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SEISMIC PERFORMANCE ENHANCEMENT OF BRIDGES USING SLIDING FRICTION ISOLATORS MOUNTED ON FLEXIBLE SUPPORTS

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SUMMARY

Sliding-friction isolators are the most promising among the developed isolation devices to achieve the desired performance of bridges during seismic events. These devices add flexibility to stiffer piers, dissipate undesirable input energy, and avoid possible concentration of ductility factor demand in piers. In this paper, an isolation system has been presented that is simple to manufacture and to easy implement in existing or new bridges. The proposed isolation system uses two-material flat sliding surface mounted on high-stiffness low-damping laminated rubber bearings in combination with low-stiffness high damping laminated rubber bearings to introduce predefined restoring force. The analysis results for an existing bridge are presented in this paper for recorded ground motions. The energy dissipation capacity of the system increases with sliding amplitude while maintaining the restoring force. It has been demonstrated that the proposed isolation system can be effectively used to enhance the seismic performance of bridges for wide range of intensity levels of expected ground motions. A simple procedure is also presented for the selection of isolation system parameters for desired performance requirements.

INTRODUCTION

The functional integrity of transportation networks after earthquakes is essential for postearthquake rescue and emergency services and for rapid rehabilitation in affected area. Bridges are the most critical elements of a transportation network, and their safety is usually assumed to be ensured by providing sufficient ductility capacity factor though most of the bridges are short of structural redundancy in general and codes are not explicit about the ductility capacity factor implied by the design. In certain situations, safety is further compromised due to improper estimation of potential earthquake hazards in the regions of moderate to high seismicity. The history of failures of highway bridges during recent earthquakes demonstrates the potential inadequacy of ductility-based design procedures followed in most countries, Priestley [1].

The concepts of isolation and energy dissipation are particularly interesting for bridges, as they require a higher degree of protection to ensure their functionality after a seismic event. Due to the specific structural and functional characteristics of bridges, it is convenient to concentrate the damage potential into a few mechanical elements that may be easily replaced after the earthquake. The isolation and energy-dissipating devices are increasingly used to correct or regularize the expected response by adding flexibility to stiffer pier, dissipating undesirable input energy and thus avoiding possible concentration of ductility factor demand in bridge piers [1]. For intense motion, limited repairable damage to piers may also be permitted even with the isolation and energy dissipating devices but the bridge decks should not be dislodged. The engineer responsible for the seismic design of a bridge with isolation and energy dissipation devices must make a fundamental trade-off between strength capacity and permitted displacements.

Isolation devices with increased thickness of commonly used laminated rubber bearing (LRB) for additional flexibility with a lead plug inserted into a performed hole for additional energy dissipation have been used to significantly reduce superstructure deformations during seismic excitation and to provide a force-limiting mechanism for the supporting substructure, Robinson [2]. These devices have performed well during recent earthquakes. However it was observed that a large energy dissipation capacity attracts large potential residual displacements in the absence of an appropriate restoring force, and improper design or characterization of anticipated ground motions may result in the failure of bridge [3]. Friction type of base isolators have also been found to be very effective as they incorporate isolation and energy dissipation in one unit. However, the performance of pure-sliding isolator is quite sensitive to variations in frequency content and amplitude of input excitation, and results in large sliding and residual displacements, Yang [4].

To reduce residual displacements, friction-pendulum system (FPS) has been developed recently in which restoring mechanism is provided by gravity, Zayas [5]. In such a system, the sliding and re-centring mechanisms are integrated in one unit. However, peak bearing displacements were of the order of peak ground displacements for large input level earthquakes. The solution for controlling displacements for large input level earthquakes while maintaining good performance for low-to-moderate input level earthquakes are several, but mainly reduce to designing a system that is very stiff at low input shaking, softens with increasing input reaching a minimum for an earthquake corresponding to damage-control limit state, and then stiffens again at higher levels of input, Kelly, [6]. For frictional pendulum systems, this can be achieved by gradually increasing the curvature of the disc progressively with sliding displacement and increasing the surface roughness. A new mathematical model for the geometry, that is intended to achieve a progressive period shift with sliding displacements, known as Variable Frequency Pendulum Isolator, has also been proposed recently though experimental evaluation and demonstration of suitability of such devices for bridges is far less extensive, Pranesh [7].

The seismic isolation devices based on friction as means of energy dissipation are the most promising among the bearings that are recently being used. The bridge superstructure isolated by friction-based bearings slides under earthquake excitations. The system is activated only when the earthquake forces overcome the static value of friction. For operational loads less than the frictional force, the system acts as rigid connection transferring the total force to the substructure. Due to imperfections in the manufacturing or due to poor maintenance, the coefficient of actual friction may be larger than the value assumed in the design. This may lead to substantial increase in force transmitted to the supporting structure in non-seismic conditions. To overcome this deficiency, flat-surface sliding isolators can be mounted on LRB. However, presence of restoring force is essential to control large sliding displacements. Such systems have more flexibility in controlling the seismic response of bridges and are easier to design and manufacture. The details and response results of a sliding-friction isolator system mounted on flexible support are presented in this paper. The enhanced seismic performance of a typical bridge with the proposed isolation system has also been demonstrated in this paper for typical input ground motions.

