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MODIFIED – MSRS ANALYSIS OF AYALA BRIDGE DUE TO SPATIAL VARIATION OF GROUND MOTION (SVGM)

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ABSTRACT: Extended structures, such as bridges, experience variations in ground motion, which cause multiple excitations in the supports. Spatial variation in ground motion is primarily influenced by factors such as incoherence, wave passage effects, and local site conditions. Philippine Highway Bridges are designed using the DPWH–BSDS 2013, in which the seismic excitations are uniform across bridge supports, neglecting the spatial variability of motion. In this research, the concern for the difference in ground motion experience between supports was addressed, considering a Multiple Support Excitation for the Ayala Bridge. The dynamic analysis was performed in ANSYS, which allows varying ground motion conditions. For the Uniform Support Excitation, the DPWH–BSDS 2013 was used for generating the Response Spectrum and used Single–Point Response Spectrum analysis. On the other hand, a Multi–Point Response Spectrum analysis was used to account for the effects of MSE through a modified response spectrum generated in MATLAB, which accounts for SVGM. A significant impact on the bridge's seismic performance was observed, as indicated by the p-values related to displacement and shear responses of 0.0012 to 0.0037 and 0.0000 to 0.0268, respectively, across all piers; and in moment response with 0.0012 to 0.0237 for piers 2 to 6. The seismic performance of the bridge is significantly affected by the type of excitation experienced by the bridge supports. Therefore, considering MSE when designing highway bridges is necessary because it can affect the overall bridge performance.

Keywords: Multiple Support Excitation, Spatial Variation of Ground Motion, Modified Response Spectrum, Medium Span Bridge, ANSYS

1. INTRODUCTION

Approximately 150 strong earthquakes are felt annually in various parts of the globe, with 134 ranging from 6.0 to 7.0, 15 from 7.0 to 8.0, and at least one per year exceeding magnitude 8.0 [1]. As part of the Pacific Ring of Fire, the Philippines is surrounded by tectonic plates. The Philippines is susceptible to violent ground disturbances due to the interactions between the Philippine Sea Plate (PSP) and the Pacific, Sunda, and Eurasian Plates. It is mentioned in the research of Smoczyk et al. [2] that there is subduction between the Pacific and Philippine Sea plates that can produce earthquakes with a maximum magnitude of 8.0 on the eastern and southeastern edges of the Philippines.

In the past few decades, numerous studies have been conducted on the seismic effects of earthquakes on buildings, bridges, and other structures. Some studies focus on the fragility of reinforced concrete structures, the inelastic behavior of frames, the story drift of buildings, the responses of extended structures to earthquakes, and other research involving buildings' structural behavior and reactions, particularly in seismically vulnerable areas during an earthquake.

Multi-mode spectral analysis is the most widely used method for seismic response analysis today. This method combines different distinct modes, using techniques such as Complete Quadratic Combination (CQC) and the Square Root of the Sum of the Squares (SRSS). It assumes that the structural system experiences uniform ground motion. This assumption might not apply to short-span bridges or multi-span bridges. Still, it should be noted that the Earth's motion is affected by varying types of soil layers and the location or distance to the epicenter of an earthquake. Extended structures such as dams, aqueducts, viaducts, medium or long-span bridges, and other bridge systems in which the supports are far from each other might experience a different response. Thus, using the current method might underestimate or overestimate the seismic force. The variation in ground motion should consider the effects of wave propagation delays, loss of coherency between support points, and the influence of local soil conditions at each location [3].

In the book by Zerva (2009), the author describes the wave passage effect as occurring due to variations in the arrival times of seismic waves at different stations, resulting from the finite speed of these waves. The incoherence effect refers to the loss of coherence in motion, which is caused by wave reflections and refractions within a heterogeneous ground medium, as well as by differences in wave superposition from a distant source. Finally, variations in local soil conditions at different stations give rise to the site response effect, which influences both the amplitude and frequency characteristics of seismic waves at the bedrock level [4].

The response spectrum analysis remains the most suitable method for the engineering community to analyze structures under multiple support excitations. Mainly because seismic designs and codes worldwide consider earthquake motions in a response spectrum Li et al. [5]. In 2012, the Vincent Thomas Bridge was analyzed using a nonlinear time history that employs spectrum-compatible spatial variable ground motions Karmakar et al. [6]. In 1991, Der Kiureghian et al. [7] presented a method of seismic evaluation of structures with multiple supports, it is essential to consider three primary components of spatially varying ground motions: time delays due to wave propagation (wave passage effect), the gradual loss of motion correlation between supports (incoherence effect), and the influence of differing soil conditions at each support location, commonly referred to as local site effects. This approach was notably utilized in the 1993 seismic study of the Golden Gate Bridge. The California Department of Transportation projected the earthquake motion of the San Francisco-Oakland Bay Bridge based on the soil and rock parameters near the bridge, as well as the anticipated earth movements at the San Andreas Fault and Hayward Fault. Since bridges are lengthy, variations in ground conditions and the difference in wave passage arrival time in supports are significant enough to account for the spatial variation of ground motion [3].

Mariano & Estores [3] explored how spatial differences in ground motions, specifically due to multiple support excitations, affect the seismic response of the Bongo short-span bridge, which is categorized under the AASHTO LRFD bridge design specifications [17]. Due to multiple support excitations, the seismic response of the Bongo Bridge experienced a significant effect, particularly on the displacement demand. Furthermore, the overall impact of multiple support excitation is not significantly different from that of uniform support excitation. As mentioned, this assumption might not be concerned with short- or multi-span bridges. Still, it should be noted that the Earth's motion is affected by varying types of soil layers and the location or distance to the epicenter of an earthquake. Multiple support excitations are commonly used in various countries to conduct parametric studies on their effects on bridge structures. Examples include the Golden Gate Bridge, Southern Poland Road Viaduct, Liohe Bridge, and other bridges in China [8]. Additionally, the Penstock Bridge in Washington, the Big Rock Wash Bridge, the Auburn Ravine Bridges, and the South Ingram Slough Bridge in California have been analyzed using the multiple support response spectrum method to assess their accuracy [9]. Harichandran investigated the effect of spatial variation of ground motion (SVGM) on the response of long-span structures to differential excitations [10,11,12], as well as reinforced concrete arch bridges, Novak et al. [13], and high-pier railway bridges, Li et al. [5].

This research investigates the effect of multiple support excitations on the seismic behavior of an existing medium-span bridge, comparing the findings with those obtained from standard response spectrum analysis. The objective is to identify whether conventional methods tend to misrepresent the actual seismic demands, either by overestimation or underestimation, and to investigate if bridges with longer spans are more vulnerable to the impacts of such spatially variable ground motions.

