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Seismic Response Analysis of Bongo Bridge Subjected to Multiple Support Excitation due to Spatial Variation of Ground Motion

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Abstract The spatial variation of ground motion (SVGM) may cause detrimental effects on extended structures such as bridges. The SVGM is mainly caused by three phenomena: the incoherence effect, wave passage effect, and the local site effect, which leads the structure to undergo multiple support excitation. In most cases, in the Philippines, the conventional response spectrum analysis per DPWH Bridge Seismic Design Specifications (BSDS) 2013 is used to perform seismic analysis of bridges. However, the method assumes that the ground motion is spatially uniform, thus ignoring the potential effect of SVGM. The study focuses on the seismic response analysis of a conventional existing highway bridge in the Philippines subjected to multiple support excitation accounting for the effect of SVGM. The researcher used the Bongo Bridge located in Ilocos Norte, originally designed using the conventional response spectrum. A method for generating a modified response spectrum that accounts for the effect of SVGM based on the fundamental principle of random vibration theory was also presented to provide guidelines for bridge engineers in the Philippines. Three cases were performed where each seismic response of the existing bridge was obtained and evaluated to determine if the application of multiple support excitation due to SVGM will cause a significant effect on the existing bridge. Based on the results, the effect of multiple support excitation to Bongo Bridge amplified the seismic response of some pier columns and de-amplified some. The study also shows that the effect of multiple support excitation decreased the displacement demand significantly on the Bongo Bridge. Since the study is limited to Bongo Bridge and the seismic response can be affected by many factors, the result may vary to other bridges. Therefore, it is still recommended to perform a parametric analysis accounting for multiple support excitation especially if the structure is situated on a varying ground type or bridges with multiple and longer spans, to determine if this phenomenon will cause a significant effect on the bridge.

Keywords Spatial Variation of Ground Motion, Response Spectrum Analysis, Random Vibration Theory, Bongo Bridge, DPWH BSDS 2013

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1. Introduction

In the Philippines, the conventional response spectrum analysis per DPWH BSDS 2013 is used in most cases for bridge seismic response analysis. However, the current method assumes that ground motion is spatially uniform. The motion depends on the localized soil layer and distance from the epicenter. Thus, extended structures such as bridges may experience different earth excitation, and the current method may under or overestimate the seismic forces. The three phenomena that are responsible for these variations in ground motions are: the wave passage effect; Incoherence effect; the difference in the local soil condition at each station or the local site effect.

The wave passage effect happens because of the difference in the arrival times of seismic waves at different stations due to the finite nature of the seismic wave velocities. On the other hand, the incoherence effect, due to reflections and refraction of the waves in the heterogeneous medium of the ground and to the differences in the manner of superposition of waves arriving from an extended source, is the loss of coherence of the motion. Lastly, the site response effect is due to the difference in the local soil conditions at each station and the way they influence the amplitude and frequency content of the bedrock [6, 8]

This phenomenon has an important effect on the response of long structures such as tunnels, dams, and bridges. In 1989, the variation in ground motion for extended structures such as bridges was observed during the 1989 Loma Prieta Earthquake [8]. Data for spatial variation of the seismic ground motion and its effect on the response of various structures was also provided by the El Centro differential array that recorded the 1979 Imperial Valley Earthquake and the Strong Motion Array in Taiwan-Phase 1 or SMART-1 located in Taiwan [6]. The 2008 Wenchuan earthquake and 2013 Lushan Earthquake also indicate, after investigation, that seismic spatial variability in the southwestern mountains of China has a significant effect on the seismic performance of some extended structures such as long-span bridges and high-pier railway bridges [3].

However, the effect of SVGM may be beneficial for most of the structures (i.e, reduction of response), but there are situations where such differential support motion may increase the response. From a practical point of view, the multiple-support ground motion may excite vibration modes not captured by using uniform ground motions and vice versa, which is more severe for longer spans. Hence the response of bridges under multiple-support ground motions is generally different from those excited by uniform or identical support ground motion [1].

Under the multiple-support excitation effect, most of the bridges utilize random vibration and response spectrum and deterministic methods in engineering applications. However, in the Philippines, multiple-support excitation may only be performed using Time-History Analysis. But time history analysis may not always be feasible, and the BSDS 2013 only recommend it to perform on important bridges or bridges near fault lines. Additionally, Time History is expensive, and the analysis requires extensive amounts of computation. Hence, most of the bridges in the Philippines are analyzed using a conventional response spectrum. While this type of analysis may be enough for some bridges, ignoring the possible effect of spatial variation of ground motion may negatively affect bridge response, which was observed in most studies conducted abroad and earthquake records [1, 2]. Also, unlike uniform seismic excitation, multiple support excitation may cause a symmetrical mode of vibration which contributes to amplifying the response of structures [3]. This study will help improve the current response spectrum analysis of DPWH-BSDS 2013 in bridge dynamic analysis and design by modifying the current method to account for the effect of spatial variation of ground motion based on the fundamental principle of random vibration theory. This will help the bridge designers in the Philippines to perform a parametric study of bridges under multiple support excitation by just using the response spectrum if Time History Analysis is not feasible, thus making it possible to account spatial variation of ground motion and its effect on the seismic response of bridges. This study may also be acknowledged in drafting design guidelines and standards for earthquake resistance of conventional highway bridges in the Philippines.

The random vibration approach is based on a statistical characterization of the set of motions at the support points, usually in terms of auto- and cross-power spectral densities. It provides a statistical measure of the response, which is not controlled by an arbitrary choice of the input motion. In this approach, the excitation is described by a random process (or field) rather than a time series and follows directly from the evaluation of the deterministic dynamic response of structures [6, 8]. This approach may be used to perform multiple support excitation, however, it is not common in engineering practice to represent ground acceleration in terms of power spectral density, instead it is represented in terms of response spectrum. To overcome this, a relationship between random vibration and response spectrum was derived, thus, a response spectrum based on random vibration can be utilized in dynamic analysis of multiple excited supports of bridges.

This study investigates the effect of multiple support excitation on an existing bridge and compares it to the conventional response spectrum analysis. By this, the researcher can determine if the conventional method per DPWH-BSDS 2013 over/under-estimated the existing bridge's seismic response, which may have a positive or negative implication in both structural strength and economic aspects of the bridge structure.

The study's main objective is to determine if there is a significant effect in the seismic response of Bongo Bridge, which was analyzed using the conventional RSA per BSDS 2013, when it is subjected to multiple support excitation. Also, to provide steps and guidelines for practical engineering application in generating a modified response spectrum, three cases were done to meet the main objective. For Case 1, the bridge was subjected to uniform ground motion using the conventional Response Spectrum based on the seismic guidelines provided by DPWH-BSDS 2013. For Case 2, the bridge was subjected to multiple excitations due to Spatial Variation of Ground

Motion (SVGM) with uniform ground type based on actual geotechnical data of the existing bridge. Lastly, for Case 3, like Case 2, the ground type was assumed to be varying. To do this, the response spectrum for each support (multiple-support response spectrum) was determined and modified to account the effect of SVGM. The peak response (displacement, bending moment, shear force) of the three cases were then extracted and compared to determine if the application of SVGM amplified or de-amplified it and if the difference is significant or not.

The study only focused on the linear seismic analysis phase of the Bongo Bridge using Multiple Support Response Spectrum and conventional Response Spectrum Analysis in the Philippine setting using the criteria for seismic analysis provided by the DPWH Bridge Seismic Design Specification 2013 (BSDS 2013). Additionally, the study did not consider the application and effect of other load cases, aside from seismic load and dead load. The effect on structural and economical aspects were not checked. The Bongo Bridge located at Ilocos Norte was used in the numerical analysis.

