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Research Article

Effect of Elastomeric Bearings in Bridge Piers

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ABSTRACT

In this paper, the influence of elastomeric bearings is investigated in terms of seismic responses under effects of severe ground motions. For this purpose, seismic performance of an isolated pier system has been analytically studied by using time history analyses. The isolation system is assembled by elastomeric bearings composed of rubber layers and steel-shims. The bearings are located between pier-top ends and box-girder of the bridge deck. Seismic solutions are obtained for isolated system and non-isolated pier system known as rigid connection. Time-dependent response quantities are obtained in transverse direction for two strong quakes. Additionally, nonlinear static procedure is carried out to obtain lateral seismic capacity. Thus, the displacement and shear force capacity are determined for the considered pier systems. Seismic responses are comparatively presented in terms of superstructure and base response values. Thanks to the isolation system, the pier has yielded at lower peak displacements and base responses with seismic demand as well. On the other hand, higher seismic capacity has been obtained in the case of isolation system and the results are presented by computed lateral capacity curves**.** The results show that the elastomeric bearing is an effective tool in the lateral strength and modal behavior of the pier system as well. However, peak displacements of the elastomeric bearing have exceeded the allowable limits related with displacement capacity.

1. Introduction

Piers are the most important structural members of a highway/railway bridge. As it is known, bridges are strategic structures and commonly used in transportation network. They are generally built to cross deep valleys or long spacings on see or rivers. Bridges are constructed and designed to meet gravity, live and dynamic loads such as earthquakes and wind forces. In this context, all seismic loads arising from inertial forces occurred in the superstructure are carried and transmitted to soil media by means of substructure components so-called as pier system.

Conventionally, piers can be connected to superstructure in two ways; first way is, most commonly used, installing seismic isolation system and the other way is to create rigid connection, i.e., monolithic construction. General section types of the piers are circular, rectangular or hollow core boxes. They are constructed as either a single column with box girders or multi-column with cap system. Although hollow core section type is designed in large dimensions, it provides great advantages such as high bending and torsional stiffness, less volume and mass.

Displacement ductility capacity of a reinforced concrete hollow pier can be satisfied of up to the value of 6 provided that adequate steel confinement is ensured [1]. From the past earthquakes, it has been understood that the main reasons of the collapse of bridges are mostly related to structural components as well as pier damages. In Northridge (1994, USA) and Kobe (1995, Japan) earthquakes, flexural and shear failures were observed in reinforced concrete piers [2, 3, 4]. From the field observations, bridges and therefore piers are very sensitive to severe ground motions and they should be attentively designed.

Analyses of the current studies have focused on the seismic effects and responses to reveal dynamic behavior. During an earthquake, dynamic forces occur in horizontal and vertical directions and in this case high seismic demands may develop in a bridge or pier system. Seismic loads happened in superstructure certainly can be merely carried by pier but this concept is not economical for long bridges and piers. However, this procedure involves different risks due to high uncertainties in ground motions. On the other hand, seismic isolation enables to shift natural period of a bridge to prevent resonance effects resulted from ground motion frequencies. Thus, pier period can be prolonged and desired performances can be obtained. Furthermore, isolation systems are used to limit/decrease the seismic demand and to dissipate seismic energy over a considered structural system. Thus, the system would have gained extra flexibility and the response forces in the pier and transmitted accelerations from ground to superstructure would be significantly decreased.

In past years, strong earthquakes occurred in western Turkey caused large damages and killed many people. In 1999 earthquakes, August 17 Kocaeli (M=7.4) and November 12 Düzce (M=7.2), thousands of people died and many buildings, bridges and other structures collapsed or heavily damaged. Due to the impact effect, Bolu viaducts on the northern Turkey highways displaced from the alignment in near fault zone. Displacement demands were resulted in high quantities and they exceeded the capacity of the isolation system. Therefore, local damages in bearings and unseating of beam ends occurred at the pier caps [5]. Farshad and Alam showed that shear deformation of the rubber exceeded the maximum allowed displacements with higher failure probability [6]. Usage of elastomeric bearing is very attractive in seismic regions and many investigations have been carried out for design of isolated bridge piers [7, 8, 9, 10].

The main perspective of this study is to present the effect of connection type between superstructure and column for a concrete pier system. Seismic behavior of the pier system is investigated under severe earthquakes recorded in Turkey. Response quantities are given comparatively for two cases, i.e., rigid construction and an isolated system by rubber bearings. From the given results, isolation system has considerable reduced the base responses and displacements. It has also extended the natural vibration period of the system. Furthermore, important recommendations are presented in terms of usage of the isolation system.