The Modified Multiple Support Response Spectrum Analysis (Modified–MSRS) is the key aspect of this research, as the present study wanted to highlight the incorporation of spatial variability of ground motions (SVGM)—specifically, the incoherence, wave-passage, and site-response effects—into the formulation of the response spectrum, which were simulated using a MATLAB-based parametric model. Additionally, the development of a site-specific modified response spectrum, as opposed to using a uniform design spectrum across supports. This spectrum was computed by convolving the stochastic ground motion parameters with the site transfer functions derived from geotechnical data.

The primary objective of this study is to evaluate whether modified multiple support excitation significantly impacts the seismic response of Ayala Bridge, a medium-span bridge. Wherein, based on the chosen methodology, the study aims to develop practical engineering steps and guidelines for generating a modified response spectrum. The research will also compare the effects on longer-span bridges when subjected to varying conditions.

To achieve this objective, the researcher will conduct the following four scenarios:

Case 1: Uniform Support Excitation (with uniform ground type)

Case 2: Multiple Support Excitation (accounts for SVGM with a uniform ground type)

Case 3: Multiple Support Excitation (accounts for SVGM with a varying ground type)

Case 4: Uniform Support Excitation (with a varying ground type)

In Case 1, the bridge is subjected to consistent ground motion based on the standard Response Spectrum method outlined in the DPWH-BSDS 2013 seismic provisions [18]. In Case 1 of this study, the term original bridge response refers to the structural behavior of the bridge as analyzed under Uniform Support Excitation (USE), following the DPWH BSDS 2013 design procedure. This baseline reflects the conventional seismic design approach used in most Philippine bridges, which does not account for the effects of spatial ground motion variability. The maximum displacement, bending moment, and shear force for all four scenarios are computed and compared to determine whether the spatial variation of ground motion (SVGM) amplifies or mitigates these structural responses, and to assess the significance of the differences observed.

2. RESEARCH SIGNIFICANCE

The significance of this research aligns directly with the United Nations Sustainable Development Goals (SDGs), specifically Goals 9 (Industry, Innovation, and Infrastructure), 11 (Sustainable Cities and Communities), and 13 (Climate Action). This study analyzes the Ayala Bridge to assess whether the seismic performance of the bridge is significantly affected. It considers that Philippine Bridges were designed based on DPWH–BSDS 2013, which only finds Uniform Support Excitation. This provides valuable insight for engineers and designers, emphasizing the importance of incorporating the effects of Spatial Variation of Ground Motion (SVGM) in the seismic design of long-span structures such as highway bridges.

3. METHODS

3.1 Research Locale Identification

This phase was used to identify conventional Philippine highway bridges. The following parameters are necessary and used in identifying which bridge to be analyzed, the following data was used: (1) bridge geometric design, which includes – clear span, material properties, and location; (2) clear span will identify the bridge classification based on the AASHTO LRFD Bridge Classification – particularly medium span bridge with at least 50.0 meters to 100.0 meters of clear span (support-to-support length); (3) availability of complete bridge and structural plans; (4) availability of geotechnical data particularly the borehole log as to determine the Site Class and Ground Type of the bridge piers; and (5) if the bridge identified is currently existing and being used by the public. The chosen bridge, which meets the parameters mentioned above, was used for the next phase of the research and submitted a letter of permission and intent to the Department of Public Works and Highways NCR; otherwise, the Ayala Bridge satisfies all the requirements and parameters mentioned.

3.2 Data Gathering Procedure

This phase gathers all the necessary information and data for the Modified Multiple Support Response Spectrum (MMSRS) Analysis of the identified medium-span bridge from Phase 1. The geometric data is essential to properly model the chosen bridge: the total bridge length, number of spans and span length, the bridge width, deck thickness, type and number of rafters, and pier bored piles. The material property is as essential as geometric data: the deck, girder, coping beam, pier column, abutment, pile foundation, and rebar strength. Geotechnical data is necessary for identifying site classification, ground type, where the bridge is situated, and the location of its pier. All this required data should come from the implementation offices of the bridges to ensure the correctness of the data. The following data were obtained for the Ayala Bridge:

Table 1. Bridge Details and Geometry

Bridge Details	
Bridge Name:	Ayala Bridge
Bridge Location:	San Miguel, Manila
Bridge ID No:	B02275LZ
Total Bridge Length	141.919 m
Number of Spans	2
Span 1 (South Span)	64.854 m
Span 2 (North Span)	77.065 m
Total Bridge Width	25.230 m
Number of Lanes	4
Number of Sidewalks	2
Length of Sidewalks	2.5m(L) & 3.6m(R)
Deck thickness	200 mm
Number of Main Girders	3
Girder Type	Truss Girders (West, Middle, and East)
Coping Beam Dimensions Pile Bent A and B	2.2mx3.0mx27.420m
Coping Beam Dimensions Pile Bent P	2.6mx3.3mx35.230m
Board Piles Diameter X Column Length - Pile Bent A	2.5m x 50.0m
Board Piles Diameter X Column Length - Pile Bent B	2.5m x 50.0m
Board Piles Diameter X Column Length - Pile Bent P	3.0m x 50.0m

Table 2. Material Properties of the Ayala Bridge

Structural Member Material Properties	
Deck	fc' = 28 MPa
Girder	fc' = 28 MPa
Coping Beam, Pier Column, Abutment, Pile Foundation	fc' = 28 MPa
Structural Steel (minimum yield strength), Fy	
Rebar ø>10mm	Grade 60, 414 MPa
Rebar ø≤10mm	Grade 40, 276 MPa
Structural Steel Shapes	ASTM A-709 Grade 36, 250 MPa
Steel Sheet Pipes	ASTM A-709 Grade 36, 250 MPa
Bridge Bearing	ASTM A-709 Grade 50W, 345 MPa
Deck Drain	ASTM A-48, 205 MPa

3.3 Design of Response Spectrum by DPWH – BSDS 2013

3.3.1 Response Spectrum for Uniform Support Excitation Spectrum

In the Philippines, the Department of Public Works and Highways – Bridge Seismic Design

Specifications (DPWH-BSDS) 2013 serves as the official guideline for the seismic analysis and design of bridges in national and government-funded infrastructure projects. This code was developed based on established international seismic design principles, primarily drawing from the AASHTO LRFD Bridge Design Specifications and relevant provisions from the American Association of State Highway and Transportation Officials (AASHTO) Guide Specifications for LRFD Seismic Bridge Design. The DPWH-BSDS 2013 adopts the Uniform Support Excitation (USE) approach, wherein all bridge supports are assumed to experience identical, synchronized ground motion during seismic events. While this assumption simplifies structural analysis, it does not account for the spatial variability of ground motion (SVGM)—including wave pas sage effects, incoherence, and varying site conditions—which are particularly significant in long-span, irregular, or multi-support bridge structures. [17,18].

