Soil-Structure Interaction and Near Fault Pulse-like Earthquakes Effects on Seismic Responses of Isolated Bridges

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Abstract— **Seismic isolation technology is an effective tool for mitigating seismic risk and improving structural performance during strong earthquakes. However, some parameters, such as earthquake and soil characteristics, influence and may reduce isolation technology's performance. This research aims to investigate the simultaneous effects of soil-structure interaction (SSI) and pulse-like earthquakes on the seismic responses of conventional and isolated bridges. Near-fault (NF) earthquakes with and without velocity pulses in their records are applied to the structure of a three-span bridge located in Vancouver (Canada), with and without considering the underlying soil. Using the direct method, three soil properties representing rock, stiff and medium soil are modeled by Abaqus software. Nonlinear time history analysis (NLTHA) is carried out, and structural responses regarding maximum deck acceleration, base shear, and displacement of the deck and the isolation systems are studied. Results demonstrate that pulse-type records cause higher seismic responses, and soil presence diminishes the negative effect of the pulse on the force demands. On average, and for the pulse-like records, the softer soil reduces the acceleration by up to 30% and base shear responses by up to 25% while increasing the displacement demand of conventional and isolated bridges by up to 80%. Therefore, careful attention should be paid to the isolation systems' design to prevent underestimating the displacement demand for pulse-like records, especially on softer soils. Responses of the different isolation systems demonstrate that the optimum design could provide the displacement demand for pulse-type records even on softer soils.**

Keywords—**seismic isolation, soil-structure interaction, near-fault records, pulse-type records, bridges**

I. Introduction

As natural disasters, strong earthquakes may cause devastating effects on seismic-prone areas. Seismic isolation systems are one of the rational and fundamental solutions for mitigating the effects of earthquakes with a significant positive effect on reducing the seismic responses of structures, as indicated by numerous post-earthquake in-field observations, experimental, and numerical research works [1, 2]. This technology has proven a good performance even in the case of not considering all the effective parameters like NF effects for the prone areas; for instance, in the case of the Bolu Viaduct bridge, the isolation system suffered a complete failure and narrowly avoided the total collapse because of excessive superstructure movement in the Duzce Earthquake in 1999 as an NF earthquake which caused large displacements in the isolation system [3].

Seismic isolation is based on reducing the fundamental structural vibration frequency to a value less than the predominant energy-containing frequencies of the earthquakes to decrease the seismic force demand to or near the elastic capacity of the structure; thereby, inelastic deformations within the structure will be obliterated or drastically diminished, and they take place in the isolation devices. The long-term advantage of these innovations is that they preserve the structure's serviceability following an earthquake, reducing the socio-economic losses and the cost of reconstruction [4, 5].

Serving as a crucial artery in transportation systems, bridges are one of the most critical infrastructures in today's modern society, especially in times of crisis, such as the period following a major earthquake. Therefore, it is required to consider all effective parameters at the design stage to ensure an adequate bridge design according to the target performance. Among different pivotal parameters, earthquake characteristics and site conditions are two of the most critical parameters affecting the seismic performance of infrastructures [6].

Ground motion records close to the ruptured fault (within 20 km) are categorized as NF earthquakes [7]. Seismic responses of structures between NF and FF records differ considerably. Many research studies reported that NF pulse-like ground motions are more destructive to the structure than that ordinary ground motions [8, 9]. NF records often have a higher PGV/PGA ratio. Frequently, they contain intense and long-period velocity pulses, which force the structure to behave in an inelastic range that may require much higher ductility

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demand and base shear than FF earthquakes, and the impulse effect may intensify the displacement of the isolation bearing [10–12].

In addition, NF records particularly amplify the seismic responses of isolated bridges when the pulse period is close to the period of the structure [13, 14], and hysteretic damping of the isolation systems might not be effective in dissipating the energy process in the first part of the pulse ; therefore the structure is prone to severe damage when the duration of the pulse is larger than the natural period of the structure [15, 16]. Consequently, the demand in the isolation system depends on the pulse duration and the ratio of pulse to the natural period of the structure, and in order to have an optimum isolation system, the characteristic strength (Q_d) of the isolation system, defined later, needs to be increased [17, 18].

The local site and SSI can also significantly influence the main characteristics of ground motions, such as amplitude, frequency content, and duration, and modify the seismic responses of isolated bridges. The extent of such influence depends on the dynamic characteristics of the bridge structure, the input ground motion characteristics, and the underlying soil's properties [19, 20]. Misrepresenting the soil effect could result in an erroneous estimation of the seismic demand and the parameters governing the design of the isolation system and the bridge, especially where the underlying soil is soft [21–23].