2. Pier System and Isolation Model

The reinforced concrete pier is selected from a constructed bridge and it has a box girder and hollow core section for the column. The total pier height is about 32m and its superstructure height is 5m. Deck thickness is variable in the range of 0.25m and 0.40m. Furthermore, bottom cap and web sections have varying form in the longitudinal direction. The deck width is 20m. The whole pier system is illustrated in Figure 1. The column section is in hollow core type with dimensions of 7m x 3m and thickness of 0.45m as seen in Figure 1. Dimensions of the pier section are constant from ground up to level of bridge deck. Concrete strength of the pier system is 30 Mpa and yield strength of the steel (f_y) is 420 Mpa. Area of longitudinal steel rebars (A_s) is 1129.2 cm^2. Since the plastic zone is expected in lower end of the pier column, a plastic hinge is defined in bottom region.

The isolation system was built by elastomeric bearings composed of laminated rubber layers with reinforced steel shims as illustrated in Figure 2. It was composed of top and bottom plates, rubber layers in a certain thickness and steel shims between rubber layers. Rubber material provides flexibility in lateral direction. On the other hand, for huge structures like long bridges, natural rubber material has inadequate vertical stiffness and hence steel shims are imposed into bearings to overcome this deficiency. Thus, rubber bearing system increases energy damping by performing high lateral displacements.

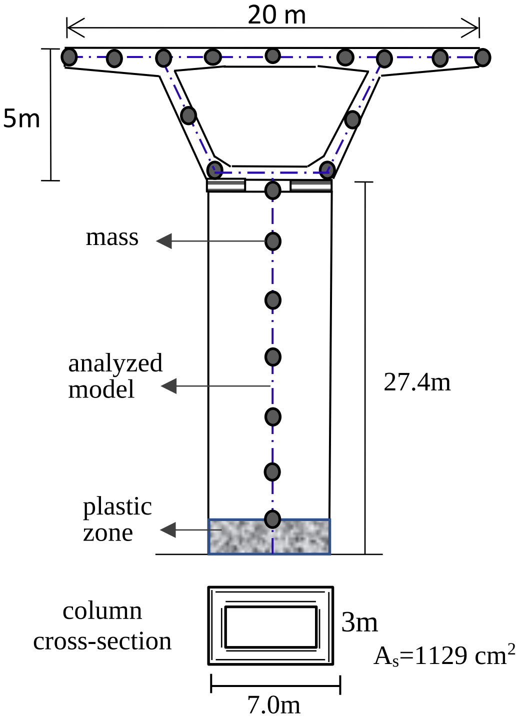


Figure 1. Bridge pier system

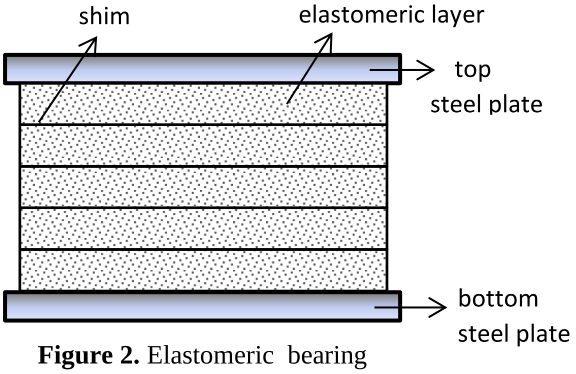


Figure 2. Elastomeric bearing

Dimensions of the pier system, structural properties of the bearing and pier column section used in this study are given in Table 1. Some stiffness values such characteristic strength are computed as well. Results of the free vibration analyses are displayed in Table 2 for both structural systems. Vibration periods showed that the elastomeric bearing has effectively extended the natural period of the pier system and it provides an important flexibility for the considered structure. Nonlinear behavior model is considered for elastomeric bearings in the solutions. For hysteretic response of the bearings, bilinear model is considered and characteristics parameters are given in Figure 3 with hysteretic loop.