SEISMIC ISOLATION SYSTEM

The dynamic response of bridges to earthquake ground motions is controlled by the inertia effects of the deck and the force-displacement and energy dissipation properties of the bearings. Since the focus of this paper is to demonstrate the effectiveness of the proposed isolation system, the bridge deck has been idealized as a rigid mass. The bridge deck is supported on a set of low-stiffness and high damping laminated rubber bearings having linear elastic properties and viscous type damping, and a set of flat sliding-friction isolators mounted on high-stiffness and low-damping laminated rubber bearings as shown in Figure 1. The flat steel block slider is rigidly connected to the deck. For operational loads, when the inertia forces are not enough to initiate sliding, the system behaves like rigid mass on LRB (Figure 2a). For moderate level of seismic input, the slider moves on the sliding surface that is made of two different materials. The material used for the inner part close to the centre of sliding surface is made of material like PTFE having low value of coefficient of friction in the range of 0.05 – 0.10. For low-amplitude sliding, the slider moves of low-friction material (Figure 2b) resulting in smaller force transmission to the supporting structure in the range of 5 to 10 percent of gravity load, the elastic design force usually recommended by codes. The low-stiffness LRB provide the restoring force mechanism and reduce residual displacements. The maximum amplitude of low-friction sliding is controlled by the size of low-friction material at sliding interface.

The effective coefficient of friction increases gradually with sliding displacement as the finite size slider is partly on PTFE and partly on material having coefficient of friction in the range of 0.15-0.30, like Teflon coated steel (Figure 2c). For large sliding displacements, the effective coefficient of friction reaches maximum value when the slider is on the material having higher coefficient of friction (Figure 2d). This provision provides high-energy dissipation at large sliding amplitudes and helps protect the deck from overturning by reducing the accelerations of the deck in extreme seismic event. However, higher forces are transmitted to the supporting system. These forces can be maintained to be lower than the ultimate capacity of the supporting structure by selecting appropriate material for the sliding surface. In this system, limited damage is expected without collapse in extreme seismic event.

In deriving the equations of motion, the normal pressure on the sliding surface in contact with the slider connected to bridge deck has been assumed to be uniform. This assumption results in linear variation of the effective coefficient of friction from lower value to higher value. The rate of variation is inversely proportional to the slider size, that is bigger is the slider size, slower is the rate of variation of effective coefficient of friction. In this paper, the coefficients of static and dynamic friction for both the materials on sliding interface have been assumed to remain constant during the motion though advanced time-dependent models for coefficient of friction based on sliding history are available in literature, Minsili [8]. This idealized single-degree-of-freedom system has been analysed for a single component of horizontal ground motion at a time and the variation of the ground motion between the supports has been neglected assuming smaller spans.

EQUATIONS OF MOTION

The equation of motion of the single-degree-of-freedom system for ground acceleration, $\ddot{u}_g(t)$ in non-sliding phase (Figure 2a), can be written in standard form in terms of deck displacement, u, Chopra [9]:

$$m\ddot{u} + (c_e + c_s)\dot{u} + (k_e + k_s)u = -m\ddot{u}_g \tag{1}$$

in which m is the total mass of the deck, k_e and c_e are the low- stiffness and high-damping coefficients of all laminated rubber bearings directly connected to the deck, and k_s and c_s are the high-stiffness and low-damping coefficients of the all laminated rubber bearings that are used to mount flat sliding surfaces. The natural period of vibration of the idealized bridge in non-sliding phase is

$$T_0 = 2\pi\sqrt{m/(k_e + k_s)} \tag{2}$$

and the energy dissipation in this phase is viscous type with damping ratio equal to

$$\zeta = (c_e + c_s) T_0 / 4\pi m \tag{3}$$

To estimate the frictional resistance, linear elastic analysis of the deck is performed using three-dimensional solid finite elements. The reactions obtained for different bearings are then used to divide the total gravity forces, $m g$, as sum of gravity forces on ordinary laminated rubber bearings, $m_e g$, and gravity forces on sliding surfaces, $m_s g$. This leads to $m = m_e + m_s$. The frictional resistance offered by the sliding surface is computed as

$$f_s = \mu m_s g \tag{4}$$

in which μ is the effective coefficient of friction and depends on the slider displacement, u_s, the size of the slider, d_s, and low-friction sliding surface dimensions, b_s (Figure 1). The sliding is activated only when the force transmitted due to earthquake excitation to the high-stiffness low-damping laminated rubber bearings supporting the sliding surfaces overcomes static value of friction, that is:

$$\left| \sqrt{(k_s u)^2 + (c_s \dot{u})^2} \right| \geq f_s \tag{5}$$

Once set in motion, the sliding bearings develop a lateral force equal to the mobilised frictional force. The restoring force in sliding phase is maintained by low-stiffness ordinary laminated rubber bearings. Seismic isolation is achieved by increasing the natural period of the structure to T_s and that is controlled by the selection of low-stiffness laminated rubber bearings used to provide restoring force, that is:

$$T_s = 2\pi\sqrt{m/k_e} \tag{6}$$

During the sliding phase, the viscous damping mechanism due to high-damping properties of ordinary laminated rubber bearings is maintained though the energy dissipation capacity of low-damping laminated rubber bearings is disabled. However, this reduction in energy dissipation capacity is more than compensated by significantly higher energy dissipation capacity of frictional forces between the sliding interfaces. The equation of motion in the sliding phase can be written as [9]:

$$m\ddot{u} + c_e \dot{u} + k_e u = -m\ddot{u}_g - f_s \operatorname{sgn}(\dot{u}) \tag{7}$$

where direction of frictional forces opposing the motion is defined through Signum function. In this equation, the frictional forces, f_s, is given by Equation 4. However, the effective coefficient of friction μ depends on the amplitude of sliding, slider size and maximum low-friction sliding surface dimensions. For low amplitude of sliding displacements (Figure 2b), that is $u_s \leq (b_s - d_s)$, the effective coefficient of friction μ is equal to μ_l, in the range of 0.05 to 0.10. For moderate amplitude of sliding, that is $(b_s - d_s) \leq u_s \leq (b_s + d_s)$, the slider is partly on surface with low coefficient of friction, μ_l, and partly on the surface with high coefficient of friction, μ_h (Figure 2c). In this case, for uniform distribution of normal pressure on the slider face, the effective coefficient of friction can be shown to vary linearly as a function of sliding displacement given by the following equation:

$$\mu = \mu_l + (\mu_h - \mu_l)\left[\frac{u_s - (b_s - d_s)}{2d_s}\right] \tag{8}$$

For high amplitude of sliding displacements (Figure 2d), that is $u_s \geq (b_s + d_s)$, the effective coefficient of friction μ is equal to μ_h, in the range of 0.15 to 0.30. Higher values of the coefficient of friction may also be used by changing the sliding surface material. The force transmitted to the supporting system, however, will be much higher for large input level motions.

