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Author(s)	ZHIPING GAN; TOSHIRO HAYASHIKAWA; TAKASHI MATSUMOTO; XINGWEN HE
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Seismic Response of Curved Grillage Girder Viaducts with Base Isolation System In Cold Region

Zhiping Gan [1]¯, Toshiro HAYASHIKAWA[2], Takashi MATSUMOTO[2]

and Xingwen HE[2]

[1]*Graduate School of Engineering, Hokkaido University, Japan*
[2] *Faculty of Engineering, Hokkaido University, Japan*

ABSTRACT

Base isolation is a quite sensible structural control strategic design in reducing the response of a structural system induced by strong ground motions. In the present study, the overall three-dimensional non-linear bridge response is examined in detail under the action of near-fault earthquake ground motions to evaluate the seismic performance of curved grillage girder viaducts equipped with base isolation system when it is used in severe cold environment. Various lead-rubber bearing (LRB) isolation systems are systematically compared and discussed. And heavy snow load in extreme condition is taken into account.

Keywords: Seismic response; Base isolation; Near fault ground motions; Lead rubber bearing; Cold region; Snow Load

1. INTRODUCTION

Highway viaducts are extremely important components in modern transportation networks. Unfortunately, such essential systems often become the victims of earthquakes. Society suffers a tremendous cost and inconvenience due to the collapse of a bridge. Even non-collapsed, the temporary lost of post-earthquake serviceability of important bridges may cause very costly disruption to vehicle traffic on major transportation arteries and is simply unacceptable.

Cold regions are part of the earth system characterized by the presence of snow and ice at least part of the year. In the cold region, snow loads provide the governing load requirements for the structural design in many northern climates or mountainous regions (Sadovský et al. 2011) . And in some particular areas, e.g., Hokkaido Ireland of Japan, both seismic and snow loads are active.

It is found that in areas with significant snow accumulation, the snow load has significant effects on the seismic response for viaduct construction.Therefore, seismic analysis is conducted to investigate the risk of viaducts in those regions considering combination loads, particularly the snow accumulation, aiming at assessment of long-term snow load for design of highway bridge structures equipped with base isolation system.

¯ Corresponding author: Email: zpgan1024@gmail.com

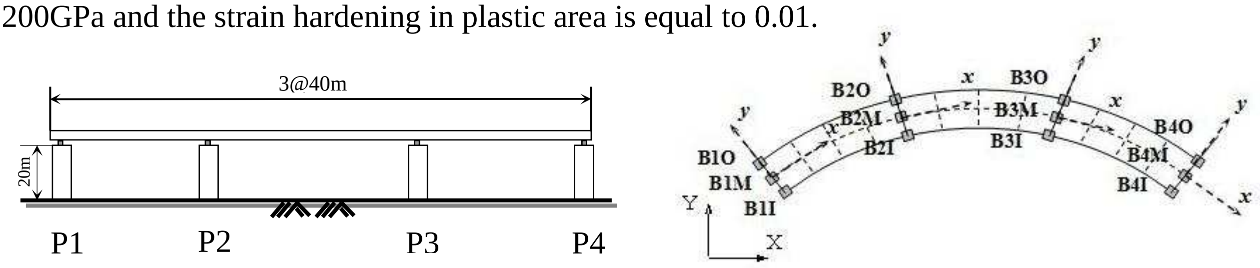
2. ANALYTICAL MODEL OF VIADUCT

The curved grillage girder viaduct considered in this analysis is a three-span continuous bridge, as shown in **Fig.1**. The overall length of 120m is divided in three equal spans of 40m, The bridge alignment is horizontally curved in a circular arc and the radius of curvature is 100m. And the height of four piers is 20m. The analytical model is shown in **Fig.2**. Superstructure and piers are modeled as beam-column elements. Superstructure is divided into 62 elements and pier is divided into 5 elements.