Aside from various conclusions drawn from the literature, little attention was paid to the effect of SSI and pulse-like earthquake records on the performance of the isolated bridges for prone areas. As a result, this research aims to look into the simultaneous effects of NF records with and without pulses in their velocity records and the effect of different soil properties on the bridge responses. Furthermore, this research aims to understand how SSI affects the records with and without pulses. Consequently, the efficiency of different isolation systems subjected to the above-mentioned situations will be investigated. The results will help to reach a more advanced comprehension of the responses of isolated bridges located on different soil strata. This understanding allows for more precise and effective isolation strategies by designing appropriate properties of the isolation systems in future projects for prone areas, when necessary, to catch the SSI and pulse effects.

II. Modeling of the Case-study Bridge

The selected case study bridge model is a typical three-span continuous concrete box girder deck highway bridge studied by Jangid *et al.* (2003), shown schematically in Fig. 1[24]. The bridge is symmetric, with three equal spans supported on two concrete single piers and abutments with a fundamental period of 0.54 s in the longitudinal direction and a damping ratio of 5%, for the conventional (fixed-base) bridge with zero skew. Table I illustrates the geometric and material properties of the bridge based on the data presented in the reference studies. In the present study, the structural modeling of the bridge and NLTHA are performed using Abaqus software [25]. Deck, piers, and abutments are modeled as Beam-column elements, and foundations and the soil stratum are modeled as solid elements. The superstructure, piers, and abutments are assumed to remain in the elastic state during seismic excitation for conventional and isolated bridges.

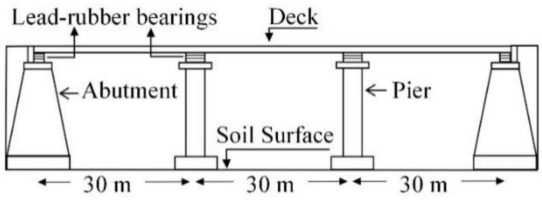

Figure 1. General elevation of the isolated bridge.

TABLE I. Material and Dimension Properties of the Bridge

Properties of the Bridge	Deck	Piers
Cross-sectional areas (m^2)	15.6	1.767
Length or height (m)	3@30	10
Modulus of elasticity (Gpa)	36	36
Mass density (kg/m^3)	2400	2400
Compressive Strength (Mpa)	30	30
Poisson Ratio	0.2	0.2

To validate the original model, a comparison of structural responses of the conventional bridge model and the results of reference papers for the Northridge record (captured at La County fire station component with PGA=0.58 g) is carried out, and the results are presented in Table II. Good agreements between the results, in terms of vibration period, base shear, and deck acceleration, are obtained with a difference lower than 5%. After validation of the model, the bridge is assumed to be in Vancouver, and the foundation is considered to be at a depth of D = 1.8 m of the soil surface.

TABLE II. Comparison of the Responses with Current Study

	Jangid *et al.* 2003	Present study	Difference %
Period (s)	0.53	0.54	1.85
Base Shear/W_{deck}	1.439	1.388	−3.54
Deck acceleration (g)	1.396	1.461	4.45

III. Isolation System

Considering the bridge is located in Vancouver as a strong seismicity area, three isolation systems as ISO-1 to ISO-3, are designed using the 6th generation hazard of earthquakes Canada [26] for an effective period of T= 2.5 s. ISO-1 is calculated and designed based on the single-mode spectral analysis and spectral displacement demand for Vancouver as a high seismicity area. Based on the literature, earthquake records with low ratios of PGA/PGV, or earthquakes with pulses in their velocity records impose a larger strength and displacement demand [13, 18]; therefore, ISO-2 is designed with higher Q_d and displacement capacity (2 times) compared to ISO-1. Finally, ISO-3 is designed based on the proposed domain by Nguyen and Guizani (2021) to provide an optimal seismic isolation system for high seismicity areas with higher post-elastic stiffness and displacement capacity compared to ISO-2 to investigate the efficacy of the optimal design on dynamic responses of the bridge subjected to earthquakes with and without pulses in their velocity records [27, 28].

The substructure is decoupled from the deck by lead rubber bearings, and the isolation system is lumped between the deck and superstructure, and only the longitudinal direction is studied for implementing seismic isolation. Link elements with bilinear behaviour based on the multi-plastic model given by Abaqus are used to model the isolation system [25].