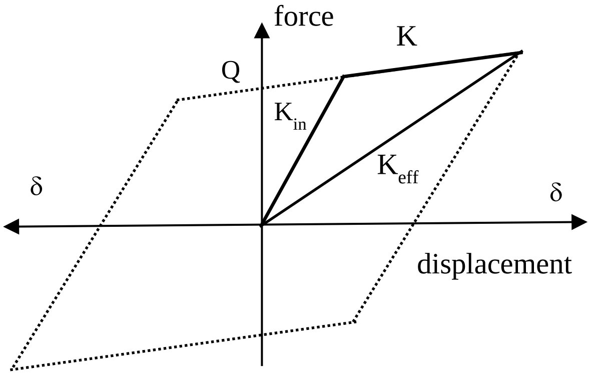


Figure 3. Behavior model of elastomeric bearing

The parameter of K_{in} denotes the initial stiffness and K is the secant stiffness related with post yield stiffness. K_{eff} is effective stiffness for the case of linear solution. Parameter of Q states bearing strength and it is obtained on the basis of hysteresis loop. As it is known, elastomeric material has high deformation capacity. However, displacement (δ) of a bearing system is a pioneer criterium for the safe design. Stiffness of a bearing system can be primarily categorized in two directions; horizontal (K_h) and vertical stiffness (K_v). As it is understood from bearing configuration, the vertical stiffness is much higher than horizontal stiffness. Mechanical characteristics of the bearings are calculated based on the following relations:

$$K_v=\frac{E.A}{\sum t_r} \qquad (1)$$

$$K_h=\frac{G.A}{\sum t_r} \qquad (2)$$

$$K_{eff}=K_h+\frac{Q}{\delta_{max}} \qquad (3)$$

$$S=\frac{\text{area under loading}}{\text{area without loading}} \qquad (4)$$

where E is compression module depending on shape factor (S) , A is the area of bearing cross-section, G is the shear module and tr is the thickness of each elastomeric layer. For a squared-shape (with size of a) bearing:

$$S=a/(4\times t_r) \qquad (5)$$

$$E=6,73\times G\times S^2 \qquad (6)$$

Compression module is obtained based on the given relations for each elastomeric bearing.

3. Seismic Analysis of the Pier System

The pier system is modeled by finite frame elements specified by proper mesh intervals in three directions. Lumped mass approximation has been considered on nodal points for all directions in the model. Mass of the pier is 3143.8 kNs^2/m. Elastomeric bearings are considered by a link element. Their structural characteristics are calculated on the basis of dimensions, properties, codes [11, 12] and formulas given in the literature [13]. Stiffness matrices of the bearings are calculated and incorporated into the system model.

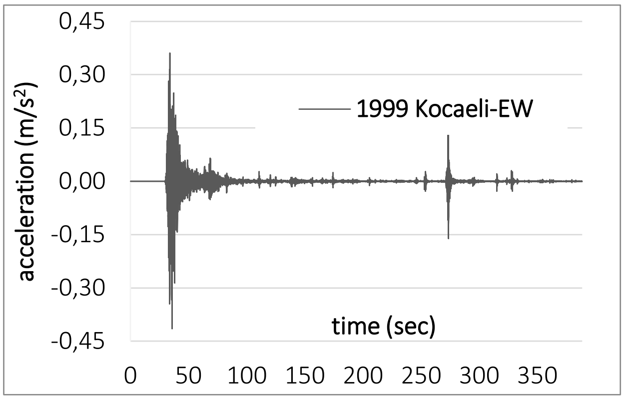
Table 1. Bearing and pier section properties

Properties	**bearing**	**Pier**
dimensions (m)	0.80×0.80	7×3×0.45
height (elas. layers) (m)	0.085	27.4
cross-sectional area (m^2)	0.64	8.19
moment of inertia as (m^4)	0.034	11.04
elasticity modulus (kN/m^2)	1.05×10^6	3×10^7
charac. strength (*kN*)	715	2.5×10^3
Shear modulus (k*N*/m^2)	1×10^3	1.25×10^7

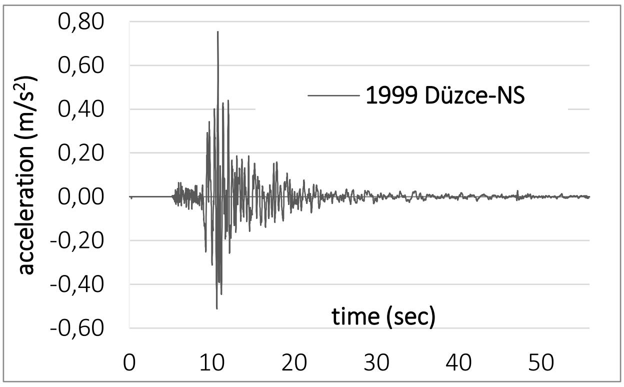
Table 2. Pier free vibration periods (sec)

Pier system	**T_1**	**T_2**	**T_3**
pier with elastomeric bearing	1.99	0.64	0.61
fixed pier without elastomeric bearing	1.42	0.65	0.61