2. Materials and Methods

Seismic analysis of the Bongo Bridge was performed using the finite element software ANSYS. A Response Spectrum Curve, following the procedure of Bridge Seismic Design Specification 2013 (BSDS) of DPWH, was obtained for single excitation (uniform ground motion) analysis and for each support location for multiple support excitation analysis. The latter was used to develop the modified response spectrum to simulate the effect of Spatial Variation of Ground Motion and be used as a new input ground motion in ANSYS software. In this study, ANSYS, MathCad, Paired T-Test, and BSDS 2013 were used to process, analyze, and interpret the gathered data and results.

2.1. ANSYS

A finite element analysis software was used in this study to simulate uniform support excitation using Single Point Response Spectrum Analysis (SPRS); and multiple support excitation using the Multi-Point Response Spectrum or MPRS features of ANSYS. In MPRS, different acceleration Response Spectrum can be assigned to different points or supports of the structure, thus, subjecting the structure to multiple excitations. However, in MPRS, ANSYS only consider local site condition and assumes that the input spectrum in each support is fully incoherent or independent, therefore neglecting, if any, the effect of wave passage and coherency loss. The researcher performed a generation of modified response spectrum to overcome this shortcoming and presented it here. This modified Response Spectrum already accounts the effect of SVGM and is then inputted to ANSYS software to carry out the analyses.

2.2. MathCad

In this study, the researcher used Mathcad to develop a program that converts the response spectrum to its corresponding power spectral density and is used to generate non-stationary time history, and finally, the modified response spectrum.

2.3. Statistical Tool

The Paired T-Test is used to compare the two population means where the observation of one sample can be paired to that of the other sample such as the Before-and-After observation on the same subject or a comparison of two different methods of measurement/treatments that are applied to the same subject.

For this study, Paired T-Test was used to compare and check if there is a significant difference in the seismic response of the uniform excitation and multiple-support excitation.

The following are the procedure and equations needed to formulate the statistical analysis:

Hypotheses (two-tailed):

- Null hypothesis, Ho: “There is no significant difference in the seismic response of the uniform excitation and multiple-support excitation”
- Alternative hypothesis, Ha: “There is a significant difference in the seismic response of the uniform excitation and multiple-support excitation”

Mean difference:

$$\bar{D} = \sum \frac{D}{N} \tag{1}$$

Sum of Squares of Difference:

$$SS_D = \sum D^2 - \left[\frac{(\sum D)^2}{N}\right] \tag{2}$$

T-Statistic:

$$t_{calc} = \frac{\bar{D} - \mu_D}{\sqrt{\frac{SS_D}{N(N-1)}}} \tag{3}$$

Critical Value or Degrees of Freedom:

$$\mathrm{df} = N - 1 \tag{4}$$

Critical Value from Statistical table:
For this study the $t_{table} = 2.571$

2.4. Bridge Details and Structural Modeling

2.4.1. Bridge Details

In this study, a conventional highway bridge which is the Bongo Bridge, located at Nueva Era, Ilocos Norte was used. The summary of the details of the bridge is shown in Table 1.

Table 1. Design Parameters for Ground Type I

Total Bridge Length (Back-to-Back of Backwalls)		245.9m
Number of spans x Span Length		7 spans x 35m
Total Bridge Width		9.54m
Number of Lanes		2
Number of Sidewalks		2
Deck thickness		200mm
Number of Main Girders		4
Girder Type		AASHTO Type V
Coping Beam Dimension @ Piers		2mx2mx9.54m
Pier Column Diameter x Pier Column Length		1.8m x 6m
Bored Piles at Abutment A & B (Dia.xLength)		1.6m x 15m
Pier Bored Piles	Pier 1, 5 & 6	2.2m x 18m
	Pier 3 & 4	2.2m x 20m

2.4.2. Structural Modeling

The structural modeling of the Bongo Bridge followed the mathematical modeling requirements of DPWH-BSDS 2013 [13]. Here, since the researcher was dealing with the dynamic behavior of the bridge, thus, the focus of the model and analyses was the substructures.

The bridge geometry was modeled, and the dynamic analysis was performed in ANSYS. The superstructure was modeled as a beam element with its cross-sectional properties (A, Ix, Iy and Iz) running through its centroid. The modeling technique is called spine modeling, a common and simple technique for dynamic analysis of bridge structures.

According to DPWH-BSDS 2013 [13], any reduction to geotechnical parameters when calculating natural period is not applied when an extremely clayey layer exists or liquefaction of soil layer affects the bridge design due to many unclear points about the mechanism of excessive vibration characteristics caused by instability of ground. Additionally, it is suggested that the boundary condition be fixed at the ground for initial analysis of the model to determine the design forces for foundation for seismic design. Therefore, for this study, and to simplify the analysis, a fixed support condition was used in the model for boundary condition in obtaining the dynamic response (displacement, shear force, and bending moment) for uniform and multiple support excitation.

Based on the as-built plan of Bongo Bridge, the connection between superstructure and piers are composed of fixed and expansion connection. In Piers 1, 3, 4 & 6, the connections are fixed, hence this part of superstructure was released in rotation and restrained in translation in longitudinal, transversal, and vertical direction of the bridge axis. Piers 2 & 5 are expansions therefore these were released in rotation and longitudinal direction but restrained in transversal and vertical direction of the bridge axis. Figure 1 shows the schematic model elevation of the Bongo Bridge, Figure 2 shows the Bongo bridge structural model in ANSYS.

2.5. DPWH Bridge Seismic Design Specifications 2013

2.5.1. Design Response Spectrum

The design response spectrum was developed using the procedure specified by the DPWH-BSDS 2013 [12]. Two procedures namely the Site-Specific Procedure and the General Procedure can be used in developing the design response spectrum. In this study, the general procedure was used. Design parameters used in this study are shown in Table 2 and Table 3 while Figure 3 shows the design response spectrum curve.

Table 2. Design Parameters for Ground Type II

Seismic Parameters		Values (per DPWH-BSDS 2013)
Peak Ground Acceleration, PGA		0.5
Short-Period Acceleration Coefficient, S_s		1.05
Long-Period Acceleration Coefficient, S_1		0.4
Characteristic Value of Ground, T_G		0.475
Ground Type (Site Class)		Type II Medium (Diluvial and alluvial ground not belonging to Types I and III)
Site Factors	F_{PGA}	0.9
	F_a	0.98
	F_v	1.6
Operational Classification		OC-II (Essential Bridge)
Minimum Analysis Requirement		Multimode Spectral Method

Table 3. Design Parameters for Ground Type I

Seismic Parameters		Values (per DPWH-BSDS 2013)
Peak Ground Acceleration, PGA		0.5
Short-Period Acceleration Coefficient, S_s		1.05
Long-Period Acceleration Coefficient, S_1		0.4
Characteristic Value of Ground, T_G		0.475
Ground Type (Site Class)		Type I Hard (Good diluvial ground and rock)
Site Factors	F_{PGA}	1
	F_a	1
	F_v	1.4
Operational Classification		OC-II (Essential Bridge)
Minimum Analysis Requirement		Multimode Spectral Method