The MATLAB Code 1: Response Spectrum Formulation for Uniform Support Excitation (Cases 1 and 4)

This MATLAB script generates design response spectra for different soil types, assuming uniform support excitation where all supports of the structure experience the same ground motion simultaneously. The generation follows the procedure of DPWH–BSDS 2013 [17].

The code simulates spectral acceleration curves for various soil types by incorporating input parameters derived from seismic hazard maps, specifically the Peak Ground Acceleration (PGA), Spectral Acceleration at short period (S_s), and Spectral Acceleration at 1-second period (S_1). These parameters are used in conjunction with site-specific amplification factors obtained from standard design spectra reference tables—F_{pga}, F_a, and F_v—which vary according to the soil classification (Soil Types I, II, and III).

For each soil type, the code performs interpolation to estimate the appropriate site amplification values based on the seismic parameters provided. It then computes key spectral quantities, such as the design spectral acceleration for the 1-second (S_{d1}) and the short-period design spectral acceleration (S_{ds}). These values are used to determine the transition period Ts, which divides the constant spectral acceleration range from the descending branch of the response spectrum.

The response spectrum is constructed as a piecewise curve consisting of three linear segments followed by a hyperbolic decay. Specifically, the curve starts from zero, rises linearly to reflect the short-period response, remains constant over a range, and finally descends hyperbolically beyond the transition period. The full spectrum is plotted for each soil type, allowing for a direct comparison of seismic demand based on subsurface conditions.

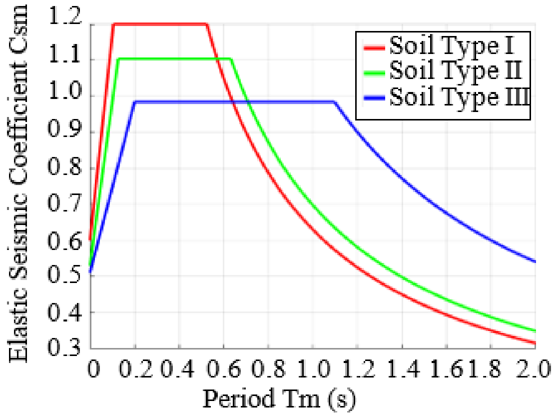

Fig.1 Design Response spectrum curve by DPWH – BSDS 2013 for Different Soil Types

3.3.2 Modified Response Spectrum for Multiple Support Excitation Spectrum

The Modified Multiple Support Response Spectrum (Modified–MSRS) approach adopted in this study deviates from the traditional MSRS analysis by explicitly accounting for the spatial variability of ground motions (SVGM) at each support location of the bridge. Unlike the conventional method which typically applies uniform or simplified ground motion input across all supports, the present approach generates site-specific response spectra using a MATLAB-based simulation that incorporates the influence of local soil conditions, wave-passage effects, and incoherence of seismic waves. This results in a unique response spectrum for each support, reflecting the variation in ground motion characteristics due to differing geotechnical profiles. By doing so, the Modified-MSRS captures a more realistic and physically consistent representation of seismic demands across the structure. It is mentioned in the research of Fauzan et al. [19], where the ground acceleration was matched and fine-tuned to the spectral acceleration of Padang Pariaman Regency to ensure compatibility with the structural location of the bridge used, which employed similar principles in this research.

This MATLAB script is developed to simulate and generate response spectra under multiple support excitations, specifically addressing Cases 2 and 3 from the seismic assessment of the Ayala Bridge. Unlike Case 1, which assumes uniform ground motion across supports, this approach incorporates spatial variability of seismic excitation along the bridge supports—an essential factor for long-span or irregular structures. The program begins by prompting the user to load a CSV file containing the baseline response spectrum data, including periods and spectral accelerations, which forms the foundation for subsequent calculations.

The variability of ground motion across different locations is represented using principles from random vibration theory, where seismic acceleration is described within the context of the Power Spectral Density (PSD) approach. The PSD matrix for ground acceleration across m supports is represented as follows, accounting for the spatially variable ground motion (SVGM) effect:

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

Here, $S_{mm}(\omega)$Ll denotes the auto-power spectral density at the mth support in the frequency domain, derived from the design response spectrum. Meanwhile, $S_{kl}(i\omega)$or S_{mm} (for m $\neq$ m) represents the cross-power spectral density, which captures the spatial variability of the seismic ground motion between different supports. The expression calculates the cross-PSD terms:

$$S_{kl}(\omega) = \rho_{kl}(\omega)\sqrt{S_{kk}(\omega)S_{ll}(\omega)} \quad (2)$$

where $\rho_{kl}(\omega)$ Is the coherency function measuring the correlation of acceleration between supports k and l? Among various existing models, this study employs the widely accepted Luco and Wong (1986) coherency model, expressed as:

$$\rho_{kl} = exp[-(\alpha * \omega * d_{kl})^2]exp\left(i\frac{\omega * d_{kl}^{L}}{V_{app}}\right) \quad (3)$$

This equation describes two principal components of spatially variable ground motion: the first exponential term represents the incoherence effect of correlation with increasing frequency and separation distance, modulated by the incoherence factor, α. Typical α values will range from 2 × 10^-4 s/m to 3 × 10^-4 s/m as suggested by Luco and Wong [5,13,14]. As indicated by Luco and Wong [5,13,14]. Higher α values result in a faster decay of coherence with increasing frequency and distance. The second exponential term accounts for the wave passage effect, introducing phase shifts due to seismic wave travel between supports. In this expression d_{kl}^{L} will be the projection of , d_{kl} is the horizontal distance between supports k and l, v_{app} is the apparent seismic wave velocity—often approximated by the shear wave velocity v_s - ω is the circular frequency, and i = $\sqrt{-1}$ [5,8,13].

The simulation integrates key physical and statistical parameters such as the incoherence factor α and the apparent wave velocity. v_{app} , inter-support distances, damping ratio ξ, and seismic duration T_s (refer to Figure 3). Based on these inputs, the code computes the auto-power spectral density (Auto-PSD) employing Kaul's method. It forms the cross-power spectral density (Cross-PSD) matrix using the complex-valued coherency function, effectively modeling how seismic waves attenuate and decorrelate during propagation.