NUMERICAL SOLUTION PROCEDURE

The seismic response of idealized bridge system is obtained by direct time integration of the equation of motion using Newmark's linear acceleration scheme with γ = 1/2, β =1/6 [9]. The values obtained for displacements, velocities and accelerations at the end of each time step are used as the initial values at the beginning of the next time step. Since the system moves from non-sliding phase to sliding phase, it essential to locate the change of phase precisely. In the integration scheme, change in the direction of sliding velocity has been used to identify the change of phase. An adaptive time-step reduction procedure has been used in which the time step is repeatedly halved till the time for zero velocity is located within a time-step. The effective coefficient of friction varies with the motion of the slider in transition phase, and therefore, an iterative technique has been used within each time-step to satisfy the equilibrium requirements within prescribed tolerances of unbalanced forces at the end of time step.

The response time histories and maximum values of deck displacement, deck acceleration, slider movement, permanent or recoverable bearing deformations, and forces transmitted to supporting system are directly obtained by time integration technique. In addition to the above response results, the cumulative energy dissipated through viscous-type damping in non-sliding phase from time t_1 to t_2 is evaluated using the following equation:

$$E_d = \int_{t_1}^{t_2} (c_e + c_s)\dot{u}^2 \, dt \tag{9}$$

which is derived using energy formulation for equation (4). In sliding phase from time t_2 to t_3 the energy dissipated through viscous-type damping of ordinary laminated rubber bearings and the energy dissipation by frictional forces between the sliding interfaces is computed using the following equation:

$$E_d = \int_{t_2}^{t_3} c_e \, \dot{u}^2 \, dt + \left| \int_{t_2}^{t_3} f_s \, \dot{u}_s \, dt \right| \tag{10}$$

which is derived using energy formulation for equation (7). In the time integration scheme, the correctness of the solution is also ensured by satisfying the energy balance equation.

EXAMPLE BRIDGE AND GROUND MOTIONS

To demonstrate the effectiveness of proposed isolation system, the dimensional details of an existing bridge structure have been used. The bridge consists of a continuous solid deck slab having 3 equal spans of 14 m each. The bridge deck is supported on 30 identical ordinary laminated rubber bearings with five bearings on each side abutments and 10 bearings on both middle piers. The total effective mass, m, of the bridge deck with superimposed dead loads is 803250 kg, and lateral stiffness of each square bearing, k_b is 2500 kN/m. For the existing bridge which uses only laminated rubber bearing, equation (1) has been used to estimate the dynamic response with values of $k_e + k_s = 30k_b$ and $c_e + c_s = 30c_b$. The fundamental time period of vibration is 0.65 seconds, and the value of c_b is evaluated by setting the value of equivalent damping ratio ζ in equation (3) equal to 0.05.

In order to analytically demonstrate the effectiveness of the proposed system, the existing laminated rubber bearing system is replaced by the combination of low-stiffness, high damping laminated rubber bearing system by setting $k_e = 10 k_b$ and $c_e = 20 c_b$, and high-stiffness low damping laminated rubber bearings with sliding surface by setting $k_s = 20 k_b$ and $c_s = 10 c_b$. The values selected are achievable with available material and the permitted size of bearings. In non-seismic conditions under operations loads, the performance of proposed system will be identical to the existing system with the selected parameters. The existing piers and abutments have been designed using working stress method by taking six percent of gravity forces as equivalent horizontal seismic forces. The ultimate horizontal force carrying capacity of the piers and abutments is approximately sixteen percent of gravity forces. Therefore, in selecting the parameters for the proposed isolation system, the lowest value of coefficient of friction, μ_l, has been taken as 0.05 (steel slider on PTFE) and the highest value for the coefficient of friction, μ_h, is taken as 0.15 (steel slider on Teflon). For numerical results, the steel slider parameter d_s has been taken as 100 mm and low-friction material dimension parameter b_s has been taken as 150 mm. The values of parameters taken in numerical analysis are based on the constraints for the example bridge that is being evaluated for retrofitting.

The seismic performance of the existing system has been evaluated first by time history analysis using acceleration time histories of recorded ground motions. A large number of available time histories recorded for two recent earthquakes, Loma Prieta 1989 and Northridge 1994 were considered. These time histories have wide variation in frequency content and peak ground acceleration values due to different epicentral distances and local site conditions for the recording stations. For each time history, average pseudo-acceleration spectrum ordinate for 5 percent damping was evaluated at time period of 0.65 seconds, the fundamental time period of the idealized existing system. The ductility factor demand imposed by each ground motion in a elasto-plastic system having elastic time period of 0.65 seconds and yield force level equal to 20 percent gravity forces was computed. Two time histories imposing a ductility factor demand in the range of 3 to 5 corresponding to damage control limit state [1] have been selected for preliminary performance evaluation. The acceleration time histories of two selected ground motions, one from Loma Prieta earthquake and one from Northridge earthquake, their normalized power spectra showing frequency content, and their pseudo-acceleration response spectra for five percent damping are presented in Figure 3. The significant engineering parameters are also given in Table 1.

