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DYNAMICS OF INELASTIC ISOLATED BRIDGES SUBJECTED TO ANALYTICAL PULSE GROUND MOTIONS

A. Tsiavos\textsuperscript{1}, B. Stojadinovic\textsuperscript{2}, K. Mackie\textsuperscript{3}

ABSTRACT

This paper aims at identifying the inelastic behavior of isolated bridges subjected to pulse ground excitation. The possibility of allowing yielding of the substructure will be investigated as an additional energy dissipation mechanism. This is important because: 1) identifying the inelastic behavior of isolated bridges will facilitate a more economical design; 2) it will be possible to correctly identify those existing isolated bridges whose strength is not sufficient to keep their response in the elastic range. The whole system of a base isolated bridge consists of three parts: 1) The superstructure with stiffness $K_{\text{sup}}$, 2) The isolation with stiffness $K_b$ and 3) The substructure below the isolation level with stiffness $K_s$. However, as the superstructure usually consists of the bridge deck, which is very stiff, it is possible to investigate the behavior of the system with a simplified 2-DOF model. The deformation of the two elements, representing the response of the pier and the isolators will be determined using the software Opensees \cite{1}. Parametric studies will be conducted for the determination of the essential parameters that define the behavior of the system.

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Dynamics of inelastic isolated bridges subjected to analytical pulse ground motions

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ABSTRACT

This paper aims at identifying the inelastic behavior of isolated bridges subjected to pulse ground excitation. The possibility of allowing yielding of the substructure will be investigated as an additional energy dissipation mechanism. This is important because: 1) identifying the inelastic behavior of isolated bridges will facilitate a more economical design; 2) it will be possible to correctly identify those existing isolated bridges whose strength is not sufficient to keep their response in the elastic range. The whole system of a base isolated bridge consists of three parts: 1) The superstructure with stiffness \( K_{\text{sup}} \), 2) The isolation with stiffness \( K_b \) and 3) The substructure below the isolation level with stiffness \( K_s \). However, as the superstructure usually consists of the bridge deck, which is very stiff, it is possible to investigate the behavior of the system with a simplified 2-DOF model. The deformation of the two elements, representing the response of the pier and the isolators will be determined using the software Opensees [1]. Parametric studies will be conducted for the determination of the essential parameters that define the behavior of the system.

Introduction

Good seismic response of bridges during strong earthquake is important for the post-earthquake recovery effort, because bridge failure can have disastrous immediate and long-term consequences. Apart from being expensive infrastructure elements, bridges are crucial parts of the transportation network of a community. Therefore, many engineering solutions have been implemented in the past to reduce the damage caused to these structures by severe earthquakes. Seismic isolation is one of the most common seismic response modification strategies used in bridge design. This strategy is often implemented by placing the bridge seismic isolation bearings between the bridge superstructure (the deck) and it substructure (the piers).

Behavior of seismically isolated bridges has been extensively studied in the past. Constantinou et al [2], Kartoum et al [3] and Tsopelas et al [4] described the effectiveness of sliding isolation systems for the response modification of bridges, both analytically and experimentally. Ghobarah and Ali [5] and Turkington et al [6] have shown that the use of lead-rubber isolation systems can also lead to an improvement of the seismic performance of the bridge. Turkington et al [6] conclude that piers should be designed to remain elastic during the

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design earthquake. Nevertheless, the investigation of the inelastic behavior of seismically isolated bridges is interesting for two main reasons.

First, reducing their base shear design force of bridge piers (the substructure) by a strength reduction factor and allowing them to respond in the inelastic range may produce more economical designs. Miranda and Bertero [7] already investigated the dependence of strength reduction factor \( R_y \) on the displacement ductility ratio \( \mu \) for fixed based structures. Constantinou and Quarshie [8], Ordonez et al. [9], Kikuchi et al. [10], and Thiravechyan et al. [11] investigated the response of yielding seismically isolated structures and agreed that allowing seismically isolated structures to yield requires careful consideration because displacement ductility demands exceeded the strength reduction factor values. Vassiliou, Tsiavos and Stojadinovic [12-14] have concluded that designing typical seismically isolated structures to behave elastically, as prescribed by current seismic design codes, is not overly conservative but a necessity that emerges from the fundamental dynamics of such structures. Constantinou and Quarshie [8] have concluded that the strength reduction factor \( R_y \)-values for the substructures of seismically isolated bridges should be in the range of 1.5 to 2.5.

