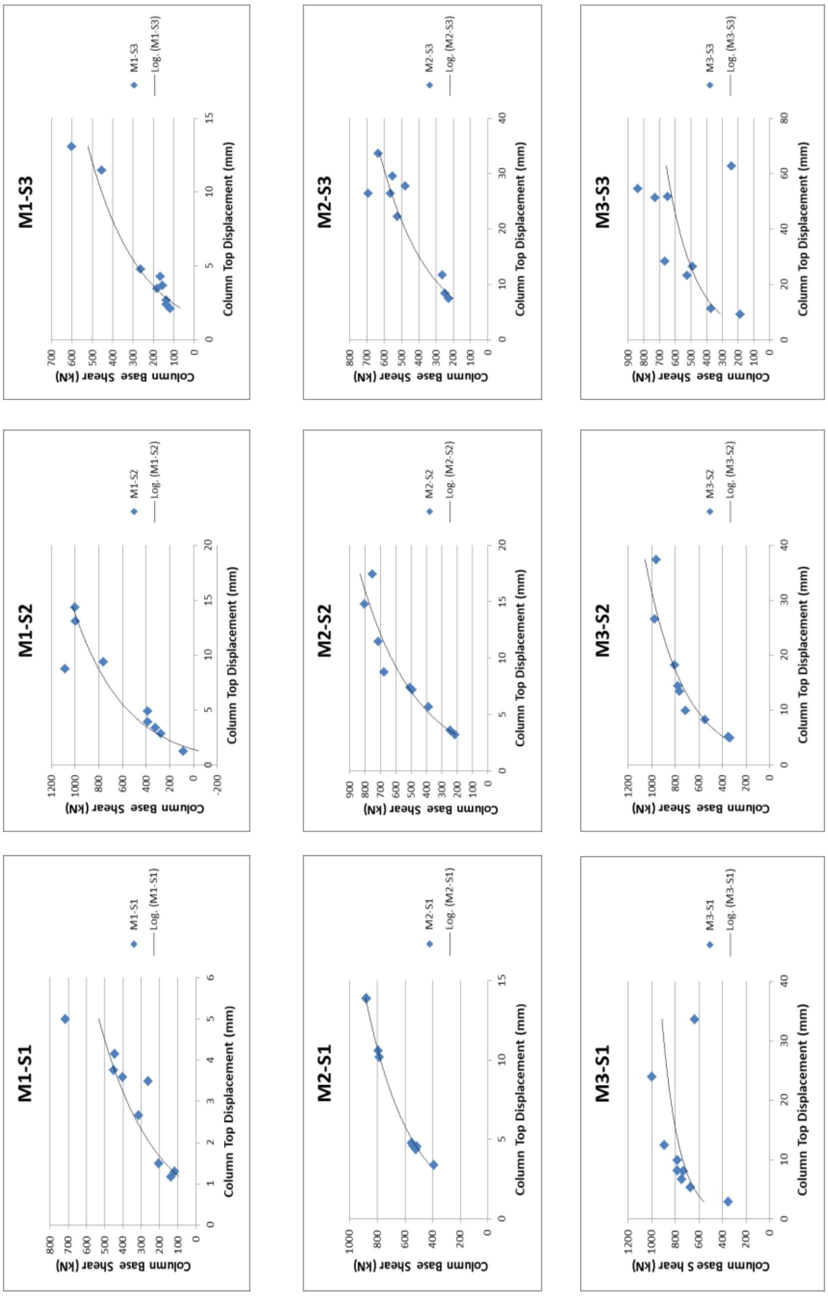


Figure 6 Time History Results for Bridge Models

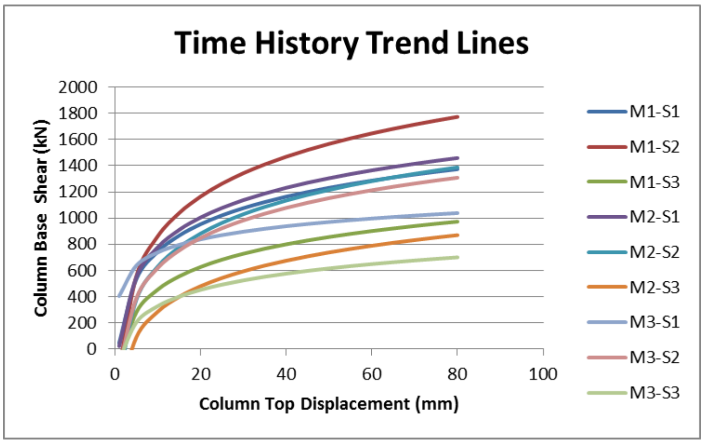


Figure 7 Comparison of Time History Result for Bridge Models

4 Conclusions

In the present study, 3 different span length bridges resting on 3 different soil conditions were considered and 9 different bridges were modelled. 9 nonlinear static pushover analysis were carried out. Afterwards, 9 different bridges were analyzed with 9 different time history analyses. In total, 81 different nonlinear time history analyses were accomplished. Analyses show that, the increasing span length of bridges cause the decrease in lateral rigidity of the bridges. In addition, after specific lateral top displacement were exceed, spans of bridges increased the rigidity of bridges. Span length of multi span continuous bridges has significant effect on lateral rigidity of bridges. Both nonlinear static pushover analysis and nonlinear time history analysis show that bridges with strong soil has higher base shear comparing to very strong and weak soil.

Nonlinear static pushover analyses of bridges were investigated and it is seen that when the top displacement of bridges reach a specific point, bridges span starts to restrain lateral displacement of bridges and the base shear of bridges reaches higher values. Lateral rigidity of M1 type bridges is higher than M2 and M3 models. Lateral rigidity of S1 type bridges is higher than the others. Lateral rigidity of S2 type bridges is lower than the others. For M1 type bridges, after top displacements reach 8mm, lateral rigidity of bridges increases. For M2 type bridges, after top displacements reach 10mm, lateral rigidity of the bridges increase. For M3 type bridges, after top displacements reach 13mm, lateral rigidity of bridges increases.

Nonlinear time history analyses shows that, M3 type bridges expose to more top displacement comparing to M1 and M2. Moreover, S2 type bridges have higher base shear comparing to S1 and S3 type bridges. SSI affect the static and also mostly dynamic behavior of the bridges. Time history analaysis give the dynamic behavior of bridges. It is seen that, with the change of soil conditions, maximum top displament of the bridges and the base shear are changing significantly. Change in soil conditions may cause increase in the base shear of column as given in time history analyses' results. Therefore, SSI shoul be taken into consideration for multispan continious bridges. Pushover curves show that M1 type bridges have more rigidity considering to M2 and M3 bridge types. Hence, span length has also significant impact on lateral rigidity of the multispan continious bridges.

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