The equivalent auto-PSD at natural frequency

$$S_{kl}(\omega_0) = \frac{4\,\xi R_a^2(\xi, \omega_0)}{\pi\omega_0 r^2} \quad (4)$$

$$r^2 = 2ln[(-\frac{\pi}{\omega_0 T_s} ln\, p)^{-1}] \quad (5)$$

Here, Ra (ξ, ω_0) is the acceleration response spectrum (ARS) amplitude for damping ratio, (commonly set at 0.05) and natural frequency (ω_0). The parameter p represents the probability that the response peaks remain within given bounds; it is typically set to 0.85 but has been found to yield improved accuracy around 0.5 in some cases, as shown by Chen and Duan [8].

Table 3. Input Parameters for MMSRS

Structural Member Material Properties	
Incoherence factor (s/m)	2e-4
Apparent wave velocity (m/s)	272.5
Distance between supports (m)	50
Damping ratio	0.05
Parameter for peak likelihood	0.85
Seismic duration (s)	20

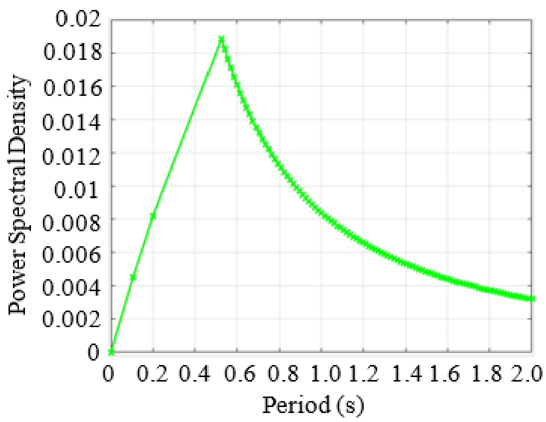

Fig.2 Auto–PSD Using Kaul Method

From these spectral components, the code generates a set of stationary stochastic ground motions, which are then transformed into non-stationary processes through the application of a modulating function. This function reflects the build-up and decay of seismic energy during an earthquake event, producing more realistic ground motion time histories. The script simulates multiple realizations to account for the randomness of seismic events. It introduces variability in the response spectrum at each pier by modifying the spectral acceleration values using a stochastic approach.

3.3.3 Response – Spectrum – Compatible Time History and the Modified Multiple Response Spectrum

The Acceleration Response Spectrum (ARS) for each support was generated by the DPWH-BSDS 2013 standards. These spectral acceleration inputs, together with Equations (1) and (4), were used to construct adjusted response spectra or compatible time histories at each support, effectively incorporating the effects of spatial variability in ground motion (SVGM).

The goal is to ensure that the resulting spatially varied seismic ground motions are non-stationary and, ideally, response spectrum compatible, adapting to non-homogeneous conditions when necessary. To achieve this, a target response spectrum was established using BSDS 2013, the complex coherence function (equation 3), and a modulating function (equation 6). Following this, the power spectral density function (1) will be determined.

Next, the stationary stochastic vector process gj(t), where j denotes the number of stations, will be simulated. To introduce the non-stationary nature of ground motion, spatially varying ground movements will be multiplied by an intensity-modulating function after initially forming them as stationary motions. This process will generate non-stationary time histories at each support location, comprising response-spectrum-compatible or modified response spectra for the computation of simulated ground motion.

An iterative method ensures that the resulting non-stationary motions conform to predefined response spectra requirements. Power spectral densities of motions will be adjusted accordingly at each location.

Modulating Function following Bogdanoff-Goldberg-Bernard Model [13]:

$$A_j(t) = a_1 * t * e^{(-a_2 * t)};\ j = 1, 2..8 \qquad (6)$$

The intensity modulating function may vary across different positions on the ground surface, depending on specific situational needs. However, the Bogdanoff-Goldberg-Bernard model will be adopted for this study to simplify the analysis with parameters. a_1= 0.906 and a_2= 1/3.

Earthquake ground motion increases from zero, reaches a steady phase, and eventually decays back to zero, exhibiting non-stationary behavior. Therefore, when modeling earthquake ground motion, its non-stationary characteristics must be carefully considered [15]. The non-stationarity of ground motion in the time domain can be described using a modulating function.

The generation of a stationary stochastic random process g_j (t) involves decomposing the power spectral density function at equation (1), which can be accomplished using Cholesky's decomposition method.

$$S(\omega, t) = H(\omega, t) * H^T(\omega, t) \qquad (7)$$

Where superscript T denotes the transpose of a matrix and $H(\omega, t)$It is a lower triangular matrix:

$$\begin{bmatrix} H_{11}(\omega,t) & 0 & 0 & 0 & 0 \\ H_{21}(\omega,t) & H_{22}(\omega,t) & 0 & 0 & 0 \\ H_{31}(\omega,t) & H_{32}(\omega,t) & H_{33}(\omega,t) & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & 0 \\ H_{81}(\omega,t) & H_{82}(\omega,t) & H_{83}(\omega,t) & \cdots & H_{88}(\omega,t) \end{bmatrix} \qquad (8)$$

Diagonal elements are natural and non-negative functions of ω; the off-diagonal elements are generally complex functions of ω.

Where the off diagonals have an element of:

$$H_{jk}(\omega, t) = \left|H_{jk}(\omega, t)\right| * e^{i*\theta_{jk}(\omega,t)} \qquad (9)$$

With,

$$\theta_{jk}(\omega, t) = \tan^{-1}\left(\frac{Im[H_{jk}(\omega, t)]}{Re[H_{jk}(\omega, t)]}\right) \qquad (10)$$

Im[.] and Re[.] denote that the imaginary and real parts of H_{jk}, respectively and θ_{jk}Is the phase angle reflecting the wave passage effect?

Note the following terms:

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

$\Delta\omega = \omega_u / N$ Is the frequency step in (rad/sec)

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

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

The stationary stochastic random process is then given by:

$$\boldsymbol{g_j(t) = 2\sum_{m=1}^{8}\sum_{l=1}^{N}\left|H_{jm}(\omega_l, t)\right|\sqrt{\Delta\omega}\cos\left[\omega_l t - \theta_{jm}(\omega_l t) + \varphi_{ml}\right]; j = 1,..,8} \quad (11)$$

Generation of non-stationary acceleration time histories $f_1(t)$:

$$\boldsymbol{f_j(t) = A_j(t) g_j(t)} \quad (12)$$

After computing $f_j(t)$, The corresponding elastic ARS can be calculated. The compatibility can be achieved through an iterative process by upgrading the PSDF shown below:

Where $S_j^i(\omega)$ represents the power spectral density (stationary) of ground motion at the j-th station for the i-th iteration and $S_j^{i+1}(\omega)$ denotes the power spectral density for the (i+1)-th iteration, $RSA_j^i(\omega)$ Is the response spectrum of the simulated motion at the j-th station for the i-th iteration.