Second, it is important to identify the existing seismically isolated bridge structures whose strength is not sufficient to keep their response in the elastic range. Seismic response of such structures [8,12-14] is characterized by large displacement ductility demands, larger than those predicted using the design approaches developed for non-isolated structures. Therefore, it is important to check if such structures have the deformation ductility capacity to meet this increased demand, and to, when necessary, design retrofits aimed at increasing the strength or the ductility capacity of the critical components of such bridges.

This study focuses on an investigation of the inelastic seismic demands for bridges seismically isolated with friction-pendulum bearings under analytical pulse ground motion excitation.

**Dynamic Modeling**

A seismically isolated bridge consists of three parts: 1) the superstructure with stiffness \( K_{sup} \), 2) the seismic isolation bearings with stiffness \( K_b \); and 3) the substructure (the piers) below the isolation level with stiffness \( K_s \). The superstructure is the bridge deck, usually a multi-cell box girder, is much stiffer and stronger than the substructure. Therefore, it is possible to investigate the seismic behavior of the system using a simplified two-degree-of-freedom model, shown in Fig. 1. Masses \( m_b \) and \( m_s \) represent the mass of the superstructure and the mass of the substructure below the isolation system, respectively. The stiffness and the damping coefficient are denoted as \( k_b \) and \( c_b \), when referring to the superstructure, and as \( k_s \) and \( c_s \), when referring to the substructure. The superstructure is assume to be rigid and is modeled only through its seismic mass. The deformation \( u_b \) is the deformation of the superstructure with respect to the base of the isolators (the top of the bent cap), and \( u_s \) is the deformation of the substructure with respect to the ground. The following quantities are defined:

1. Fixed-base period and cyclic frequency:
\[ T_s = 2\pi \sqrt{\frac{m_s}{k_s}}, \quad \omega_s = \sqrt{\frac{k_s}{m_s}} \] (1)

2. Isolation period and cyclic frequency:

\[ T_b = 2\pi \sqrt{\frac{m_b}{\omega_b}}, \quad \omega_b = \sqrt{\frac{\alpha_b k_b}{m_b}} \] (2)

3. Non-hysteretic structural and isolation damping ratio:

\[ \xi_s = \frac{c_s}{2m_s\omega_s}, \quad \xi_b = \frac{c_b}{2m_b\omega_b} \] (3)

4. Mass ratio:

\[ \gamma_m = \frac{m_b}{m_b + m_s} \] (4)

The strength of the isolation system comprising friction pendulum bearings is determined as follows:

\[ Q = m_b\mu_f g \] (5)

Dynamic equilibrium of the isolated structure and the base isolation system gives:

\[ m_b\ddot{u}_b + (m_b + m_s)\ddot{u}_s + F_s = -(m_b + m_s)\ddot{u}_g \] (6)

Dynamic equilibrium of the isolated structure gives:

\[ m_b\ddot{u}_b + m_b\ddot{u}_s + F_b = -m_b\ddot{u}_g \] (7)

Consequently, equations (6) and (7) become equations of motion of the combined structure-isolation system. The resistance force \( F_s \) of the substructure and the isolators \( F_b \) are modeled using the bilinear models presented in Fig. 1. When dividing equations (6) and (7) by \((m_b+m_s)\) and \(m_b\) respectively, equations (8) and (9) are derived.

\[ \gamma_m\ddot{u}_b + \ddot{u}_s + F_s/(m_b + m_s) = -\ddot{u}_g \] (8)

\[ \ddot{u}_b + \ddot{u}_s + F_b/m_b = -\ddot{u}_g \] (9)
A model representing equilibrium equations (8) and (9) was developed using the finite element software framework OpenSees [1]. The hysteretic behavior of the seismic isolation bearings and the isolated substructure is simulated using a Bouc-Wen [2] model.