Nonlinear time history analysis is implemented for the considered pier under effects of seismic ground motions by using a software code [14]. In the time history analyses, kinematic model has been considered for the hysteretic behavior. Two strong earthquake motions happened and recorded in Kocaeli (Mw=7.4, 1999) and Bolu (Düzce, Mw=7.2, 1999) provinces in Turkey. They are selected due to their high destructiveness as seen from field observations after the earthquakes occurred. As is known, many people died and thousands of buildings collapsed or severe damaged. The considered earthquakes 1999 Kocaeli-EW and 1999 Düzce-NS records are given in Figure 4.



a. kocaeli record for EW component (1999)

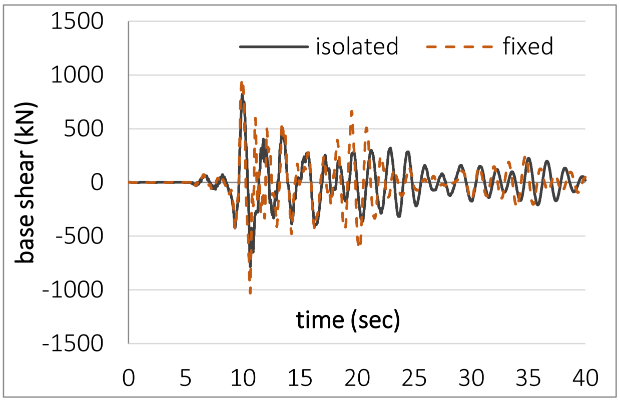


b. düzce record for NS component (1999)

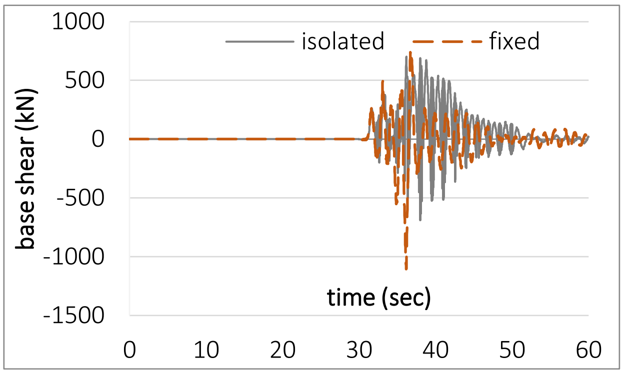
Figure 4. Acceleration records used in the analyses

Under strong ground motions given above, seismic responses are computed for two structural cases: i.e., the first one is base isolated pier system and the second case considers rigid connection type (non-isolated), it means that no isolation mechanism. All earthquake responses are comparatively presented and drawn by graphics for both cases. In Figure 5, seismic response quantities are illustrated in terms of total base shear of the pier system. As seen, the isolated system decrease distinctly the maximum shear forces, generally can be critical in designs, in compared to rigid connection type. The amount of decrease in maximum shear forces is much higher in case of Kocaeli earthquake.

The response comparisons given in Figure 5 are realized for pier displacements as well. From Figure 6, although some displacement values are to be lower than those of the fixed system, the rubber isolation system has quite limited and decreased the maximum displacements. As it is well known, maximum displacements play a key role in structural performance and most codes suggest some rules to limit these values. Researches have focused to overcome these maximum displacement problems that may lead to collapse of a structural system. As is seen from the Figure, usage of elastomeric bearing is a very effective tool to keep the maximum displacements in acceptable limits.