2.1. Superstructure and substructure

The bridge superstructure consists of a reinforced concrete deck slab that rests on three I-shape steel girders, equally spaced at an interval of 2.1m. The girders are interconnected by end-span diaphragms as intermediate diaphragms at uniform spacing of 10m. And the total weight of superstructure is 8.82MN.

In the presented study the viaduct is supported by four steel box section piers, having the same height of 20m. The width of box section is 2.4m, while the thickness is 0.05m. Characterization of the non-linear pier structural is based on the fiber flexural element modeling. The element is divided in 5 longitudinal parts, which, as well are subdivided in 12 transverse divisions. The stress-strain behavior is described by a bilinear model. The yield stress is 235.4MPa, the modulus of elasticity is 200GPa and the strain hardening in plastic area is equal to 0.01.



(a) Side view of the viaduct

(b) Plain view of the viaduct

Fig.1: Three-span Continuous Bridge Viaduct

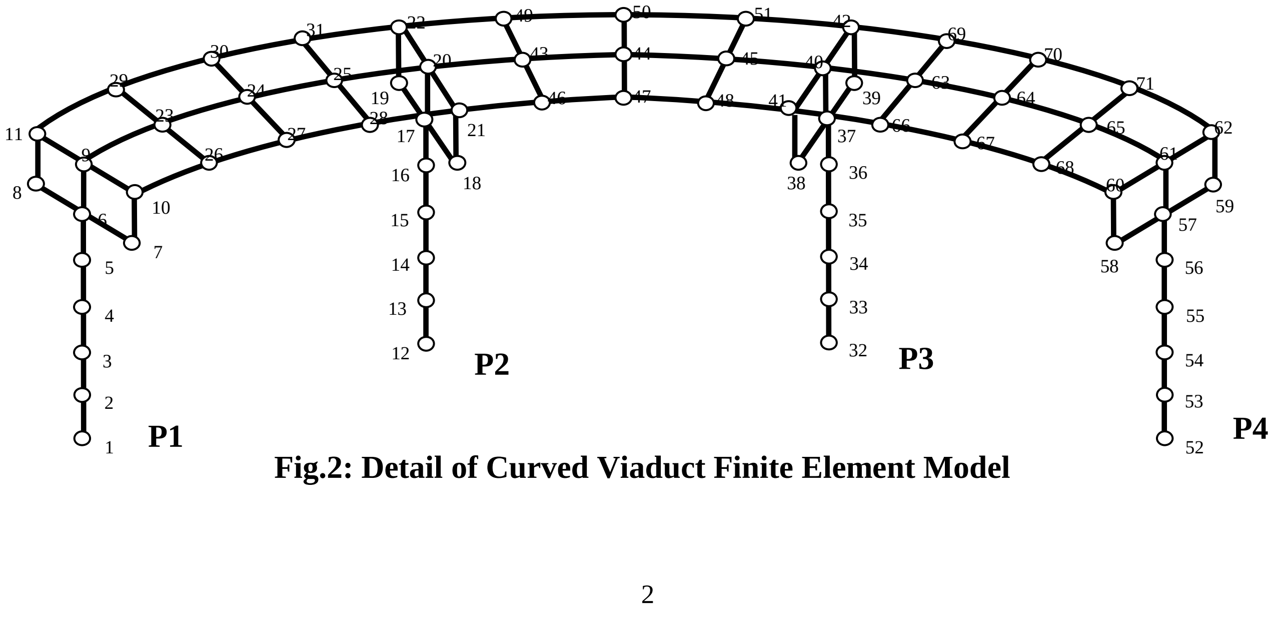


Fig.2: Detail of Curved Viaduct Finite Element Model

2.2. Bearing supports

As shown in **Fig.3**, the rubber-based bearing isolation system consists of layers of rubber and steel, with the rubber being arranged with steel plates one by one for horizontal flexibility and vertical stiffness. LRB consists of a lead-plug insert which provides its characteristic hysteretic energy-dissipation effect. The material lead could provide large initial stiffness and after yielding it has good anti-fatigue performance. Under normal conditions, LRB bearings behave like regular bearings. However, in the event of a strong earthquake, with the utilization of this base-isolation system, the superstructure of a bridge is decoupled from its substructure, and the response of the superstructure to the dynamic seismic loading is altered favorably and the seismic dynamic energy transferred to the superstructure is reduced (Rinna Tanaka et al. 2010). Thus seismic inertial loads are reduced and the seismic damage the structure acquires is drastically reduced.