Table 1. Engineering parameters for ground motions used in performance evaluation

Earthquake	Loma Prieta, 1989	Northridge, 1994
Recording Station ID and Component *	47380 : North-South	24088 : North-South
Peak Ground Acceleration, g	0.35	0.43
Response Spectra Ordinate, g, ζ = 0.05	0.64	0.98
Ductility Factor Demand, f_y = 0.2mg, T = 0.65 sec	4.50	3.70

* Source: Engineering Strong Motion Data Center, CISN/TriNet, California

RESPONSE RESULTS

The response results in terms of total deck displacement and acceleration, permanent and recoverable bearing deformations, and forces transmitted to supporting system have been obtained utilizing the above-mentioned procedure. The response results have been obtained first for the existing bearing system, and then by replacing the existing bearing system with the proposed isolation system. The time histories of deck displacement, deck acceleration, force transmitted to piers and energy dissipated are shown in Figures 4 and 5 for two isolation systems for both selected ground motions. The maximum values of deck displacement, deck acceleration, force transmitted to piers, residual displacements and energy dissipated at the end of ground motion are summarised in Table 2 for both cases and for both acceleration time histories.

Table 2. Summary of response results

Earthquake	Loma Prieta, 1989		Northridge, 1994	
Performance Parameter	Existing System	Proposed System	Existing System	Proposed System
Maximum Deck Displacement, (mm)	77	81	112	132
Maximum Deck Velocity, (mm/sec)	784	516	1077	842
Maximum Deck Acceleration, g	0.79	0.50	1.13	0.70
Total Force Transmitted to Supports, (kN)	5733	2350	8361	3746
Residual Displacement, (mm)	0.00	3.14	0.00	3.28
Energy Dissipated per Unit Mass, $(m/sec)^2$	0.68	0.90	0.79	2.71

The results clearly demonstrate that the isolation system is extremely effective in reducing the transmitted forces at the expense of increased displacements. However, in the proposed system, even for intense ground motion, deck displacements are within limits due to permanent restraint offered by low-stiffness high-damping laminated rubber bearings. The energy dissipation in the proposed system is significantly higher compared to the existing system, and it helps reduce the maximum deck acceleration. The permanent deformations even in the intense ground motions are small as the system has a permanent restoring force mechanism. The transmitted-force displacement histories for both ground motions are presented in Figure 6 for the proposed system. It is evident that the energy dissipation capacity of the proposed system increases with increasing intensity of ground motion though at the expense of transmitting higher force to piers due to higher coefficient of friction.

DESIGN GUIDELINES

The proposed system provides maximum flexibility in achieving the desired performance parameters for all levels of seismic excitations. For non-seismic operational load condition, the combined stiffness and damping parameters need be selected in the identical procedure that is used for laminated rubber bearings in existing bridges. The properties of low-stiffness high-damping bearings define the magnitude of permanent restoring force. The selection of slider material and two sliding surface materials defines the two coefficients of friction used in the formulation. These coefficients of friction control the force transmitted to supporting systems in moderate and high intensity ground motions. When using the proposed system for retrofitting an existing bridge, the design force level and ultimate capacity of the supporting system will restrict the values of the coefficients of friction and the choice for sliding surface materials. The slider dimensions control the rate of change of coefficient of friction and the low-friction sliding surface dimensions control sliding displacements for serviceability limit state. The system can be used in most situations by adjusting the parameters of the proposed system using the above-mentioned guidelines.

In the proposed system, the coefficient of friction between the sliding interfaces has been assumed fixed, and the motion of the slider from one surface to other has been assumed to be smooth. Experimental investigations and basic constitutive laws for typical sliding materials clearly demonstrate the complex friction-behaviour during both sliding and transition phases, and the behaviour may depend on response memory, Olsson [10]. Therefore, applications of proposed system in practice will require experimental verification because the effects of response memory and Stiction effects have been neglected in the initial phase of development.

CONCLUSIONS

The proposed isolation system uses the combination of low-stiffness high damping laminated rubber bearings and two-material flat sliding surface mounted on high-stiffness low-damping laminated rubber bearings. The proposed system is simple to manufacture and easy to implement in existing or new bridges. The designer has maximum flexibility in the selection of parameters to control the response for non-seismic operational loads, for moderate intensity ground motions and for high intensity ground motions. The system has the capacity to dissipate large amount of energy while maintaining a pre-defined restoring force. It has been demonstrated in this paper that the proposed system can be effectively used to enhance the seismic performance of bridges to desired level for wide range of frequency contents and intensity levels of expected ground motions. Experimental verification for the values of effective coefficient of friction used in the design of such systems is however recommended for practical applications.