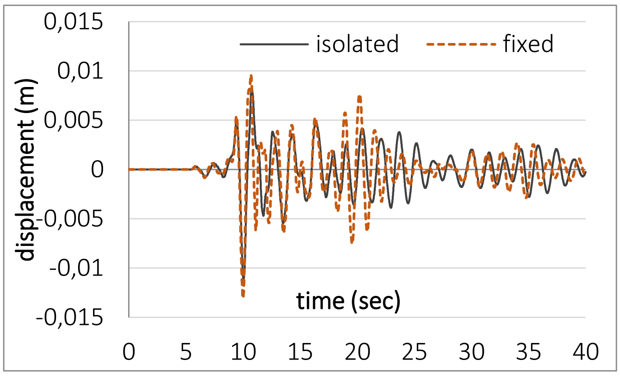


a. base responses for Düzce-NS earthquake

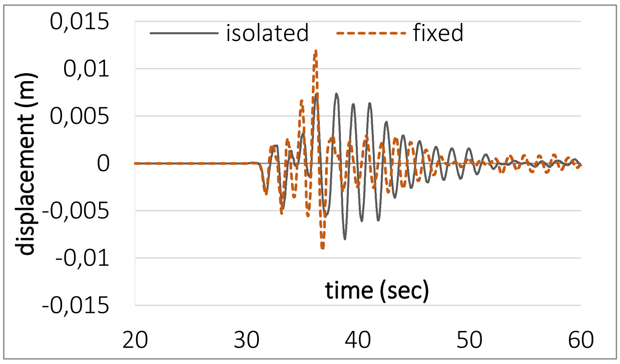


b. base responses for Kocaeli-EW earthquake

Figure 5. Base shear forces for different pier systems

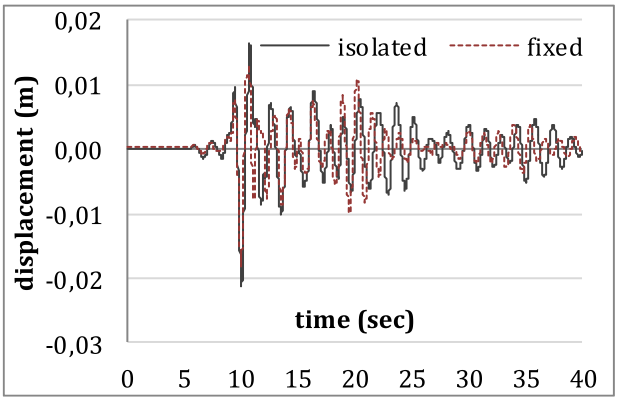


a. displacements for Düzce-NS earthquake

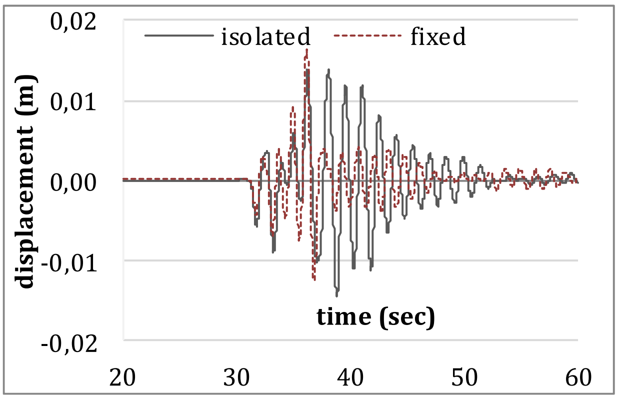


b. displacements for Kocaeli-EW earthquake

Figure 6. Pier displacements for different pier systems



a. deck displacements in Düzce-NS earthquake

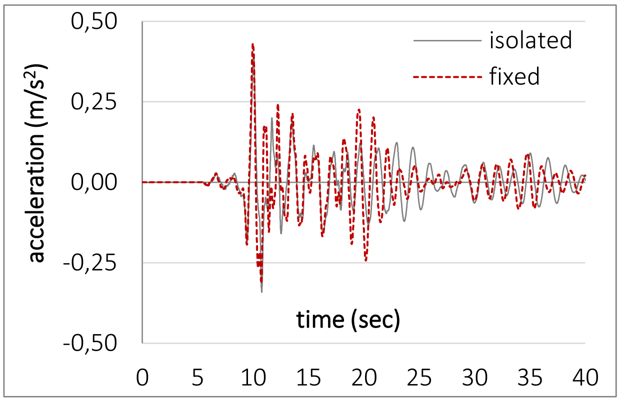


b. deck displacements in Kocaeli-EW earthquake

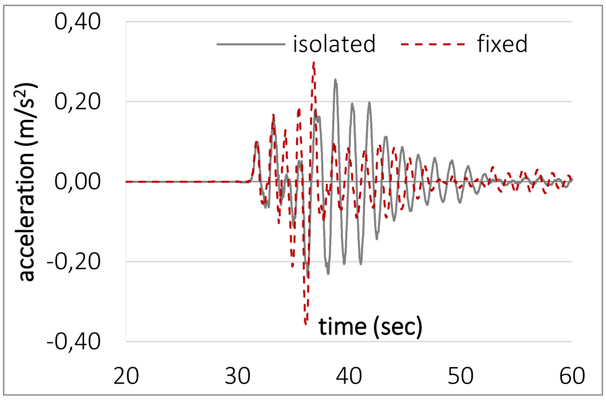
Figure 7. Deck displacements for different systems and earthquakes

Absolute deck-displacements are calculated as well and displayed in Figure 7. From the figures, it has been realized that the superstructure-displacements distinctly increase in the second phase of the earthquakes especially for the Kocaeli earthquake motion. Since the isolation system has high lateral displacement capacity, the deck system having massive mass reacts like a rigid body movement over the base isolation instruments. Therefore, elastic behavior model can be taken into account in the designs for superstructure of a bridge system.

