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A SIMPLIFIED METHOD FOR PRELIMINARY ASSESSMENT OF SEISMIC FORCES IN ISOLATED HIGHWAY BRIDGES WITH MASSIVE PIERS

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Abstract

Seismic isolation, using nonlinear isolators, is often used to lengthen the fundamental period of vibration and to reduce inertia forces of highway bridges. Nevertheless, engineers often use elastic equivalent seismic analysis methods to determine the displacements and internal forces. The simplified single-mode spectral analysis (SMSA) is a quick and simple analysis to be conducted for preliminary design or evaluation of seismically isolated bridges. However, SMSA neglects the effects of inertia in the substructure elements located under the isolators, which can lead to an underestimation of piers internal forces, particularly if their masses are important. In this paper, a new simplified approach is proposed for the seismic design and evaluation of isolated highway bridges with massive piers. A decoupled SMSA is proposed wherein massive piers are first analyzed as free standing cantilevers using their fundamental modes of vibration without the presence of the superstructure. The isolated superstructure is analysed separately as a rigid body supported by the isolators. The design seismic forces are computed from a Square Root of the Sum of the Square (SRSS) of the contributions from the piers and the superstructure. To validate the proposed simplified method, 11 highway bridges of different geometries, stiffnesses, and deck to pier mass ratios are modeled and analyzed in the longitudinal direction. The results of these analyses indicate that pier inertia forces must be taken into account when the mass of the piers reaches 10% to 15% of the mass of the superstructure. The proposed method is simple to implement and is shown to be accurate as compared to multimodal spectral analyses.

Keywords: highway bridges; seismic isolation design; massive piers; response spectrum analysis; simplified method

1. Introduction

Seismic isolation of highway bridges can be economical for the rehabilitation of existing bridges or construction of new bridges. Seismic isolation is used to lengthen the fundamental period of vibration to reduce inertia forces promoting rigid body motions and the control of structural deformations by increasing damping. Seismic analysis of isolated bridges is a highly non-linear problem. Nevertheless, engineers often use elastic equivalent static force methods to determine displacements and internal forces for this structural system. In the 2014 CAN/CSA-S6 Canadian Highway Bridge Design Code [1] it is permitted to use the single-mode spectral analysis (SMSA) for simple isolated bridge structures. The method is also used as a quick and simple analysis tool for preliminary design or seismic evaluation of more complex structures. However, SMSA neglects the effects of inertia forces in the substructure elements located under the isolators (mainly the piers), which can lead to an underestimation of piers internal forces, especially when their masses are important.

In this paper, a new simplified approach is developed for seismic design and evaluation of isolated highway bridges with massive piers. The presence of isolators has little effects on the piers natural frequency of vibration. Therefore, a Decoupled SMSA, labelled as DSMSA, is proposed wherein the massive piers are first analyzed using their fundamental mode of vibration without the presence of the superstructure. The resulting pier forces are then combined to the forces computed from SMSA using the Square-Root-of-Sum-of-the-Squares (SRSS) modal combination approach.

To validate the proposed simplified method, 11 highway bridges were modeled and analyzed in the longitudinal direction using seismic input motion from Vancouver, BC, Canada. The proposed method is shown to be more accurate than other simplified methods where a fraction of the pier's mass is added to the isolated deck, as proposed in the 2014 AASHTO Guide Specifications for Seismic Isolation Design (GSSID) [2]. It is also simpler to implement than the method where the bridge is represented by a two dynamic degrees-of-freedom (DOF) system [3].

2. Response Spectrum Analysis of Isolated Highway Bridges

With the rapid development of the structural analysis software, non-linear time-history analysis (NLTHA) becomes easier to perform but the method still remains complex because the engineer has to select and scale proper earthquake accelerograms (artificial, synthetics or real records) to fit the elastic design spectrum. This can lead to a large variability in the seismic analysis and different engineers may obtain different results for a given bridge structure. This is why response spectrum analysis is still preferred in consulting offices for most projects, except for special cases for which codes explicitly require that more complex analyses like NLTHA be conducted.