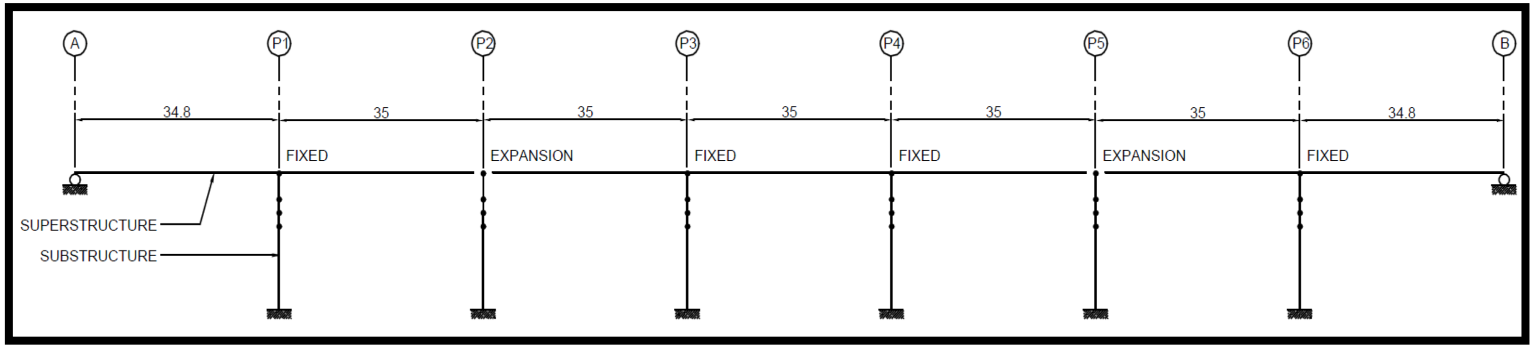


Figure 1. Schematic Model Elevation

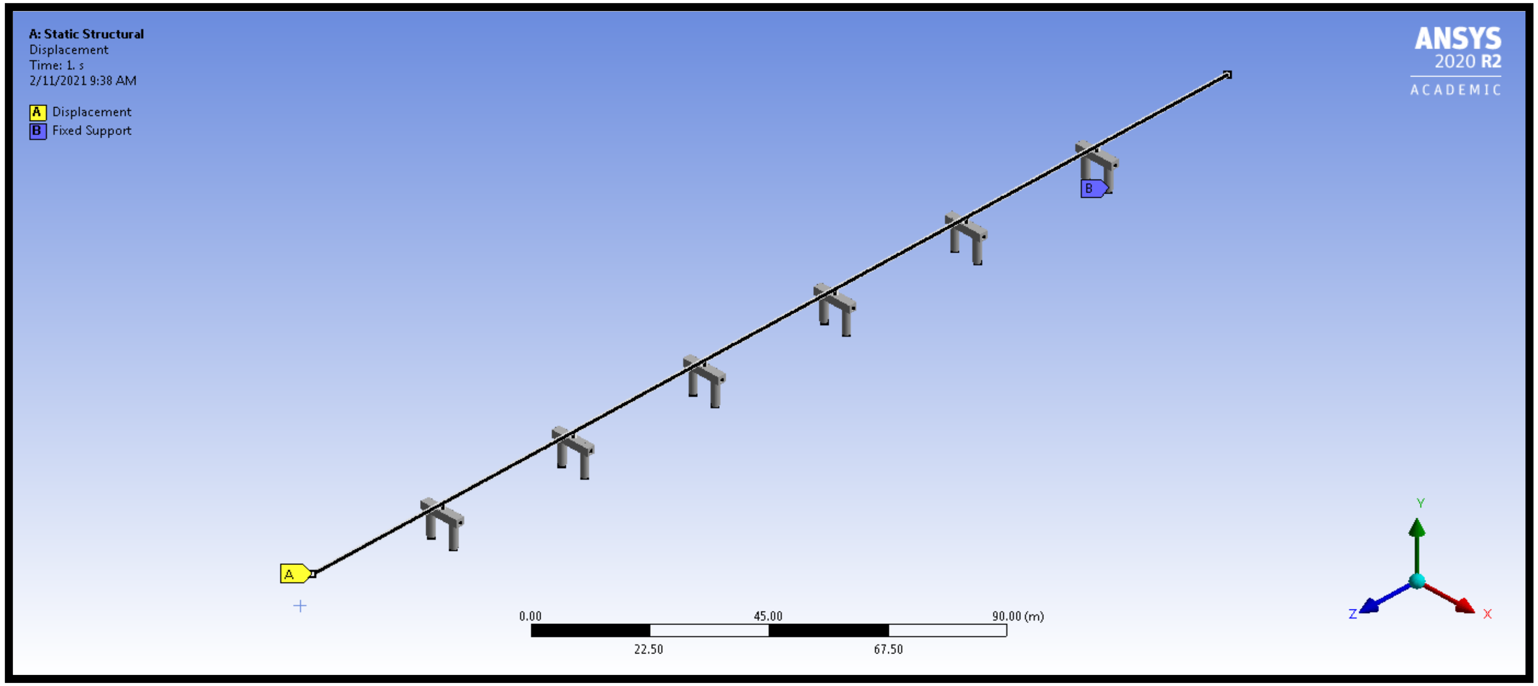


Figure 2. Bongo Bridge Structural Model in ANSYS

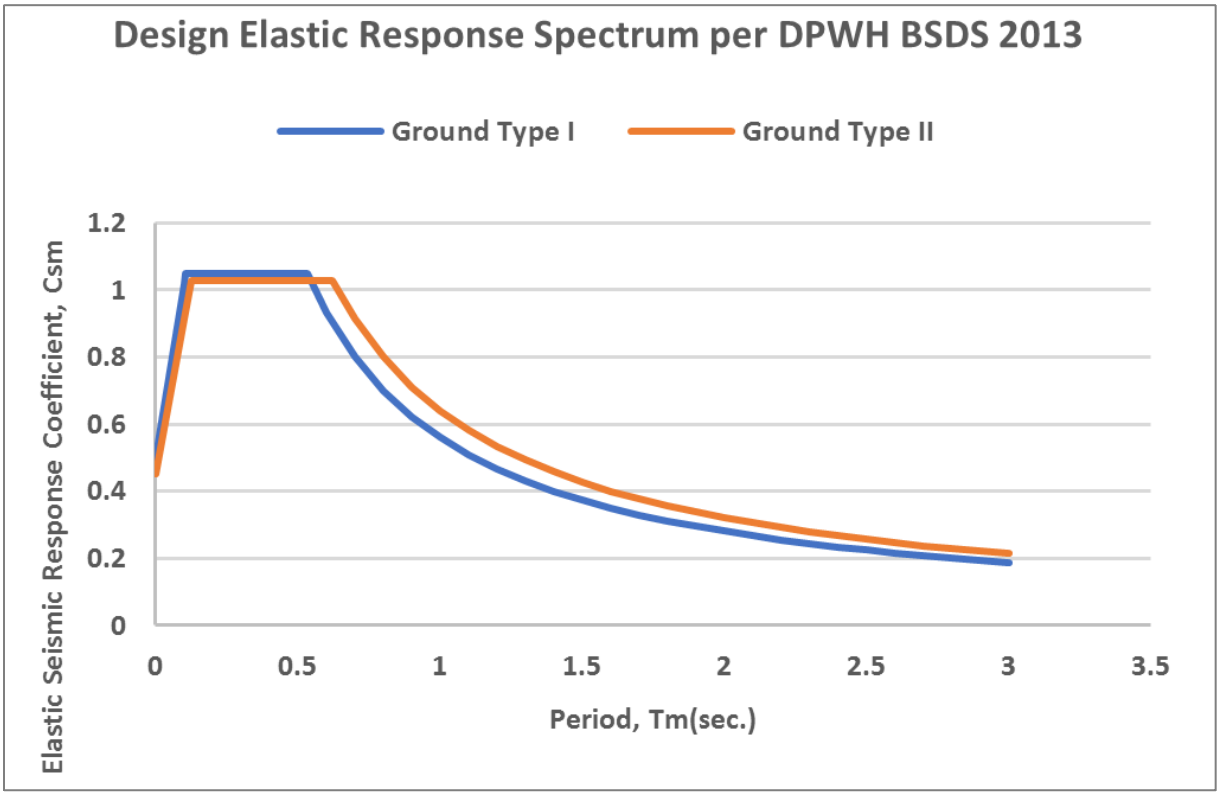


Figure 3. Design Response Spectrum Curve

2.6. Simulation of Spatially Variable Ground Motion

2.6.1. Random Vibration Theory

The modeling of Spatial Variation of Seismic Ground Motion was based on the fundamental principle of random vibration theory. In random vibration theory, the seismic ground acceleration is expressed in terms of its Power Spectral Density (PSD). Therefore, the PSD matrix of the ground acceleration for the m supports accounting the effect of SVGM is expressed as:

$$S(\omega) = \begin{bmatrix} S_{11}(\omega) & S_{12}(\omega) & S_{13}(\omega) & \cdots & S_{1m}(\omega) \\ S_{21}(\omega) & S_{22}(\omega) & S_{23}(\omega) & \cdots & S_{2m}(\omega) \\ S_{31}(\omega) & S_{32}(\omega) & S_{33}(\omega) & \cdots & S_{3m}(\omega) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ S_{m1}(\omega) & S_{m2}(\omega) & S_{m3}(\omega) & \cdots & S_{mm}(\omega) \end{bmatrix} \quad (5)$$