Additionally, deck accelerations are compared to obtain the reduction ratios in the maximum values. From the Figure 8, maximum-accelerations of the superstructure have also developed with higher values in non-isolated system with reference to the isolated system. Peak ground accelerations resulted in strong ground motions are reduced by the isolation system and transferred from substructure to superstructure. It should be noted that soil characteristic would considerable affect the response values and it should be avoided the amplify effect of the soft soil. Because dominant period of this soil type may cause to resonance effect in case of period-extending of the bridge/pier system by using isolation system.



a. accelerations in Düzce-NS earthquake



b. accelerations in Kocaeli-EW earthquake

Figure 8. Deck accelerations for different structural systems and earthquakes

Lateral seismic capacity of a structural system plays a vital role and it is an important factor in earthquake resistant designs. All seismic design processes aim to provide an adequate lateral-stiffness by considering different concepts such as isolations and dampers. Pushover curves are used to obtain seismic performances in engineering designs. Nonlinear modal pushover analyses have been implemented to obtain lateral capacity of the considered system.

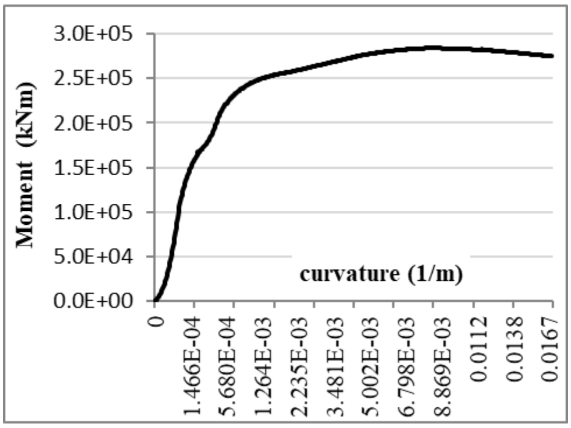


Figure 9. M-K curve for pier

In defining of section capacity moment-curvature relationship provides valuable characteristic [15]. For nonlinear behavior, moment-curvature (M-K) diagram is obtained for the pier section by considered steel reinforcements. As concrete material behavior, Mander [16] model is considered for stress-strain relationship in the solutions. The moment-curvature diagram is obtained as given in Figure 9.

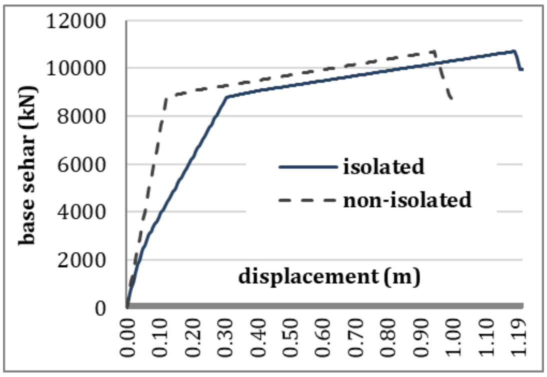


Figure 10. Capacity curves for the pier systems

In Figure 10, capacity curves are illustrated comparatively for both earthquake motions. These curves show elastic zone, post-yield zone and failure zones for the studied pier systems. As is seen, the base isolation has increased the lateral displacement capacity of the system and this increase-amount reaches up to 20% value. Furthermore, a minor increase is seen in the maximum base force for the lateral capacity. Seismic performance of the pier system is determined for maximum earthquake level by considering hard clay soil layer.

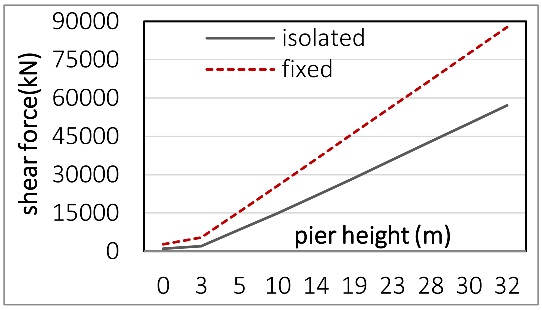
Design spectrum parameters are defined according to Turkish Building Seismic Code-2018 [15]. Thus, spectral acceleration coefficients of the design spectrum are obtained by the values of S_{ds}=1.345 (at short period) and S_{d1}=0.563 (at long period). These parameters reflect the soil influences to the design spectrum. The peak ground acceleration value is considered by the value of 0.646g. Under these conditions, performance requirements of the pier system are calculated for the assigned designed spectrum and the performance objectives of the pier system are comparatively given in Table 3.