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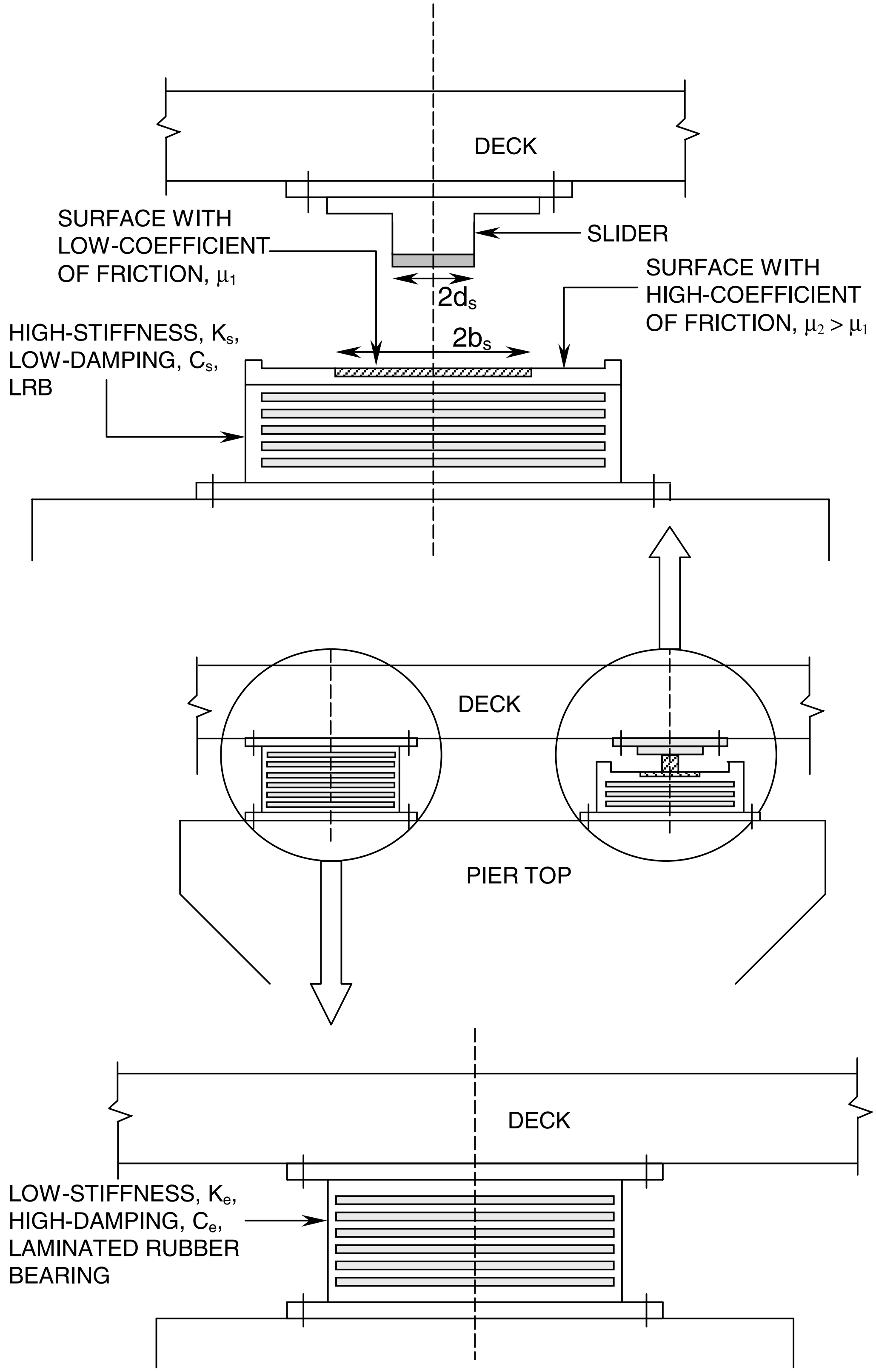
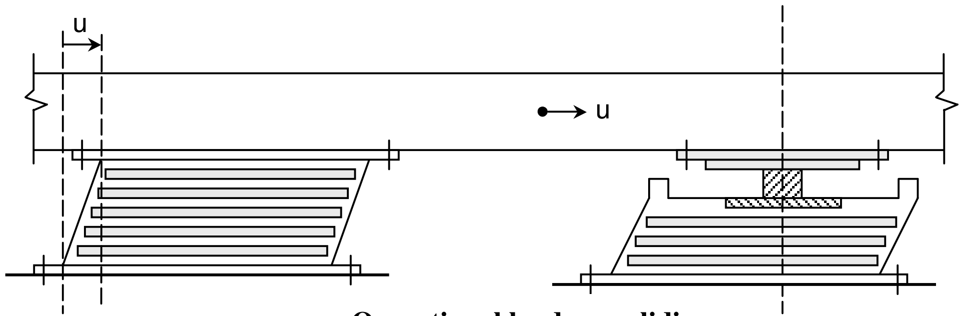
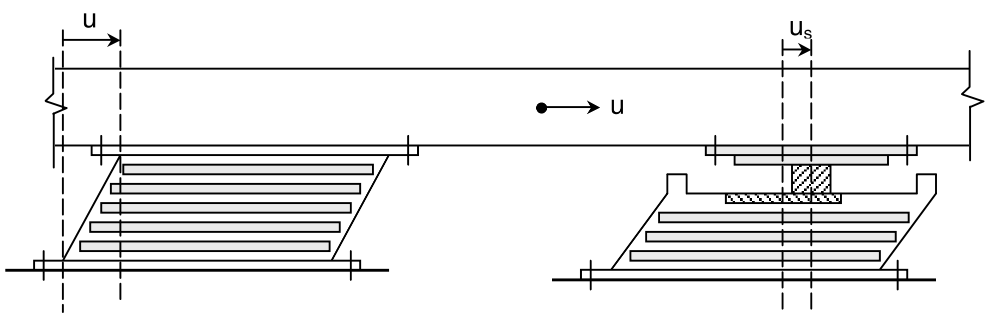


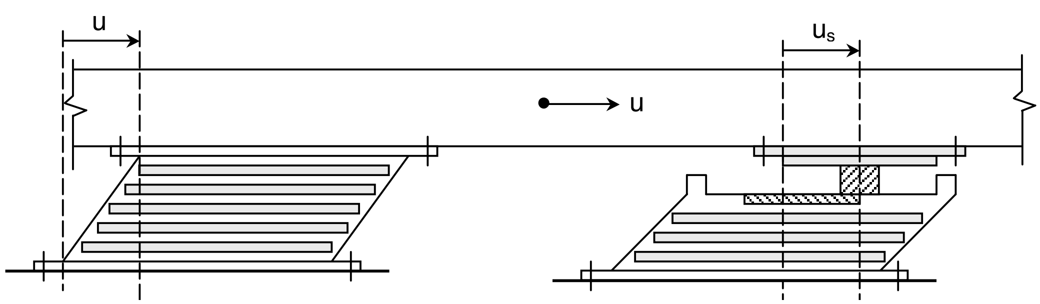
Figure 1. Proposed isolation system: Two material sliding surface mounted on high-stiffness, low-damping laminated rubber bearing in combination with low-stiffness, high-damping laminated rubber bearing.