Where $S_{mm}(\omega)$ is the auto-power spectral density function in frequency domain at mth excitation point and can be obtained using the design response spectrum by applying the Kaul Method using (8). On the other hand, $S_{kl}(\omega)$ or S_{mm}(m≠ m), is the cross-power spectral density function in frequency domain that characterized the spatial variability of the ground motion and can be obtained using (6).

$$S_{kl}(\omega) = \rho_{kl}(\omega)\sqrt{S_{kk}(\omega)S_{ll}(\omega)} \quad (6)$$

Where $S_{kk}(\omega)$, $S_{ll}(\omega)$ and $S_{kl}(\omega)$ are the auto-power spectral density function at *k*th and *l*th support and their cross-power spectral density function, respectively. The $\rho kl(\omega)$ is the coherency function of the accelerations at *k*th and *l*th supports. Various model of coherency functions has been developed in recent years but in this study the most widely used and most quoted coherency model, by Luco and Wong 1986, was used and is expressed as:

$$\rho_{kl} = exp[-(\alpha\omega d_{kl})^2]exp\left(i\frac{\omega d_{kl}^l}{v_{app}}\right) \quad (7)$$

Equation (7) characterized the two distinct phenomena of SVGM. On the right-hand side, the second term characterizes the wave passage effect, whereas the first term characterizes the incoherence effect. The incoherence factor, α, controls the exponential decay of the function where the typical values range from 2x10-4s/m to 3x10-4s/m [11, 3]. In this study, a value of 2x10-4s/m was used. On the other hand, d_{kl}^l is the projection of d_{kl} which is the horizontal distance between the two supports. The surface apparent velocity of seismic waves along the surfaces is vapp may be approximately set to $v_{app} = v_s$, where v_s is the shear wave velocity, for engineering practice [10]. Finally, ω is the circular frequency and $= \sqrt{-1}$.

For response spectrum analysis, PSD function must be transformed from the given response spectrum. In this study, for standard bridges, the Kaul method was used, and the auto-PSD model is given by:

Kaul Method (1978):

$$S(\omega_0) = \frac{4\xi R_a^2(\xi,\omega_0)}{\pi\omega_0 r^2} \tag{8}$$

Where:

$$r^2 = 2\ln\left[\left(-\frac{\pi}{\omega_0 T_s}\ln p\right)^{-1}\right] \tag{9}$$

In (8), Ra(ξ,ω0) is the acceleration response spectrum and to be obtained based on DPWH-BSDS 2013; ω_0 is the natural angular frequency and ξ is the damping ratio usually taken as 0.05; $S(\omega_0)$ is the equivalent auto-PSD curve corresponding to the given Acceleration Response Spectrum; T_s is the seismic duration and; p, is the probability of the peaks that do not cross with the given positive or negative barriers which usually assumed p=0.85, but yields a better result in most cases for p=0.5 according to study [1].

2.6.2. Modified Response Spectrum

The acceleration response spectrum at each support using DPWH-BSDS 2013 was obtained. Using these response spectra, response-spectrum-compatible non-stationary time histories and the corresponding modified response spectra at each support that fully accounts for the effect of SVGM were obtained. The modified response spectra were inputted in ANSYS as the new response spectra acceleration to carry out the analysis.

First, (5) must be calculated then decomposed at every time instant t under consideration which can be done using the Cholesky's Decomposition method:

$$S(\omega,t) = H(\omega,t)\cdot H^T(\omega,t) \tag{10}$$

Where superscript T denotes the transpose of a matrix and H(ω,t) is a lower triangular matrix:

$$H(\omega,t) = \begin{bmatrix} H_{11}(\omega,t) & 0 & 0 & 0 & 0 \\ H_{21}(\omega,t) & H_{22}(\omega,t) & 0 & 0 & 0 \\ H_{31}(\omega,t) & H_{32}(\omega,t) & H_{33}(\omega,t) & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & 0 \\ H_{81}(\omega,t) & H_{82}(\omega,t) & H_{83}(\omega,t) & \cdots & H_{88}(\omega,t) \end{bmatrix} \tag{11}$$

Whose diagonal elements are real and non-negative functions of ω and the off-diagonal elements are generally complex function. The off diagonal has an element of:

$$H_{jk}(\omega,t) = \left|H_{jk}(\omega,t)\right| e^{i\theta_{jk}(\omega,t)} \tag{12}$$

$$\theta_{jk}(\omega,t) = \tan^{-1}\left(\frac{Im[H_{jk}(\omega,t)]}{Re[H_{jk}(\omega,t)]}\right) \tag{13}$$

Where θ_{jk} is the phase angle reflecting the wave passage effect.

The stationary stochastic random process can be determined using the given equation:

$$g_j(t) = 2\sum_{m=1}^{8}\sum_{l=1}^{N}\left|H_{jm}(\omega_l,t)\right|\sqrt{\Delta\omega}\cos[\omega_l t - \theta_m(\omega_l,t) + \varphi_{ml}];\ j = 1,..,8 \tag{14}$$

Where:

$\omega_l = l*\Delta\omega$; l = 1, 2, … , N

$\Delta_\omega = \omega_u/N$ is the frequency step (rad/sec)

ω_u = cut-off frequency (the frequency beyond which the PSDF ordinate has negligible value) (rad/s)

$ø_{ml}$ = independent random phase angles, uniformly distributed over the interval $[0,2\pi]$

However, the non-stationary characteristics of earthquake ground motion should be considered. In this case, a modulating function can be used to consider its non-stationary characteristics. For this study, the modulating function according to Bogdanoff-Goldberg-Bernard Model was used to simplify the analysis and is given by:

$$A_j(\omega,t) = A_j(t) = a_1\cdot t\cdot e^{(-a_2\cdot t)};\ j = 1,2,..,8 \tag{15}$$

For this study, a_1 = 0.906 and a_2 = 1/3. The generation of non-stationary acceleration time history is given by:

$$f_j(t) = A_j(t)g_j(t) \tag{16}$$

The elastic acceleration response spectrum can then be computed, and to achieve compatibility, an iteration process must be performed by upgrading the PSDF shown below:

$$S_j^{i+1}(\omega) \to S_j^i(\omega)\left[\frac{RSA_j(\omega)}{RSA_j^i(\omega)}\right]^2 \tag{17}$$

Where $S_j^i(\omega)$ is the power spectral density (stationary) of the ground motion at *j*-th station for i-th iteration and $S_j^{i+1}(\omega)$ for (i+1)-th iterations. $RSA_j(\omega)$ is the target response spectrum at station *j*, and $RSA_j^i(\omega)$ is the response spectrum of the simulated motion at the *j*-th station for the *i*-th iteration. The new PSD $S_j^{i+1}(\omega)$ is then used in the random field simulation and the iterations are repeated until satisfactory agreement between the target response spectrum and the simulated response spectrum is achieved. It should be noted that the iteration scheme is not expected to perfectly converge at all frequencies as the number of iterations increases [11].