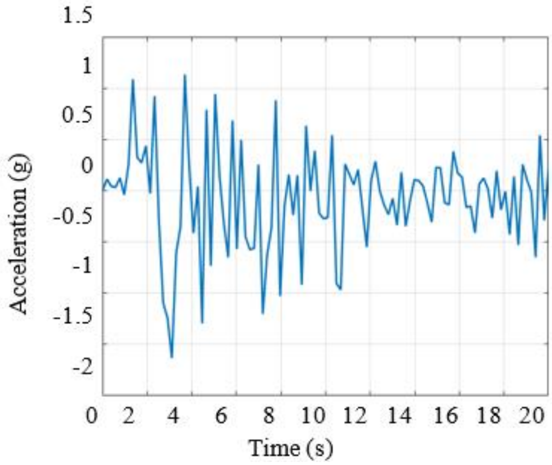

Fig.3 Non-Stationary Acceleration Time History

The target response spectrum at station j is denoted as RSAj (ω). The updated $PSD\ S_j^{i+1}(\omega)$ It is then employed in the random field simulation. Iterations continue until a satisfactory agreement between the target and simulated response spectra is achieved.

Figure 6 shows the Modified Response Spectra for Soil Type 1, highlighting the variability in seismic demand across Pier Groups 1, 2, and 3.

Similarly, Figure 7 presents the spectra for Soil Type 2, and Figure 8 illustrates those for Soil Type 3, both emphasizing how differences in soil conditions and spatial incoherence of ground motion influence the seismic response at various pier locations. These variations are essential inputs for analyzing differential support movement and structural deformations in bridges subjected to asynchronous excitation.

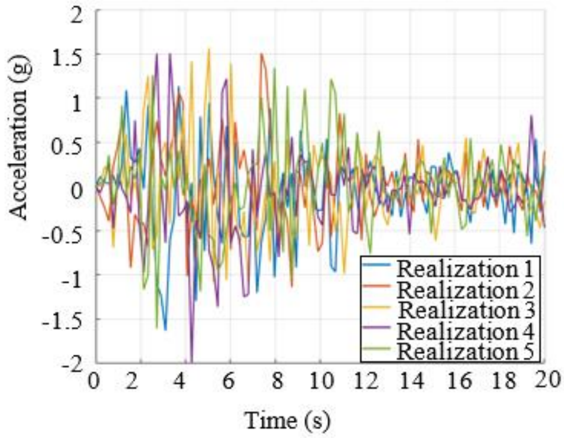

Fig.4 Non -Stationary Acceleration Time History (Multiple Realizations)

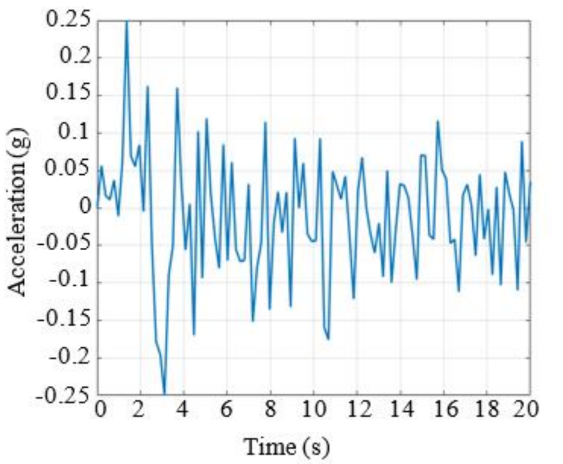

Fig.5 Stationary Stochastic Process (First Realization)

A Modified Response Spectra is generated for each of the soil type to consider the varying soil conditions of each supports of the bridge.

3.4 Modeling and Analysis for Uniform and Multiple Support Excitation

The present study implements four different cases for the Ayala Bridge. The Ayala Bridge is subject to the following cases:

Case 1: Uniform Support Excitation (with uniform ground type)
Case 2: Multiple Support Excitation
Case 3: Multiple Support Excitation
Case 4: Uniform Support Excitation (with a varying ground type)

These were assessed using ANSYS's Multi-Point Response Spectrum (MPRS) analysis feature to capture the influence of spatial ground motion variation. Cases 3 and 4 require varying ground types since most existing bridges were already erected on varying ground types. In general practice, the single-point response spectrum is commonly used. This assumption could lead to less accurate seismic response predictions, as it may overlook the different demands experienced by each bridge pier. In this study, varying ground conditions were explicitly incorporated in Cases 3 and 4 to evaluate how such variability influences the seismic behavior of the Ayala Bridge.

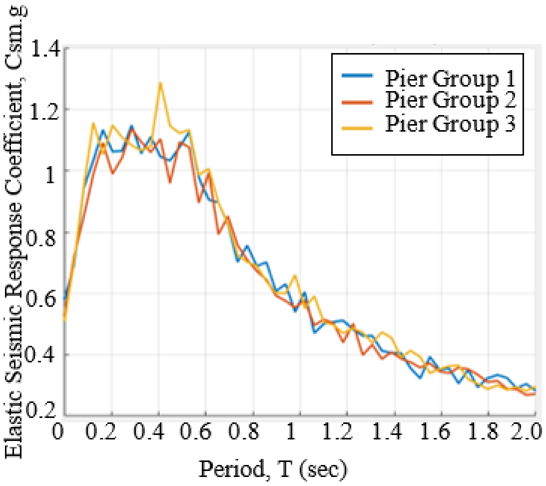

Fig.6 Modified Response Spectra for Soil Type I

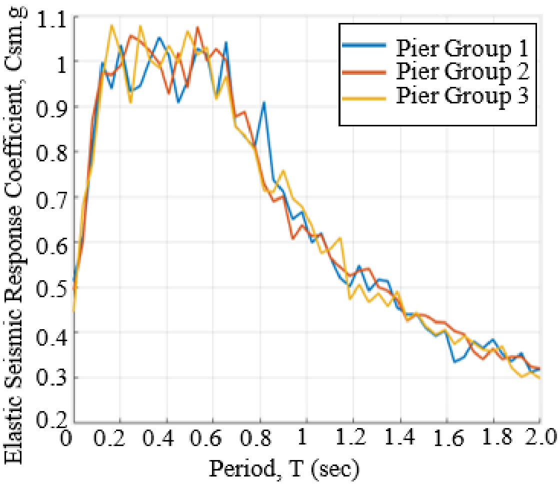

Fig.7 Modified Response Spectra for Soil Type II

Although the differing soil types assigned to each pier are hypothetical, the primary goal is to illustrate how spatial variation in ground motion affects the bridge's seismic response under Multiple Support Excitations (MSE).

