EVALUATION OF THE APPLICABILITY OF SIMPLIFIED SINGLE-MODE SPECTRAL ANALYSIS IN THE PRELIMINARY SEISMIC DESIGN OF ISOLATED BRIDGE ACCORDING TO TCVN 11823:2017

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TÓM TẮT: Động đất là một trong những tác nhân gây ra nhiều thiệt hại đối với con người và tài sản xã hội, đặc biệt là với công trình hạ tầng thiết yếu như cầu. Gối cách chấn là giải pháp thiết kế kháng chấn hiệu quả, được đặc biệt áp dụng rộng rãi trong thiết kế chống động đất cho cầu và mang lại hiệu quả cao trong việc bảo vệ kết cấu. Nội dung tính toán thiết kế gối cách chấn cho kết cấu cầu được đề cập trong các tiêu chuẩn trên thế giới, tuy nhiên còn chưa rõ ràng trong TCVN 11823:2017. Bài báo trình bày phương pháp phân tích đơn giản hóa dạng dao động cơ bản áp dụng trong thiết kế sơ bộ gối cách chấn cho kết cấu cầu, tính toán dựa theo tiêu chuẩn TCVN 11823:2017. Độ tin cậy của phương pháp phân tích đơn giản hóa được đánh giá thông qua so sánh kết quả phân tích với phương pháp phân tích phi tuyến theo lịch sử thời gian. Kết quả nghiên cứu giúp đưa ra các khuyến cáo cần thiết đối với các kỹ sư thiết kế trong việc áp dụng cho tính toán thiết kế gối cầu cách chấn, góp phần bổ sung vào việc phát triển tiêu chuẩn về tính toán và thiết kế gối cầu chống động đất tại Việt Nam.

TỪ KHÓA: Kết cấu cầu, gối cầu cách chấn, phương pháp phân tích một dạng dao động, phân tích phi tuyến theo lịch sử thời gian.

ABSTRACT: Earthquakes are one of the factors that cause a lot of damages to people and social property, especially to essential infrastructure such as bridges. Seismic isolation bearings are considered an effective seismic design solution, especially widely applied for bridge structures, and offer high efficiency in structural protection. The design calculation of seismic bearings for bridge structures is mentioned in world standards, but not clearly specified in TCVN 11823:2017. This paper presents a simplified analysis method for the fundamental vibration mode of bridges applied in the preliminary design of seismic isolation bearings, calculated according to TCVN 11823:2017. The reliability of the simplified method is evaluated by comparing the analysis results with the nonlinear time-history analysis method. The obtained results allow for providing necessary suggestions for design engineers in applying seismic isolation calculations, contributing to the development of standards for the seismic-resistant design of bridges in Vietnam.

KEYWORDS: Bridge, seismic base isolation, single-mode spectral analysis, time-history nonlinear analysis.

1. INTRODUCTION

Earthquakes are one of the deadliest and most dangerous natural disasters. The level of irreparable destruction, loss of life, and crippled infrastructure caused by earthquakes lead to high economic costs in rescue, containment, reconstruction, and recovery. Recovery from an earthquake requires considerable time and financial contributions, often failing to reach the affected areas due to the extensive losses.

Bridges are essential components in the transport infrastructure systems, which play an important role in socio-economic development. The bridge structure is characterized by a long span, the mass is mainly concentrated at the top while the substructures are generally a system of piles and abutments. Therefore, they are particularly vulnerable to lateral impacts, especially earthquakes.

In strong earthquake regions, the bridge structures are frequently protected by seismic base isolation (SBI). The basic principle of this technique consists in lowering the lateral stiffness of the structure, thereby extending its fundamental vibration period from the dominating energy concentration period range of earthquakes. This device enables preventing the majority of the kinetic energy of earthquakes from being transferred into structural components, hence minimizing seismic forces. This technique has many advantages, especially in maintaining an elastic behavior of structural elements and therefore minimizing damage during earthquakes, preserving the functionality of the structure and contributing to saving lives, socio-economic resilience after the earthquake, reducing the cost of construction, ease of technology integration into new and existing bridges, ease of maintenance and replacement, etc. As a result, this technique is being more and more popular in the world [1, 2].

The hysteretic behavior, (i.e., the force-displacement relationship), of seismic isolators is interdependent on several parameters and conditions, in particular the architecture and nature of the components of the system [3-5]. There are several hysteretic models that can represent the force-displacement relationship of SBI systems with varying degrees of sophistication and complexity [3, 4, 6-8]. Among them, the nonlinear hysteretic models are the most complex, but they can also best and most faithfully represent the real behavior of certain systems, such as elastomeric-based isolators with a stiffening of the material under large deformations. The bilinear model is nevertheless the simplest nonlinear model and also the most used for the analyses of the isolated bridge structures, allowing to capture of the essence of the behavior of the most common isolators. The viscoelastic model is an equivalent linear model, based on the bilinear model, used in linear analyses, such as spectral analyzes [3, 4, 9-14]. These two models are also adopted as basic design codes and implicitly recognized as being sufficiently reliable and accurate for basic seismic isolation systems [15-17].