The global model of the isolated bridge and soil, and the bilinear force-displacement relation of the Seismic Isolation System (SIS), are shown in Fig. 2 and the SIS parameters are presented in Table III, where Q_d is the characteristic strength that is the force required at zero displacement, K_d represents the post-elastic stiffness, K_u stands for the elastic stiffness, K_{eff} is the effective stiffness at the maximum displacement in the isolation system, D_{max}, and effective damping as β.

IV. Soil Model and Properties

Accounting for the effect of SSI, an elastic-perfectly plastic behaviour is assigned for the soil domain using the Mohr-Coulomb yield criterion [29]. The 8-node brick elements (C3D8) are applied to the soil deposit model as a rectangular shape of 130 (m) in length and 20 (m) in width. Three different non-liquefiable homogeneous soil profiles are adapted and studied as Rock, Soil-C (stiff soil), and Soil-D (medium soil) based on the site classification in CSA (S6-19) [27]. In addition, considering the fact that most amplifications occur within the first 30 m of the soil profile, soil depth is considered to be 30 m [30]. The characteristics of each soil type are presented in Table IV, where E is the Elastic modulus, ρ represents the density, C stands for the cohesion stress, ϑ is the Poisson's ratio, ø defines the friction angle, Vs is shear wave velocity, Ψ represents dilatancy, and ξ is the damping ratio. To avoid the reflection of waves at the finite boundaries of the soil model, Infinite solid continuum (CIN3D8) with 8-node linear, as a one-way infinite brick element provided by Abaqus, are used in the longitudinal direction, which is the direction of the study, and fixed boundaries for the transverse direction with free rotations are used in this study. The earthquake acceleration records are directly applied to the grid points along the rigid base of the soil in the longitudinal direction.

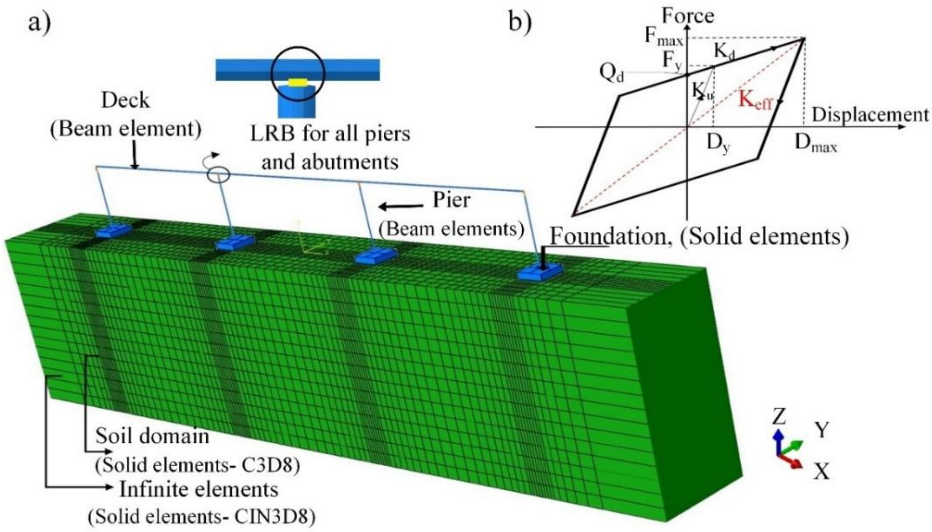

Figure 2. The global model of the isolated bridge and soil, and the bilinear force-displacement relation of the Seismic Isolation System (SIS) (a) Isolated bridge model and soil (b) bilinear force-displacement behaviour of SIS.

TABLE III. Isolation Properties

ID	Location	T (s)	K_{eff} (N/m)	K_u (N/m)	Q_d (N)	K_d (N/m)	D_{max} (mm)	β %
ISO-1	Piers	2.5	7,750,000	228,250,000	450,000	3,240,000	100	35
	Abutments	2.5	3,550,000	101,500,000	200,000	1,550,000	100	35
ISO-2	Piers	2.5	7,750,000	453,250,000	900,000	3,240,000	200	35
	Abutments	2.5	3,550,000	202,000,000	400,000	1,550,000	200	35
ISO-3	Piers	2.5	7,895,000	455,700,000	900,000	5,700,000	400	20
	Abutments	2.5	3,775,000	202,800,000	400,000	2,800,000	400	20

The surface-to-surface contact between the foundation and the soil surface is modeled as an interaction interfacial behaviour following the algorithm implemented by Abaqus [25]. The interface stiffness values control the relative interface movement in the normal and tangential directions. Hard contact is used in the normal direction, and the penalty method is defined for tangential behaviour.