Table 3. Performance targets for maximum earthquake

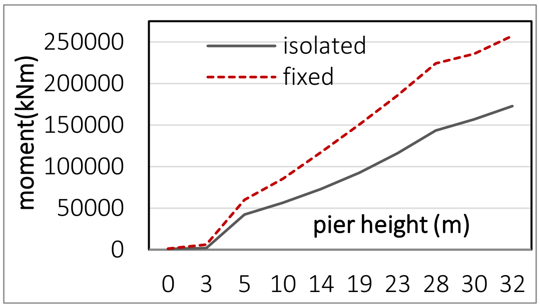
pier type	**V_p** (kN)	**d_p** (m)	**S_{ap}** (m/s^2)	**S_{dp}** (m/s^2)
pier with elastomeric bearing	6642	0.219	0.24	0.204
fixed pier without elastomeric bearing	8198	0.133	0.301	0.116

As seen, the isolation device has reduced the demand forces arising from quake motion. By using isolation system, while the displacement demand of the pier system has increased from 0.106m (d_p) to 0.219m (d_p), the shear force value (V_p) decreases from 8198 kN to 6642 kN thanks to flexibility of the elastomeric bearing. On the other hand, the spectral displacements (S_d) and accelerations (S_a) have shown large variations as seen from the Table 3. While the deck accelerations have decreased for the isolated structure, the displacements have considerably increased due to the high-self displacements of the elastomeric bearing. As a result, the isolation system has distinctly modified the behavior of the system and thus the pier-performance has increased advantageously about 20% by increasing displacement capacity.

Response variations in the pier are also investigated under effects of strong ground motions. For this purpose, each pier system is analyzed for seismic effects and response variations are obtained for fixed and isolated system in terms of parameter of the pier height. Figure 11 shows a comparison for response variations in the pier for the Düzce earthquake. Additionally, the variations in the pier system are compared in Figure 12 for the Kocaeli earthquake in terms of pier height. As seen, the isolation system has distinctly reduced response quantities and it becomes more efficient as the pier length increase. The results show that an isolation system would largely decrease response values (shear forces and bending moments) especially for very long piers.

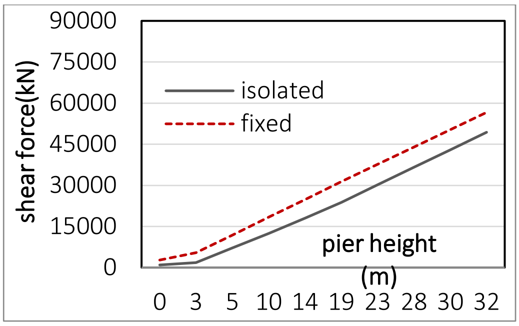


a. shear force variations along the pier heights

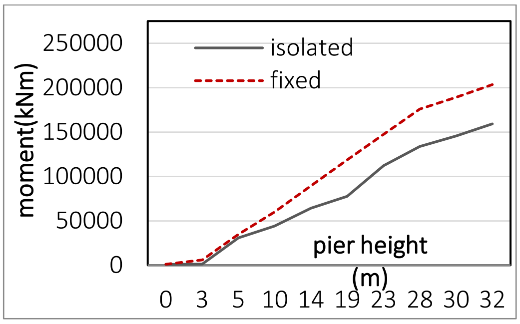


b. moment variations along the pier heights

Figure 11. Response variations for Düzce earthquake



a. shear force variations along the pier heights



b. moment variations along the pier heights

Figure 12. Response variations for Kocaeli earthquake

The peak displacements of the elastomeric bearing is also investigated under effects of considered strong ground motions. Maximum displacement of a bearing is a crucial parameter in design process. In this study, the maximum displacement value is limited by the value of 1,5×t_r which is prescribed by [17] code of Caltrans. In Figure 13, the variations of bearing displacements are illustrated for both equations. Additionally, the peak displacements of the elastomeric bearing are comparatively given in the Table 4. As seen from the graphic and table, peak displacement (0,174m) of the elastomeric bearing exceed the allowable displacement (0,128m) in case of Düzce-NS quake. On the other hand, the peak displacement (0,115m) of the Kocaeli-EW quake is in acceptable limits. The results show that the displacement capacity of the elastomeric bearing is insufficient for the strong earthquake and this case may lead to drop off the superstructure and therefore severe damages in the pier system could occur due to large displacements.

