ASSESSMENT OF THE E031 CODE BOUNDARY LIMITS FOR ACCURATELY CAPTURING CRITICAL RESPONSES IN BASE-ISOLATED BUILDINGS

EVALUACIÓN DE LOS LÍMITES DE VARIACIÓN DE LA NORMA E031 PARA LA OBTENCIÓN PRECISA DE LAS RESPUESTAS CRÍTICAS EN EDIFICACIONES CON AISLAMIENTO DE BASE

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ABSTRACT

In Peru, the seismic design code mandates the use of seismic isolation in essential type A1 buildings located in the highest seismic zones (3 and 4). Natural rubber bearings, both with and without lead cores, are the most used; however, their dynamic properties can vary significantly due to various factors, which are considered in the design using Lambda property modification factors. This study aims to analyze the influence of these variations on the response of the isolation system and to evaluate the sufficiency of the limits established by Peruvian code E031, known as the “Upper Bound” and “Lower Bound”, in capturing the critical seismic responses of these structures. To achieve this, a comprehensive parametric analysis was conducted to investigate how variations in the dynamic properties of the isolators affect the overall response of the isolation system. The equivalent lateral force analysis procedure was used to assess these impacts. As a result, curves were generated illustrating the variation in key parameters such as base shear force, effective damping, maximum displacement and lateral restoring force in different scenarios. The findings reveal that certain states of variation lead to more critical responses than those indicated by the Upper and Lower Bounds specified in the standard. This suggests that the current criteria may not adequately encompass all possible scenarios, highlighting an urgent need for a review and update of the code to ensure the safety and effectiveness of base-isolated building designs in seismic-prone areas.

Keywords: seismic isolation, parametric analysis, property modification factors, bounding method of analysis, structural response

RESUMEN

En Perú, la norma de diseño sísmico exige el uso de aislamiento sísmico en los edificios esenciales de tipo A1 ubicados en las zonas sísmicas más altas (3 y 4). Los aisladores de caucho natural, tanto con núcleos de plomo como sin ellos, son los más utilizados; sin embargo, sus propiedades dinámicas pueden variar significativamente debido a diversos factores, los cuales son considerados en el diseño mediante los factores de modificación de propiedad Lambda. Este estudio tiene como objetivo analizar la influencia de estas variaciones en la respuesta del sistema de aislamiento y evaluar la suficiencia de los límites establecidos por el código peruano E031, conocidos como "Límite Superior" y "Límite Inferior", para capturar las respuestas sísmicas críticas de estas estructuras. Para ello, se realizó un análisis paramétrico exhaustivo para investigar cómo las variaciones en las propiedades dinámicas de los aisladores afectan la respuesta general del sistema de aislamiento. Se utilizó el procedimiento de análisis de fuerzas laterales equivalentes para evaluar estos impactos. Como resultado, se generaron curvas que ilustran la variación de parámetros clave como la fuerza cortante en la base, el amortiguamiento efectivo, el desplazamiento máximo y la fuerza restitutiva lateral en diferentes escenarios. Los hallazgos revelan que ciertos estados de variación conducen a respuestas más críticas que las indicadas por los límites "Límite superior" y "Límite inferior" especificados en la norma. Esto sugiere que los criterios actuales pueden no abarcar adecuadamente todos los escenarios posibles, lo que resalta la necesidad urgente de una revisión y actualización del código para garantizar la seguridad y efectividad de los diseños de edificios con aislamiento sísmico en áreas propensas a sismos.

Palabras Clave: aislamiento sísmico, análisis paramétrico, factores de modificación de propiedad, método de análisis por límites, respuesta estructural

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1. INTRODUCTION

1.1. BACKGROUND

Seismic isolation is a structural design approach intended to mitigate the effects of seismic forces on buildings and infrastructure by introducing flexibility at the foundation level [1]. This flexibility, combined with energy dissipation mechanisms, decouples the superstructure from ground motions, leading to reduced accelerations and damage in the structure above the isolation layer [2].

The behavior of seismic isolation systems is governed by the properties of their core components. Elastomeric bearings, commonly used in seismic isolation, are characterized by their capacity to deform under shear forces while providing vertical load-carrying capacity. Their performance is typically described using nonlinear properties, such as the characteristic strength (Q_d) and post-elastic stiffness (K_d). These parameters significantly influence the system's effective stiffness, damping, and overall seismic response.

The Peruvian seismic code E031 [3] introduces specific guidelines for the design and analysis of seismic isolation systems, including the application of property modification factors (λ) to account for variations in the nonlinear properties of isolators. These factors ensure that the system remains effective under realistic conditions, reflecting potential manufacturing tolerances, aging, environmental effects, heating, loading rate, and scragging effects.

1.2. PROBLEM STATEMENT

The properties of seismic isolators are inherently variable, and this variability must be incorporated into the analysis and design of base-isolated structures. These properties are influenced by the materials from which the isolators are fabricated; for elastomeric isolators, they are primarily determined by the characteristics of rubber and lead. Design standards, using lambda factors, define ranges of variation for each nonlinear parameter. However, as these variations originate from distinct materials, they do not necessarily occur simultaneously or in the same proportion. Thus, limiting the evaluation to the upper bound, where all properties are maximized, or the lower bound, where all properties are minimized, may overlook potentially critical conditions. A more comprehensive assessment requires exploring intermediate scenarios.

1.3. OBJECTIVES

The primary objective of this study is to evaluate the sufficiency of the Upper and Lower Bound limits defined by the Peruvian seismic design code E031 in capturing the critical seismic responses of base-isolated essential buildings. To achieve this, the study aims to:

1. Analyze the impact of variations in the dynamic properties of natural rubber bearings, with and without lead cores, on key structural response parameters such as base shear force, effective damping, maximum displacement, and restoring force.
2. Conduct a parametric analysis considering the seismic conditions of zones 3 and 4 in Peru, alongside different soil profiles (S0, S1, S2 and S3) to simulate diverse seismic scenarios.
3. Compare the results of this analysis with the E031 code's upper and lower bound limits, assessing their adequacy in capturing the most critical seismic responses.

1.4. SCOPE

This study focuses on evaluating the behavior of seismic isolation systems in essential A1-type buildings (public and private health sector establishments of second and third level, as regulated by the Ministry of Health of Peru), subjected to the seismic conditions of zones 3 and 4 in Peru, which are classified as high and very high seismicity areas according to E031 code. The analysis includes four soil profiles (S0, S1, S2 and S3) and employs a parametric approach to assess how variations in the dynamic properties of natural rubber bearings, with and without lead cores, impact the structural response. Using the equivalent lateral force (ELF) method, key parameters such as base shear force, maximum displacement, effective damping, and lateral restoring force will be examined. The results will be compared with the Upper and Lower Bound limits set by the E031 code to determine the adequacy of these limits in capturing critical structural responses.

2. LITERATURE REVIEW

2.1. SEISMIC ISOLATION SYSTEMS

Base isolation strategies generally adopt two fundamental approaches, both of which share certain key characteristics.