The force-displacement relationship of LRB is trilinear hysteretic (Hwang JS et al. 2002), as shown in **Fig.4**. *K1* is initial stiffness and *K2* is yield stiffness. Considering the possibility of large deformation caused by drastic seismic response, *K3* is introduced to represent the strain hardening at a high shear strain. *F1* is yield force and *F2* is design force. Three bearings systems are discussed in the present study, in which all fix support cases are added as comparison to evaluate the base isolation performance of LRB bearings. And the effect of snow load is also taken into account. The bearing configuration is summarized in **Table 1**.

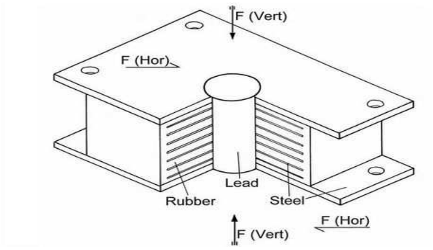


Fig.3: LRB device

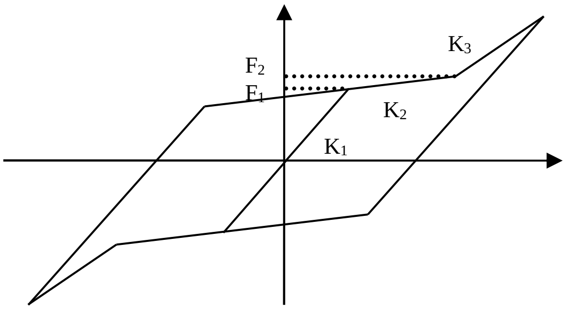


Fig.4: Analytical Model of LRB

Table 1: Bearing configuration

Case	Bearing	Bearing type	Snow load
1	LRB-S-350	LRB	null
2	LRB-S-350HS	LRB	heavy
3	LRB-S-500	LRB	null
4	LRB-S-500HS	LRR	heavy
5	ALL-FIX	fix support	null
6	ALL-FIX HS	fix support	heavy

3. NUMERICAL RESULTS

The analysis on the highway viaduct model is conducted using an analytical method based on the elasto-plastic finite displacement dynamic response analysis. The tangent stiffness matrix, considering both geometric and material nonlinearities is adopted in this study, being the cross sectional properties of the nonlinear elements prescribed by using fiber elements. The implicit time integration Newmark scheme is formulated and used to directly calculate the responses, while the Newton-Raphson iteration method is used to achieve the acceptable accuracy in the response calculations. The damping of the structure is supposed a Rayleigh's type, assuming a damping coefficient of the first two natural modes of 2%.

Structural responses are examined for all selected types of bearings under the action of earthquake wave. The input motion used for response analysis are acceleration-time history obtained from the Hyogoken-Nanbu earthquake. Dynamic response analysis of substructure has been focused on a central pier(P3) because central piers support double weight and consequently, the most severe seismic response is found in this structural member (Ruiz Julian FD et al. 2004). The extreme heavy snow load which has a density of 3.5kN/m^2 is considered in the present study, as suggested (Hayashikawa T 2000).

3.1. Natural vibration analysis

Calculation of natural vibration characteristics of highway viaducts is crucial for prediction of their structural behaviour during strong earthquakes. According to the recommendations of Specifications of Highway Bridges, the fundamental natural period of the isolated viaducts with LRB systems are selected to be long enough. The characteristics of the LRB bearings are selected to obtain fundamental periods of 1.435s and 1.273s, respectively.