Specifically, the force-displacement behavior of the most available SBI is generally idealized by the bilinear model shown in Figure 1 (a) [4]. Energy dissipation per cycle, representing the equivalent damping ratio of the system, is evaluated by the area under the hysteresis curve for a complete cycle at the design displacement, D_{max} [3].

Accordingly, the seismic response of the isolated-bridge structure is strongly nonlinear and the solution of such a nonlinear system can be solved easily through the nonlinear time-history analysis (NLTHA) method. However, solving systems with a large number of degrees of freedom by the NLTHA method may require an exorbitant amount of time. Also, the enormous amount of output results from such systems may be so detailed that it is impractical for engineers to summarize. Even for single-degree-of-freedom (SDOF) systems, the number of different loading cases needed to be solved may be quite large. Thus, there will always be a need for good approximate methods of analysis of nonlinear systems.

Currently, the equivalent linearization method is the best-known approximation method. The underlying premise of this method is that the inelastic response of the structure can be adequately modeled using a fictional viscoelastic damping structure whose stiffness and damping characteristics are selected such that D_{max} of the two systems are approximately equal.

When the (equivalent) elastic linear method is employed, it is obviously noted that the correct estimation of the elastic linear properties is crucial for the results. Structural engineers never stop seeking more accurate linear elastic methods to approximate peak responses of nonlinear systems. Meanwhile, many studies have been contributed to evaluate the accuracy of different methods proposed in the literature. However, these methods still need evaluation in seismic excitation to get better insights into their suitability for the analysis and design of seismically isolated bridges.

The single-mode spectral analysis (SMSA)

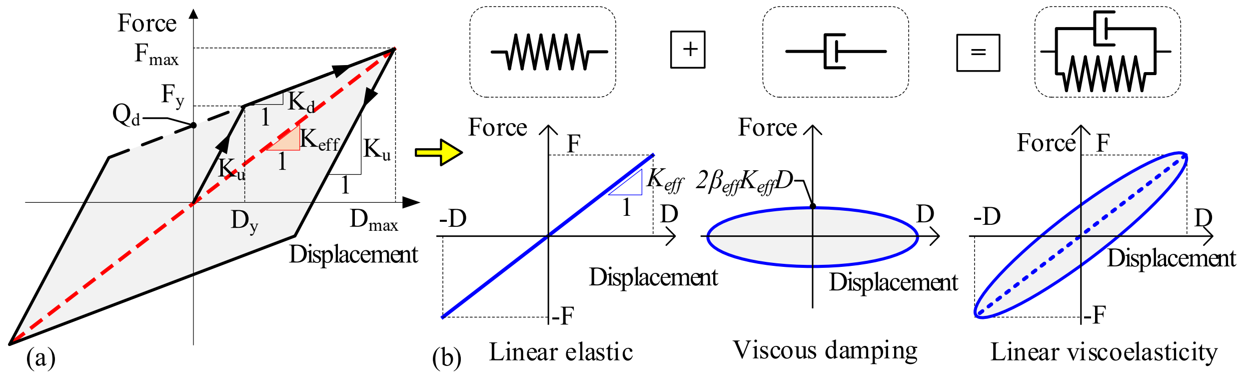

Figure 1. Simplified behavior model of SBI: (a) Bilinear hysteresis, (b) Equivalent viscoelastic model

method, which is commonly presented in the design standards, is one such method. However, the accuracy level of this method is not well-established. The inherent hysteresis damping of the SBI is replaced by equivalent viscous damping, which may lead to an erroneous estimate of the peak responses.

The main objective of this research is to evaluate the applicability of the single-mode spectral analysis (SMSA) method, which is applied to the preliminary seismic design of isolated bridges in accordance with TCVN 11823:2017.

To achieve the objectives laid out above, a parametric study is carried out on a typical isolated bridge. The SMSA and NTLHA methohs are employed to establish the seismic demand (D_{max}, F_{max}) of the isolated bridge variants generated by the parametric study. A comparison of the results obtained by two methods is performed to evaluate the performance of the SMSA method.