In tangential behaviour, based on suggested domains in the literature final friction coefficient of μ= 0.5 is used [31].

Overall, 1300 elements for the bridge, 23520 C3D8R, and 480 CIN3D8 elements for the soil domain are used. A mesh sensitivity analysis validated this choice (less than 1% tolerance, in terms of displacements and stresses at control stations within the structure and soil domain).

V. EARTHQUAKE RECORD SELECTION AND CALIBRATION

All earthquake records are selected among the strong historical earthquakes with magnitude 6–7.5 (Richter scale). Four NF pulse-like and four NF records without pulses in their velocity records with rupture fault distance within 20 (km) captured on rocks are selected from the Pacific Earthquake Engineering Research (PEER) strong motion database [32]. The reason for extracting these records on rocks is that minor changes in the ground motions occur in rocks. Therefore, the earthquake ground motions applied at the soil base are closer to the original input ground motions released from their sources. The second reason for choosing the mentioned records is related to studying the effects of existing pulse on the dynamic responses of the conventional and isolated bridges with and without SSI effect.

To compare the results, all records are scaled to 0.32 g, which is the PGA associated to the uniform hazard design spectrum, 6th generation (CNB2020), recommended for Vancouver for 2% probability of exceedance in 50 years, on a site class A (rock) [26]. It should be mentioned that the interference of different source mechanisms, such as directivity effects, and focal mechanisms (strike-slip, normal or reversing faulting), is not considered during the selection of records. Details of the selected ground motions in Table V show that pulse-like records contain low PGA/PGV ratios, less than 10 (1/s), and higher PGD values. In comparison, PGA/PGV ratios for records without pulses are higher (more than 12 (1/s)) with lower PGD values. Furthermore, the spectral acceleration of records in Fig. 3, shows that pulse-like records have higher responses in the vicinity of the period related to the conventional bridge, and the high values of spectral acceleration continue even in long periods such as the isolated bridge’s period.

Although the period shift in the isolated bridge will move the structure to the low energy-containing frequencies of the earthquake records, the seismic force demand for the pulse-like records is still higher than the design spectrum and also higher than the records without pulses.

TABLE IV. MECHANICAL PROPERTIES OF SOILS

Soil	E (MPa)	ρ (kg/m^3)	υ	C (KPa)	Ø (°)	V_s (m/s)	ψ	ξ (%)
Rock	24960	2600	0.2	2.50E+04	48	2000	7	5
Soil-C	1323	2100	0.26	0	40	500	5	5
Soil-D	430	1900	0.32	0	35	300	4	5

TABLE V. NF EARTHQUAKE RECORDS ADOPTED IN THE ANALYSES

ID	Earthquake	Station	Magnitude (Mw)	R_{rup} (km)	PA (g)	PV (cm/s)	PD (cm)	PGA/PGV (1/s)	T_p (s)
P-1	Kobe	Kobe University	6.9	0.9	0.32	63.9	18.3	4.9	1.49
P-2	Loma Prieta	Lexington Dam	6.9	5.0	0.32	74.5	23.7	4.2	1.57
P-3	Northridge	Pacoima Dam	6.7	7.0	0.32	31.7	4.7	9.9	0.59
P-4	Kocaeli	Gebze	7.5	10.9	0.32	72.2	67.0	4.3	5.99
NP-1	Parkfield	Turkey flat	6.0	5.3	0.32	16.5	2.8	19.0	NA
NP-2	Loma Prieta	Gilroy Array	6.9	9.6	0.32	25.8	5.7	12.2	NA
NP-3	Morgan Hill	Gilroy Array	6.2	14.9	0.32	9.7	1.4	32.5	NA
NP-4	Tottori	OKYH07	6.6	15.2	0.32	14.7	6.4	21.3	NA