The first approach involves incorporating an isolation layer with low lateral stiffness between the structure and its foundation. This isolation layer significantly lengthens the natural period of the structure compared to its fixed-base natural period. As illustrated in the elastic design spectrum (Fig. 1),

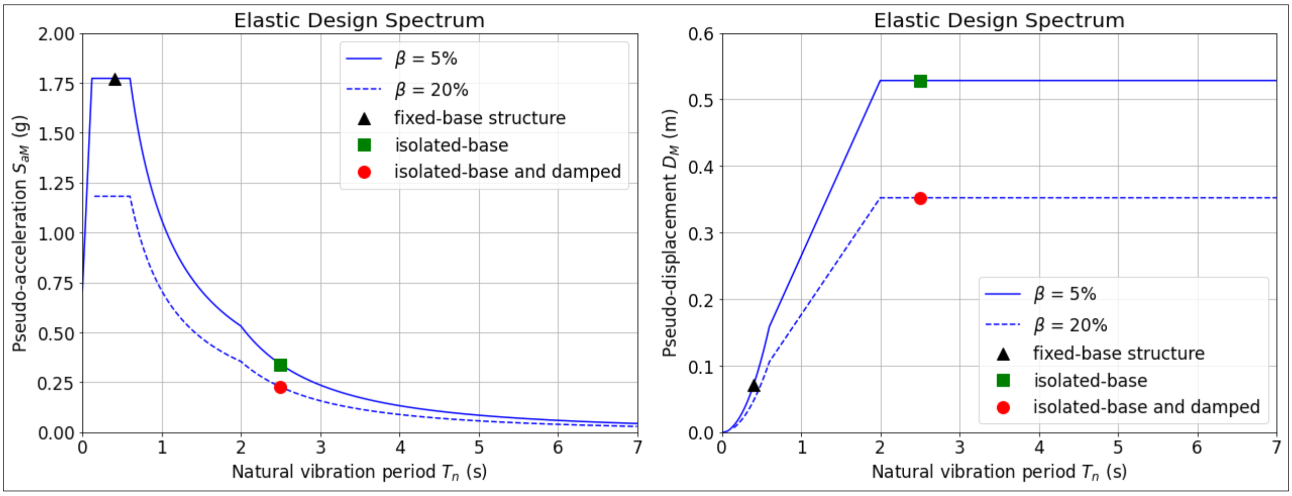

Fig. 1. Elastic design spectrum (pseudo-accelerations and pseudo-displacements).

this period elongation effectively reduces pseudo-acceleration and, consequently, the seismic forces acting on the structure. However, this comes at the cost of increased deformation. Notably, this deformation is predominantly localized within the isolation layer, resulting in minimal deformation within the superstructure. Even in the absence of damping, this type of isolation system proves effective, as its benefits arise primarily from period lengthening. Nonetheless, the inclusion of damping further enhances the system's performance by reducing both the forces transmitted to the structure and the deformation experienced by the isolation layer [2].

2.2. TYPES OF SEISMIC ISOLATORS

Low-damping natural rubber isolators, lead-rubber elastomeric isolators, and friction pendulum sliding isolators represent the most used seismic isolation systems in engineering practice. These systems are valued for their lateral flexibility, which facilitates effective energy dissipation and re-centering capabilities, while maintaining vertical stability under the building's weight and accommodating large displacements. The force-displacement response of these isolators is inherently nonlinear and hysteretic, and it can be accurately represented using rigid-linear, bilinear, or tri-linear models [4].

Given that this study focuses exclusively on the application of elastomeric isolators with and without lead cores, a detailed description of these specific types will be provided in the following sections.

2.2.1. LEAD RUBBER BEARING (LRB)

Elastomeric bearings used in seismic isolation systems consist of bonded alternating layers of rubber and steel shims (Fig. 2). Rubber exhibits unique characteristics compared to conventional materials, including high elastic deformability, exceptional elongation at break, and almost incompressibility behavior [5].

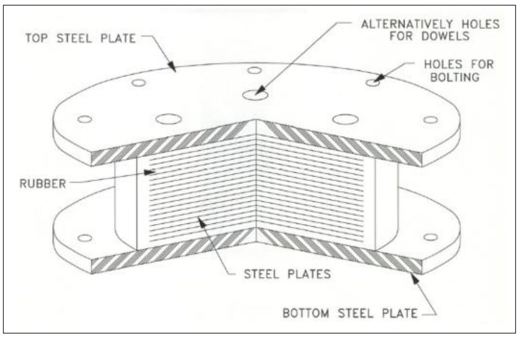

Fig. 2. Construction of an elastomeric bearing. [5]

Lead rubber bearings (LRB) are typically made with low-damping natural rubber and incorporate a lead core at the center of the isolator. The inclusion of the lead core significantly enhances the isolator's ability to absorb and dissipate seismic energy [5].

The lateral force-displacement behavior of a LRB isolator can be idealized by the bilinear hysteretic loop shown in Fig. 3 [1,4].

The bilinear model is characterized by three key parameters: K_d, K_e, and Q_d. In the case of elastomeric isolators, these parameters are influenced by the material properties (rubber and lead) as well as the geometry of the isolator, as detailed in equations 1 and 2.

$$K_d = \frac{GA}{T_r} \quad (1)$$

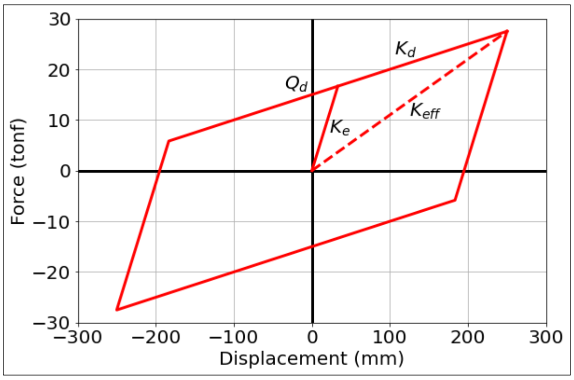

Fig. 3. Bilinear model. [4]

Where K_d is the post-elastic stiffness of the isolator, G is the shear modulus of the elastomer, A is the cross-section area, and T_r is the total thickness of the rubber.

Where Q_d is the characteristic strength of the isolator, σ_L is the effective yield stress of the lead, and A_L is the area of lead.

$$Q_d = \sigma_L A_L \text{..}(2)$$

The elastic stiffness K_e is either estimated from available hysteresis loops from tests or as a multiple of K_d. According to Naeim and Kelly [4], for LRB isolators, it is possible to use $K_e = 10K_d$.

Effective properties are calculated according to equations 3 and 4.

$$K_{eff} = K_d + \frac{Q_d}{\Delta} \text{......................................} (3)$$

$$EDC = 4\, Q_d \left(\Delta - d_y\right) \text{............................} (4)$$

Where K_{eff} is the effective stiffness of the isolator, and Δ is the deformation of the isolator.

Where EDC is the Energy Dissipated per Cycle, and d_y is the yield displacement, calculated as $d_y = Q_d/(K_e - K_d)$

2.2.2. NATURAL RUBBER BEARING (NRB)

Natural rubber bearings are constructed in a similar manner to lead-rubber bearings (LRB), with the key distinction being the absence of a lead core. NRB isolators are characterized by an effective damping ratio of less than 5% [5].

The mechanical response of NRB is typically modeled as linear elastic, which can be viewed as a special case of the bilinear model where Q_d is omitted [4].

2.3. PROPERTY MODIFICATION FACTORS (LAMBDA FACTORS)

Seismic bearings exhibit distinctive attributes that are not widely recognized by most registered design professionals (RDP). A critical aspect of these devices is the inherent variability and uncertainty in their mechanical properties, necessitating comprehensive testing to accurately characterize their behavior. This is primarily due to the custom-designed nature of seismic bearings, which are fabricated using proprietary methods and non-traditional materials, such as composites, lead, and elastomers [6].

The mechanical properties of seismic isolators may vary over time due to aging, caused by the continuous vulcanization of the rubber, and exposure to environmental contaminants. Additionally, their behavior during seismic events is influenced by factors such as heating, load history, and scragging effects. Variations may also arise between individual isolators due to manufacturing differences. Some of these influences contribute to an increase in stiffness and strength, which will cause changes in the effective period and damping, while others lead to a reduction in those parameters [4].

Given that their properties evolve over time and are impacted by independent phenomena, the precise state of seismic bearings at the time of a controlling earthquake remains inherently uncertain [6].

The property modification lambda factors provide a quantitative measure of the variability in isolator properties due to specific influencing effects. For instance, if an effect results in a 10% increase or a reduction of 5% in a nominal property like Q_d, the corresponding lambda factors would be $\lambda_{max} = 1.10$ and $\lambda_{min} = 0.95$, respectively.