2. OVERVIEW OF THE SIMPLIFIED METHOD

2.1. Simplified model of isolated bridges

The simplified method in computing nonlinear systems was introduced by Jacobsen [18], after which it was extensively applied by Hudson [19]. The original idea involved an approximation of the nonlinearities effects by an equivalent viscous damping model of SDOF under a sinusoidal force [18] or an earthquake-like excitation [19]. Equivalent linear models have been developed in the past decades. Generally, they can be classified into two main groups according to the definition of the equivalent period of vibration (or equivalent stiffness). The first group includes methods with the equivalent period defined using the post-elastic stiffness at design displacement of systems. In the second group of the existing equivalent linear methods, the equivalent stiffness of the equivalent linear systems is determined using other derived or fitted formulas.

The simplified analysis method may be used for isolated bridges which respond predominantly as a SDOF system with no coupling of displacement between any two or three coordinate directions. This method shall be performed independently along two perpendicular axes [16, 20]. Specifically, the design of seismically isolated bridges allows to consider the bridge superstructure as a horizontal rigid diaphragm so that all the isolators experience the same displacement. Their properties can therefore be lumped into a unique equivalent isolator. A lumped mass represents the mass of the superstructure plus a portion of the substructure. An equivalent viscoelastic element with properties evaluated at the expected peak displacement models the equivalent isolator. The bridge can therefore be modeled as a SDOF system, as illustrated in Figure 2. The substructure mass can be reasonably ignored or taken into account by adjusting the superstructure mass [14]. The vertical ground motion component has not been taken into account as it does not affect significantly the horizontal response of the bridge, which is of prime importance [21].

As mentioned above, the hysteretic behavior of most available seismic isolators can be idealized by a bilinear force-displacement relationship as shown in Figure 1 [4, 15, 17, 22, 23]. Typically, the initial elastic stiffness, K_u, is high enough to respond to the stability of bridge structure under the effect of non-seismic loads and to produce the yield displacement D_y is nearly equal to zero ($D_y \approx 0$), and therefore, it has no practical noticeable effects on the response of isolated bridges [23]. The post-elastic stiffness, K_d, and the initial characteristic strength, Q_d, are

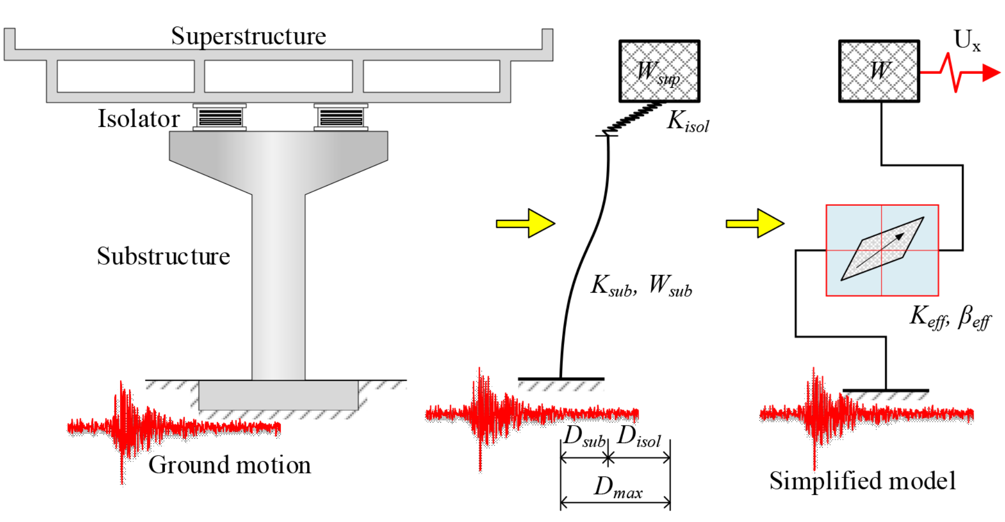

Figure 2. Typical seismic-isolated bridge and simplified SDOF model

determined the main hysteretic parameters of the bilinear hysteresis governing the seismic response of isolated bridge [3, 4, 17, 24].

2.2. Simplified single mode spectral analysis

By using the equivalent linear system for structural analysis, the spectral modal analysis is often used to maximize the efficiency of the linear system. In this way, the SMSA method is a simplified form of modal spectral analysis approach, based on the first isolated mode only (i.e., the fundamental mode of isolated bridge structures), and is particularly useful for the preliminary design and sizing of simple isolated bridges. This method consists of a spectral analysis of an equivalent SDOF linear system, representing the nonlinear isolated bridge structure, characterized by an effective stiffness (K_{eff}) and an equivalent viscous damping (β_{eff}), calculated at the peak displacement. The determination of these effective parameters has been interested by many authors for a long time [10, 25, 26]. According to the SMSA method, the substructure weight (i.e., the pier structures) is ignored or incorporated into the seismic weight of SDOF system (50% substructure weight) thereby eliminating the effects of vibration components of the pier structures.