![Seismic isolation bearing and Substructure diagrams](image)

**Figure 1.** Parameters of the 2-DOF model of a base isolated bridge

**Ground motion excitation**

The ground motion acceleration used for this study is an analytical symmetric Ricker pulse [16, 17] with a pulse period $T_p=0.5$ and pulse peak acceleration $a_p=0.8g$ given by Eq.10 and presented in Fig. 2:

$$\ddot{u}_k (t) = a_p (1 - \frac{2\pi^2 t^2}{T_p^2})^2 e^{\frac{12\pi^2 t^2}{T_p^2}} \quad (10)$$

![Symmetric Ricker pulse ground motion acceleration graph](image)

**Figure 2.** Symmetric Ricker pulse ground motion acceleration
Methodology

The analysis method used in this study involves determining the displacement ductility ratio $\mu$ of the substructure for a certain predetermined value of the strength reduction factor $R_y$. The structural model shown in Fig. 1 is subjected to the pulse ground motion excitation presented in Fig. 2. The vibration period of the seismic isolation bearings $T_b$ is selected first. The strength of the isolation system is determined by the choice of the bearing friction coefficient $\mu_f = 0.03$. Then, an elastic analysis is conducted to calculate the maximum elastic force and displacement demands for the substructure with vibration period $T_s$. After these values are determined and the strength reduction factor value $R_y$ is selected, the yield strength and the yield displacement of the substructure can be easily calculated. The requested displacement ductility ratio $\mu$ is computed from the results of an inelastic analysis for the model with the design properties (yield strength, yield displacement) calculated above.

Response to analytical pulse excitation

The symmetric Ricker pulse (Fig. 2) is used to excite the model (Fig. 1) with $m_b = 180$ tons and $\gamma_m = 0.9$. The vibration period of the substructure $T_s = 0.2$ sec, whereas the vibration period of the isolated structure $T_b = 2$ sec. The substructure is designed to respond inelastically with strength reduction factor $R_y = 2$. The acceleration time history for both elements of the model due to the analytical pulse excitation is shown in Fig. 3. The corresponding displacement time history is shown in Fig. 4.

![Figure 3. Acceleration time history response of the model due to analytical pulse ground motion excitation](image-url)
The maximum acceleration of the isolated deck is significantly lower than that of the substructure due to the orthogonality between the pier vibration mode \((T_s=0.2 \text{ sec})\) and the seismic isolation vibration mode \((T_b=2 \text{ sec})\). Moreover, the dominant period of the motion of the deck is elongated comparing to the one of the pier, showing how the dynamics of the seismically isolated system changes the nature of the excitation of the isolated superstructure. The high frequency oscillations observed in the response of the substructure are attributed to the choice of very high initial stiffness for the isolators: this increases the interaction of the isolated structure and the substructure.

**Parametric analysis**

The parameters that influence the dynamic response of the model of a seismically isolated bridge (Fig. 1) are:

a) The strength reduction factor \(R_y\).
b) The isolation period \(T_b\).
c) The mass ratio \(\gamma_m\).
d) The hardening ratio \(\alpha_s\) of post-yield to pre-yield stiffness of the substructure

**Influence of the strength reduction factor \(R_y\)**

The influence of the strength reduction factor \(R_y\) on the inelastic displacement demand of the substructure of the bridge with \(T_b=2\text{ sec}, \gamma_m=0.9\) and \(\alpha_s=10\%\), is presented in Fig. 5.
Figure 5. Displacement ductility ratio $\mu$ vs. substructure vibration period $T_s$ for different values of the strength reduction factor $R_y$.

As shown in Fig. 5, the displacement ductility demand remains roughly equal to the value of the strength reduction factor in the long and medium substructure vibration period ranges. However, displacement ductility demand grows exponentially once the vibration periods of the substructure become shorter than 0.5 sec. As reported by Constantinou and Quarshie [8], typical bridge pier vibration periods (as defined by Eq. 1) range between 0.1 sec and 0.5 sec. Therefore, data in Fig. 5 indicated that most typical bridge piers are subject to large ductility demands if they yield and respond to a ground motion in the inelastic range. For instance, a typical California bridge pier with a circular cross section with a diameter of 2.4 m [18] has a vibration period $T_s=0.24$ sec (Eq. 1). If the strength reduction factor $R_y$ used to design this pier is 3, the corresponding displacement ductility demand would be larger than 8, a value that cannot be easily satisfied by the ductility capacity of the pier. This result confirms the findings in the study by Constantinou and Quarshie [8] who concluded that the strength reduction factors for the substructures of seismically isolated bridges should be between 1.5 and 2.5.