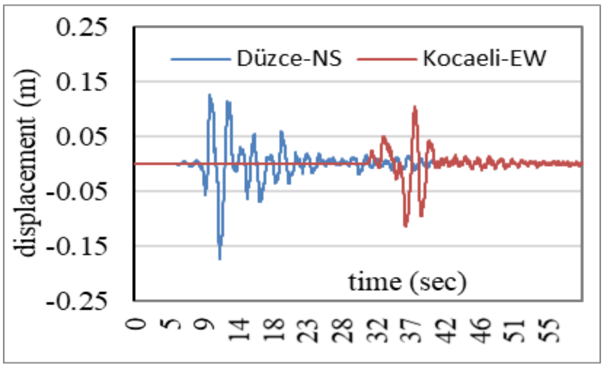


Figure 13. Displacements of the elastomeric bearing

Table 4. Peak displacements of the bearing

Earthquake	δ_{max} (m)	$\delta_{allaowable}$ (m)
Düzce-NS	0.174	0.128
Kocaeli-EW	0.115	0.128

Furthermore, the earthquake energy is also measured in the pier system as illustrated in Figure 14. While the isolation system requires lower forces demanded by the earthquake motion, it provides higher energy capacity by means of capable of high displacements. The results show that the usage of a seismic isolation device is very effective tool, especially for bridges, in reducing of high seismic demands. The isolation system accomplishes this process by shifting the fundamental period of the structural system and by keeping away from the peak regions in a spectrum curve.

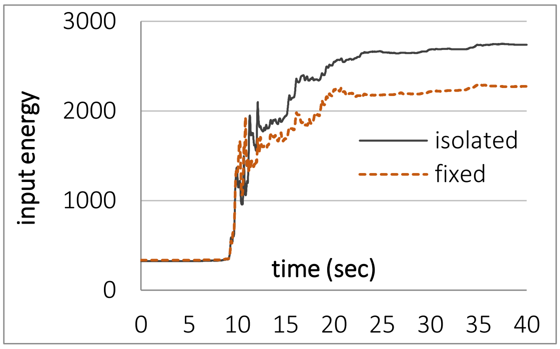


Figure 14. Demand energy for the pier system

4. Conclusions

This study has focused on effectiveness of an isolation system used in a reinforced concrete bridge-pier. For this purpose, the base-isolated pier is comparatively studied in terms of connection type between the superstructure and the pier-column under effects of strong and recorded ground motions. Two structural types are considered: an isolated and non-isolated pier system. Elastomeric bearings have been mounted between deck girder and pier-top ends in the pier system. Seismic response quantities are obtained in lateral direction by using static pushover procedures and nonlinear dynamic analyses in time history domain. The following conclusions are obtained from the present research:

- The isolation system has prolonged the natural vibration periods and it has enabled high flexibility that would provide more seismic performance. Since bridge or pier system has high period values, it should be avoided from the resonance range (for soft soil, especially) in the case of extending period.
- Using seismic isolation system has decreased the demands caused by earthquakes and increased the seismic capacity. Considerable reductions have been observed in the maximum base responses for the isolated pier system whereas the non-isolated system has yielded higher response quantities.

- The reduction in the maximum base shear forces is 25% in Düzce earthquake and 36% in Kocaeli earthquake. As seen from the presented figures, the amount of decrease varies depending on structural characteristics and earthquake motion as well. Because, earthquakes occur in random manner and they contain large uncertainties. The structure interacts with the earthquake in a complex form.
- Maximum displacements play a key role in engineering designs and the elastomeric bearings have distinctly limited and decreased the maximum displacement of the pier top-end.
- Due to high flexibility of the isolation system, absolute displacements in the superstructure have increased and massive deck system moves easily like a rigid body motion over the base isolation instruments. Therefore, elastic behavior model can be considered for the deck system.
- The isolated system has reduced the peak deck-accelerations and they are about 0.33g for Düzce earthquake and 0,25g for Kocaeli earthquake. Whereas, these maximum values are, respectively, 0,42g and 0,35g for the non-isolated pier system.
- Lateral stiffness capacity of the pier system has been comparatively displayed via pushover curves. Results showed that the elastomeric bearings have provided higher displacement capacity and therefore more seismic capacity up to 20% and a small increase in shear capacity.
- Peak displacements in the elastomeric bearing have exceeded the bearing capacity. Extremely large displacements in the bearings may lead to drop off the superstructure and dislocation of the bearing can develop with overturning of pier system. As a result, the displacement capacity of the elastomeric bearing is insufficient in case of a strong earthquake.
- For general inferences for the effectiveness of the rubber isolation system, extensive studies should be implemented over various pier types and different soil conditions by using nonlinear performance analyses.

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7. Conflict of interest statement

There is no conflict of interest with any person / institution in the article prepared

8. Ethics committee approval

The author declares that there is no need to obtain permission from the ethics committee for the article prepared.

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