It assumes that D_{max} is the deck displacement relative to the ground, W is the seismic weight of equivalent SDOF of isolated bridge model, K_{eff} is the effective stiffness of equivalent linear system.

$$D_{\max} = D_{sub} + D_{isol} \tag{1}$$

The statically equivalent seismic force can be determined as:

$$F = C_{smd}W = \frac{C_{sm}W}{B} = K_{eff}D_{\max} \tag{2}$$

The effective period of equivalent system, T_{eff}, is given by:

$$T_{eff} = 2\pi\sqrt{\frac{W}{K_{eff}\,g}} \tag{3}$$

K_{eff} is the sum of the effective stiffness of all isolators supporting the superstructure segment.

$$K_{eff} = \sum_{j=1}^{n} K_{eff,j} = \sum_{j=1}^{n} \frac{K_{sub,j}K_{isol,j}}{K_{sub,j} + K_{isol,j}} \tag{4}$$

where,

$K_{sub,j}$ is stiffness factor for substructure unit *"j"*, depicted in Figure 2;

$K_{isol,j}$ is stiffness factor for isolator unit placed on substructure unit *"j"*, depicted in Figure 2.

The corresponding equivalent damping ratio, β_{eff}, shall be determined as follows:

For a single isolator and substructure unit *"j"*:

$$\beta_{eff,j} = \frac{Energy\ dissipated\ per\ cycle}{2\pi K_{eff,j}D_{\max,j}^2} = \frac{4Q_{d,j}\left(D_{isol,j} - D_{y,j}\right)}{2\pi K_{eff,j}D_{\max,j}^2} \tag{5}$$

For multiple unite of isolator and substructures supporting a continuous segment of the superstructure:

$$\beta_{eff} = \frac{4\sum_{j=1}^{n} Q_{d,j}\left(D_{isol,j} - D_{y,j}\right)}{2\pi\sum_{j=1}^{n} K_{eff,j}D_{\max}^2} \tag{6}$$

where,

$Q_{d,j}$ is the characteristic strength of the isolator unit.

$D_{y,j}$ is the isolator yield displacement

D_{max} is the total deck displacement relative to ground

$D_{sub,j}$ is the displacement of substructure unit *"j"*, depicted in Figure 2.

$D_{isol,j}$ is design displacement across isolator unit placed on substructure unit *"j"*, depicted in Figure 2.

Further, as illustrated in Figure 1, the dissipated energy by the hysteresis loop is depended on the maximum displacement. Meanwhile, the seismic displacement, which shall match the design spectrum and the bilinear behavior, is unknown and an iterative procedure is usually employed [3, 10, 27, 28].

3. ELASTIC RESPONSE SPECTRUM ACCORDING TO TCVN 11823:2017

In the design of isolated bridges, according to the vibration period of the structure, the elastic response spectrum, which is essential seismic input in the analysis, must be used to obtain the seismic responses (maximum forces and displacements). In this section, an overview of calculating the elastic response spectrum according to TCVN 11823:2017 [29] is presented.

The elastic coefficient is directly related to the elastic ground response spectra. With the period of vibration not longer than 4,0s and 5% damping, the elastic seismic response coefficient for mode "m" is taken as:

$$C_{sm} = \frac{1{,}2A.S}{T_m^{2/3}} \le 2{,}5.A \tag{7}$$

where T_m is the period of vibration mode "m", (s), which is determined based on the norminal, unfactored mass of the component or structure.

A is acceleration coefficient specified in Appendix H, TCVN 9386:2012 [30].

S is the site coefficient specified in Table 1 as follows:

Table 1. Site coefficient according to TCVN 11823:2017 [29]

Site coefficient	Soil profile type			
	I	II	III	IV
S	1,0	1,2	1,5	2,0

For bridges located on soil profiles III or IV and in areas where the coefficient "A" is not less than 0.30, C_{sm} need not exceed 2.0A. For soil profiles III and IV, and for modes orther than the fundamental model that have preriods less than 0.3s, C_{sm} shall be taken as:

$$C_{sm} = A\left(0.8 + 4.0T_m\right) \tag{8}$$

If the period of vibration for any mode exceeds 4.0s, the value of C_{sm} for that mode shall be taken as:

$$C_{sm} = \frac{3A.S}{T_m^{4/3}} \tag{9}$$

Isolated bridges usually have a damping ratio in excess of 5%, and to account for this higher level of damping, a damping coefficient B shall be included in the equation for C_{smd}.

$$C_{smd} = \frac{C_{sm}}{B} \tag{10}$$

Although the TCVN 11823:2017 does not mention the damping factor, this factor can be referenced from the AASHTO 1999 as follows:

Table 2. Damping factor according to AASHTO 1999

Damping factor	Damping ratio βeff (%)						
	< 2	5	10	20	30	40	50
B	0,8	1,0	1,2	1,5	1,7	1,9	2,0

For intermediate values of damping ratio β_{eff} (%), the damping factor can be calculated by linear interpolation. It should be noted that the use of B-factors to scale response sepctra is unreliable for hysteretically damped isolation systems with equivalent viscous damping ratios in excess of 30%. In these cases, a nonlinear time-history analysis is recommended using the actual hysteresis loop rather than equivalent damping ratios and B-factors. If the dampers are truly viscous, then B-factors greater than 1.7 may be used.