Natural vibration analysis of the model of viaduct supported on six different cases is carried out, as shown in **Table 2**. According to the calculation result of natural period program, the increment of weight (i.e. the increment of mass) causes the increment of natural period, as predicted. Thus, this is the first unfavorable phenomena caused by the snow load.

Table 2: Fundamental Natural Frequencies and Periods

Case	Bearing	ω [rad/sec]	T[sec]	ratio to T of fix
1	LRB-S-350	4.379	1.435	1.68
2	LRB-S-350HS	4.025	1.561	1.82
3	LRB-S-500	4.936	1.273	1.49
4	LRB-S-500HS	4.537	1.385	1.62
5	ALL-FIX	7.340	0.856	1
6	ALL-FIX HS	6.785	0.926	1.08

3.2. Shear force-displacement response at bearing

Shear Force-Displacement relationship at bearing is an important response parameter for seismic analysis. To limit peak shear force, the bending moment transferred to the base of piers is under control; to limit the maximum bearing displacement, deck displacement is limited and collision between deck and abutment is avoided (Mendez Galindo et al. 2010). Shear force-displacement response at bearing of different cases are shown in **Fig.5**.

Comparing LRB cases with fix support cases, it is clear that LRB evidently reduce inertial forces acting on bridge piers and this is just the function of the base isolation system. The snow load effect in this section is clear as well, with the increment of weight, both peak shear force and maximum bearing displacement increase significantly. By the comparison of case 1 (null snow load case) and case 2 (heavy snow load case), it could be found that a suitable LRB device in null snow load condition could reach its safety limitation because the drastic increment of maximum displacement which tends to exceed the ultimate displacement value suggested by the device manufacturer.

3.3. Bending moment-curvature response

In most cases, structural damage due to earthquakes can be attributed to the plastic hinges formed at piers of the bridge, which are subjected to earthquake sustain maximum loading. The bending moment at the base of piers is considered to be a good measure to decide the damage level. Bending Moment-Curvature Response at the base of piers are shown in **Fig.6**.

The yield moment of the pier is 84.8MN, and therefore inelastic deformation occurs in all the cases. However, LRB bearings can substantially reduce the seismic forces on piers by comparison of LRB cases and fix support cases. And again, snow load obviously increase the damage level in all the cases. A proper designed base isolation system (case 1), could be damaged severely in heavy snow condition (case 2).