Figure 4 shows the Auto-PSD for Bongo Bridge at each support for analysis case, Case 2 uniform ground type (ground type II), while Figure 5 shows the Auto-PSD for Bongo Bridge at each support for analysis case, Case 3 varying ground type (ground type I and II). On the other hand, Figure 6 and Figure 7 show the modified response spectra considering spatial variabilities of ground motion, for analysis case, Case 2, and Case 3, respectively.

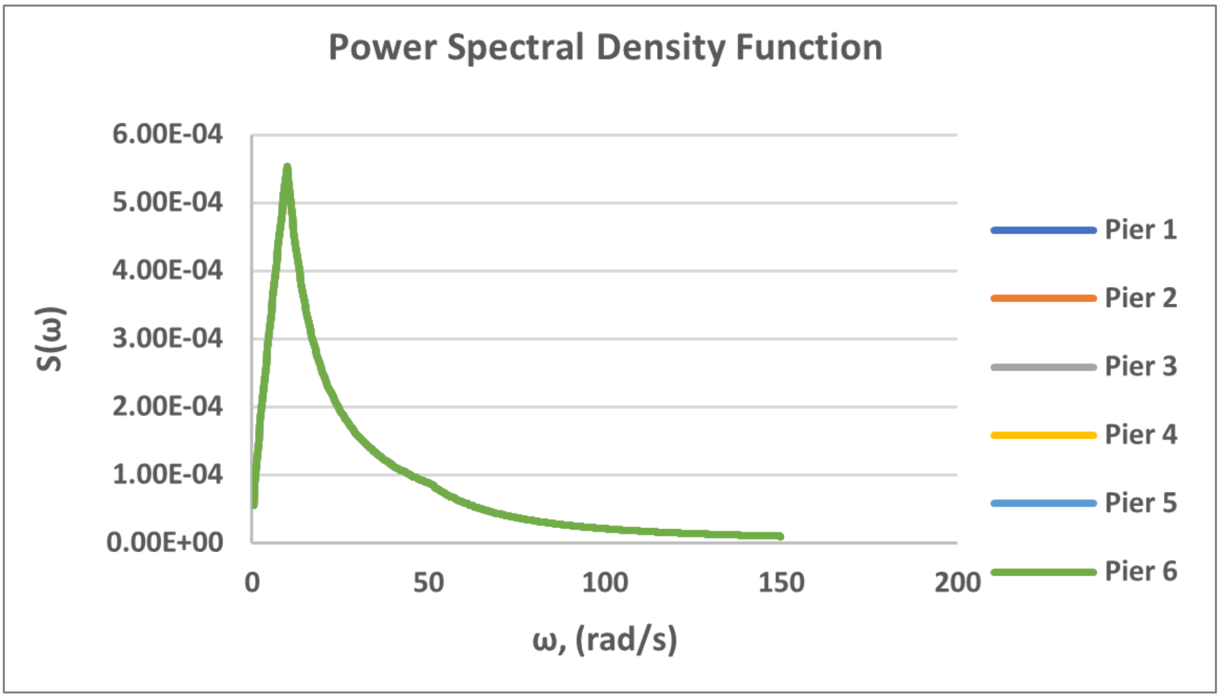


Figure 4. Auto-PSD for Case 2 Uniform Ground Type

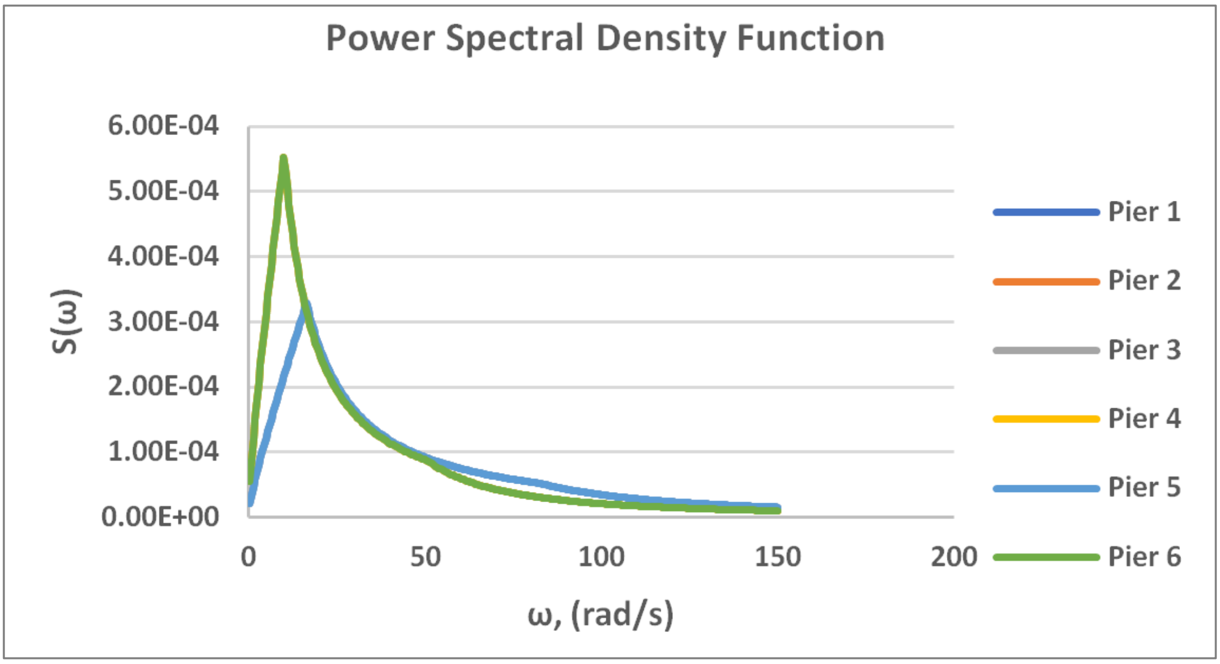


Figure 5. Auto-PSD for Case 3 Varying Ground Type

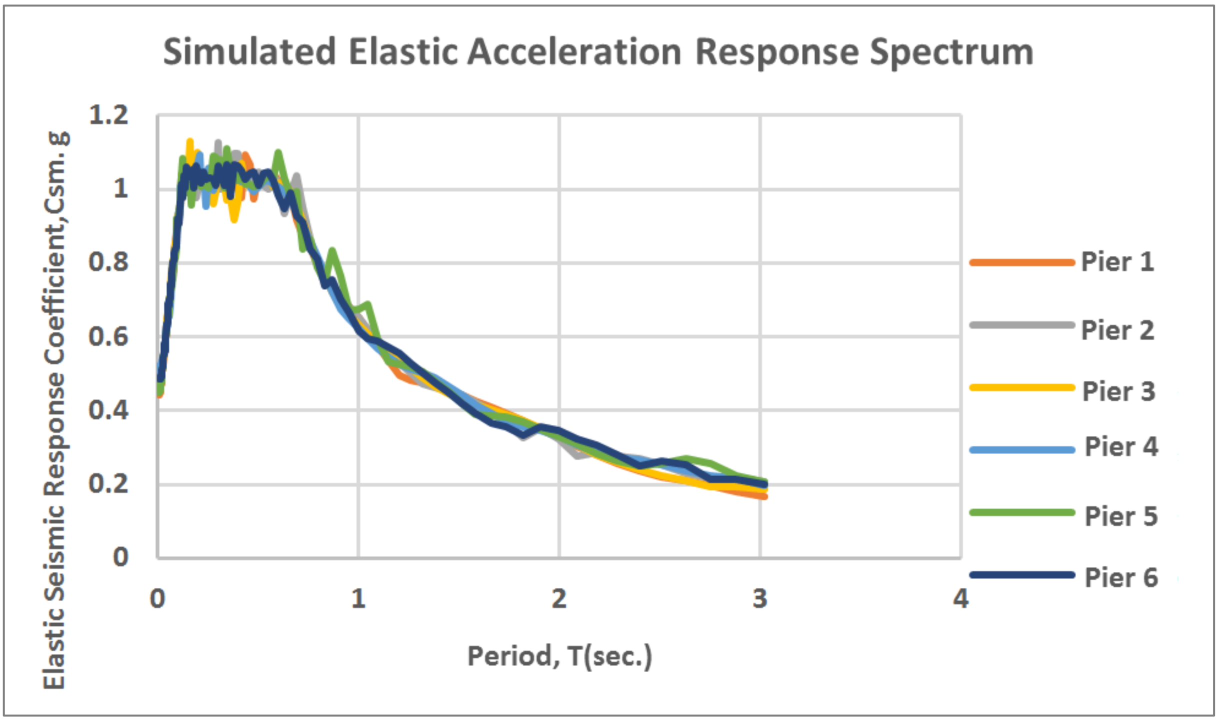


Figure 6. Auto-PSD for Case 2 Uniform Ground Type

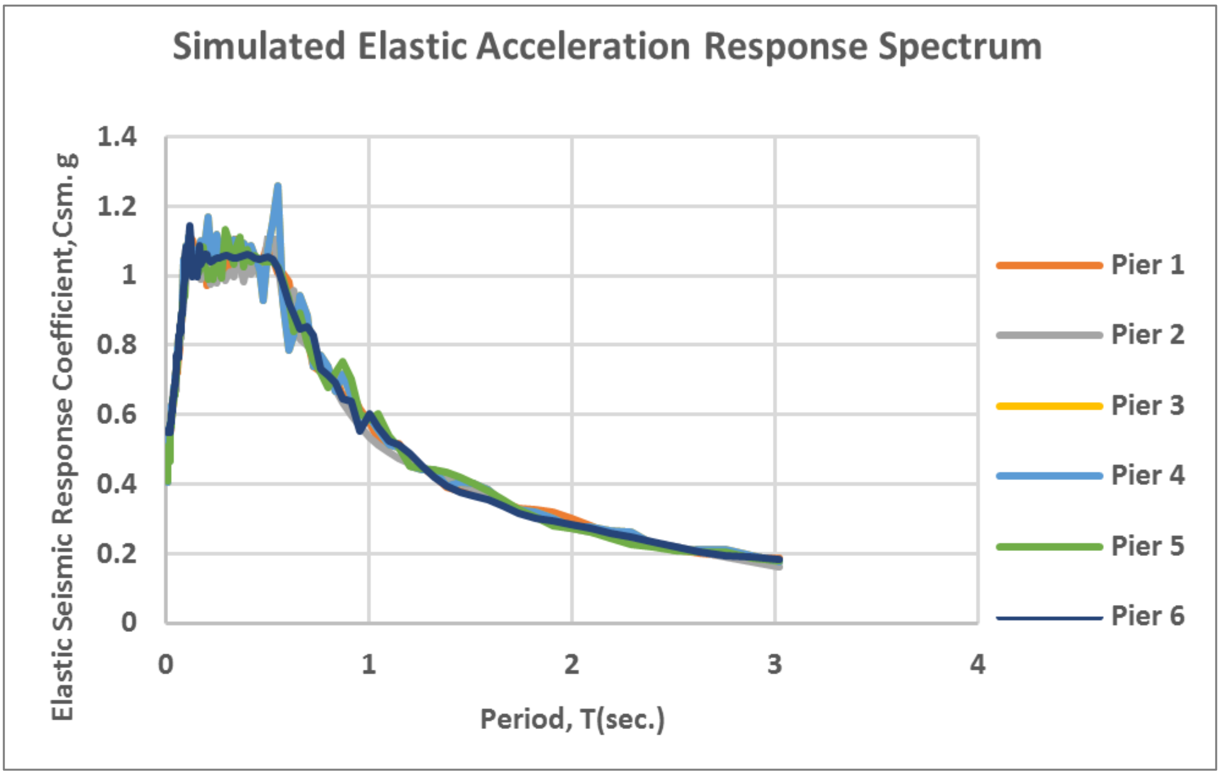


Figure 7. Auto-PSD for Case 3 Varying Ground Type

2.7. Analysis Cases

The purpose of this study is to determine if the SVGM will have a significant effect on the seismic response of the existing bridge using the multiple support response spectrum analysis of ANSYS and present the steps in generating a modified response spectrum that can account SVGM. Additionally, this study will serve as a guideline for generating and the use of the modified response spectrum in engineering practice in the Philippines. To achieve this, the following cases were implemented:

Case 1: Uniform ground excitation

Case 2: Wave passage effect and incoherence effect (with uniform ground type)

Case 3: Wave passage effect and incoherence effect (with varying ground type)