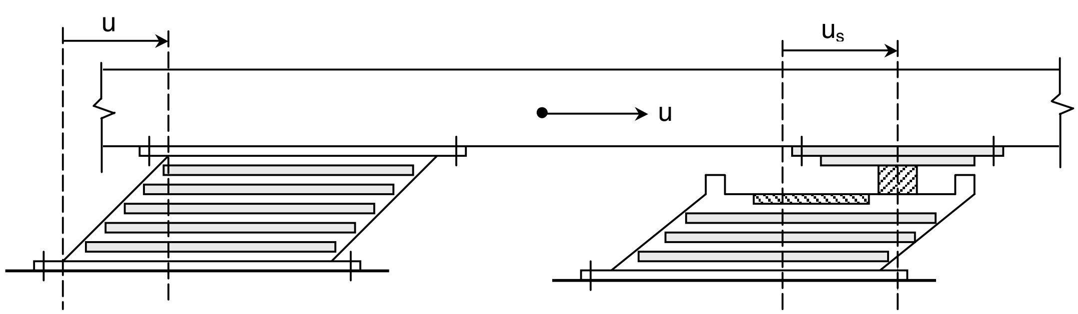
a. Operational loads: no sliding



b. Low input: low amplitude sliding on low-friction surface



c. Moderate seismic input: moderate amplitude sliding on variable-friction surface



d. High seismic input: high amplitude sliding on high-friction surface

Figure 2. Deformations in proposed isolation system for different input levels.

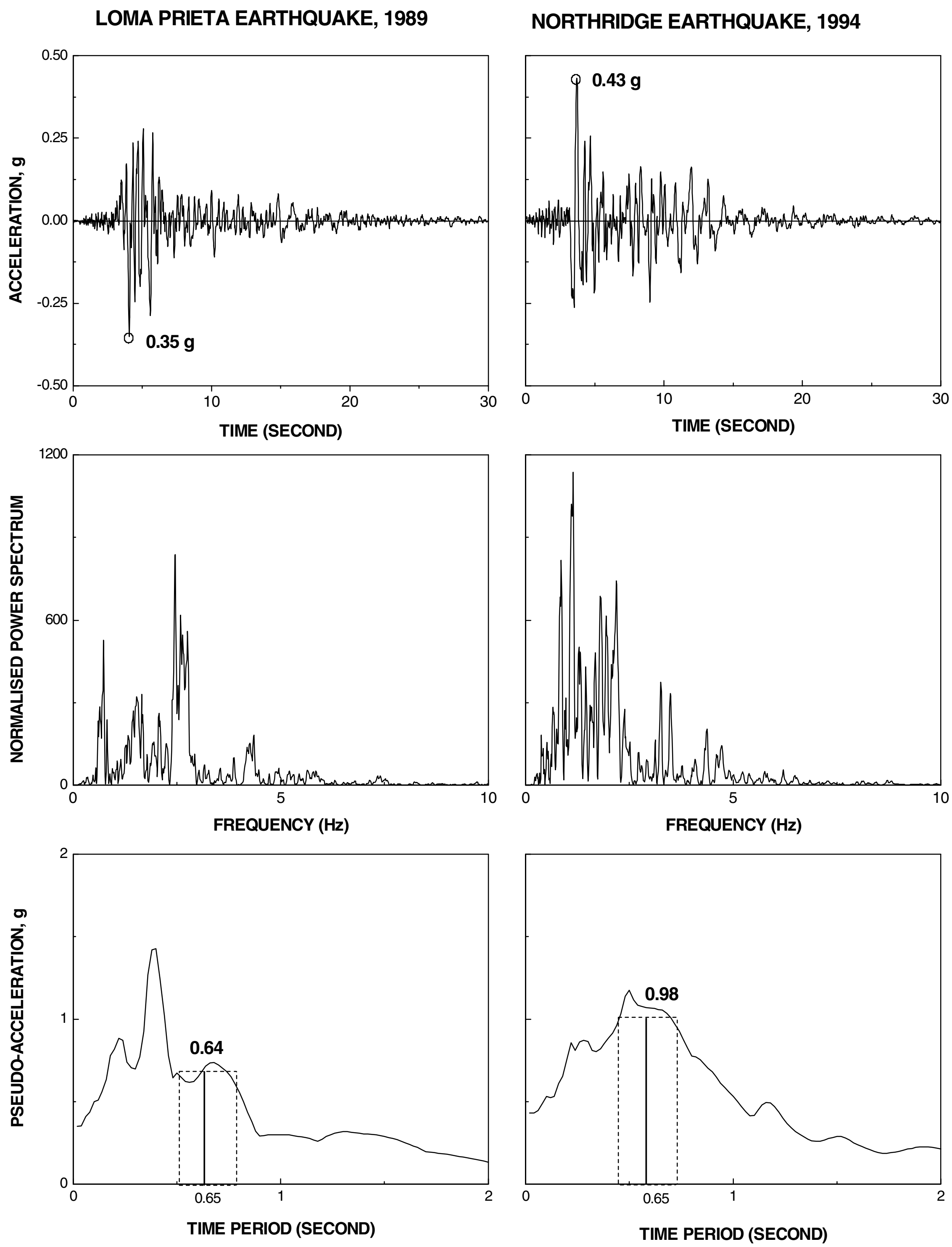


Figure 3. Acceleration time histories, normalized power spectra, and pseudo-acceleration response spectra for selected ground motions.