The data in Fig. 5 also show that the rate of increase of displacement ductility demands slows as the strength reduction factor $R_y$ increases from 2 to 4.

Influence of the isolation period $T_b$

The influence of the isolation period $T_b$ on the inelastic displacement demand of the substructure of the bridge with $R_y=2$, $\gamma_m=0.9$ and $\alpha_s=10\%$, is presented in Fig. 6. Evidently, the isolation period does not affect the ductility demand for substructures whose vibration period is longer than approximately 0.8 sec. However, the trends in the displacement ductility demand for structures with shorter vibration periods are not clear, other than the displacement ductility demand grows quickly.
Influence of the mass ratio $\gamma_m$

As illustrated in Fig. 7, different mass ratios for an isolated bridge with strength reduction factor $R_y=2$, isolation period $T_b=2$ sec and $a_s=10\%$ lead to increases in displacement ductility demands for the substructure in the short and the medium period ranges: the increases emerge when $T_s$ is shorter than 1.5 sec. Note that the displacement ductility demand decreases for systems with higher values of $\gamma_m$, namely for bridges designed with a very comparatively heavy deck. This, however, increases the gravity loads on the piers, potentially affecting their behavior in ways that were not analyzed in this study.

Figure 6. Displacement ductility ratio $\mu$ vs. substructure vibration period $T_s$ for different values of the isolation period $T_b$

Figure 7. Displacement ductility ratio $\mu$ for alternate values of mass ratio $\gamma_m$
Influence of the hardening ratio $\alpha_s$ of the substructure

The influence of the hardening ratio $\alpha_s$ (Fig. 1) of the structure with $R_y=2$, $\gamma_m=0.9$ and $T_b=2$ sec on the displacement ductility demand of the pier is shown in Fig. 8. Changing the hardening ratio in the medium and long period range has no effect on the displacement ductility demand. Reduction of the hardening ratio from 10% to 1% increases the ductility demands for the substructure significantly in the short period range, while the reduction from 1% to 0 has practically no further detrimental effect.

![Figure 8. Displacement ductility ratio $\mu$ for alternate values of hardening ratio $\alpha_s$.](image)

Conclusions

A selection of findings from an investigation of the inelastic response of a model of seismically isolated bridge structures to an analytical pulse ground motion excitation was presented in this paper. Dynamic analyses of the time history of the model response show that the inelastic response of this seemingly simple structural system is quite complex because of the strong interaction between the substructure (bridge piers), the isolation bearings and the isolated superstructure.

The main findings were derived by computing the largest displacement ductility demand spectra and observing how different model parameters affect the displacement ductility demand for the substructure. The parameter that has the largest effect on the displacement ductility demand for the substructure of a base isolated bridge is the strength reduction factor $R_y$. The computed displacement ductility demand spectra indicate that this demand exceeds the values of the strength reduction factor for substructures with periods shorter than 0.5 sec, and that it grows quickly as the substructure period shortens further. This means that the well-known “equal displacement” rule does not apply for typical bridge piers, implying that designed such piers to behave inelastically should be done with significant caution. These findings confirm the recommendations made by Constantinou and Quarshie [8] and reinforce the limits on
substructure displacement ductility they proposed.

The use of comparatively heavy bridge superstructures, resulting in higher mass ratios $\gamma_m$, is advantageous considering the decrease of the ductility demands for the piers. Less effective, but still beneficial, is the increase of the hardening ratio of the substructure above the value of 1%. There is no clear trend in the influence of the isolation period $T_b$ on the inelastic behavior of the substructure.

The accuracy of these findings is being improved by using a broad sample of real ground motion records and by wider and denser sampling of the design parameter space.

References

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