4. PARAMETRIC STUDY

In this section, a parametric study was performed to evaluate the applicability of the SMSA method in the preliminary seismic design of isolated bridge. To do so, a comparison of obtained seismic responses between the SMSA method and the NLTHA method was performed, in which the NLTHA method includes the effects of the pier structure vibrations. A typical isolated bridge model is employed for analysis, as shown in Figure 3.

It assumes that the seismic weight of the bridge superstructure is W_{sup} = 16000kN. The cross-section of pier is circle with a diameter of 2.2. m, the height of pier is approximately 5.0 m. The pier is made of reinforced concrete, the material properties include Young's modulus E = 27000 Mpa, the weight density ρ = 23.56 kN/m^3, and the poisson ratio υ = 0.2. The pier is rigidly constrained at the bottom.

In the preliminary design, the isolated bridge can be modelled by a simplified model, where all the isolation units are lumped into a unique equivalent isolator. The properties of the equivalent isolator are selected based on the previous results and in reference to a typical high damping rubber bearings [4, 24, 31, 32] as follows:

K_u = 715.4kN/mm, K_d = 0.01K_u, Q_d = 0.025W_{sup}.

For apply the single-mode spectral analysis, the seismic weight of SDOF is calculated by the weight of superstructure and 50% weight of substructure, as follows:

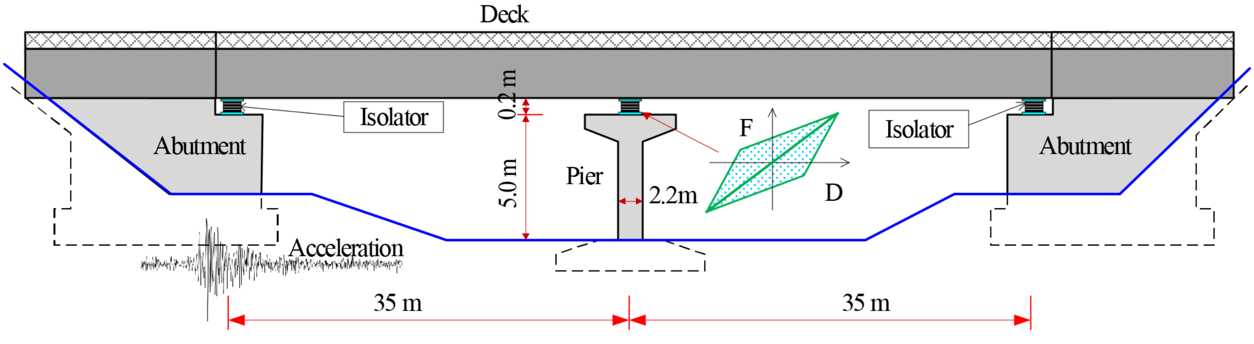

Figure 3. Typical seismic-isolated bridge model (case study)

Table 3. Earthquake records were selected for analyses

Earthquake	Station	Mw	Hypocenter distance (km)	PGA (g)
El Centro, 1940-05-19	CA - Array Sta 9; Imperial Valley Irrigation District	6.9	12.2	0.355
Kobe, 1995-01-16	Nishi-Akashi, Japan	6.9	19.9	0.51
Northwest China, 1997-04-11	Jiashi, China	6.1	27.7	0.3

$$W = W_{\sup} + 0.5W_{sub} = 16224(kN)$$

The stiffness of substructure can be calculated as a single cantilever column as follows:

$$K_{sub} = \frac{3EI}{h^3} = \frac{3}{5^3} \times 27 \times 10^6 \times \frac{1.1^4}{4} = 237.184(kN / mm)$$

The bridge is located in Son La, supported on soil class II and 5% damping. The elastic response spectrum of location is plotted in Figure 4(a).

To perform NLTHA, a suite of three recorded ground motions is selected as shown in Table 3. These accelerograms are scaled by the method proposed by Nguyen Xuan Dai [33, 34] to match the target spectrum of SonLa.

Figure 4 shows the response spectra of matched accelerograms [see in Figure 4(a)] and the difference between the mean spectrum of selected accelerograms and the target spectrum calculated by TCVN 11823:2017 [see in Figure 4(b)].

Figure 5(a) shows the typical displacement history of the isolated bridge substructure subjected to El-Centro earthquake scaled record. The nonlinear behavior of the isolator is also plotted in Figure 5(b).