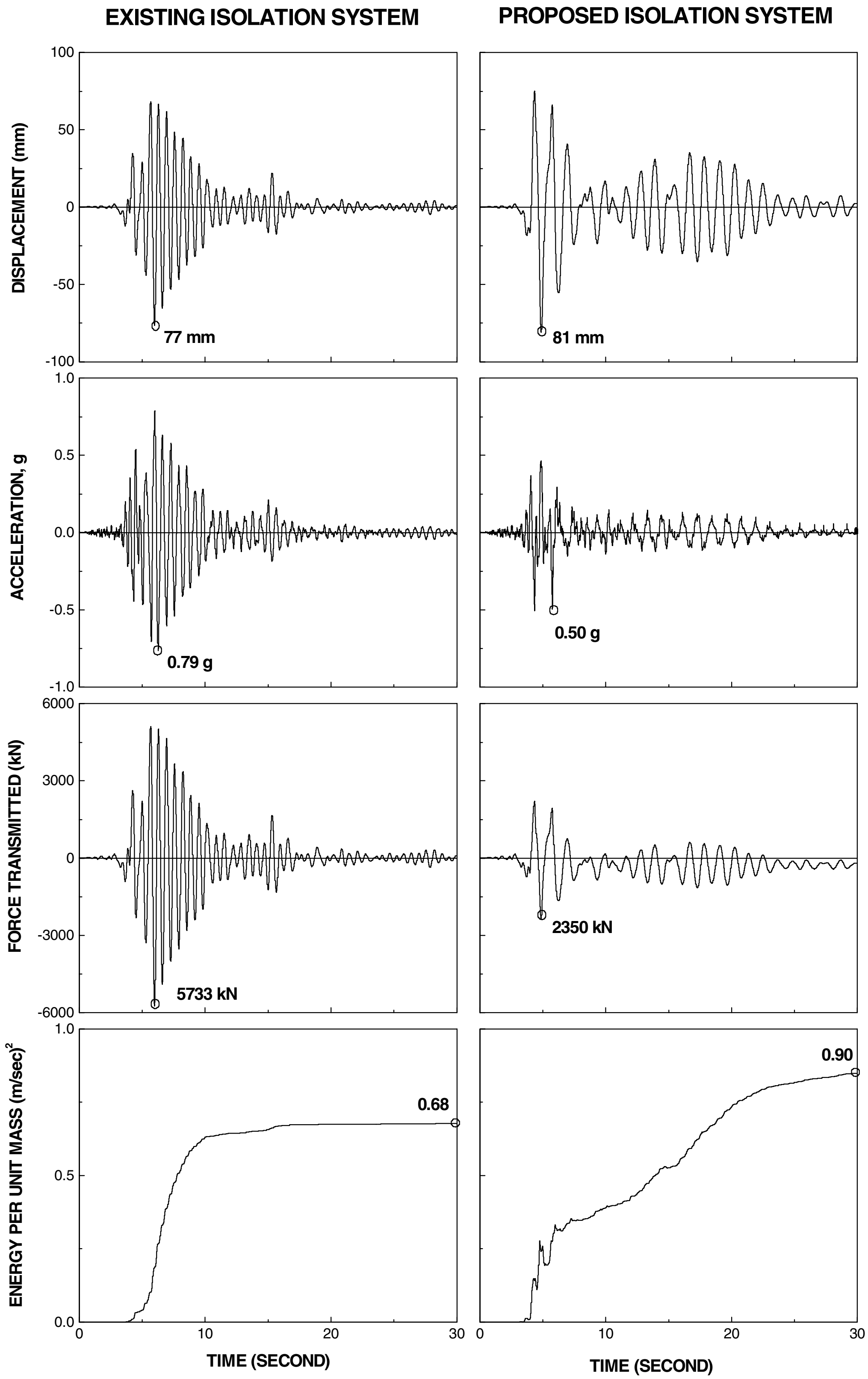


Figure 4. Comparison of performance parameters for recorded ground motion of Loma Prieta Earthquake, 1989.