2.1 Single mode spectral analysis (SMSA) method

The single mode spectral analysis (SMSA) is an equivalent static analysis method that is used for the design of regular isolated bridges or for the preliminary design of more complex structures. The bridge is represented as a single-degree-of-freedom (SDOF) system where the deck is free to move above the isolators. The piers are considered massless. The stiffness of the piers (K_{pier}) can be taken into account by combining them with the stiffness of the isolators (K_{iso}). As shown in Fig 1, bridges with isolators exhibiting a bilinear horizontal force-displacement hysteresis are reproduced by an equivalent elastic system having an effective stiffness (K_{eff}), an effective period (T_{eff}) and an equivalent viscous damping ratio (β_{eff}). As specified in codes, design forces and displacements are obtained by reducing the calculated spectral acceleration (S_a) or displacement (S_d) by a damping reduction factor (B) that accounts for the equivalent damping ratio to obtain.

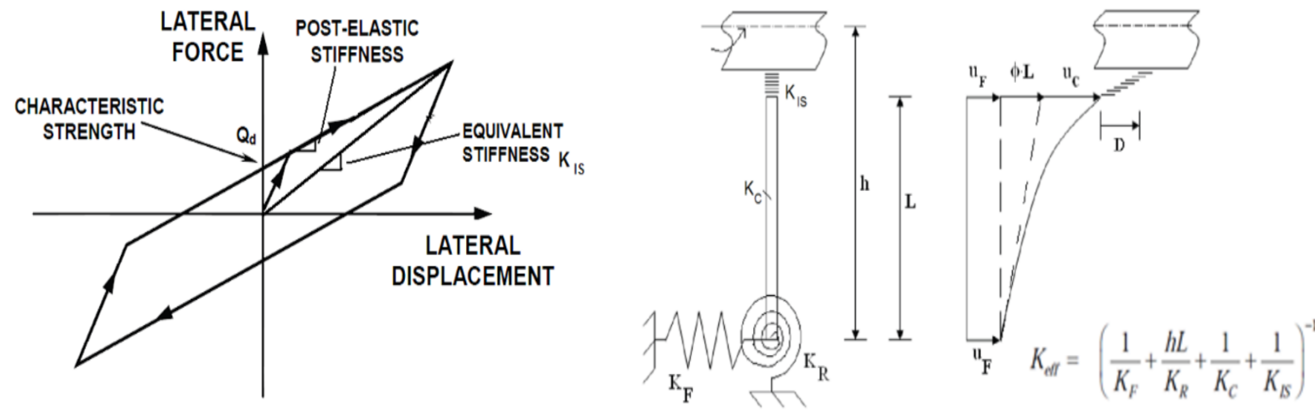

Fig.1 – Idealized Force-Displacement Relation of Typical Seismic Isolation (left) and Seismically Isolated Bridge with a Flexible Substructure (right) (source Constantinou et al., 2011 [5])

2.2 Others simplified analysis methods

In the AASHTO GSSID examples [2], an alternative to the SMSA is proposed to take into account the mass of the piers by adding a fraction (1/3) of the pier mass on the deck to increase shear forces. This procedure has been tested on the 11 bridges analysed in this paper. The method must be used with caution because the isolated period of the bridge is virtually elongated by the added pier mass. This longer period can lead to significant underestimation of the total horizontal seismic force when compared to that obtained from the original SMSA.

A two dynamic DOF model has been proposed by Wei and al. 2013 [3] to include the inertial effect of the pier. In this simplified method, the analysis is divided in two SDOF systems: the isolated superstructure and the participating mass of the substructure. The latter is assumed to include the pier cap and one third of the columns mass. The calculations can be easily performed using a spreadsheet. The method is iterative, as is the case for SMSA. The results are obtained using the SRSS modal combination of the two modal contributions. In [3], the procedure was tested for two bridges with ratios of the mass of the piers with respect to the mass of the deck equal to 16%. The maximum difference in the shear force compared to the one calculated with the multimodal spectral analysis (MMSA) was 9%. This was less than the difference observed (up to 47%) when using the original SMSA method.

