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Effect of soil-structure interaction on the response of bridge isolated with rubber bearing

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Research Article

Effect of soil-structure interaction on the response of bridge isolated with rubber bearing

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Abstract

Soil-structure interaction effect on the analysis of continuous bridge provided with rubber bearings and subjected to earthquake ground acceleration is studied. The rubber bearing is provided between the piers and deck slab and also between abutments and deck slab. The finite element method is used to model both the bridge structure and the soil. A beam element is used to model the continuous bridge, whereas a four-noded plane strain element is used to model the soil. The response parameters considered for the study are the base shear and relative displacement between pier and deck slab. It is concluded from the study that soil-structure-interaction has considerable influence on the behaviour of the isolated bridge structure and considering the soil-structure-interaction effect is either beneficial or detrimental to the bridge structure.

Keywords: Continuous bridge, isolation, soil-structure interaction, finite element method, earthquake ground motion.

Introduction

Earthquakes are the most unpredictable, disastrous natural events which are created in the earth's crust. Due to earthquakes, the base of the structure perceives high-frequency movements, which affect the inertial forces of the structural or non-structural components. Bridges which are the main links in the transportation system may receive considerable damages during the earthquakes. Isolation of the bridges using laminated rubber bearing or sliding bearing is one of the most innovative techniques used in present days in order to avoid the large forces transferred to the bridges. However, in the traditional analysis and design of isolated bridges, the piers are assumed to be fixed at the base and their behaviour is assumed to be completely independent of foundation and supporting soil. However, in practice the behaviour of superstructure, footing, and soil are interdependent and the stiffness of each unit affects the behaviour of other units. All the three components, the soil, superstructure, and footing are integral units of the load-carrying system and for more realistic analysis, it is required to consider superstructure, foundation, and soil as a single system. In the realistic condition there exist interaction between bridge structure, foundation, and supporting soil mass. Until recently general concession between engineers and researchers was that soil-structure interaction (SSI) is beneficial to the response of structure because it provides additional flexibility and damping to the structural systems [1]. Hence for the acceptable analysis of the continuous bridge, footing and soil have to be considered as one system. Soil structure interaction analysis considers superstructure, foundation, and soil system as a single unit. There are many studies to investigate the effect of soil-structure interaction on the response of the bridge isolated with rubber bearing subjected to earthquakes [1-11]. However, in these studies, the soil is modelled using a Winkler model. According to this hypothesis, deformation in the soil at a point depends on the load applied at that point only. But it can be seen from the studies that under seismic excitation SSI system become infinite and is to be represented accordingly. The finite element method may be more realistic to consider

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the actual behaviour of soil compared to the Winkler model. Also in all these studies, only the flexibility effect of the soil on the response of the bridge is investigated. Hence, in the proposed study, the effect of soil-structure interaction on the response of the bridge isolated with rubber bearing is studied. Also, the finite element model is used for the analysis.

Methodology

The isolated bridge structure considered for the study is a typical continuous bridge. The superstructure is divided into deck and piers connected at the nodes. The structural members are modelled using finite elements with one horizontal degree of freedom whereas, rubber bearing is idealized as a spring with two nodes. One end of the spring is connected to the deck whereas, the other end connects the pier. Soil is modelled using a plane strain rectangular element having four nodes at the corner. The behaviour of soil is assumed as elastic, homogeneous, and continuous. Hard rock is situated below the base of the soil mass and hence both horizontal and vertical displacements are restrained at the base of the soil mass. To replicate the infinite soil medium, springs, and dashpot systems are attached to the edges of the soil [12-13]. The time-dependent second-order equation for the bridge structure-foundation-soil system can be expressed as

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F(t)\} \quad (1)$$

Where [M] is the mass matrix, [K] is the stiffness matrix and [C] is the damping matrix of structure and soil, $\{u\}$ $\{\dot{u}\}$ and $\{\ddot{u}\}$ are displacement, velocity, and acceleration vectors. $\{F(t)\}$ is the nodal load vector and is given by the equation.

$$\{F(t)\} = -[M_s]\{I\}\ddot{u}_g(t) \quad (2)$$

Where [Ms] is the mass matrix corresponding to structural degrees of freedom only. The stiffness matrix and mass matrix for each element of the superstructure, rubber bearing, foundation, and soil are obtained and is added to compute the overall dynamic equation for the isolated bridge on soil considering soil-structure interaction. The matrix C can be obtained as

$$C = \alpha K + \beta M$$

α and β are the Rayleigh constants and are obtained using the first two frequencies. Equation 1 is solved using Newmark's method with time interval Δt = 0.0004 sec to obtain various parameters such as velocity, acceleration, and displacement at different intervals of time during earthquake ground motion.