3.4.1 Geometry Modelling of Ayala Bridge in ANSYS Software

The modeling of the Ayala Bridge was carried out using ANSYS software, beginning with the geometric definition of the structure in ANSYS Space Claim. As shown in Figure 10, the overall configuration of the bridge, including spans, supports, and connections, was first established in the modeling environment. The modeling process followed a systematic workflow to ensure that each structural element was accurately represented.

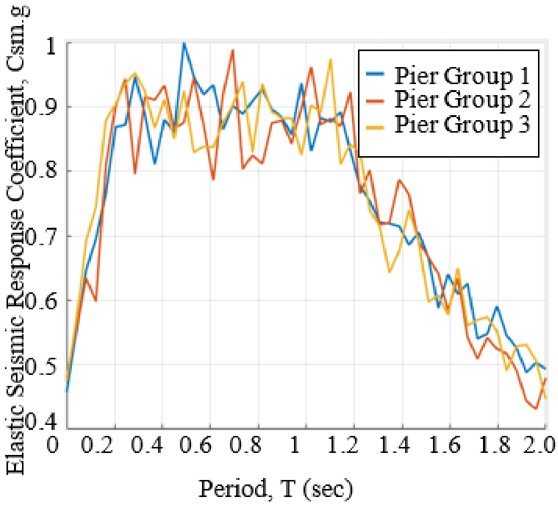

Fig.8 Modified Response Spectra for Soil Type III

Step 1 involved creating lines that represent the geometric layout of each element of the bridge, such as girders, piers, and cross beams. These lines served as the base geometry for the model. In Step 2, various cross-sections were defined based on the structural requirements, which included sections for the girders, piers, and other superstructure components. Step 3 focused on assigning these cross-sections to the corresponding lines, effectively converting them into beam elements with defined properties. Once all beam elements were created, Step 4 involved establishing connectivity across the entire structure using the "Share" option in ANSYS to ensure a continuous and integrated model. This step is crucial for ensuring that nodes are shared adequately between connected elements.

To accurately represent the different components of the bridge, several cross-sectional details were defined, including the typical beam cross-section with its corresponding beam properties, the pier cross-section, which illustrates the assigned beam properties used to simulate its structural behavior, and the superstructure cross-section. For the superstructure, the beam section properties were modified to reflect specific design considerations, ensuring that the material characteristics, geometric dimensions, and response behavior align with the intended structural performance.

3.4.2 Structural Modeling – Static Structural Analysis

All structural members were idealized using appropriate element types in ANSYS. The geometry is automatically transferred to ANSYS Mechanical. First, point masses were applied. To account for the additional dead loads on the bridge, such as the road slab, railings, and sidewalks, point masses were applied to the model. These masses were calculated based on the tributary area method and placed at key locations on the structure.

The six piers of the Ayala Bridge are categorized into three groups according to their positions along the structure. Group 1 consists of Pier 1 and Pier 2, Group 2 comprises Pier 3 and Pier 4, while Group 3 includes Pier 5 and Pier 6. Because the piers within each group are located close to one another, it is assumed they share similar soil conditions. This classification facilitates the assignment of distinct ground motions corresponding to the soil type for each group.

Pier groups:
Group 1: Pier 1 and Pier 2
Group 2: Pier 3 and Pier 4
Group 3: Pier 5 and Pier 6

Then, the boundary conditions were established. All piers were modeled as fixed supports. Additionally, standard gravity was applied to the entire structure to account for the self–weight and other vertical loads.

Table 4. Point Mass Values

Pier Group	Point mass (kg)
PG1 Point Mass	394142
PG2 Point Mass	862803
PG3 Point Mass	468196

3.4.3 Structural Modeling – Modal Analysis

The Modal Analysis utilized the structural model developed in the previous section. To ensure a reliable dynamic response representation, an exploration of the number of mode shapes was conducted until a mass participation of at least 95% was achieved. The final number of modes used in the analysis was 300, which indicates the complexity of the bridge model and its dynamic behavior.

3.4.4 Structural Modeling – Response Spectrum Analysis

In this model, six response spectra (RS) accelerations are applied, each corresponding to one of the six piers of the bridge. The analysis generates results including displacement, shear force, and bending moment for each pier, which are critical in evaluating the structural response under seismic loading. To analyze different scenarios, the response spectrum points generated from MATLAB were manually entered for each RS acceleration input. These scenarios represent all possible combinations of soil types and excitation cases.

4. RESULTS

This section presents the results of the structural analysis, categorized into four main cases based on the type of seismic excitation applied to the bridge model:
Case 1: Uniform Support Excitation (with uniform soil type)
Case 2: Multiple Support Excitation (with uniform soil type)
Case 3: Multiple Support Excitation (with varying soil type)
Case 4: Uniform Support Excitation (with varying soil type)

4.1 Displacement Response

The two-way ANOVA test revealed that the Excitation Effect significantly influenced displacement in Piers 1 to 6, with p-values ranging from 0.0012 to 0.0269. This suggests that different excitation types (uniform vs. multiple support) led to notable variations in displacement behavior for all the piers.

These significant effects on the displacement demand, the considerable p-value ($p = 0.0085$) indicates that differential support movement under MSE leads to increased deformation demands, potentially affecting serviceability and expansion joint design.

Table 5. Displacement Response

Pier	p – value
1	0.0269
2	0.0269
3	0.0064
4	0.0012
5	0.0037
6	0.0027

On the other hand, Soil Effect and the Interaction Effect between soil and excitation were not statistically significant across all piers. This implies that variations in soil conditions had a negligible impact on displacement, and that the combined influence of soil and excitation does not produce synergistic or antagonistic effects on structural displacement. Displacement responses are primarily driven by the type of ground motion excitation rather than by changes in subsoil conditions.