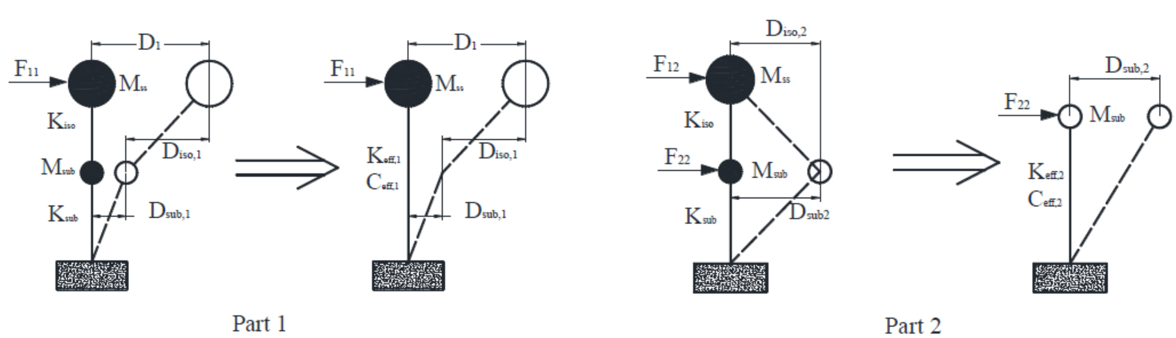

Fig.2 – SDOF system and deformed shapes for Parts 1 and 2 (Source Wei et al. 2013 [3])

2.2 Multimode spectral analysis (MMSA) method

The multimodal spectral analysis (MMSA) is an equivalent linear analysis that works with the same principles as for the SMSA discussed previously. However, it generally requires using a structural analysis software. The isolators are modeled with effective linear properties and equivalent viscous damping properties must be defined in the isolated modes of the structure. A hybrid design response spectrum is used in which the ordinates are reduced by the damping reduction factor B for the isolated modes, i.e. for periods longer than 0.8 times the effective fundamental period (T_{eff}) when using the Canadian bridge code [1].

2.3 Proposed decoupled single mode spectral analysis (DSMSA) method

In the decoupled single mode spectral analysis (DSMSA) method, two analyses are performed: 1) SMSA of the isolated superstructure, and 2) a standard multimodal spectral analysis of the seismic response of the piers alone. The results of the superstructure analysis and the pier analysis are then combined using the SRSS approach. Alternatively, the analysis of the piers can be performed by manual calculations by considering only their first vibration modes. Like the procedure proposed in [3], the DSMSA is based on the assumption that the isolators are enough flexible to let the piers vibrate freely.

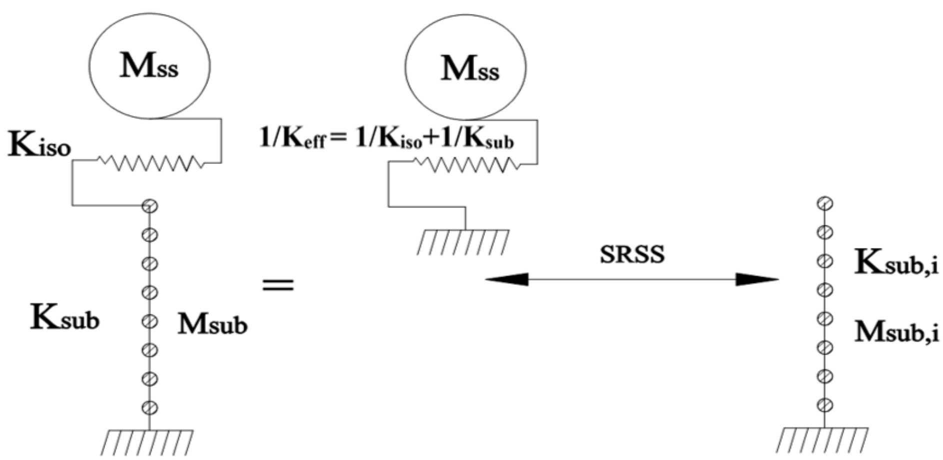

Fig.3 –Single DOF and Multime DOF systems in the DSMSA

3. Analysis of 11 bridges

Standard highway bridges were studied to determine when pier's mass must be accounted for in the seismic analysis and validate the proposed decoupled single mode spectral analysis (DSMSA) method. Analyses were conducted on 11 different bridges with standard structural systems including concrete slab on steel girders, concrete slab on pre-stressed concrete girders, and thick slab and concrete box girders. Table 1 shows the characteristics of bridges analyzed. The characteristics of the structures studied have been adapted from actual bridges built in Canada[1]. Bridges nos. 2 to 7 represent parametric variations of the same bridge to cover a larger range of cases. The ratios of the mass of the piers with respect to the mass of the deck vary from 7% to 86%.