Results and Discussion

The finite element discretization of a three-span bridge structure considered for the analysis is shown in Figure 1. As shown in the figure, the superstructure is supported on two piers and the abutments. The isolation system consists of linear rubber bearings and is placed between the deck slab and pillars and between the deck slab and abutments as shown in the figure. Each span of the bridge structure is equal to 30 m. The piers are 8 m in height. The various geometric and material properties considered for the continuous bridge is shown in Table 1. The effect of considering soil-structure interaction on the analysis of continuous bridge isolated with rubber bearing is studied for a soil having three different stiffness. These soils are termed as S1, S2, and S3. The soil S1 is relatively softer than soils S2 and S3, whereas, the soil S3 has the highest stiffness as observed from Table 2.

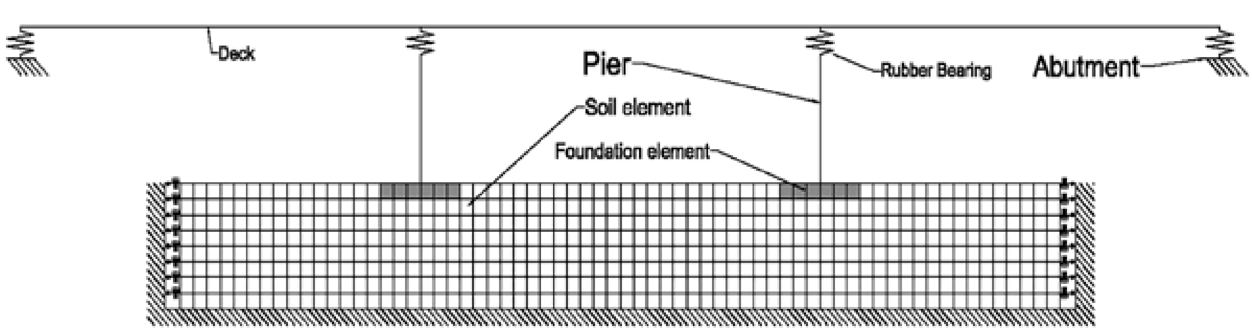


Fig 1: Finite element discretization of the isolated bridge, footing and supporting soil.

Table 1: Geometric and material properties of isolated bridge.

Modulus of elasticity (kN/m^2)	2.2 x 10^7
Size of pier	1 m x 1 m
Size of deck	1 m x 1 m
Mass density on deck slab (kN sec^2/m^4)	2.5
Mass density on columns (kN sec^2/m^4)	2.5

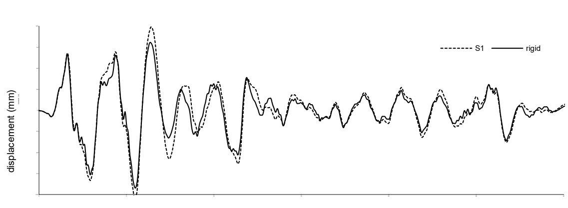
Table 2: Material properties of three types of soils considered for the study.

Properties of soil	Type of soil		
	Soft(S1)	Medium (S2)	Hard (S3)
Elastic modulus, E (kN/m^2)	6000	12000	60000
Mass density (kN sec^2/m^4)	2	2	2
Poisson's ratio	0.33	0.33	0.33

The time period of the rubber bearing is equal to 2 sec. Two earthquakes considered for the study are the Northridge earthquake and the El Centro earthquake. The peak ground acceleration for the Northridge earthquake is 0.556 g whereas, it is equal to 0.296 g for the El Centro earthquake. Also, among these, the Northridge earthquake is the near-fault (NF) earthquake and the El Centro earthquake is the far-field (FF) earthquake.