The Peruvian Standard E031 and ASCE 7-22 [7] define nominal design properties as the average values obtained over three cycles of motion and classify property modification lambda factors into three categories:

1. λ_{ae}, addressing aging and environmental effects.
2. λ_{test} or λ_{tvs}, accounting for heating, loading rate, and scragging effects.
3. λ_{spec} or λ_{fab}, capturing allowable manufacturing variations.

For each parameter governing the force-displacement behavior of the isolator, six lambda factors are specified: $\lambda_{ae,max}$, $\lambda_{ae,min}$, $\lambda_{tvs,max}$, $\lambda_{tvs,min}$, $\lambda_{fab,max}$, and $\lambda_{fab,min}$. In the case of a lead-rubber isolator modeled using bilinear behavior, two distinct sets of these six factors are required: one for the post-elastic stiffness (K_d) and another for the characteristic strength (Q_d).

The three "max" lambda factors are combined to derive the maximum system factor λ_{max}, while the three "min" lambda factors are similarly combined to determine the minimum system factor λ_{min}. According to Peruvian Standard E031 and ASCE 7-22, these combinations are calculated using equations 5 and 6, respectively.

$$\lambda_{max} = \left(1 + 0.75\left(\lambda_{ae,max} - 1\right)\right) \lambda_{tvs,max}\, \lambda_{fab,max} \qquad (5)$$

$$\lambda_{min} = \left(1 - 0.75\left(1 - \lambda_{ae,min}\right)\right) \lambda_{tvs,min}\, \lambda_{fab,min} \qquad (6)$$

This approach enables the quantification of the variability in each nonlinear property of the seismic isolator, ensuring that these variations are appropriately considered during analysis and design processes.

2.4. PERUVIAN CODE E031 SEISMIC ISOLATION

The Peruvian Code E031 Seismic Isolation [3] establishes the minimum requirements for the design and construction of buildings that incorporate any type of seismic isolation system. In general, the code specifies the general requirements for the design of isolated structures, details the procedures for seismic analysis, establishes criteria for selecting the appropriate type of analysis, and provides guidelines for testing seismic isolation devices.

Among the general design requirements, the code introduces property modification factors, known as lambda (λ) factors, which account for the variability in the nominal design parameters specific to each type of isolator. Furthermore, Article 13.4 mandates the development of two analytical models: one based on the maximum properties of the isolators, referred to as the "Upper Bound" and the other based on the minimum properties, termed the "Lower Bound". For each response parameter of interest, the design is based on the most unfavorable result obtained from these two models, ensuring the resilience of the structure under both maximum and minimum property conditions.

3. METHODOLOGY

3.1. DESCRIPTION OF CASE STUDY BUIDLINGS

In accordance with the Peruvian Code E030 Seismic-Resistant Design [8], new A1-category buildings must incorporate base isolation systems when located in high-seismicity zones (specifically, zones 3 and 4). Thus, this study evaluates seismic responses under conditions specific to these zones, incorporating soil classifications S0, S1, S2 and S3 to capure the full range of subsoil variability.

To standardize the analysis, the seismic weight of the model building is set as 10,000 tons. This normalization facilitates consistent derivation of isolator properties based on target period and damping, ensuring that while the nonlinear properties of the isolation system are scaled in accordance with seismic weight, the isolation system's behavior remains unaffected by the specific weight value. This methodological approach enables a precise parametric analysis across varying seismic scenarios, supporting rigorous evaluation of isolator performance under diverse ground and seismic conditions.

3.2. SEISMIC ISOLATION SYSTEMS CHARACTERISTICS

For this study, the isolation system is designed using elastomeric natural rubber bearings, both with and without lead cores. Consequently, a bilinear model is adopted to calculate the nonlinear properties of the seismic isolation system (Q_d and K_d). The values of Q_d and K_d are proposed values, so

TABLE I
Nominal values of the nonlinear properties of the isolation system in each study case

Zone	Soil	T (s)	β_{eff} (%)	Q_d (ton)	K_d (ton/m)
Z4	S0	3.50	10	132.7	2757.9
Z4	S1	3.50	15	249.4	2482.3
Z4	S2	3.50	20	384.8	2192.6
Z4	S3	3.50	25	649.1	1877.9
Z3	S0	3.50	10	103.2	2757.9
Z3	S1	3.50	15	194.0	2482.3
Z3	S2	3.50	20	327.8	2192.6
Z3	S3	3.50	25	550.8	1877.9

that the effective damping obtained with these parameters is the target value indicated in **Table I**, and the effective stiffness obtained results in the target vibration period indicated in the same table.

The target periods and damping ratios considered in each scenario are detailed in columns "T" and "β_{eff}" of **TABLE I**. Softer soil conditions lead to larger displacements, thus, higher target damping values are proposed for these cases. An effective target period of 3.50 seconds is adopted for all cases to ensure that the fundamental vibration period falls within the constant displacement range of the design spectrum.

To account for variations in the properties of the seismic isolators, the lambda property modification factors for elastomeric bearings specified in Table 2 of the Peruvian Standard E031 Seismic Isolation will be applied, as summarized in **TABLE II**.

TABLE II
Property modification lambda factors for Class I isolators. Adapted from E031 code.

Factor	Q_d	K_d
λ_{max}	1.50	1.30
λ_{min}	0.80	0.80

3.3. ANALYSIS PROCEDURE

3.3.1. EQUIVALENT LATERAL FORCE ANALYSIS

The equivalent lateral force analysis procedure is a method that assumes the superstructure behaves nearly as a rigid body, concentrating displacements at the isolation level, thereby resulting in movement like a single-degree-of-freedom system [1]. Additionally, this procedure is essential as it establishes the minimum design forces and displacements [1,3,8].

The E031 standard [3] presents the equations and steps for the equivalent lateral force analysis, summarized as follows:

1. An initial maximum displacement value, D_M, is proposed.
2. With known values of Q_d and K_d, the effective stiffness is calculated using equation (3).
3. The energy dissipated per cycle, EDC, is calculated following equation (4).
4. The system's effective damping, β_{eff}, is determined by equation (7).

$$\beta_{eff} = \frac{EDC}{2\pi K_{eff} D_M^2} \quad (7)$$

5. The damping factor, B_M, is obtained from Table 5 of E031 standard.
6. The maximum displacement, D_M, is computed using equation (8).

$$D_M = \frac{S_{aM} T_M^2}{4\pi^2 B_M} \quad (8)$$

7. If the calculated D_M value differs from the initial assumption, the process returns to step 2, iterating until convergence.

Once the iterative process is complete, the base shear force is computed using equation (9).

$$V_b = K_{eff} D_M \quad (9)$$

Finally, the restoring force of the isolation system is calculated. Section 9.4 of the E031 standard specifies that the seismic isolation system must be designed to produce a lateral restoring force at maximum displacement that exceeds by at least 0.025 W_s the lateral force corresponding to 50% of the maximum displacement. Applying the bilinear model expressions results in equation (10).

$$F_{D_M} - F_{0.5D_M} \geq 0.025W_s$$

$$(Q_d + K_d D_M) - (Q_d + 0.5K_d D_M) \geq 0.025W_s$$

$$\frac{0.5K_d D_M}{W_s} \geq 2.50\%$$

From this point onward, the expression on the left-hand side of the inequation will be referred to as the Restoring Force, which must meet or exceed 2.50%.

$$F_R = \frac{0.5K_d D_M}{W_s} \quad (10)$$

3.3.2. PARAMETRIC ANALYSIS

To account for potential variations in the nonlinear properties of seismic isolators, a total of 50 values within the variation range of each nonlinear property (Q_d and K_d) will be considered, resulting in 2500 cases for each combination of seismic zone and soil type.