Table 1 - Properties of the bridges studied

Bridge Nos.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
n spans	2	4	4	4	4	4	4	2	2	2	2
Deck	Box girder	Slab on girder	Slab on girder	Slab on girder	Slab on girder	Slab on girder	Slab on girder	Slab on girder	Slab on girder	Slab	Slab on girder
Material	Reinforced concrete	Steel	Steel	Steel	Steel	Steel	Steel	Steel	Prestressed concrete	Prestressed concrete	Steel
H*(m)	7.90	28.70	28.70	17.00	17.00	8.00	8.00	10.00	7.06	8.50	4.55
W_{deck} (kN)	22654	39077	39077	39077	39077	39077	39077	17110	9834	10573	5131
W_{pier} (kN)	3756	33737	18786	17892	10512	5507	4206	4567	1020	751	972
T_{bridge} (s) Non-isolated	2.07	2.19	2.16	1.38	1.38	0.71	0.72	0.70	0.97	1.44	0.37
W_{pier}/W_{deck}	17%	86%	48%	46%	27%	14%	11%	27%	10%	7%	18%

*H = height between fixity (footing) and the bottom of the pier cap

Lead Rubber Bearings (LRB) were chosen as isolators for all the bridges analysed. This type of isolator was selected because it is suitable for all structures and is less expensive compared to friction pendulum systems that are used for high axial load applications. The dimensions and the characteristics of the isolators were computed to limit the equivalent viscous damping ratio to 30% for which a damping reduction factor B = 1.7 is specified in CAN/CSA-S6-14 code [1]. If a design engineer wishes to select isolators having higher damping, the code requires that advanced dynamic analysis or non-linear time-history analysis (NLTHA) be performed.

3.1 Single mode spectral analysis (SMSA)

Single mode spectral analyses have been conducted on bridges using a spreadsheet design tool. The procedure is simple and includes the flexibility of the substructure that is combined with the isolator to compute the effective stiffness. The calculation is iterative because the dynamic properties of the LRB (K_{iso}, β_{eff}) are function of the displacement. Hence, the assumed displacement is changed until the computed displacement is the same as the one assumed. Table 2 shows the results of SMSA for the 11 bridges.

[1] Cima+ Consulting Engineers (Montreal, QC Canada), 2015, Personnal Communication.

Table 2 – Single mode spectral analysis (SMSA) according to CAN/CSA-16-14 [1]

Properties	**Bridge No**										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
K_{sub} (kN/mm)	45,8	40,3	40,3	95,3	95,3	348,8	348,8	166,7	45,5	21,3	166,7
K_{iso} (kN/mm)	11,9	28,2	28,2	21,2	21,2	18,4	18,4	7,8	4,6	5,1	2,4
K_{eff} (kN/mm)	9,4	16,6	16,6	17,3	17,3	17,5	17,5	7,5	4,2	4,1	2,3
T_{eff} (s)	3,11	3,08	3,08	3,01	3,01	3,00	3,00	3,04	3,07	3,22	2,98
β_{eff}	0,34	0,33	0,33	0,34	0,34	0,35	0,35	0,34	0,35	0,36	0,35
B (Reduction factor)	1,77	1,76	1,76	1,78	1,78	1,79	1,79	1,78	1,80	1,81	1,80
S_a (g)	0,19	0,19	0,19	0,20	0,20	0,20	0,20	0,20	0,19	0,19	0,20
S_a /B (g)	0,11	0,11	0,11	0,11	0,11	0,11	0,11	0,11	0,11	0,10	0,11
d_{iso} (mm)	206	153	153	205	205	235	235	241	230	213	241
d_{bridge} (mm)	260	260	260	250	250	247	247	252	253	264	245
$V_{tot} = V_{tot\ base}$ (kN)	2451	4303	4303	4337	4337	4329	4329	1882	1060	1085	570
V_{tot}/W_{deck}	11%	11%	11%	11%	11%	11%	11%	11%	11%	10%	11%

3.2 Multimodal spectral analysis (MMSA)

Multimodal spectral analysis has been conducted on the bridges using the computer program SAP2000 [13]. As for the SMSA, the MMSA procedure is iterative for the same reasons. Like for the other elements of the bridges, the isolators are modeled with beam elements. At each iteration, the properties of the isolators and the hybrid response design spectra are calculated in a spreadsheet and entered in the model until the displacement calculated is the same as the one assumed. The forces are computed using the square root of the sum of the squares (SRSS). Table 3 shows the results of the MMSA for the 11 bridges.