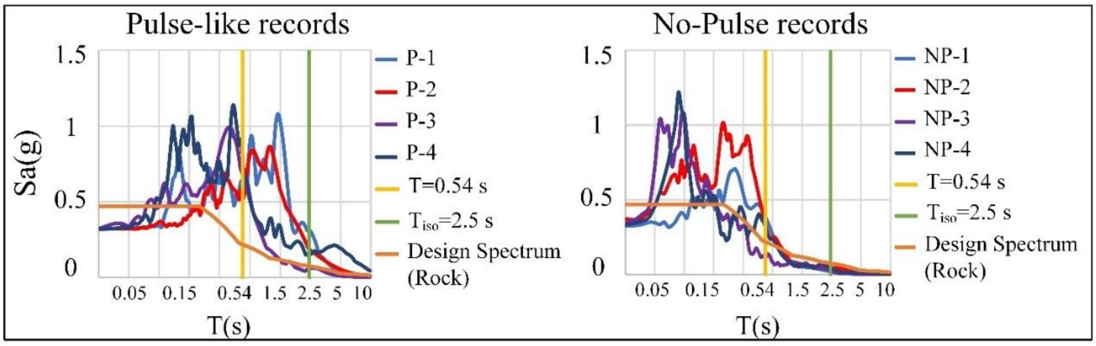

Figure 3. Spectral accelerations of the scaled records on Rock (class A), log scale.

VI. Analysis Programme and Procedure

All calibrated records are input at the base of the conventional and isolated bridge variants, first without considering the presence of the soil where the base of the bridge is fixed and then with modeling the soil using the direct approach. The bridge variants are analyzed by NLTHA in Abaqus software, first for the static gravity dead load to obtain initial stress conditions and then for dynamic loading conditions. The structural responses of NLTHA, including the maximum acceleration on top of the deck, base shear, and displacement of the bridge deck and isolation systems, are studied as seismic demands. Results are discussed in the following sections.

A. Effect of Pulse-like Records and SSI on the Acceleration Responses

The maximum acceleration in the conventional and isolated bridge, as shown in Fig. 4, is higher in pulse-like records compared to records without pulses. On average, the maximum acceleration responses of the conventional bridge are higher by the factor of 2, 2, 1.6, and 1.6 for No-Soil, Rock, Soil-C, and Soil-D conditions.

For the isolated bridge, this factor is 2, 2, 1.7, 1.6 for Iso-1, 1.4, 1.4, 1.1, 1.1 for Iso-2 and 1.6, 1.6, 1.3, and 1.3 for Iso-3, showing better control of the acceleration responses in ISO-2, and ISO-3, as the effect of the pulse is mitigated by reducing the differences between pulse-like records and records without pulses. In addition, the acceleration responses of the pulse-like records in conventional and isolated bridges show a decreasing trend on softer soil, while in records without pulses, the difference between the responses on different soil is not noticeable.

To study the effect of soil, all responses are normalized by the responses of the No-soil condition, and the results are shown in Fig. 5. In the case of a ratio of more than one, responses are amplified, and the effect of SSI is unfavorable. In contrast, when the ratio is negative, SSI is favorable and reduces the responses.

As shown in Fig. 5, soil has a noticeable positive effect in pulse-like records by diminishing the pulse effect and reducing the acceleration responses from No-soil condition to Soil-D by the average of 30%, 27%, 21%, and 23% for the conventional, ISO-1, ISO-2, and ISO-3 bridge variants, respectively.

In contrast, soil does not play an important role in amplifying or de-amplifying the acceleration responses in NF records without pulses.

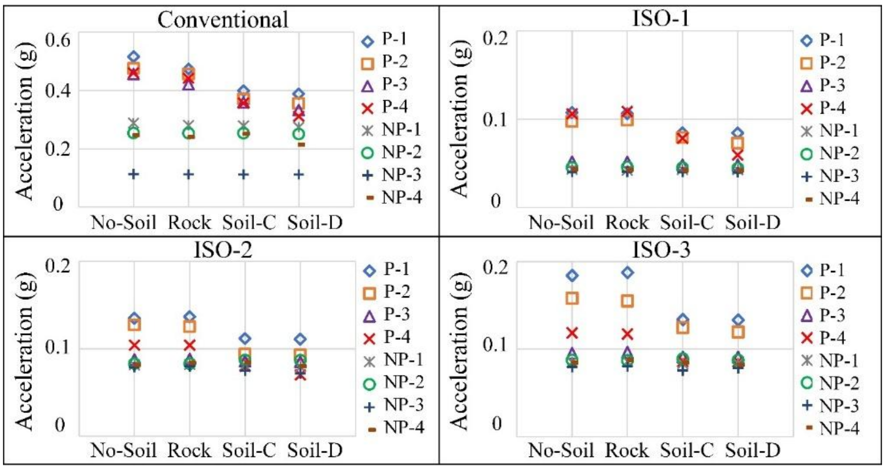

Figure 4. Maximum acceleration responses.