The variation ranges are defined by the minimum and maximum values of Q_d and K_d, obtained by applying the property modification λ factors to their respective nominal values, as shown in equations (11a), (11b), (12a) and (12b).

$$Q_{d,max} = Q_{d,nom} \times \lambda_{max} \text{ ....(11a)}$$

$$Q_{d,min} = Q_{d,nom} \times \lambda_{min} \text{ ....(11b)}$$

$$K_{d,max} = K_{d,nom} \times \lambda_{max} \text{ .... (12a)}$$

$$K_{d,min} = K_{d,nom} \times \lambda_{min} \text{......................(12b)}$$

Fig. 4 shows 50 values within the variation range for both Q_d and K_d, where each red point on the graph represents an individual analysis case in which Q_d has a value between $Q_{d,min}$ and $Q_{d,max}$, and K_d has a value between $K_{d,min}$ and $K_{d,max}$. The green square in Fig. 4 represents the "Lower Bound" specified by the E031 standard, where Q_d and K_d take their minimum values, and the black triangle in the same figure represents the "Upper Bound" as specified by the E031 standard, where Q_d and K_d take their maximum values.

In addition, two extreme cases are also highlighted, which are Case A Bound which considers the maximum value of K_d and the minimum value of Q_d, and Case B Bound which considers the minimum value of K_d and the maximum value of Q_d.

These analyses will be conducted considering seismic zones 3 and 4, along with soil profiles S0, S1, S2 and S3.

3.3.3. EVALUATION CRITERIA

For each analytical case, the following seismic response parameters of the isolation system are evaluated:

1. Base shear force, normalized by seismic weight (V_b/W_s), expressed as a percentage (%).
2. Effective damping of the isolation system (β_{eff}), also expressed as a percentage (%).

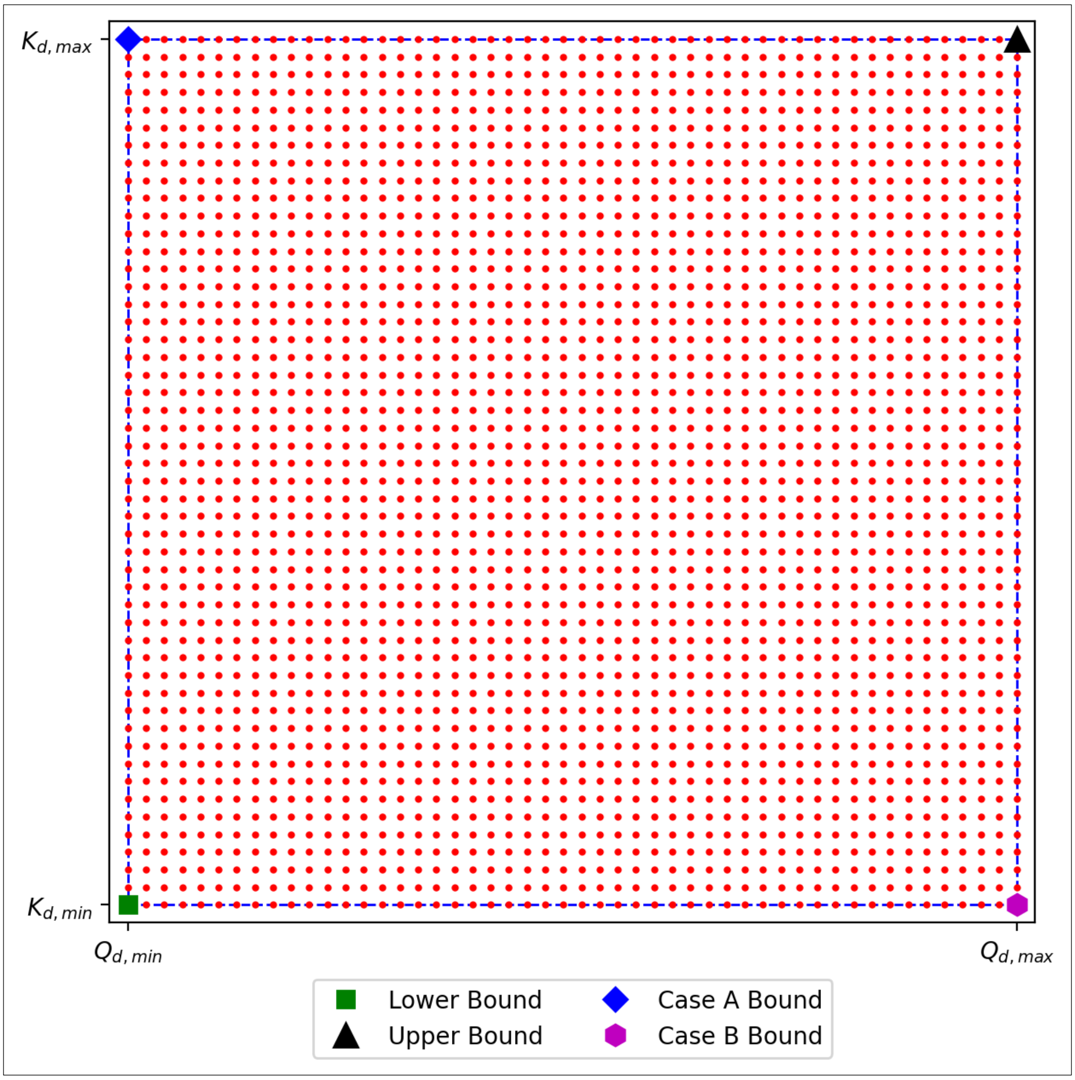

Fig. 4. Cases of analysis. Each point on the graph represents an analysis case with a value of Kd and Qd within their respective ranges of variation.

3. Maximum displacement of the isolation system (D_M), reported in meters (m).
4. Lateral restoring force (F_r), normalized by seismic weight and calculated following the equation (10).

Upon calculating these parameters, an assessment is conducted to determine if the "Lower Bound" and "Upper Bound" cases indeed represent the most critical response states achievable for a base-isolated structure.

4. RESULTS AND DISCUSSION

4.1. EFFECTIVE DAMPING AND DISPLACEMENT

The fundamental vibration period falls within the constant displacement region of the design spectrum because the nonlinear properties of the isolators were initially calculated assuming a nominal period of 3.50 seconds, which is always greater than T_L. Consequently, the maximum displacement D_M is directly influenced by the effective damping β_{eff}.

Fig. 5 and 6 illustrate that effective damping tends to be constant when Q_d and K_d vary at the same rate. However, when Q_d and K_d vary at different rates, effective damping no longer remains constant. Specifically, effective damping increases as the parameters approach the Case B Bound and decreases as they approach the Case A Bound.