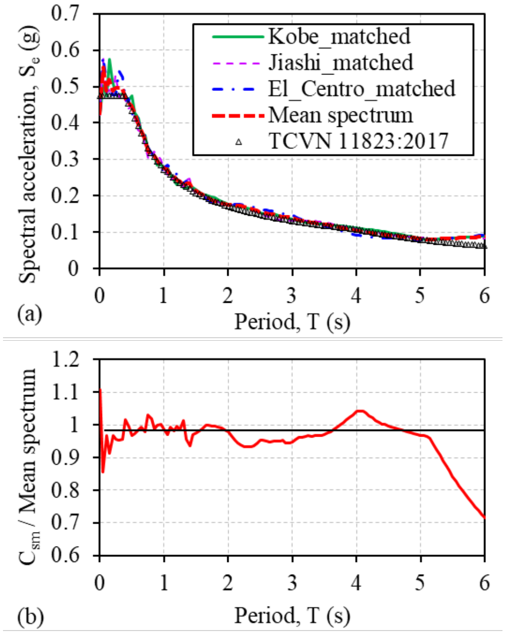

Figure 4. Ground motion records for analyses

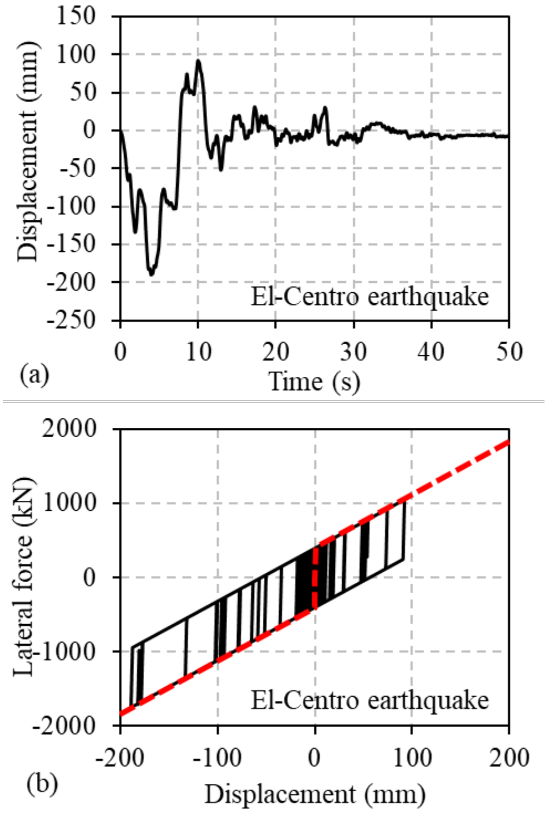

Figure 5. Nonlinear responses of isolated bridge subjected to matched ground motion of El-Centro earthquake

To evaluate the accuracy of the SMSA method, a comparison of seismic response between the SMSA method and nonlinear time-history analysis method is performed. To do so, the average of peak seismic response of isolated bridges, subjected to 03 scaled ground motion records, analyzed by time-history analysis method was used to compare with the responses by the SMSA method. For this model, the seismic weight of superstructure is W_{sup} = 16000kN, while the weight of substructure is taken to be zero to eliminate potential impacts of vibration modes of the pier structure. The obtained results are presented in Table 4 below.

Table 4. Comparisons of seismic responses between the SMSA and NLTHA

Analysis method		F_{max} (kN)	D_{max} (mm)
SMSA		**1734.54**	**193.85**
NLTHA	Kobe earthquake	1815.27	205.91
	El-Centro earthquake	1750.18	189.53
	Jiashi earthquake	1856.39	219.37
	Average	**1807.28**	**204.94**

It shows a good agreement between obtained results from the SMSA and the NLTHA methods. More specifically, the SMSA results are slightly lower (around 5%) than those of the NLTHA method. This difference may derive from the difference between the mean spectrum of 03 selected accelerograms and the target spectrum of the standard [see in Figure 4(b)]. Another potential cause is the replacement of the hysteresis damping of the isolator by the equivalent viscous damping in the SMSA method. Despite that, the error is small in this case, suggesting that the SMSA method is reliable.

A parametric analysis was carried out using various weight ratios between the substructure and superstructure to evaluate the suitability of the SMSA method concerning the effect of the substructure's vibration modes. The substructure weight is considered to be constant. In the framework of this study, the sensitivity of the seismic responses is investigated on the assumption that the weight ratios are less than 5% (corresponding to the case where the substructure is relatively lighter compared to the superstructure). The obtained results of lateral forces and displacements are shown in Figure 6(a) and (b), respectively.