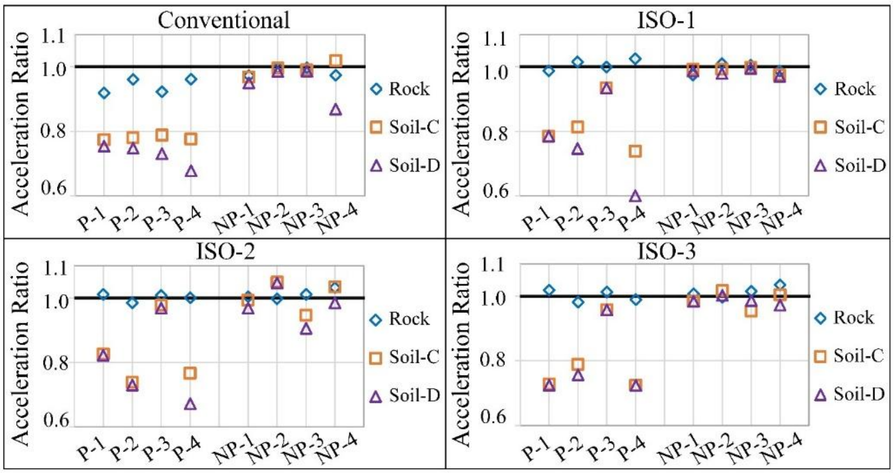

Figure 5. Acceleration ratio (SSI/Fixed-base).

In the majority of the cases, the SSI effect is neutral, and the average difference between the soil-D and No-soil conditions is 6%, 2%, 2%, and 1% for the conventional, SO-1, ISO-2, and ISO-3, respectively.

B. Effect of Pulse-like Records and SSI on the Base Shear Responses

As shown in Fig. 6, the maximum base shear responses have the same trend as the acceleration responses showing higher responses for pulse-like records compared to no-pulse records.

On average, the maximum base shear responses of the conventional bridge are higher in pulse-like records by the factor of 1.9, 1.9, 1.6, and 1.6 for No-Soil, Rock, Soil-C, and Soil-D conditions. For the isolated bridge, this factor is 1.7, 1.5, 1.4, 1.4 for Iso-1, 1.3, 1.2, 1.2, 1.2 for Iso-2, and 1.5, 1.4, 1.3, and 1.3 for Iso-3.

Based on the normalized base shear responses shown in Fig. 7, soil has a noticeable positive effect in most pulse-like records, and responses are reducing from Rock to Soil-D. On average, the base shear responses of the pulse-like records in both conventional and isolated bridges are reducing from No-soil condition to Soil-D by an average of 24%, 17%, 6%, and 12% for the conventional bridge, SO-1, ISO-2, and ISO-3, respectively.

In contrast and for NF records without pulses, the soil effect is positive in reducing the responses of the conventional bridge by an average of 12%, but it plays either a neutral or negative role in isolated bridges in most of the cases by increasing up to 8% in some records depending on the isolation system properties.

C. Effect of Pulse-like Records and SSI on the Displacement Responses

A higher displacement on top of the deck and in isolation systems is observed in pulse-like records for all bridges, as it is shown in Fig. 8.

On average, the displacement demand in pulse-type records is higher than records without pulses up to 3, 10, 8, and 8 times for the conventional bridge, ISO-1, ISO-2, and ISO-3, respectively, for all soils.

In the conventional bridge, the displacement responses are less scattered in records with no pulse and show less sensitivity to the SSI effect.