Effect of soil-structure interaction on the time history response

Variation of base shear and relative displacement (difference in displacements between deck and pier) with time for the isolated bridge structure on soft, medium, and hard soils subjected to El Centro and Northridge earthquakes are shown in Figures 2 and 3, respectively. The corresponding responses for the isolated bridge structure on a rigid base are also shown in the respective figures for comparison. The peak relative displacement and base shear are also tabulated in Table 3.



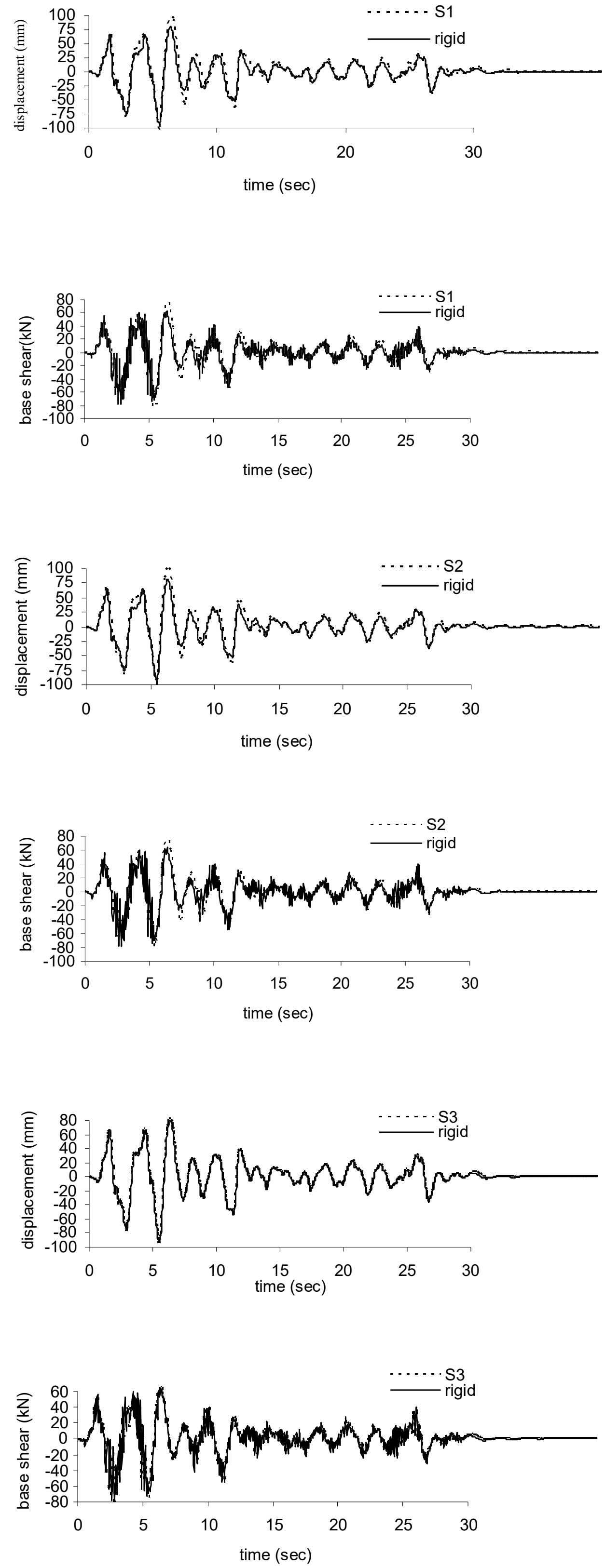


Fig 2: Response of the isolated bridge at various intervals for the El Centro earthquake.