Table 3 - Multimodal spectral analysis (MMSA) according to CAN/CSA-16-14 [1]

Properties	**Bridge No.**										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
$K_{isolator}$ (kN/mm)	11,83	1,99	1,93	1,49	1,45	1,23	1,23	1,33	1,16	2,54	0,34
β_{eff} : Damping	0,34	0,33	0,33	0,35	0,35	0,35	0,35	0,35	0,35	0,36	0,35
B : Reduction factor	1,77	1,77	1,76	1,79	1,79	1,79	1,79	1,79	1,80	1,81	1,80
T_{eff} (sec)	3,15	3,10	3,11	2,96	3,00	3,00	3,01	3,01	3,08	3,23	2,97
$d_{isolator}$ (mm)	208	139	146	188	196	235	234	234	229	214	240
d_{bridge} (mm)	266	286	279	252	254	249	248	251	254	266	245
V_{tot} (kN)	2448	5292	4848	4617	4497	4341	4338	1904	1066	1090	572
V_{tot}/W_{deck}	10,8%	13,5%	12,4%	11,8%	11,5%	11,1%	11,1%	11,1%	10,8%	10,3%	11,1%
$V_{tot\ base}$ (kN)	2622	9586	6826	8424	6340	5327	5058	3269,7	1216	1146	882,5
$V_{tot\ base}/W_{deck}$	12%	25%	18%	22%	16%	14%	13%	19%	12%	11%	17%

3.3 Decoupled single-mode spectral analysis (DSMSA)

Multimodal spectral analyses have been conducted on the 11 bridge structures. Shear forces in the piers were first determined from the single mode spectral analysis (SMSA). The second analysis on the isolated piers was then performed to obtain seismic induced shear forces without the superstructure. The second analysis was performed using the SAP2000 analysis software but could have been done manually as is done for building structures. The shears forces from both analyses were then combined using the SRSS approach, as for the MMSA. Table 4 shows the results of the DSMSA.

Table 4 - Decoupled single mode spectral analysis (DMSA)

Bridge No.	1	2	3	4	5	6	7	8	9	10	11
V_{SMSA} (kN)	2451	4303	4303	4337	4337	4329	4329	1882	1060	1085	570
V_{pier} (kN)	1252	9402	6603	8376	5580	3317	2811	2780	655	420	682
V_{tot} (kN)	2753	10340	7881	9432	7067	5454	5162	3357	1246	1164	889

4. Results and discussion

The ratios of the shear forces in the piers obtained using the SMSA and DSMSA methods are presented in Fig. 4. All values are normalized with respect to the shear forces from the MMSA and the results are presented as a function of the pier mass ratio. Note that the MMSA results are considered to be the reference solution to be reproduced by the simplified analysis methods. One objective of the research was to determine the mass ratio beyond which inertia forces in the piers must be taken into account in the analysis. For the bridges analysed in this study, the results indicate that pier inertia forces must be considered when the ratio of the mass of the piers with respect to the mass of the deck reaches 10% to 15%. As shown, internal shear forces can be underestimated by more than 20% for larger ratios. Similar results were obtained for the bending moments.