For Case 1, the analysis was carried out in ANSYS using the design response spectrum per DPWH-BSDS 2013 utilizing the SPRS analysis feature. It was assumed that the wave propagates in the direction from Abutment A to Abutment B, hence $d_{kl}^{L} = d_{kl}$. For Case 2, the analysis was carried out in ANSYS using the modified response spectrum utilizing the MPRS analysis feature. The ground type reference for Case 1 and Case 2 is ground type II. In Case 3, originally Bongo bridge was erected on a site where the ground type is uniform along its span. However, this may not be the case for other bridges already erected or to be erected as the ground type may vary. For this case, since a single point response spectrum is only considered in general practice, the most critical ground type is being used for the entire bridge to simplify the seismic analysis. However, this assumption may cause an inaccuracy such as an over- or underestimation of the bridge's seismic response since each pier's local demand may be overlooked. The Case 3 was performed just to demonstrate the possible effect on the seismic response of the bridge erected in varying ground types. The ground type reference for Case 1 is the ground type I, and Case 3 is the ground type I and II. The seismic responses (displacement, shear force, bending moment) of the Bongo Bridge from the two cases were compared to check, specifically for cases 2 and 3, if the responses were amplified or de-amplified when the existing bridge was subjected to multiple support excitation. To do this, the researcher used the Paired T-Test to determine if there are significant differences between the seismic responses of the bridge under Case 1 & Case 2; and Case 1 & Case 3.