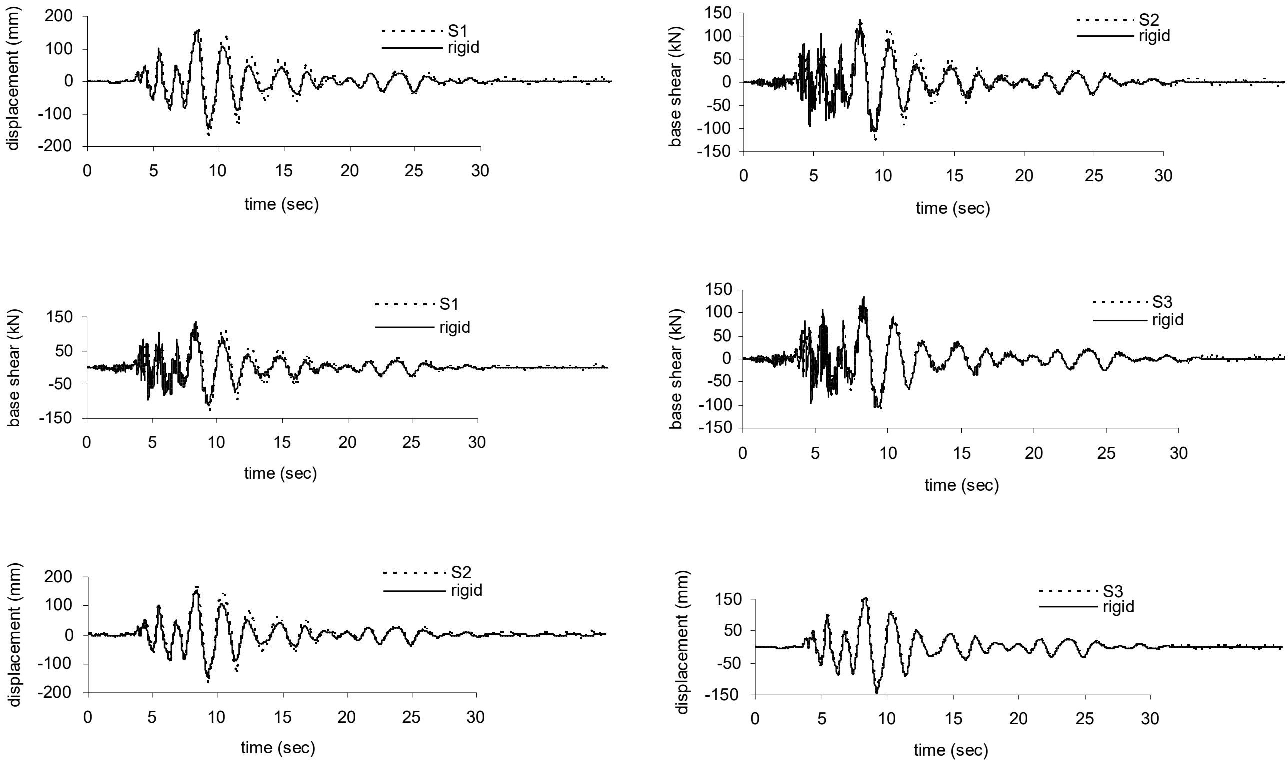


Fig 3: Response of the isolated bridge at various intervals for the Northridge earthquake.

Table 3: Peak responses of the bridge on S1, S2, and S3 types of soils.

Earthquake/soil type	Relative displacement (mm)				Base shear (kN)			
	S1	**S2**	**S3**	**rigid**	**S1**	**S2**	**S3**	**rigid**
El Centro	105.5	101.6	93.9	92.4	81.5	78.7	78.8	78.2
Northridge	163.6	168.1	157.3	156.9	127.8	128.6	126.2	137.7

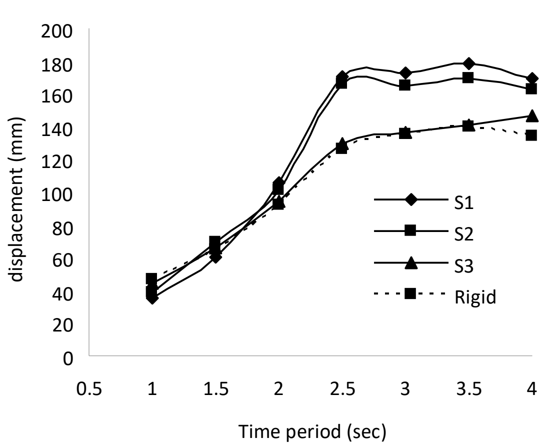
It can be observed from the figures that