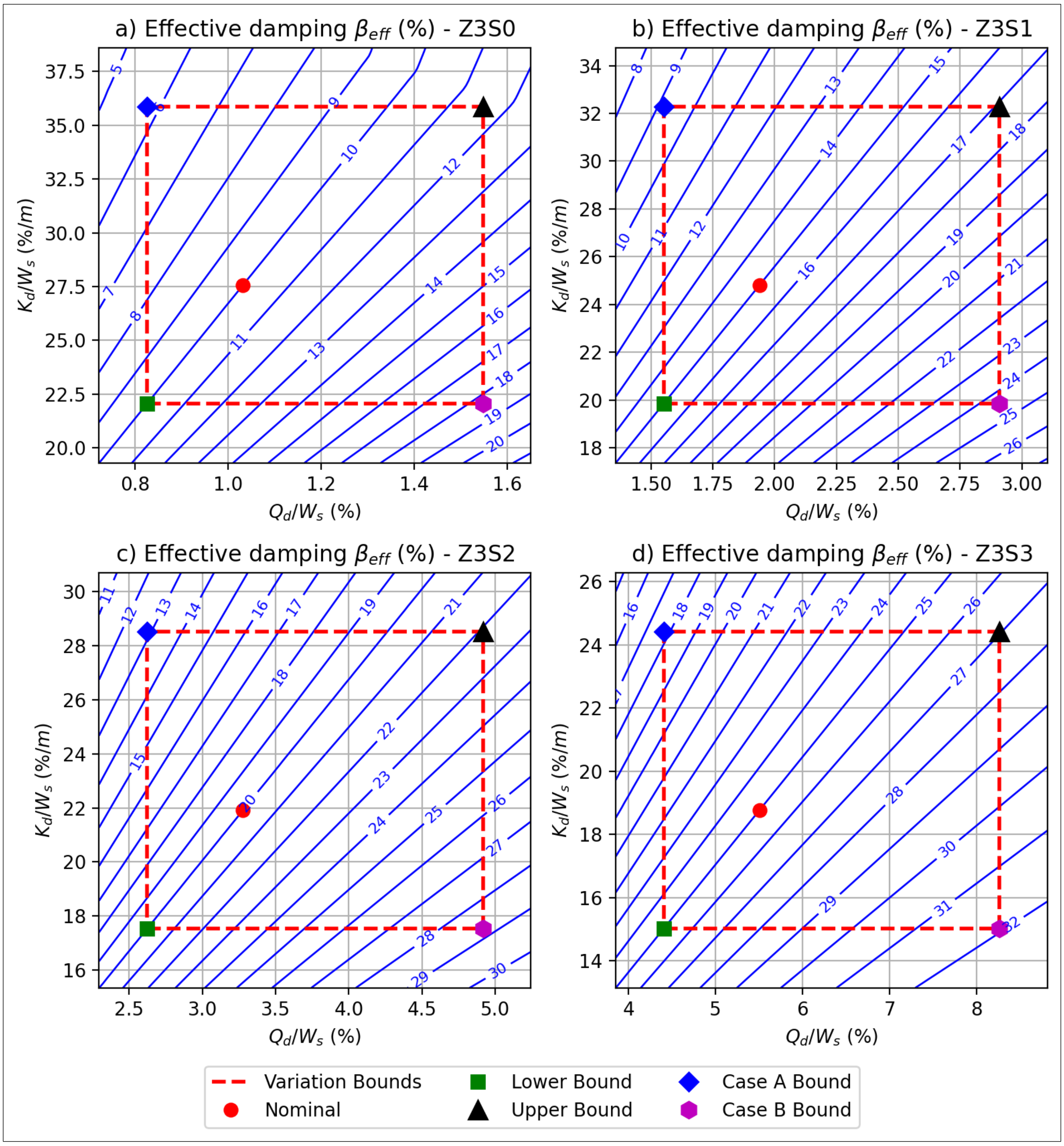

Fig. 5. Effective damping variations as a function of Q_d and K_d under seismic conditions for Zone 3 and across the four soil profiles.

Similarly, Fig. 7 and 8 show that the maximum displacement D_M also remains constant when Q_d and K_d vary at the same rate. However, when these parameters deviate independently, D_M decreases as the parameters approach the Case B Bound, and increases as they approach the Case A Bound.

In certain instances, such as for Z4S0 and Z3S0, the curves exhibit a shift in their trend as Q_d and K_d approach their maximum values. This change is attributed to the fact that, in these cases, the vibration period was found to be shorter than T_L, resulting in the system moving out of the constant displacement region of the spectrum. This can be observed in Fig. 9 and 10.

4.2. BASE SHEAR FORCE

Fig. 11 and 12 indicate that for the more flexible soil profiles, S2 and S3, a higher base shear force is observed in the Upper Bound. In contrast, for the stiffer soil profiles, such as S0 and S1, a greater base shear force is achieved in the Case A Bound compared to the Upper Bound. This behavior is observed consistently in both seismic zones 3 and 4.

4.3. LATERAL RESTORING FORCE

Fig. 13 and 14 illustrate that, across both seismic zones and all four soil types, the highest lateral

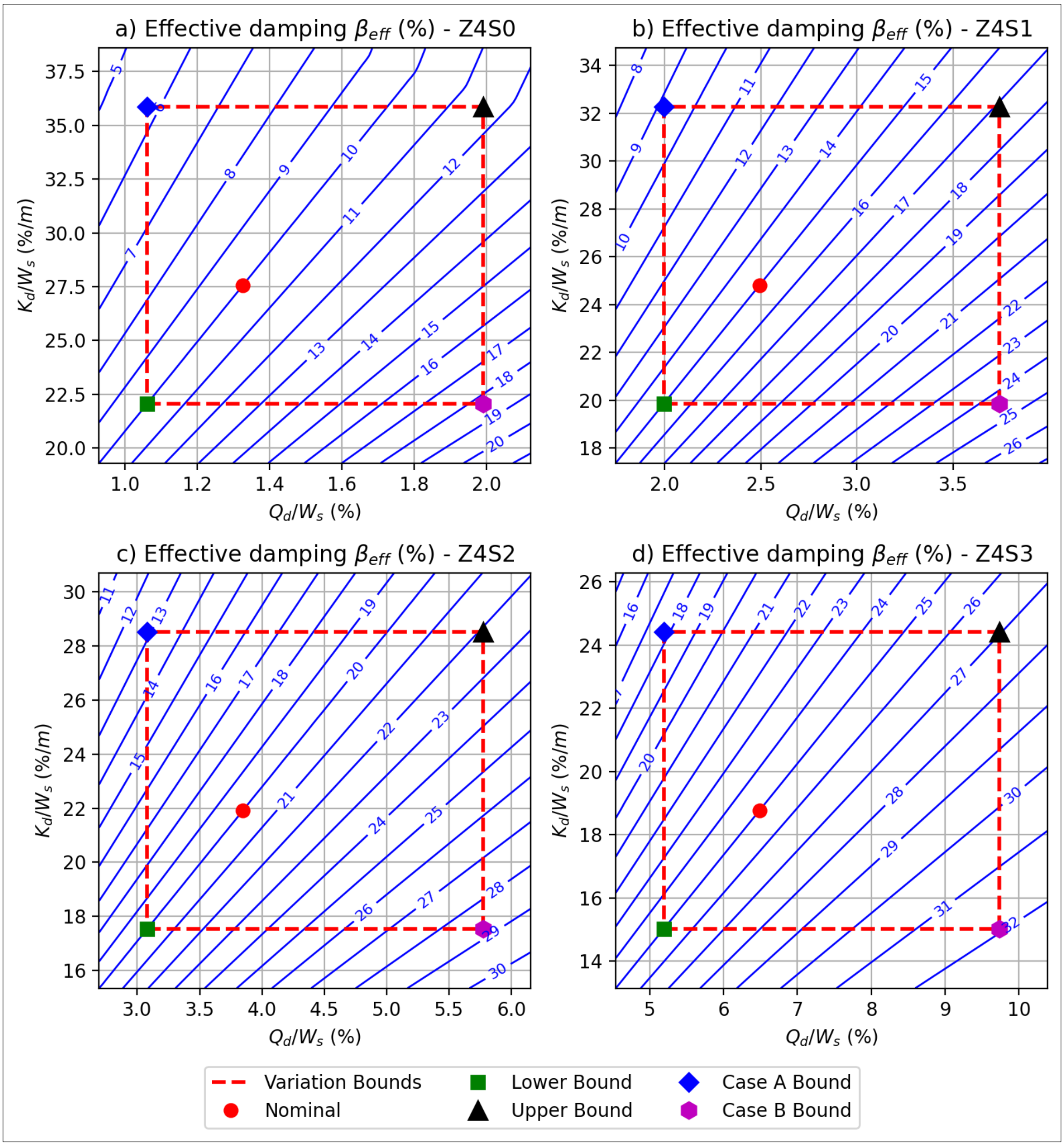

Fig. 6. Effective damping variations as a function of Q_d and K_d under seismic conditions for Zone 4 and across the four soil profiles.

restoring force is obtained in the Case A Bound, followed by the Upper Bound, then the Lower Bound, with the lowest restoring force observed in the Case B Bound.

Given that Peruvian Code E031 requires a minimum lateral restoring force of 2.50%, the most critical scenario for compliance is the Case B Bound, as it yields a lower restoring force compared to the Upper and Lower Bound cases.