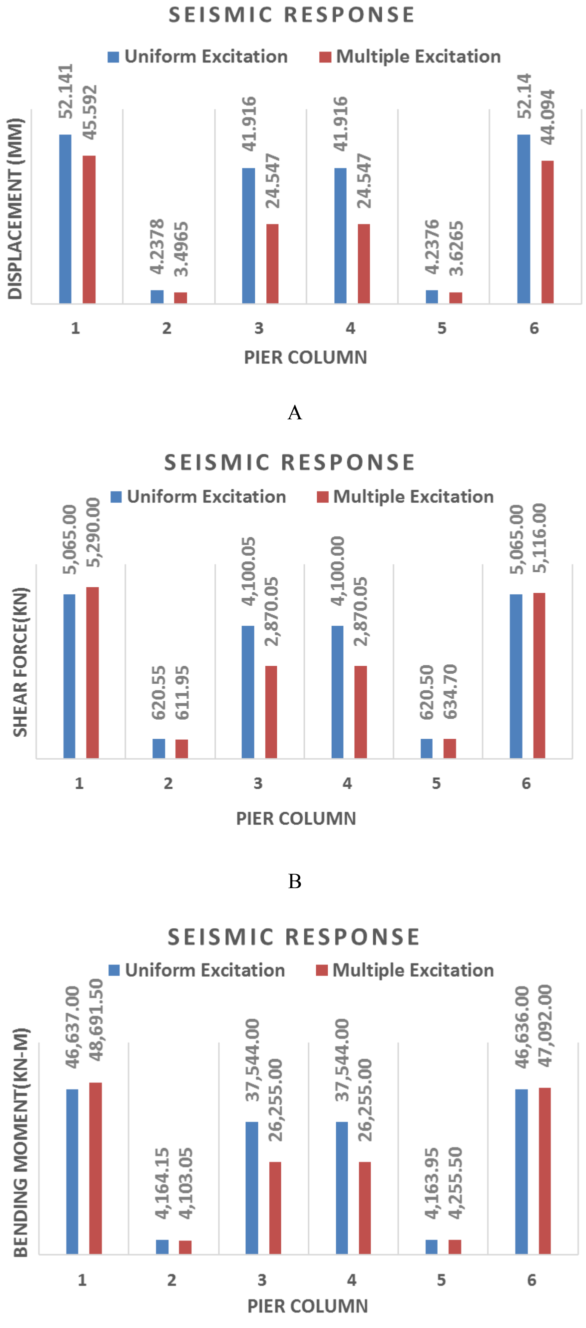
3. Result

3.1. Case 1 vs. Case 2

In Figure 8A, it can be observed that the displacement in all pier columns decreased by 12% to 41% when the bridge was subjected to multiple support excitation. Pier 1 and Pier 6 displacements decreased by about 15%; while for Pier 3 and Pier 4 decreased significantly by about 41%; Lastly, Pier 2 and Pier 5 decreased by about 17%.

Figure 8B shows the internal shear force in the pier columns. It can be observed that the shear forces in Pier 1, Pier 5, and Pier 6, when subjected to MSE, slightly increased by 1% to 4.5%. For Pier 1 and Pier 5, the shear force increased by 2.2% and 4.5%, respectively, while Pier 6 increased by 1%. However, the shear forces in Pier 2, Pier 3, and Pier 4 decreased by 1.4% to 30%. For Pier 2, the shear force decreased by 1.4% while that of Pier 3 and Pier 4 decreased by 30%.

Figure 8C shows the bending moment in the pier columns. It can be observed that the bending moment in Pier 1, Pier 5, and Pier 6, when subjected to MSE, slightly increased by 1% to 4.4%. For Pier 1, the bending moment increased by 4.4%; for Pier 5, the bending moment increased by 2.1%; for Pier 6, the increase is about 1%. However, the bending moment in Pier 2, Pier 3, and Pier 4 decreased by 1.47% to 30%. For Pier 2, the bending moment decreased by 1.47%, while that of Pier 3 and Pier 4 decreased by 30%.



A

B

C

Figure 8. Seismic Responses at Pier Columns: Case 1 vs. Case 2

Table 4. Paired T-Test Results (Case 1 vs. Case 2)

Seismic Response	Mean Diff., $\bar{D}$	SS_D	T-Statistic, t_{calc}	df	Critical Value, t_{table}	Remarks
Displacement	8.448	283.747	2.747	5	2.571	*tcalc > ttable = Ha*
Shear Force	363.058	2288310	1.315	5	2.571	*tcalc < ttable = Ho*
Bending Moment	3339.508	1.92E+08	1.319	5	2.571	*tcalc < ttable = Ho*

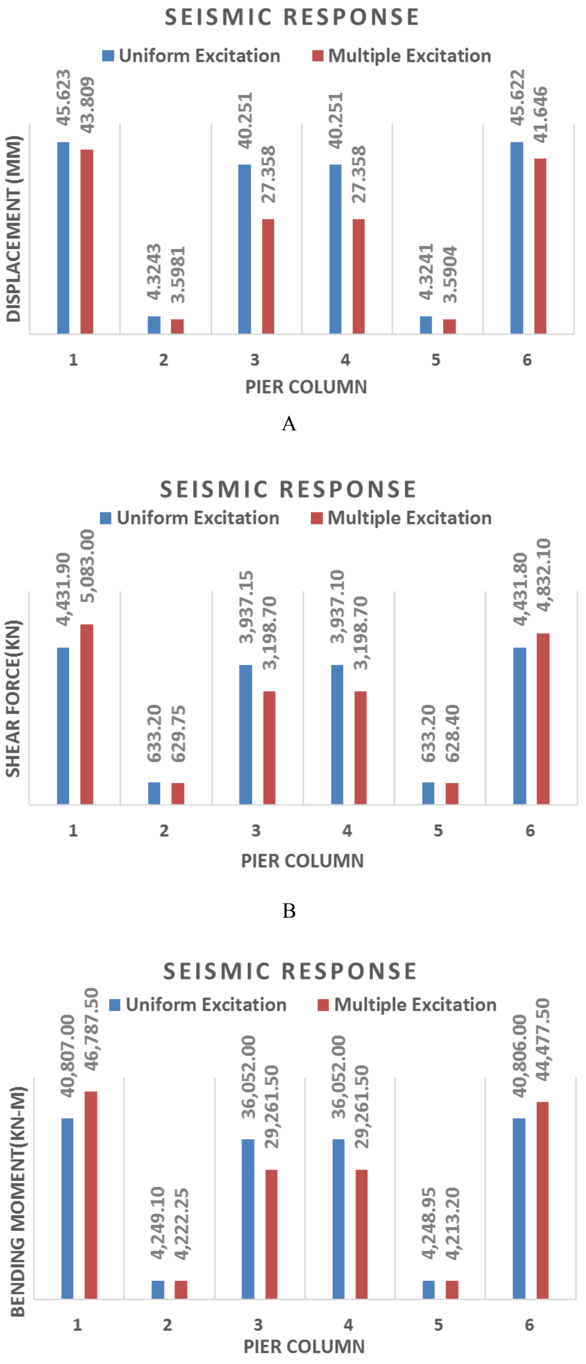
The evaluation of the results using Paired T-Test is shown in Table 4. For the displacement demand, since the calculated t-statistic is greater than the critical value, the null hypothesis (Ho) is rejected and shows that there is a significant difference in the displacement of the uniform excitation and multiple support excitation, specifically, the displacement demand decreased. For shear force, since the calculated t-statistic is less than the critical value, the null hypothesis (Ho) is accepted and shows no significant difference in the sheer force of the uniform excitation and multiple support excitation. For the bending moment, since the calculated t-statistic is less than the critical value, the null hypothesis (Ho) is accepted and shows no significant difference in the bending moment of the uniform excitation and multiple support excitation.

3.2. Case 1 vs. Case 3

In Figure 9A, it can be observed that the displacement in all pier columns decreased by 3.9% to 32% when the bridge was subjected to multiple support excitation. Pier 1 and Pier 6 displacements decreased by 3.9% and 8.7% respectively; while for Pier 3 and Pier 4 decreased significantly by about 32%; Lastly, Pier 2 and Pier 5 decreased by about 16.8%.

Figure 9B shows the internal shear force in the pier columns. It can be observed that the shear forces in Pier 1 and Pier 6, when subjected to MSE, increased by 9% and 14.69% respectively. However, the shear forces in Pier 2, Pier 3, Pier 4, and Pier 5 decreased by 0.5% to 18.75%. For Pier 2 and Pier 5, the sheer force decreased by 0.5% only while that of Pier 3 and Pier 4 decreased by 18.75%.

Figure 9C shows the bending moment in the pier columns. It can be observed that the bending moment in Pier 1, and Pier 6, when subjected to MSE, increased by 14% and 9% respectively. However, the bending moment in Pier 2, Pier 3, and Pier 4 and Pier 5 decreased by 0.6% to 18.83%. For Pier 2 and Pier 5, the bending moment decreased by 0.6% while that of Pier 3 and Pier 4 decreased by 18.83%.