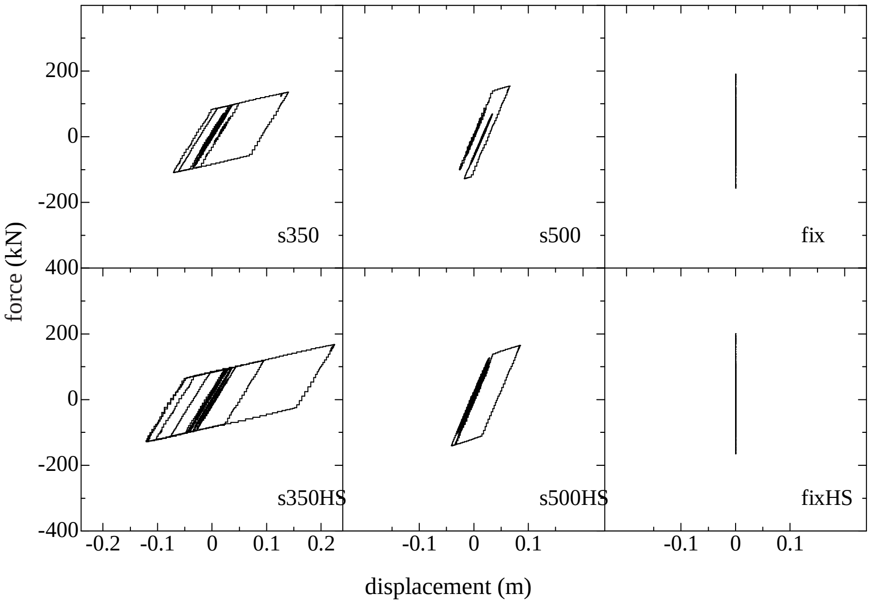


Fig.5: Shear Force-Displacement Response at Bearing

3.4. Energy-time history

During earthquake, input energy flows from the ground to structure and should be dissipated by structure vibration, damping mechanism and plastic deformation. Energy is used as an alternative response factor to evaluate response quantities like force or displacement to examine the seismic damage effect on bridge structures. The performance of the bearing systems is analyzed by comparing the energy-time histories, as shown in **Fig.7**.

The obtained results show that the amount of seismic energy inputted to the viaduct depends highly on the structural characteristics such as natural period and damping properties. LRB system with lower stiffness has more deformation capability, therefore could dissipate more strain energy. And in heavy snow condition, energy is dissipated significantly. This is because the snow load increases the bearing displacement and inelastic deformation of pier, as shown in above sections.

3.5. Displacement-time history at top of pier

Based on the experiences after the 1995 Kobe earthquake, a large number of bridge suffered flexural failure at their base did not collapse, but large residual displacements at the top of pier made the structures unusable, unsafe, and in some cases irreparable. According to the Specifications (JRA 2002), residual displacement at top of pier should be less than hundredth of the pier height. Displacement-time histories of different cases are shown in **Fig.8**.

In the null snow load condition, residual displacement which is caused by the residual curvature generated by inelastic deformation at the pier base and deformation of base isolator, is observed only in the fix support case (case 5). This result means the base isolation function works well in the null snow load condition. But, in the heavy snow condition, residual displacement is observed in all the cases. And the maximum displacement increases meanwhile. This is one more unfavorable effect of snow load.