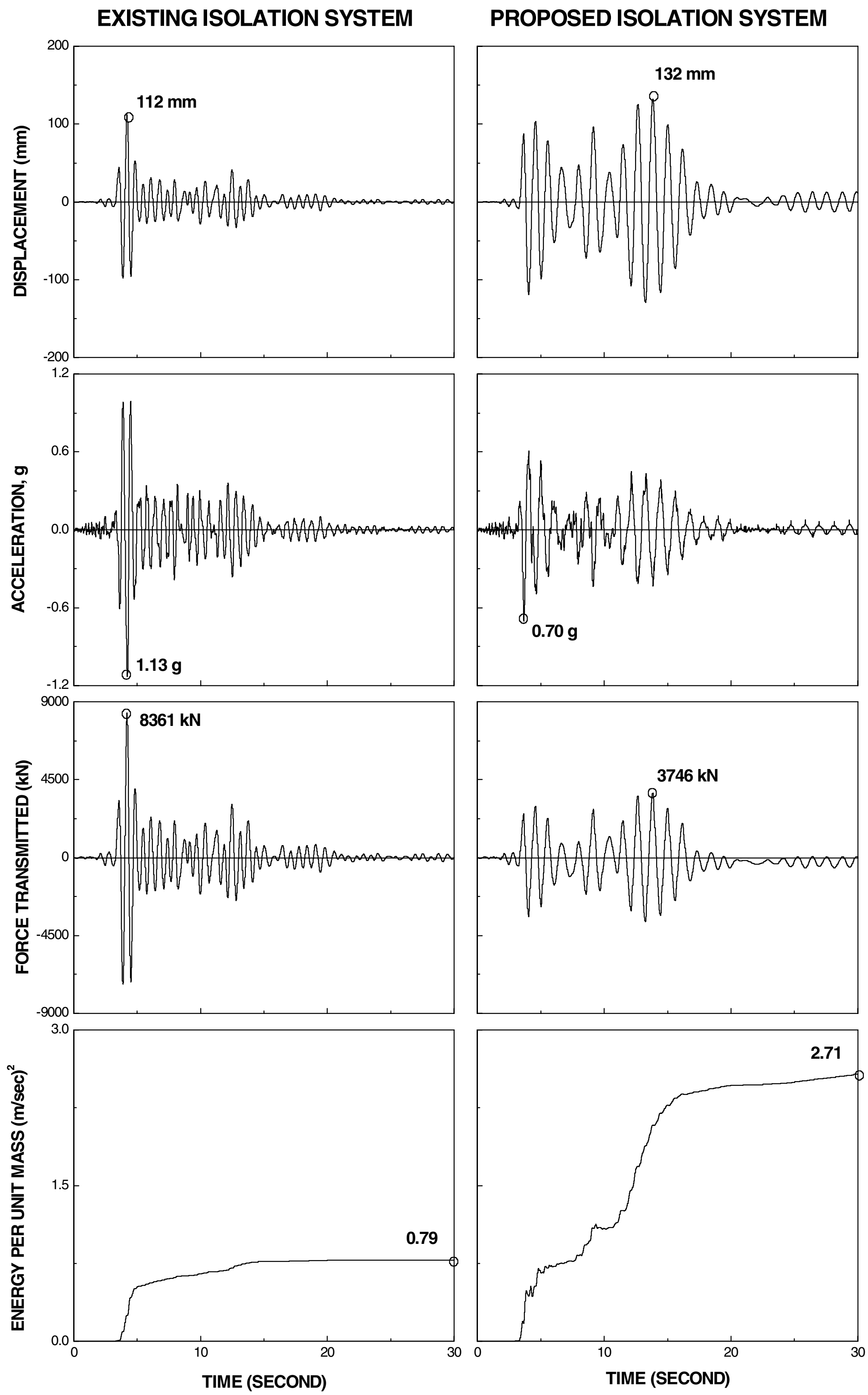


Figure 5. Comparison of performance parameters for recorded ground motion of Northridge Earthquake, 1994.

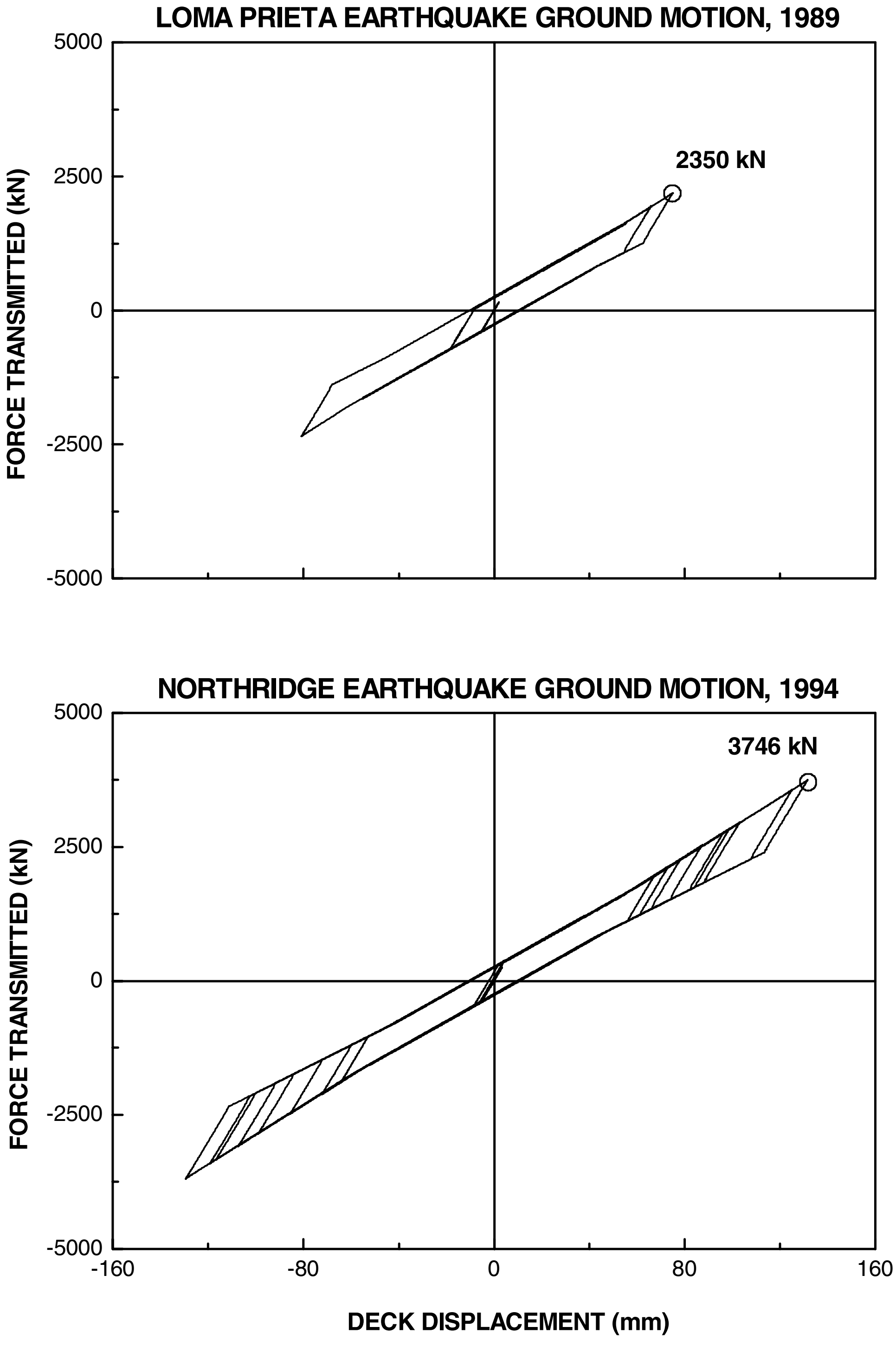


Figure 6. Total force transmitted to supports with respect to deck displacement.