A

B

C

Figure 9. Seismic Responses at Pier Columns: Case 1 vs. Case 3

Table 5. Paired T-Test Results (Case 1 vs. Case 3)

Seismic Response	Mean Diff., $\bar{D}$	SS_D	T-Statistic, t_{calc}	df	Critical Value, t_{table}	Remarks
Displacement	5.506	170.729	2.308	5	2.571	$t_{calc} < t_{table}$ = Ha
Shear Force	72.283	1643400	0.309	5	2.571	$t_{calc} < t_{table}$ = Ho
Bending Moment	665.267	1.39E+08	0.309	5	2.571	$t_{calc} < t_{table}$ = Ho

The evaluation of the results using Paired T-Test is shown in Table 5. Based on the results, for displacement demand, since the calculated t-statistic is less than the critical value, therefore the null hypothesis (Ho) is accepted and shows that there is no significant difference in the displacement of the uniform excitation and multiple support excitation. For shear force, since the calculated t-statistic is less than the critical value, the null hypothesis (Ho) is accepted and shows no significant difference in the sheer force of the uniform excitation and multiple support excitation.

For bending moment, since the calculated t-statistic is less than the critical value, the null hypothesis (Ho) is accepted and shows no significant difference in the bending moment of the uniform excitation and multiple support excitation.

4. Discussions

While the conventional response spectrum is the most common and practical method used in dynamic analysis of bridges, the method however might over or underestimate the seismic response of the bridge. Because of Spatial Variation of Ground Motion (SVGM), structures may undergo multiple-support excitation and the most affected structures by this are the extended structures such as bridges. [2] emphasizes the detrimental influence of multiple support excitation on the seismic response of arch bridges regardless of their span. According to [5], this non-uniformity effect of ground motion led to significantly greater values of stresses compared to that of the uniform excitation when they observed the response of a concrete viaduct. On the other hand, the significant effect of the variation of ground motion in the seismic response of long-span and high-pier bridges was also observed [3]. Moreover, a considerable difference in seismic response with or without multiple support excitation was observed for a bridge founded on a non-uniform soil profile [4].

The result of the study agrees with the abovementioned studies. In Case 1 versus Case 2, since the ground type was uniform, the resulting design response spectrum was the same at all supports, making the excitation at supports still uniform regardless of using the MPRS. However, the discrepancies in the results were caused by incorporating the effect SVGM (incoherence effect and wave passage effect). Additionally, the effect of multiple support excitation may be beneficial (reduced the demand) to the bridge [7]. Based on the results of this study, the effect of SVGM was evident, and the seismic response in some piers reduced especially for the displacement where reduction was significant, thus, the study is consistent with the abovementioned statement.

In Case 1 versus Case 3, the reference ground type for the design response spectrum used was Ground Type I for Case 1 and Ground Type I & II for Case 3. The basis of this case is that, in practice, since the current code, BSDS 2013, only uses a single response spectrum, therefore the ground type that will generate large acceleration is being used. However, since the method ignores the ground variability, the local demand at each pier is being ignored and may lead to over- or under-estimation of the seismic demand. Based on the results, when the variation of ground type or site class was considered in the analysis, the seismic response amplified in some piers while the others were de-amplified, thus the conventional method, based on these results, underestimated the seismic response which can affect the strength of the pier columns while the overestimated piers can affect the economical aspect of the structure especially for a capacity based designed structure. Nevertheless, the effect of multiple support excitation considering the variability of ground type to the seismic response of the Bongo bridge was not significant.

The seismic response for Pier 2 and Pier 5 is small because of the expansion connection and the mass participating in this mode shape is small. On the other hand, Piers 1, 3, 4 and 6 have a higher seismic response because of the fixed connection hence the superstructure inertial force transmits directly into the pier columns. Additionally, the mass participation factor of these piers (1, 3, 4 & 6) is higher compared to other mode shapes, resulting in a higher seismic response.

These results may not be the same as other bridges and significant differences may arise depending on the site condition and structural configuration of the bridge, therefore, it is still recommended to perform a multiple support excitation accounting the effect of SVGM especially when the ground type is varying or multiple support bridges with longer spans or longer overall span and bridges in higher seismic demand area. Additionally, as the result shows an increase in seismic demand in some piers, it is therefore advantageous to conduct multiple support excitation analyses to cover this increase in demand to provide a higher seismic resistant structure. At the same time, the decrease in seismic response can provide a more economical design of bridges.

5. Conclusions

In the Philippines, the method used for seismic analysis of bridge structures, in most cases especially for conventional bridges, is the conventional response spectrum analysis based on the DPWH BSDS 2013 guidelines. However, it is known that this method assumes that the ground motion is uniform, thus the supports excite uniformly. But multiple support excitation may arise due to the spatial variation of ground motion. Spatial variation of ground motion (SVGM) may negatively affect structures, especially for extended structures such as pipelines, dams, or bridges. Based on the study, the following conclusion has been drawn:

1. Based on the results of Case 1 versus Case 2, the effect of multiple support excitation was inconsistent since some piers have their seismic response increased while some decreased. Here, the site effect does not play a major role since the ground type is uniform at each support. The discrepancies were caused by adding the effect of wave passage and incoherence effect. It shows here that these components of SVGM have a beneficial effect as they decreased the piers displacement by 12% to 41%. On the other hand, these components have a minor effect on the sheer force as it increased by a maximum of 4.5% only in Piers 1, 5 and 6 and have a beneficial effect for Piers 2, 3 and 4 as it decreased by a maximum of 30%. Lastly, these SVGM components have a minor effect on the bending moment as it increased by a maximum of 4.4% only in Piers 1, 5 and 6 and have a beneficial effect for Piers 2, 3 and 4 as it decreased by a maximum of 30%.
2. Based on the results of Case 1 versus Case 3, the effect of multiple support excitation amplified the seismic response of some Piers and de-amplified some. When the effect of ground type variability was included, it decreased the displacement demand of the piers by a maximum of 32%. On the other hand, the shear forces increased by a maximum of 14.69% for Piers 1 and 6 but decreased by a maximum of 18.75% for Piers 3, 4 and 5. Lastly, the bending moment at Piers 1 and 6 increased by a maximum of 14% while in Piers 2, 3 and 5, decreased by a maximum of 18.83%. This indicates that the local site effect plays a major role in the seismic analysis and should not be ignored as it may over or underestimate the seismic demand of the structure especially when using the conventional response spectrum analysis which can affect the strength and economical aspect of the structure especially for a capacity-based design structure.
3. According to the statistical analysis performed using Paired T-Test, for Case 1 vs. Case 2 scenarios, the multiple support excitation decreased the displacement demand in the piers significantly. The rest (shear, moment) has no significant difference from that of the uniform support excitation. For Case 1 vs. Case 3, although there's a large increase/decrease in the response in some piers, the overall effect of multiple support excitation has no significant difference to that of the uniform support excitation.

Although the seismic response analysis performed in this study was limited to Bongo bridge, the method may still be valid for other similar types of bridges, but the results do not guarantee to be the same. Additionally, a general trend in the seismic response cannot be determined because several factors can affect the output such as the proximity of the bridge to the fault line, ground type, structural system of the structure, span length, etc., thus the results are generally depending on the records or data used and because of that, it is still recommended to include the multiple support excitation effect in the seismic analysis and design of similar bridge especially when the bridge is located where the ground type is varying. Finally, because there was a significant difference in the seismic response of uniform and multiple support excitation, specifically in the displacement demand, the conventional RSA based on BSDS 2013 overestimated the displacement demand of the Bongo Bridge, and the effect of SVGM became beneficial to the bridge, according to the results. However, it shows that the SVGM has no significant effect to the seismic response, specifically in shear force and bending moment, this effect should not be overlooked especially for those piers whose seismic demand increased. Thus, the structural adequacy and performance of the pier columns must still be checked against these forces. As for the piers whose seismic demand decreased, it's up to the designer which one is to adopt as it may affect the bridge structure's economical aspect, especially for a Capacity-Based designed bridge.

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