4.2 Shear Response

The analysis of shear forces indicated that Excitation Effect was highly significant across all piers ($p < 0.05$), especially for Piers 2 to 6, where p-values reached zero. This consistent significance suggests a strong sensitivity of shear forces to excitation type, which aligns with expectations, as differential ground motion can induce abrupt force reversals or spikes in shear demand.

Table 6. Shear Response

Pier	p – value
1	0.0268
2	0.0000
3	0.0000
4	0.0000
5	0.0000
6	0.0000

Table 7. Bending Moment Response

Pier	p – value
1	0.0570
2	0.0271
3	0.0068
4	0.0012
5	0.0037
6	0.0024

These highly significant p-values for shear force ($p = 0.0000$) imply a critical deviation in shear demand when spatial variability of ground motion is considered. This result suggests a possible underestimation of shear forces under USE, which may lead to inadequate shear reinforcement and increased vulnerability to shear-related failure modes during strong seismic events.

As with displacement, the Soil Effect and the interaction Effect were not significant for any pier. This confirms that variability in soil stiffness or properties has limited influence on internal shear forces, and that excitation independently drives the structural shear response.

4.4 Two-Tailed Hypothesis

In general, the seismic performance of the Ayala Bridge is based on the modeling and analysis conducted. When the Ayala bridge is subjected to varying soil conditions and different types of excitations – uniform support excitations and multiple support excitations. The Ayala Bridge seismic performance is significantly affected by the kind of excitation to which it was subjected, Multiple Support Excitations. Thereby, suggesting that the consideration of the DPWH–BSDS 2013 that the bridge piers under uniform excitation neglect the significant effect of multiple support excitations. Particularly on the Ayala Bridge, displacement and shear demand on all its bridge piers are critical.

In bridge consideration on the other hand, Pier 1 is the only pier that shows no significance, but this may be because it reflects the cumulative buildup of rotational effects farther along the structure, suggesting a spatial propagation of moment sensitivity to excitation, otherwise all pier shows significant impact on the bending moment demand of the Ayala Bridge.

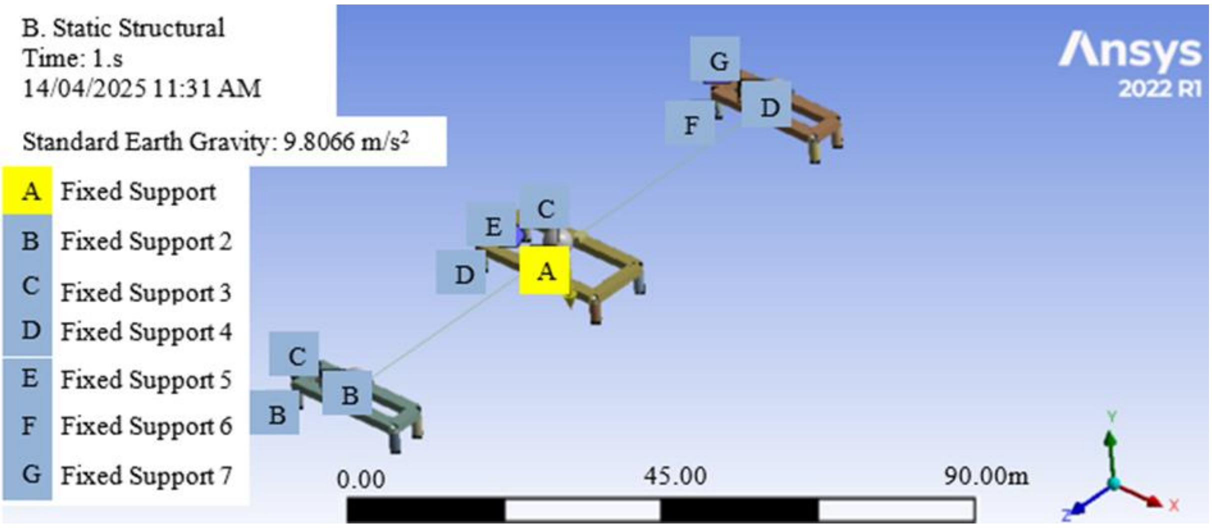

Fig.9 Ayala Bridge Structural Model Point Mass Application, and Boundary Conditions and Response Spectrum Analysis in ANSYS

Therefore, the null hypothesis, Ho: Soil type and interaction have no significant effect on the displacement, shear, and moment response of the structure, is accepted. While the alternative hypothesis, H0: the excitation type has a significant impact on all seismic response variables, displacement, shear, and moment, is accepted.

4.5 Comparison of Results of Displacement, Shear, and Bending Moment Response

The amplification and attenuation values presented in this study were derived through a comparative analysis between the structural responses obtained from the proposed Modified Multiple Support Response Spectrum (Modified–MSRS) method and those based on the conventional Uniform Support Excitation (USE) approach, as prescribed in the DPWH Bridge Seismic Design Specifications (BSDS) 2013. The USE method assumes synchronous ground motion at all supports. It does not account for the spatial variability of seismic input. In contrast, the Modified–MSRS incorporates asynchronous support excitations by simulating site-specific ground motion characteristics through a MATLAB-generated response spectrum.

The comparison revealed that consideration of Multiple Support Excitation (MSE) resulted in notable changes in the structural response parameters. Specifically, the displacement response exhibited a significant amplification, ranging from 12.24% to 29.75% relative to the baseline USE results. Similar trends were observed in the internal forces, where shear observed an amplification of 19.95% to 30.84% across the bridge piers and bending moment responses showed both amplification of 29.36% in the pier 1 of the bridge and attenuation of 41.26% to 52.13% in piers 2 to 6 of the bridge pier, which depends on the location and dominant mode shapes of the structure.

These findings underscore the importance of incorporating spatial variability effects in seismic analysis, particularly for long-span bridges, as reliance on uniform excitation may lead to underestimation or misrepresentation of actual seismic demands.