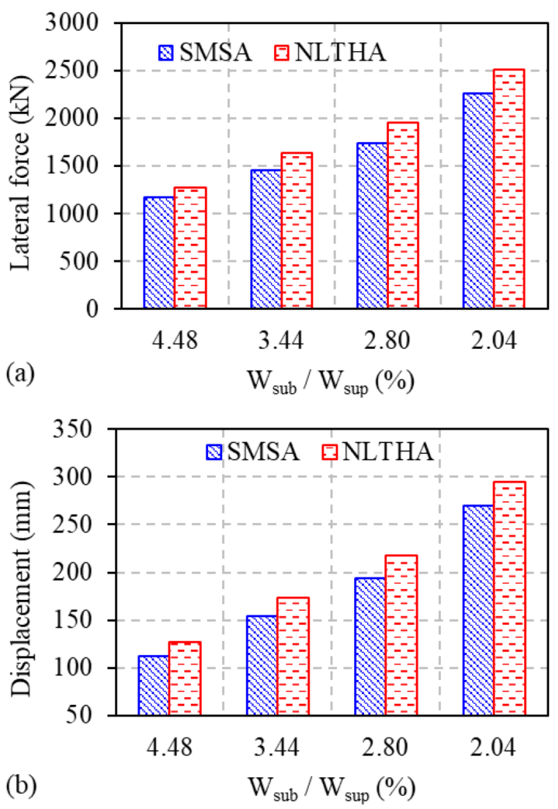

Figure 6. Comparisons of seismic responses between the SMSA and NLTHA

As observed in Figure 6, the seismic responses predicted by the SMSA method are unconservative when compared to the results of the NLTHA method. The differences are found in the range of 8% - 12%. In the author's opinion, these inaccuracies are acceptable in the context that the deviation between the response spectra of ground motions and the target spectrum was around 5% [see in Figure 4(b)], and the design procedures also include the system property modification factors.

5. CONCLUSION

The article performs a parametric study on the simplified analysis procedure of isolated bridge structures. The applicability of the SMSA method in the seismic design of isolated bridges was investigated by comparing seismic responses with the NLTHA method. In the framework of this study, the following conclusions can be drawn:

- The SMSA method provides a good agreement with the NLTHA method, suggesting that it is reliable for application in seismic analysis of isolated bridges.

- When the mass of the substructure is not considered, the SMSA method gives almost exact peak responses in lateral force and displacement.

- Within the range of weight ratio between the substructure and the superstructure of less than 5%, the SMSA method ensures critical accuracy with a variance of roughly 10%.

Notwithstanding the above, this paper conducted a parametric study on the seismic responses of isolated bridges with a rather limited scope. Further studies shall be carried out on the larger range of weight ratios as well as the impact of substructure flexibility to generalize and complement the findings of the report.

REFERENCES

[1] Morgan, T.A. and S.A. Mahin. (2011). The use of base isolation systems to achieve complex seismic performance objectives. 2011: *Pacific Earthquake Engineering Research Center.*

[2] Guizani, L. (Year). Sur l'isolation sismique des ponts au Canada. in *10e Colloque sur la progression de la recherche québécoise sur les ouvrages d'art*.

[3] Buckle, I., et al. (2006). Seismic isolation of highway bridges. 2006: MCEER, *University at Buffalo*, the State University of New York.

[4] Naeim, F. and J. M. Kelly. (1999). *Design of seismic isolated structures: from theory to practice*. 1999: John Wiley & Sons.

[5] Constantinou, M.C., et al. (1999). *Property modification factors for seismic isolation bearings.*

[6] Saidou, A. (2012). *Étude du comportement en compression-cisaillement d›isolateurs sismiques en caoutchouc.* Université de Sherbrooke.

[7] Kikuchi, M., T. Nakamura, and I.D. Aiken. (2010). Three-dimensional analysis for square seismic isolation bearings under large shear deformations and high axial loads. *Earthquake engineering & structural dynamics.* r. 39(13): p. 1513-1531.

[8] CSI. (2020). CSI analysis reference manual for SAP2000, ETABS, SAFE, CSiBridge, and PERFORM 3D. *Computers and Structures Berkeley,* CA.

[9] Guizani, L. and O. Chaallal. (2011). Mise en conformité sismique des ponts par isolation de la base – Application au pont Madrid au Québec. *Canadian Journal of Civil Engineering.* r. 38(1): p. 1-10.

[10] Jara, M., et al. (2012). Improved procedure for equivalent linearization of bridges supported on hysteretic isolators. *Engineering Structures.* r. 35: p. 99-106.

[11] Hwang, J.S. and J.M. Chiou. (1996). An equivalent linear model of lead-rubber seismic isolation bearings. *Engineering Structures.* r. 18(7): p. 528-536.