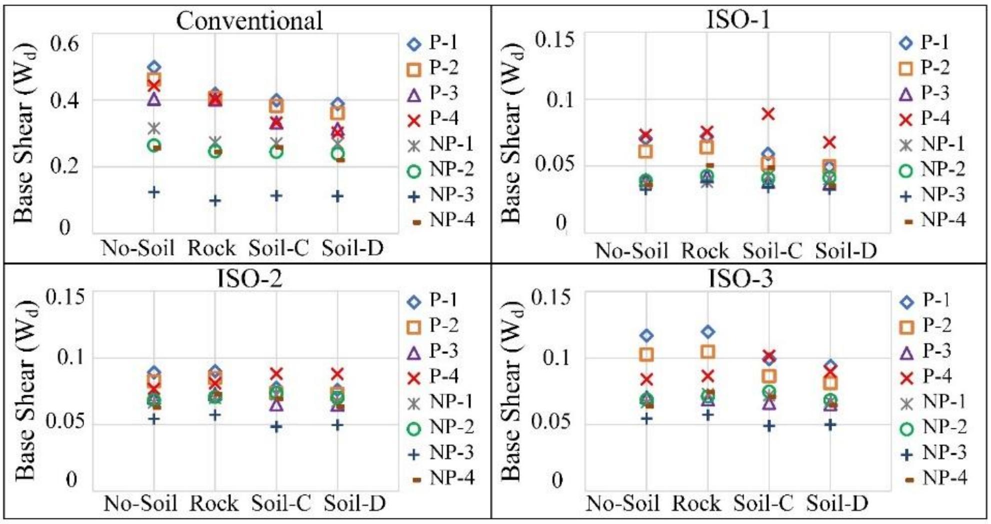

Figure 6. Maximum base shear responses.

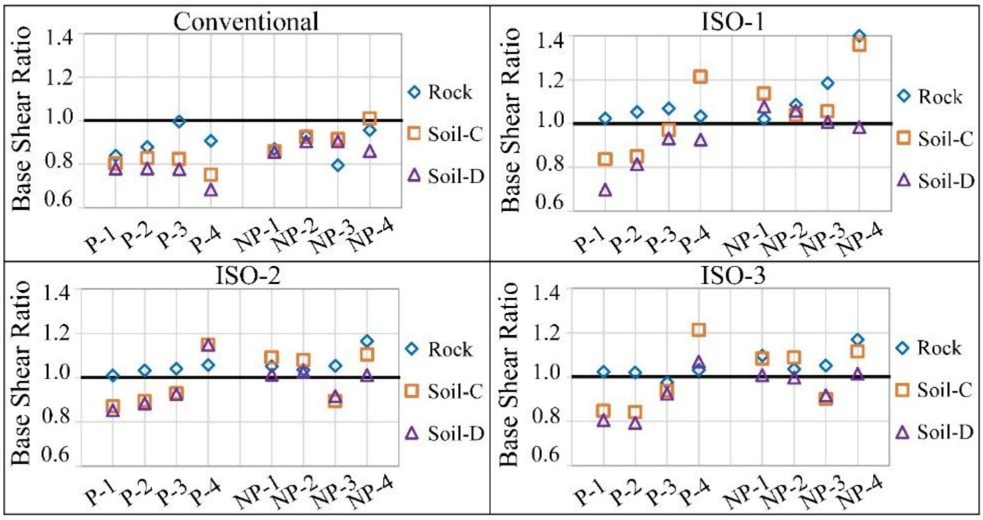

Figure 7. Base shear ratio (SSI/Fixed-base).

In the isolated bridges, while all records without pulses show the displacement demand less than the designed displacement for isolation systems confirming the effectiveness of this technology for strong earthquakes without pulses in their records, in most of the pulse-like records, displacement demands are higher than the designed displacement in ISO-1. In ISO-2, Increasing the displacement capacity and the characteristic strength reduces the number of earthquake records with higher displacement demand than the displacement capacity.

In ISO-3, which is an optimal design for strong seismicity areas with higher displacement capacity, characteristic strength, and post-elastic stiffness compared to ISO-1 and ISO-2, the displacement demand is less than the designed displacement in all pulse-like records, showing a need for special attention in the design of the isolation systems in high seismicity areas prone to pulse-like earthquake records.

The normalized displacement ratio in Fi. 9 shows that soil is a detrimental factor, increasing the displacement demand in pulse-like records up to 4 times and in records without pulses up to 2.5 times. However, the effect of soil on the isolated bridges depends on the isolation system properties. On average, the displacement demand increases on Soil-D compared to No-soil condition by 55%, 40%, 77%, and 70% in pulse-like records and 10%, 85%, 85%, and 85% in records without pulses for the conventional bridge, ISO-1, ISO-2, and ISO-3, respectively.

VII. Discussion and Conclusion

This paper studied the simultaneous effects of NF earthquakes with and without pulses in their velocity records and the SSI effect on three-span conventional and isolated bridges. Seismic responses of the bridge without the presence of the soil are compared to those considering the SSI effects in the direct approach. Three different soil properties representing the rock, stiff and medium soil, have been selected. The role of soil characteristics has been evaluated by considering the bridge founded on different soil strata subjected to strong NF pulse-like and no pulse-like records.