5. CONCLUSIONS

This research successfully achieved its primary objective of evaluating the seismic performance of the Ayala Bridge – a medium-span bridge - when subjected to multiple support excitations and varying conditions and determining whether this is significant to the overall performance of the Ayala Bridge. The following conclusions were drawn based on the analysis conducted at the Ayala Bridge:

- The Modified Multiple Support Response Spectrum (MMSRS): The goal of establishing practical engineering procedures and guidelines for creating a modified response spectrum was achieved by first generating an Acceleration Response Spectrum (ARS) using the DPWH – BSDS 2013 standards. Additionally, a MATLAB program was developed to produce a Modified Multiple Support Response Spectrum (MMSRS) that incorporates the influences of Spatial Variation of Ground Motion (SVGM). This modification process integrates various physical and statistical parameters, such as the incoherence factor (α), apparent wave velocity, inter-support distance, damping ratio, and seismic duration. Simultaneously, the developed code computes the Auto-Power Spectral Density (Auto-PSD) based on Kaul’s method and derives a cross-power spectral density (Cross-PSD) matrix using a complex-valued coherency function. This captures how seismic waves degrade and become incoherent as they travel between supports. And from these spectral components, the code generates a set of stationary stochastic ground motions, which are then transformed into non-stationary processes through the application of a modulating function. This function reflects the build-up and decay of seismic energy during an earthquake event, producing more realistic ground motion time histories. The same MATLAB code can be used to generate Modified Multiple Support Response Spectrum (MMSRS).
- Based on the analysis of the Ayala Bridge when subjected to four different cases exhibiting the same displacement response, the Ayala Bridge is significantly affected by the type of excitation to which the bridge pier was subjected. The ANOVA shows a p-value of 0.0012 to 0.0037 across all piers, indicating that the displacement response of the Ayala Bridge is significantly affected by the type of excitation it was analyzed with. Therefore, the significant impact of Multiple Support Excitations calls for the attention of structural designers and the DPWH, as the design does not account for this type of excitation. Thereby implying that further analysis is needed when designing a bridge to consider this type of excitation. Similarly, comparing it to the original bridge response of the Ayala Bridge, a significant amplification of the displacement response was observed, increasing from 12.24% to 29.75%. Additionally, the considerable impact of the displacement response of the Ayala Bridge is an essential factor in bridge design.
- On the shear response of the Ayala Bridge, based on the ANOVA, it exhibits a p-value of 0.0268 on Pier 1, and a 0.0000 p-value on Piers 2 to 6, which
- shows a highly significant effect on the shear response of the Ayala Bridge. This indicates that the Ayala Bridge is significantly affected by the type of excitation its support has experienced. Validating the displacement response of the Ayala Bridge, which exhibited the same response. Therefore, considering Multiple Support Excitation (MSE) could benefit bridge design economically, but it may also require additional structural considerations. On the other hand,

comparing it to the original response of the Ayala Bridge under original design considerations, the bridge experiences an amplification of 19.95% to 30.84%. Additionally, the shear response of the bridge is a critical factor for the bridge's structural limitations.

- In the ANOVA of the bending moment response of the Ayala Bridge, unlike the displacement and shear response, one pier exhibits an insignificant effect on the multiple support excitations, particularly Pier 1. However, this may be because it reflects the cumulative buildup of rotational effects farther along the structure, suggesting a spatial propagation of moment sensitivity to multiple excitations. Otherwise, all piers show a significant impact on the bending moment demand of the Ayala Bridge. On the other hand, a significant p-value of 0.0012 to 0.0237 for Piers 2 to 6 shows that the type of excitations significantly affects the bending moment response of the Ayala Bridge. Similarly, at the bending response, an amplification of 29.36% was experienced for pier 1, and attenuation of piers 2 to 6 from 41.26% to 52.13%. Therefore, further analysis that considers Multiple Support Excitations is a critical aspect in designing bridges and extended structures. Furthermore, the bending moment response of the bridge is also a crucial aspect in the bridge's structural limitations.
- The result of each pier's responses on the displacement, shear, and bending moment response shows that the bridge seismic response is greatly affected by the type of excitation. There is a good agreement between the ANOVA test and values obtained when compared to the original bridge response of the Ayala Bridge. Therefore, assuming a uniform support excitation on all bridge supports when designing neglects the significant effect of multiple support excitations on the bridges' seismic response.
- The results of the analysis of when the Ayala Bridge was subjected to varying conditions, including the effect of excitation, the impact of the type of soil, and the interaction. The researcher concludes that the seismic performance of the Ayala Bridge is significantly affected by the type of excitation, thereby reiterating the importance of considering multiple support excitation. On the other hand, the soil type and the interaction between soil and excitation show no significant effect on the Ayala Bridge seismic performance.
- The result of the analysis only shows and validates the results of the previous research, where a significant effect on the displacement response of the short-span bridge was noticed when subjected to multiple support excitation. Furthermore, a more adverse effect was experienced by a longer span bridge when subjected to multiple support excitations. It not only shows a significant impact on the displacement response but further extends its influence on the shear and bending moment response of the medium span bridge. It is safe to assume that as the bridge support-to-support distance increases, a more detrimental effect is experienced and significantly affects the bridge's seismic performance.

The present study addressed a more comprehensive understanding of Multiple Support Excitation (MSE), by analyzing a medium span bridge – Ayala Bridge having a span length of 50.0 meters to 100.0 meters, when subjected to multiple support excitations through generating a Modified Multiple Support Response Spectrum (MMSRS) which accounts for the Spatial Variation of Ground Motion (SVGM). The present study concluded that the type of excitation – uniform or multiple support excitation (USE – MSE) significantly affects the seismic performance of medium span bridges, particularly the displacement, shear force, and bending moment response of the bridge. Therefore, the developed MATLAB code for generating a Modified Multiple Support Response Spectrum (MMSRS), which incorporates the effects of Spatial Variation of Ground Motion (SVGM), represents a valuable step toward enhancing seismic bridge design practices. Given that current design codes do not account for asynchronous support excitation, this tool offers a more realistic approach to evaluating dynamic response. However, further validation against recorded earthquake data and integration with widely used structural analysis software are recommended to support its practical application in real-world bridge engineering.

While this study utilized hypothetical variations in soil conditions to simulate the effects of spatially varying ground motion (SVGM) under Multiple Support Excitation (MSE), the results effectively demonstrate the sensitivity of bridge response to differential seismic inputs. This approach served as a controlled sensitivity analysis to isolate the impact of spatial variability. However, for a more realistic and location-specific seismic assessment, future research is recommended to incorporate actual site-specific geotechnical data along the bridge alignment. Given the diverse geological and geotechnical conditions across the Philippines, integrating field-based soil profiles and shear wave velocity data could further enhance the applicability of the Modified-MSRS method in national bridge design practice. Nonetheless, the hypothetical conditions used in this study reflect common scenarios in long-span bridge projects where piers are founded on varying subsoil layers, supporting the general relevance of the findings.

Furthermore, this present study also recommends the use of Nonlinear Time History Analysis (NTHA) in future research to further enhance the assessment of spatial ground motion variation. NTHA would allow the model to account for time delays across different piers more accurately, providing a deeper understanding of the dynamic behavior of bridges under spatially varying seismic excitations.

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