[12] Iwan, W. (1980). Estimating inelastic response spectra from elastic spectra. *Earthquake Engineering & Structural Dynamics.* r. 8(4): p. 375-388.

[13] Jara, M. and J.R. Casas. (2006). A direct displacement-based method for the seismic design of bridges on bi-linear isolation devices. *Engineering Structures.* r. 28(6): p. 869-879.

[14] Leroux, M., R. Tremblay, and P. Léger. (2017). New simplified method for preliminary assessment of seismic forces in isolated highway bridges with massive piers. *Journal of Bridge Engineering Structures - American Society of Civil Engineers.* r.

[15] ECS. (2005b). Eurocode 8: Design of structures for earthquake resistance. Part 2: Bridges. *European Committee for Standardization Brussels.*

[16] CSA-S6. (2019). *CSA-S6-19,* Canadian highway bridge design code. *Canadian Standards Association.*

[17] AASHTO. (2014). *Guide specifications for seismic isolation design*. 2014. Washington, D.C.: American Association of State Highway and Transportation Officials.

[18] Jacobsen, L.S. (1930). *Steady forced vibration as influenced by damping.* Trans. ASME-APM.r. 52(15): p. 169-181.

[19] Hudson, D. (Year). Equivalent viscous friction for hysteretic systems with earthquake-like excitations. in *Proceedings 3rd World Conference on Earthquake Engineering*.

[20] AASHTO. (2020). *AASHTO LRFD Bridge Design Specifications 9th Edition*. American Association of State Highway and Transportation Officials: Washington, DC.

[21] Tubaldi, E., S. Mitoulis, and H. Ahmadi. (2018). Comparison of different models for high damping rubber bearings in seismically isolated bridges. *Soil Dynamics and Earthquake Engineering.* r. 104: p. 329-345.

[22] CSA, C. (2014b). *Standard S6-14.* Commentary on CSA S6-14, Canadian Highway Bridge Design Code, Canadian Standards Association, Mississauga, ON.r.

[23] Dicleli, M. and S. Buddaram. (2006). Effect of isolator and ground motion characteristics on the performance of seismic-isolated bridges. *Earthquake engineering & structural dynamics.* r. 35(2): p. 233-250.

[24] Nguyen, X.D. and L. Guizani. (2020). Optimal seismic isolation characteristics for bridges in moderate and high seismicity areas. *Canadian Journal of Civil Engineering.* r. 48(6): p. 642-655.

[25] Liu, T., et al. (2014). Evaluation of equivalent linearization analysis methods for seismically isolated buildings characterized by SDOF systems. *Engineering structures.* r. 59: p. 619-634.

[26] Koval, V., R. Tremblay, and C. Christopoulos. (Year). Isolation and Damping Mitigation Strategies for Bridges in Western and Eastern North America. in *Proceedings of 15th World*

Conference on Earthquake Engineering, Lisbon, Portugal, Paper.

[27] Koval, V., C. Christopoulos, and R. Tremblay. (2016). Improvements to the simplified analysis method for the design of seismically isolated bridges in CSA-S6-14. *Canadian Journal of Civil Engineering.* r. 43(10): p. 897-907.

[28] Guizani, L. (Year). Isolation sismique et technologies parasismiques pour les ponts au Québec: Mise au point. in *14e Colloque sur la progression de la recherche québécoise sur les ouvrages d'art*.

[29] TCVN-11823-3:2017. (Vietnam national standard - Highway Bridge Design Specification. in *Part 3: Loads and load Factors*. Ministry of Science and Technology.

[30] TCVN-9386:2012. (2012). *Vietnam national standard - Design of structures for earthquake resistances*. Ministry of Science and Technology.

[31] Nguyen, X.D., V.T. Nguyen, and H. Nguyen. (2022). Evaluation of Applicability of Seismic Base Isolation for Bridges According to Vietnamese Codes, in *CIGOS 2021, Emerging Technologies and Applications for Green Infrastructure*. Springer. p. 217-225.

[32] Nguyen, V.T. and X.D. Nguyen. (2021). Effects of ground motion spectral shapes on the design of seismic base isolation for multi-story building according to Eurocode 8. *Innovative Infrastructure Solutions*. r. 6(3): p. 1-13.

[33] Dai Nguyen, X. (2022). A proposed method for selecting and scaling recorded seismic accelerations according to TCVN-9386: 2012. *Journal of Science and Technology in Civil Engineering (STCE)-HUCE.* r. 16(1): p. 100-112.

[34] Nguyễn, X.Đ. và V.T. Nguyễn. (2021). Hiệu chỉnh giản đồ gia tốc động đất đáp ứng theo tiêu chuẩn Việt Nam. *Tạp chí Khoa học Công nghệ Xây dựng.* r. 3: p. 69-77.