1) The displacement and base shear of the isolated bridge on soft and medium soils at different times is not similar to that of the bridge on a rigid base.
2) Comparison of peak relative displacement of the bridge on soft soil with that of the bridge on the rigid base shows that the peak relative displacement increases for both types of earthquakes due to consideration of soil-structure interaction.
3) The peak relative displacement of the bridge on medium soil also increases for both types of earthquakes when the effect of soil-structure interaction is considered in the analysis.
4) The peak base shear response of the bridge on soft soil when the soil-structure interaction effect is considered is larger than that of the bridge without considering soil-structure interaction for El Centro earthquake, whereas it is lesser for the bridge with soil-structure interaction compared to the bridge without considering soil-structure interaction for Northridge earthquake.
5) The peak base shear response for the bridge structure on medium soil considering soil-structure interaction is almost similar to that of the bridge structure without considering soil-structure interaction for the El Centro earthquake, whereas it is lesser for the bridge with soil-structure interaction compared to the bridge without soil-structure interaction for Northridge earthquake.
6) In the case of hard soil, the response of the bridge considering the soil-structure interaction effect is almost similar to that of the bridge without considering soil-structure interaction for both the earthquakes.

7) Thus, it can be said that the soil-structure interaction effect may be either beneficial or detrimental for the bridge subjected to earthquake ground motions depending upon the type of soil and earthquakes. The soil-structure interaction effect may be beneficial for one type of earthquake, whereas it may be detrimental for another type of earthquake. In addition, the beneficial or detrimental effect is also influenced strongly by the type of foundation foil. The soil-structure interaction may be beneficial for one type of soil whereas, it may be detrimental for another type of soil. Hence, the response of bridge isolated with rubber bearing may be underestimated or overestimated if the soil-structure interaction effects are not considered in the analysis and hence the soil-structure interaction effect needs to be considered for the realistic analysis of isolated bridges subjected to earthquakes.

Effect of soil-structure interaction on the time period of isolation

One of the parameters that affect the response of the bridge isolated with rubber bearing is the time period of the isolation system. It depends on the stiffness and mass of each of the rubber bearings. The effect of soil-structure interaction on a bridge isolated with rubber bearing having different time periods is also studied. In order to study this, the response of the isolated bridge is obtained at various isolation time periods ranging from 1 sec to 4 sec. The peak base shear and relative displacement at various isolation time periods for the isolated bridge resting on soft, medium, and hard soils is plotted in Figures 4 and 5 for El Centro and Northridge earthquakes.



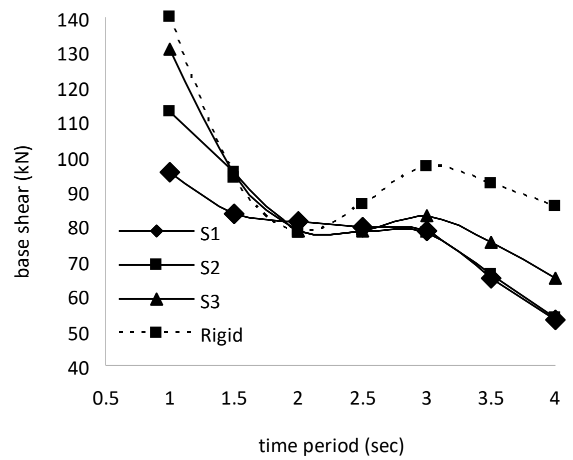
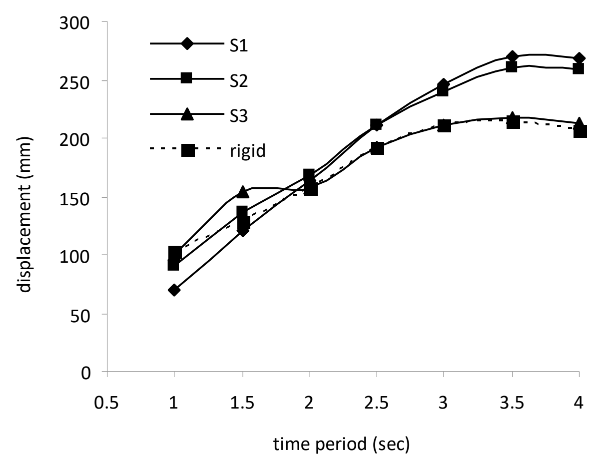


Fig 4: Time period versus displacement and base shear responses for El Centro earthquake.