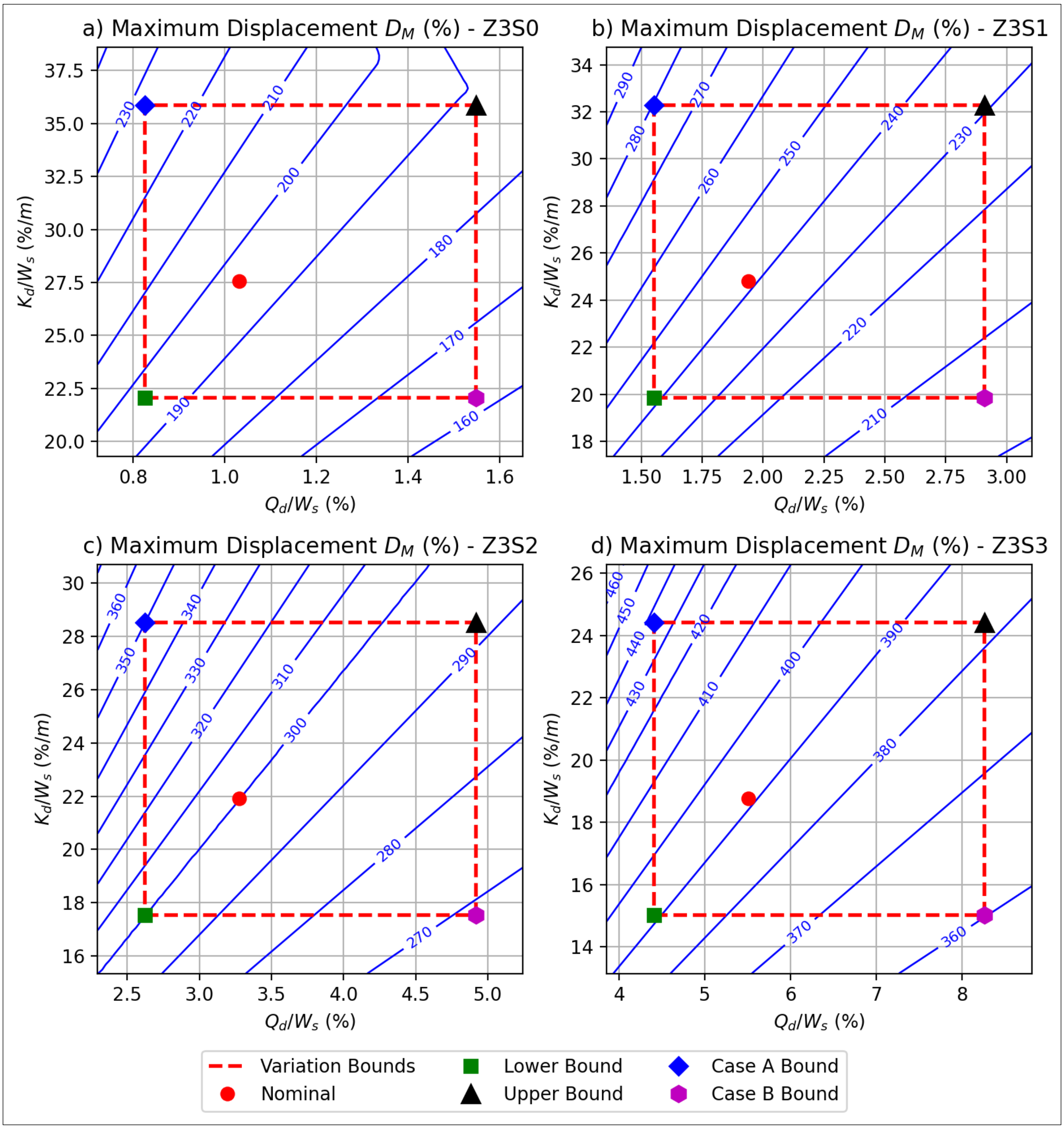

Fig. 7. Maximum displacement variations as a function of Q_d and K_d under seismic conditions for Zone 3 and across the four soil profiles.

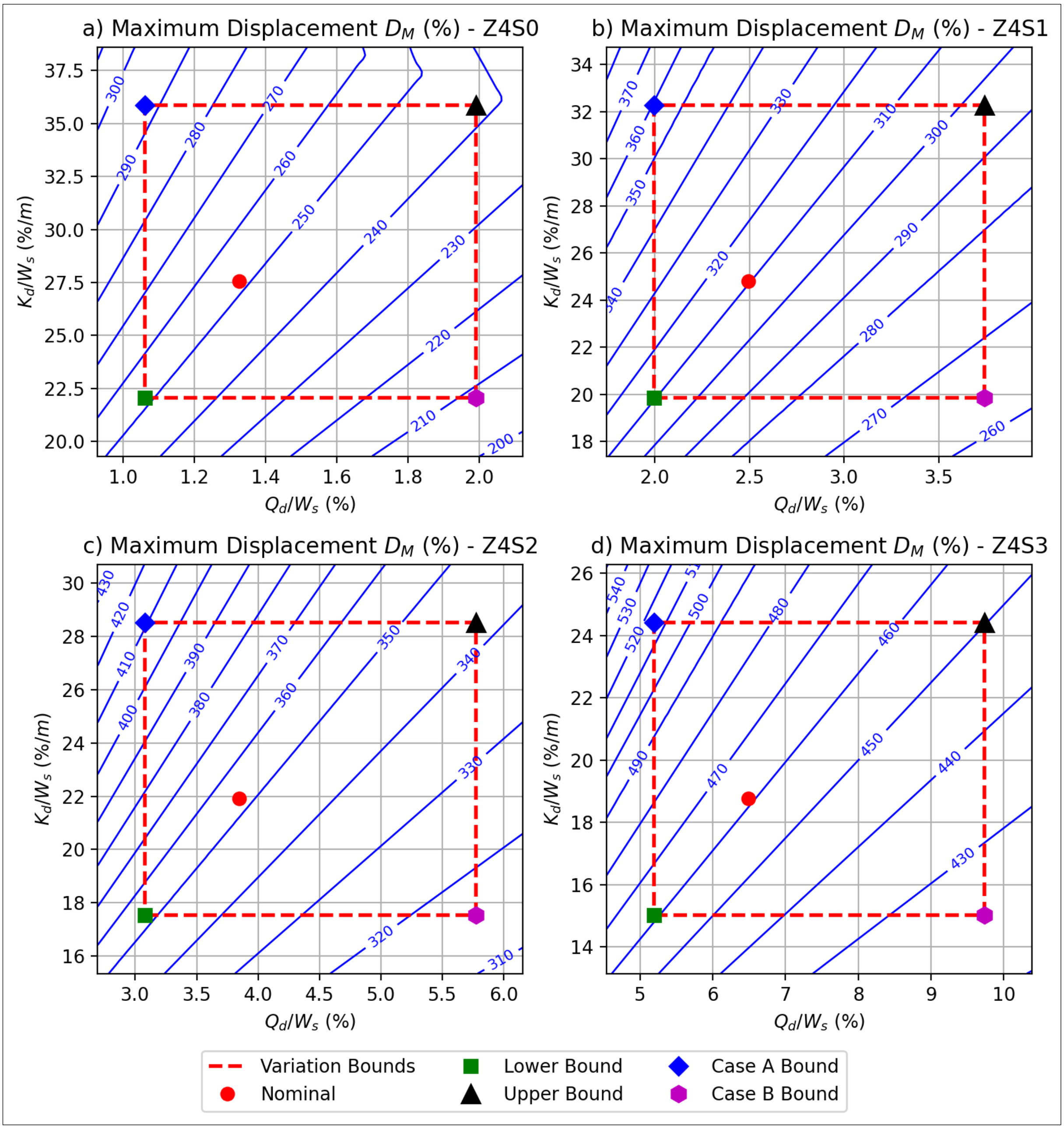

Fig. 8. Maximum displacement variations as a function of Q_d and K_d under seismic conditions for Zone 4 and across the four soil profiles.