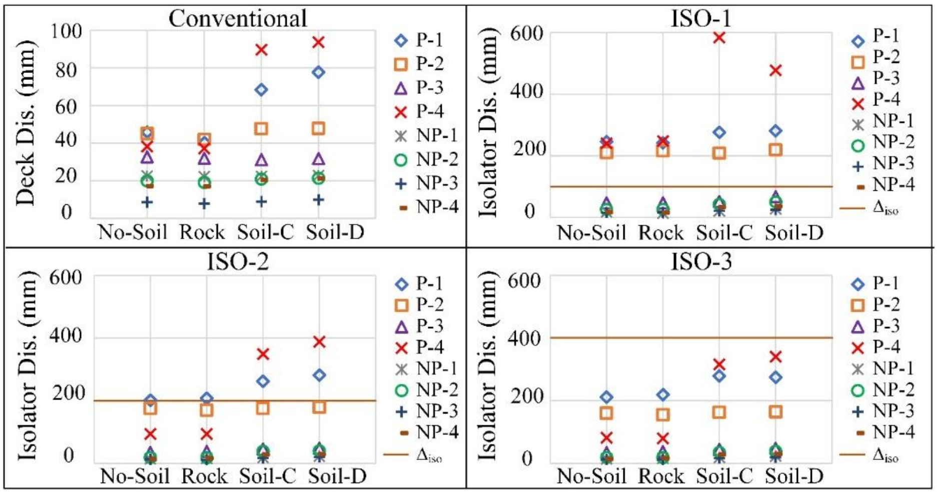

Figure 8. Maximum displacement responses.

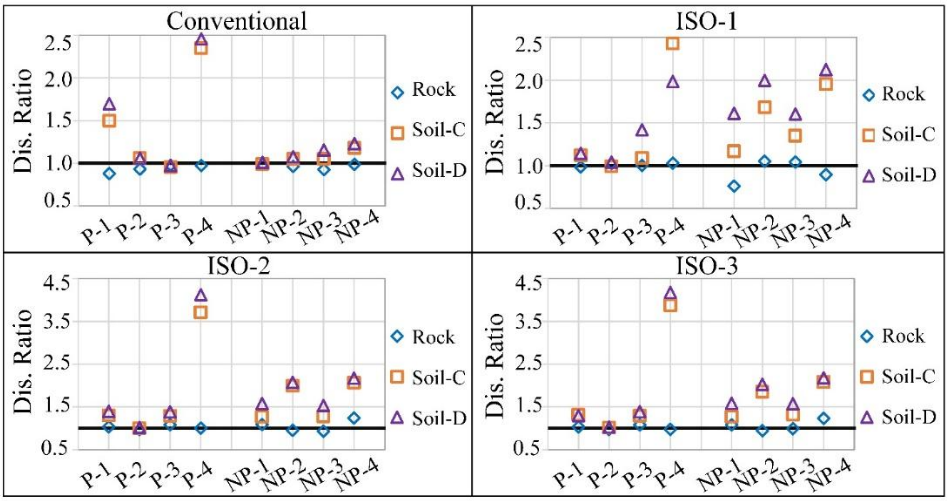

Figure 9. Displacement ratio (SSI/Fixed-base).

Responses of NLTHA lead to the fact that pulse-like records cause higher dynamic responses in terms of force and displacement demand compared to records without pulses.

In addition, while considering that soil plays a positive role in pulse-type records by reducing the acceleration and base shear responses on softer soils, it does not show a notable effect in records without pulses.

Moreover, pulse-type records need higher displacement capacity in both conventional and isolated bridges, and the regular designing process of isolated bridges underestimates the displacement demand. Therefore, the optimum design of isolation systems with a higher displacement capacity is recommended for high seismicity areas to meet the displacement demand, despite the fact that they attract higher forces compared to the common design process of isolation systems. Consequently, careful attention needs to be paid to designing the isolation systems on softer soils as the displacement demand could be two times more than the case of ignoring the soil effect.

CONFLICT OF INTEREST

The authors declare no conflict of interest in this study.

AUTHOR CONTRIBUTIONS

Conceptualization, L.G., N.G., and N.C.; methodology, L.G., N.G., and N.C; writing, review and editing, L.G., N.C. All authors have read and agreed to the published version of the manuscript.

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