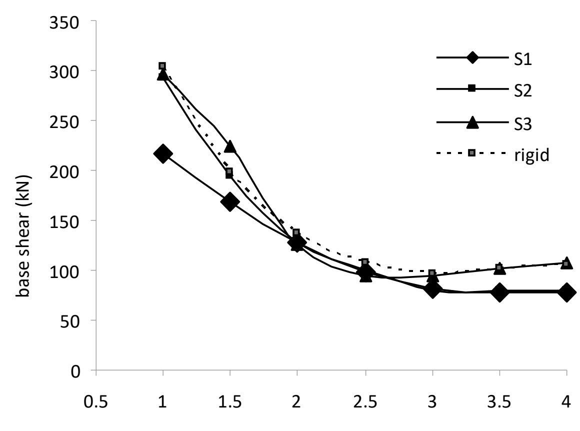


Fig 4: Time period versus displacement and base shear responses for Northridge earthquake.

From the figures, it can be observed that:

1) For the bridge structure subjected to the El Centro earthquake, considering soil-structure interaction effect on displacement response

for soft and medium soil is beneficial up to an isolation period of 1.5 sec after which it is detrimental. However, consideration of soil-structure interaction effect on base shear response is beneficial for both soft and medium soils at all the time periods except at a time period of 2 sec where it is detrimental for soft soil and has not much effect for medium soil.

2) For the bridge structure subjected to the Northridge earthquake, the soil-structure interaction effect on displacement is beneficial up to an isolation period of 2 seconds and for the isolation period above 2 seconds, the soil-structure interaction effect is detrimental for both the soft and medium types of soils. The effect of soil-structure interaction on the base shear response is, however, beneficial for all the values of isolation period for the isolated bridge on soft soil and has not much effect for medium soil. The displacement and base shear response of the bridge on hard soil considering the effect of soil-structure interaction is almost similar to the corresponding response of the bridge without considering soil-structure interaction indicating that soil-structure interaction has not much effect on the isolated bridge resting on hard soil at all the isolation periods.
3) Thus, the beneficial or detrimental effect of considering soil-structure interaction in the analysis of isolated bridges is also affected by the isolation period. Depending on the isolation period of rubber bearing, the soil-structure interaction effect may be beneficial or detrimental to the response of the bridge.

Summary and Conclusions

The effect of soil-structure interaction on the response of the bridge isolated with rubber bearing is studied. In this study, the soil and structure are modelled using the finite element method. The response obtained from the analysis of the bridge with the soil-structure interaction effect is compared with the response obtained without considering the soil-structure interaction effect. Following conclusions are drawn from the study:

1) Response of the bridge considering soil-structure interaction is different from the response of the bridge without considering soil-structure interaction.
2) Soil-structure interaction effect on the response of the bridge is influenced considerably by the type of earthquake. Depending on the type of earthquake, the soil-structure interaction effect may be either beneficial or it may be even detrimental to the structure.
3) The beneficial or detrimental effect of soil-structure interaction depends significantly on the type of foundation foil.
4) The beneficial or detrimental effect of considering soil-structure interaction in the analysis of the isolated bridge is also affected by the isolation period. Depending on the isolation period of rubber bearing, the soil-structure interaction effect may be either beneficial or detrimental to the response of the bridge.
5) Response of bridge isolated with rubber bearing may be underestimated or overestimated if the effect of soil-structure interaction is neglected in the analysis and hence the soil-structure interaction effect needs to be considered for the realistic analysis of isolated bridges subjected to the earthquakes.

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