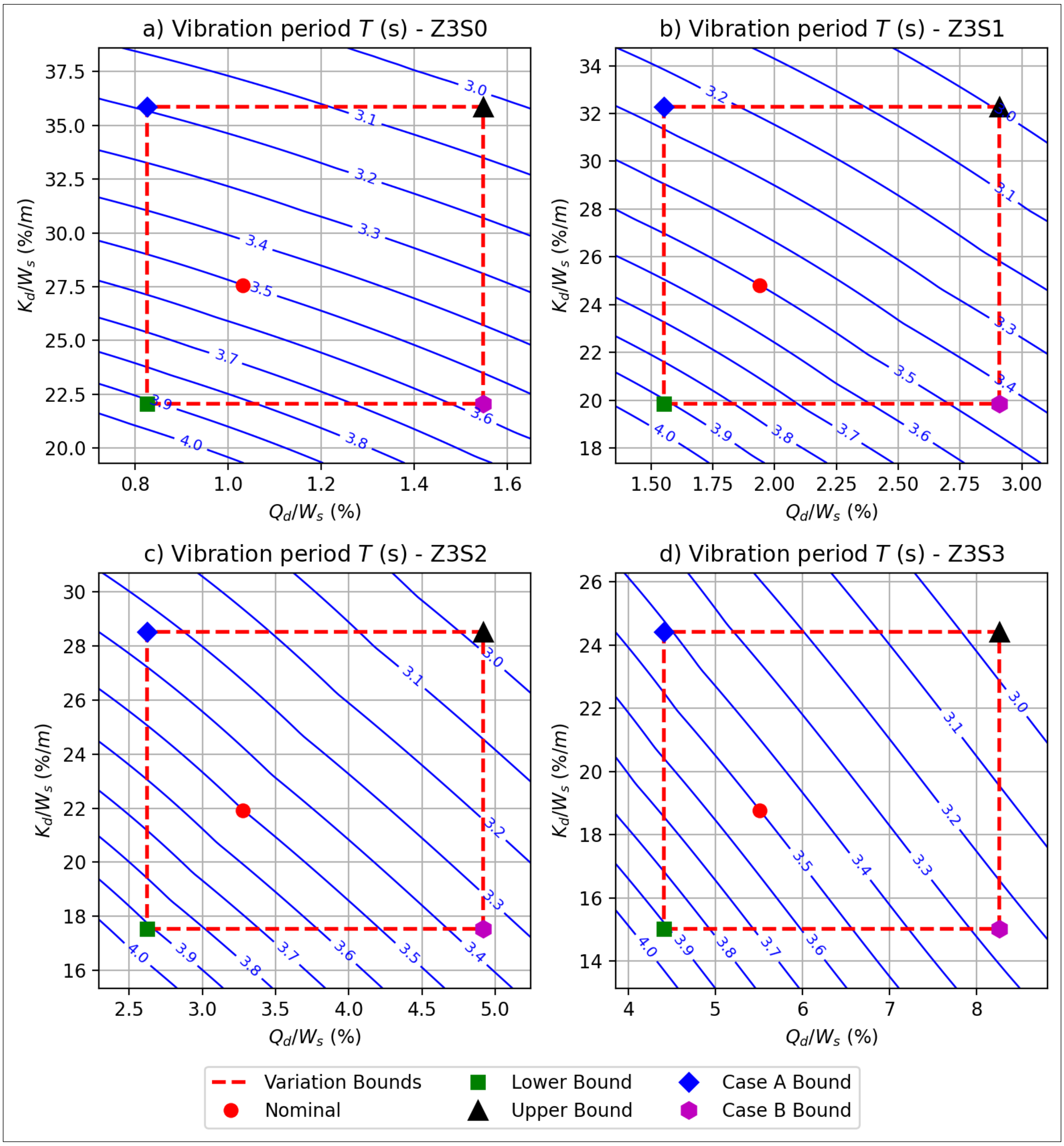

Fig. 9. Vibration period variations as a function of Q_d and K_d under seismic conditions for Zone 3 and across the four soil profiles.

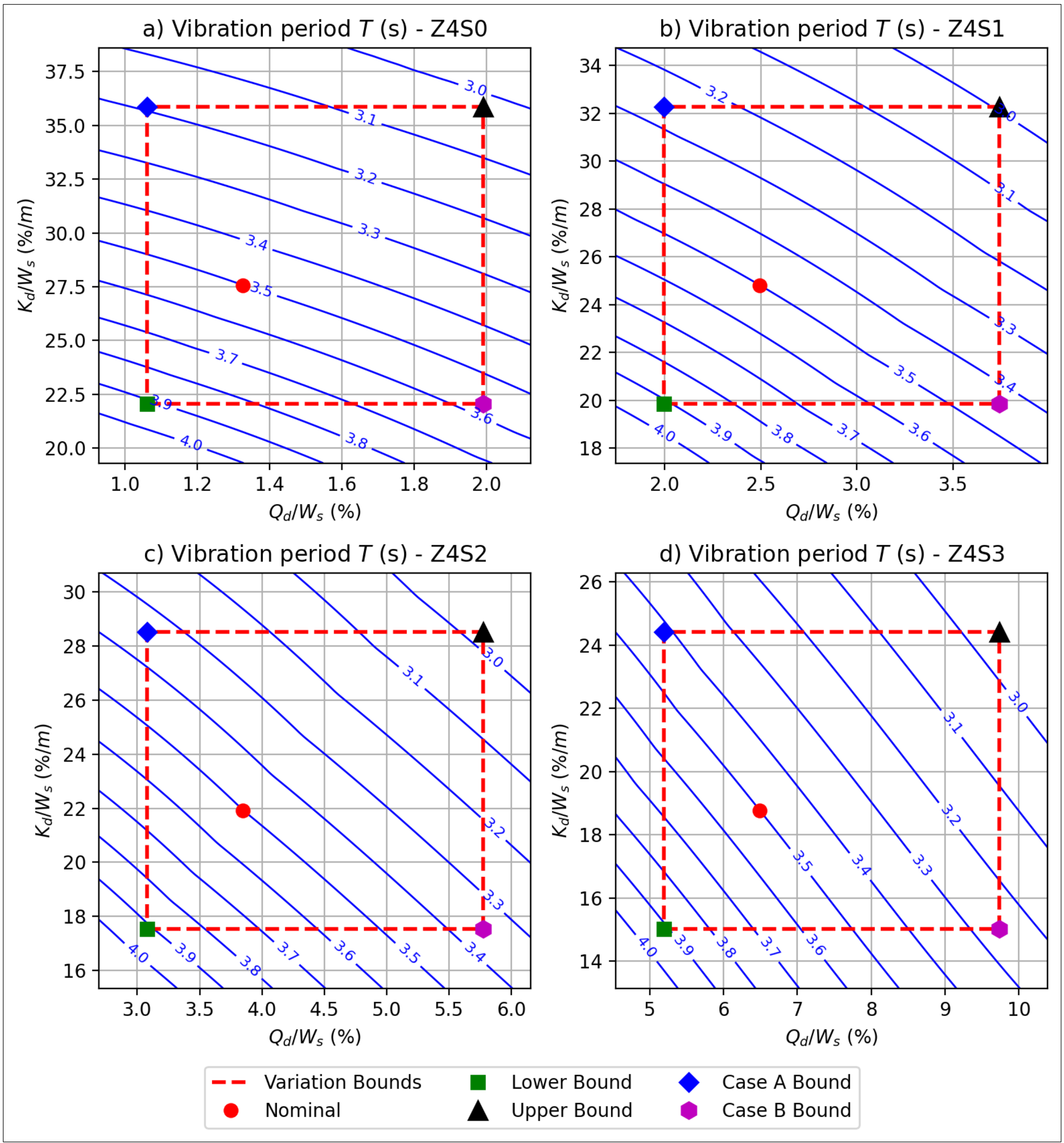

Fig. 10. Vibration period variations as a function of Q_d and K_d under seismic conditions for Zone 4 and across the four soil profiles.