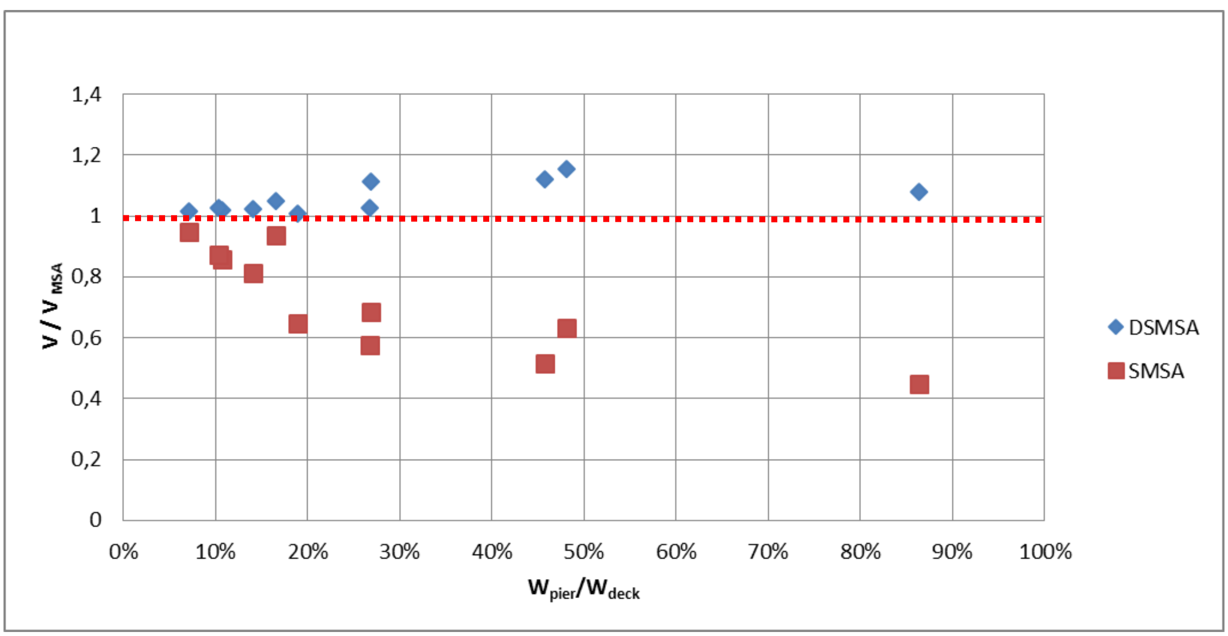

Fig. 4 – Shear Forces DSMSA and SMA in comparison with MMSA

The results in Fig. 4 also show that the proposed decoupled single mode spectral analysis (DSMSA) is accurate for all bridges analysed. The DSMSA calculates practically the same shear forces than that for the MMSA for 7 bridges and slightly overestimates shear forces for 4 bridges having larger mass ratios. Unlike the SMSA method, the proposed DSMSA method overestimates the shear forces by less than 20%, even for bridges having mass ratios as high as 86%.

The results obtained can be explained by comparing the fundamental periods of the piers with and without the presence of the isolators. The results of the modal analyses are presented in Table 5. As shown, the periods of the piers do not vary much when the isolators are added, indicating that the isolators do not affect much the vibration response of the piers. This explains why the DSMSA method can provide accurate seismic force demand predictions. However, when the height of the pier becomes more important, the isolators affect more the pier's periods, which also impacts the accuracy of the method.

Table 5 - Fundamental period of the bridges analysed and accuracy of the DSMSA.

Bridge No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
W_{pier}/W_{deck}	17%	86%	48%	46%	27%	14%	11%	27%	10%	7%	19%
H (m)	7.90	28.70	28.70	17.00	17.00	8.00	8.00	10.00	7.06	8.50	4.55
T_{pier} (s)	0.29	0.93	0.83	0.47	0.42	0.16	0.16	0.22	0.21	0.23	0.11
$T_{pier\ isolated}$ (s)	0.25	0.70	0.62	0.42	0.38	0.15	0.15	0.21	0.20	0.20	0.11
$\mathbf{V_{DSMSA}/V_{MMSA}}$	**1.05**	**1.08**	**1.15**	**1.12**	**1.11**	**1.02**	**1.02**	**1.03**	**1.02**	**1.02**	**1.01**

5. Conclusions

A new simplified analysis method, decoupled single mode spectral analysis (DSMSA) method, has been presented for the analysis of seismically isolated highway bridges. The DSMSA method is proposed to improve the current single mode spectral analysis (SMSA) where the mass of the piers is neglected. To assess the accuracy of the DSMSA, a comprehensive parametric study has been performed using the multi-mode spectral analysis (MMSA) as the reference solution.

A comparative evaluation has been performed for the internal pier forces for 11 highway bridges with total pier mass to deck mass ratios ranging from 7% to 86%. The results of these analyzes indicated that pier inertia forces must be taken into account in the seismic design of isolated highway bridges when the ratio of the mass of the piers with respect to the mass of the deck reaches and exceeds 10% to 15%. The results from the proposed decoupled DSMSA method were compared to those from the code based multi-mode spectral analysis (MMSA) and pier internal forces are very close to each other when the ratio of the mass of the piers with respect to the mass of the deck is less than 25%. For bridges for which the ratios of the mass of the piers with respect to the mass of the deck are larger than 25%, the computed pier internal forces are larger than the more rigorous MMSA, with a difference of less than 20%. The proposed DSMSA is therefore recommended for preliminary seismic design of isolated highway bridges. It retains computational simplicity and yet improves significantly the accuracy of the SMSA simplified method where only the flexibility of the piers is considered while neglecting the mass of the piers.

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