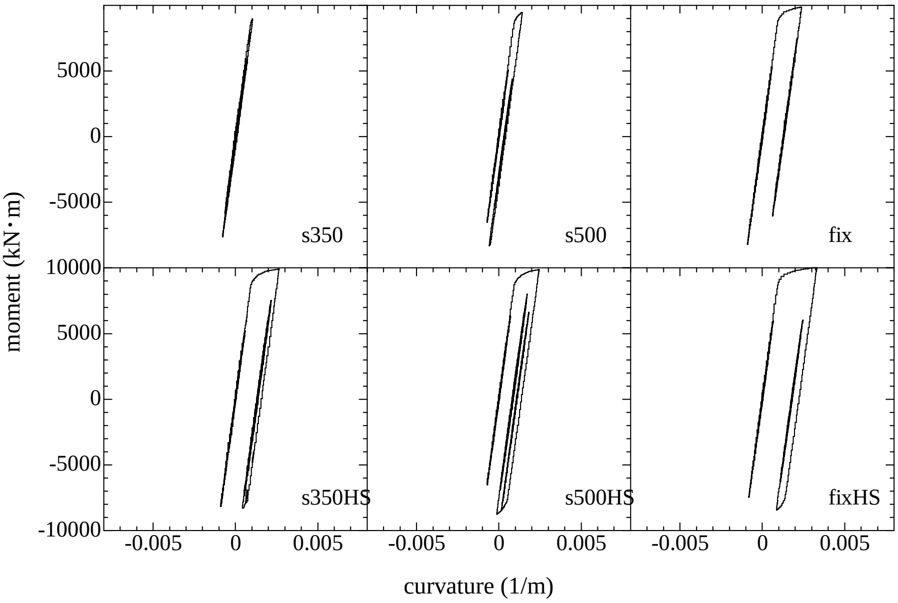


Fig.6: Bending Moment-Curvature Response

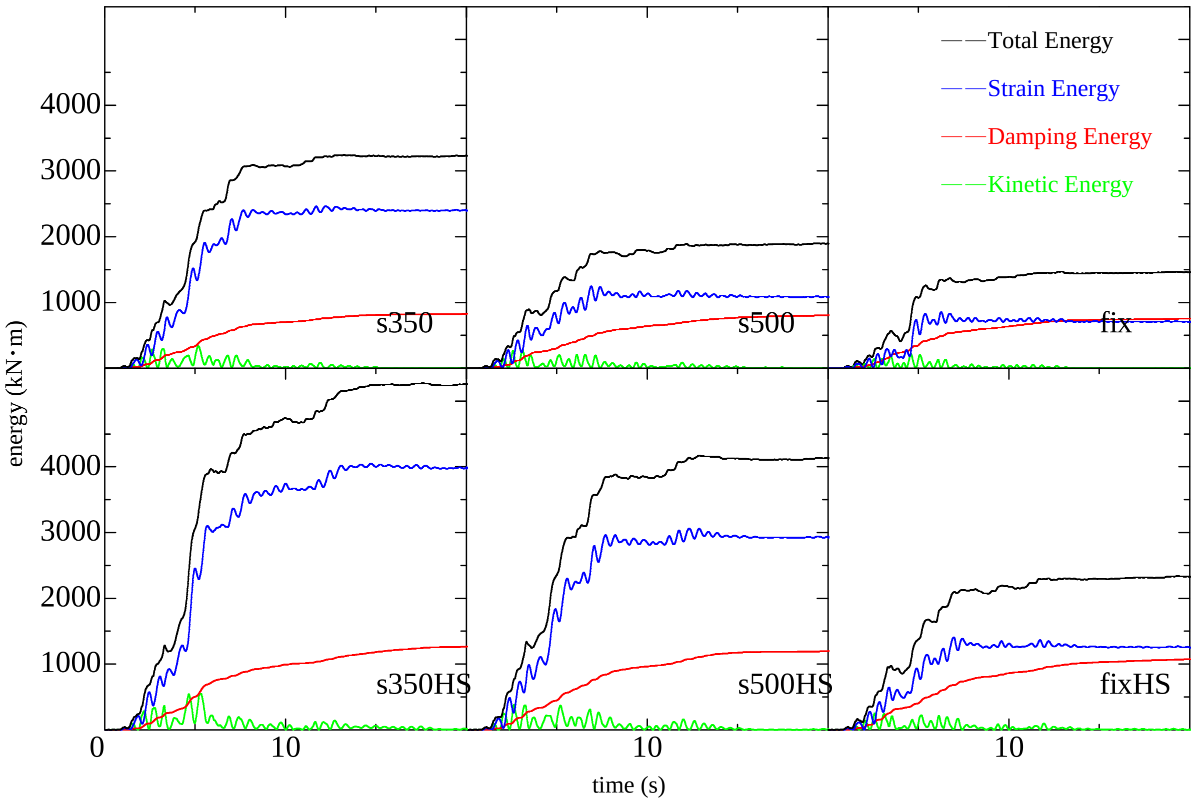


Fig.7: Energy-Time History

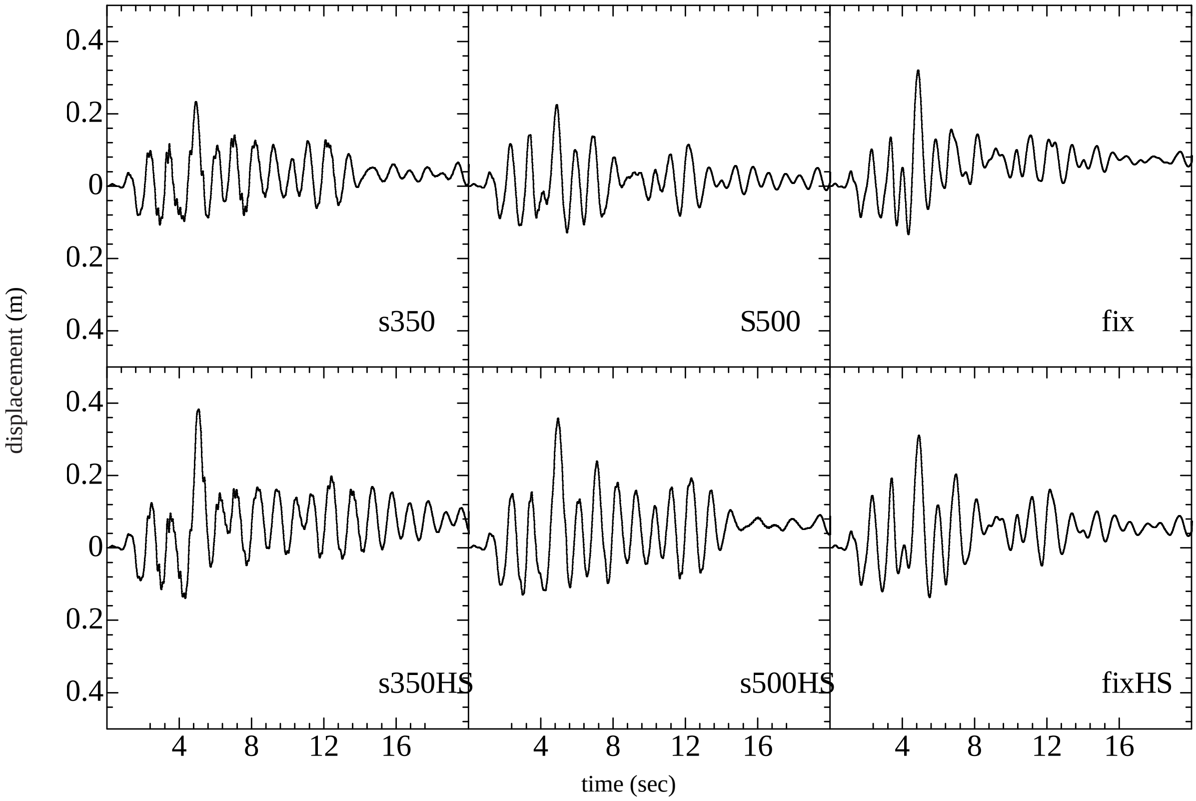


Fig.8: Displacement-Time History at Top of Pier

4. CONCLUSIONS

In the present study, nonlinear dynamic analysis of a finite element model of highway viaduct with various support configuration is carried out. Seismic responses are studied and compared to investigate the influence of snow load on the overall behaviour of the bridge supported on the different types of bearing supports. The following is a summary of conclusions based on the results discussed in each section:

(1) According to the mechanism of the LRB device, LRB device with smaller dimension usually has lower stiffness. LRB with low stiffness has better performance. Longer natural period and more bearing deformation make it dissipate more energy generated by earthquake ground motion. This is just the function of isolation system. But the problem is, the deformation capacity of a LRB device with smaller dimension is less as well, i.e. the product fails easily and encounters hardening effect easily. It is strongly suggested that a proper LRB device should be carefully chosen, satisfying not only performance but also safety.

(2) Snow load drastically weakens the base isolation function. It increases force, moment, displacement and deformation in all the cases. Snow load should be considered as a pure unfavorable factor in seismic analysis. It must be emphasized that, in the heavy snow condition a proper designed LRB device with relative smaller size and less deformation capacity could be destroyed by the over-limited deformation caused by snow load.

(3) Although the harm of snow load is so significant, a well planned snow plowing schedule could easily solve this problem. Under the winter season scheme of many cold regions, there are still some bridges left unplowed and inaccessible during the snow season, additional attention should be paid on theses bridges.

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