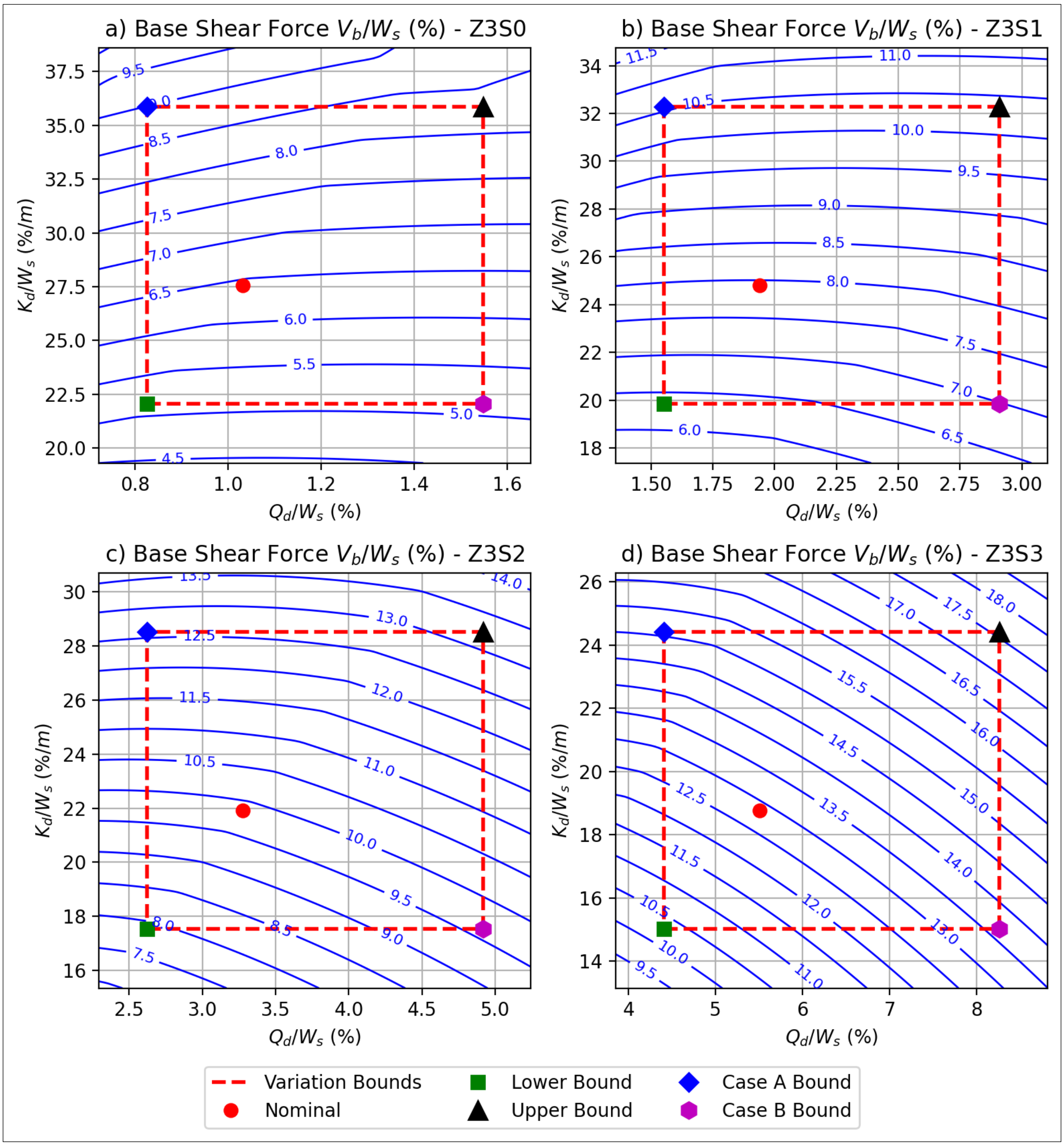

Fig. 11. Base shear force variations as a function of Q_d and K_d under seismic conditions for Zone 3 and across the four soil profiles.

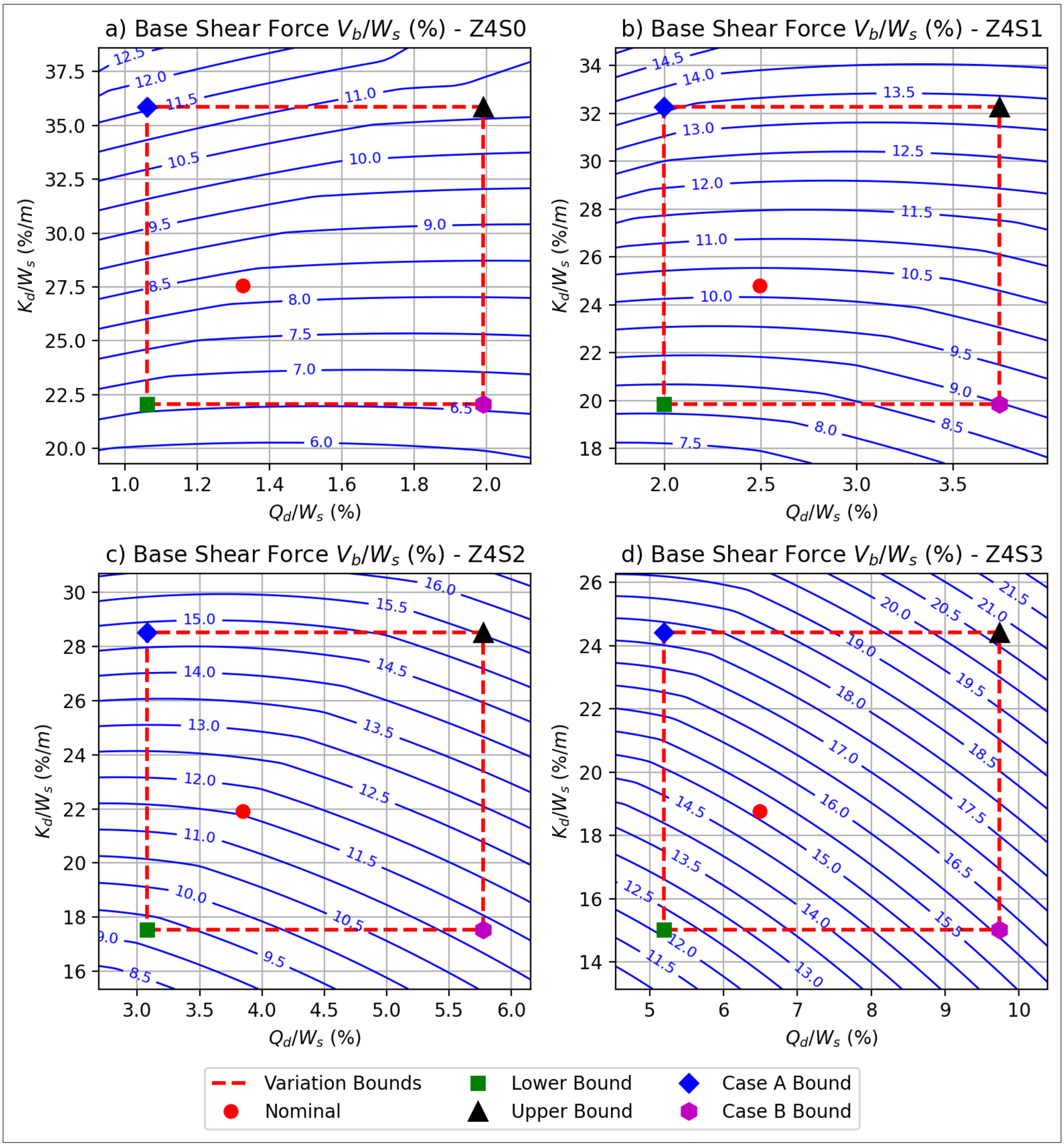

Fig. 12. Base shear force variations as a function of Q_d and K_d under seismic conditions for Zone 4 and across the four soil profiles.

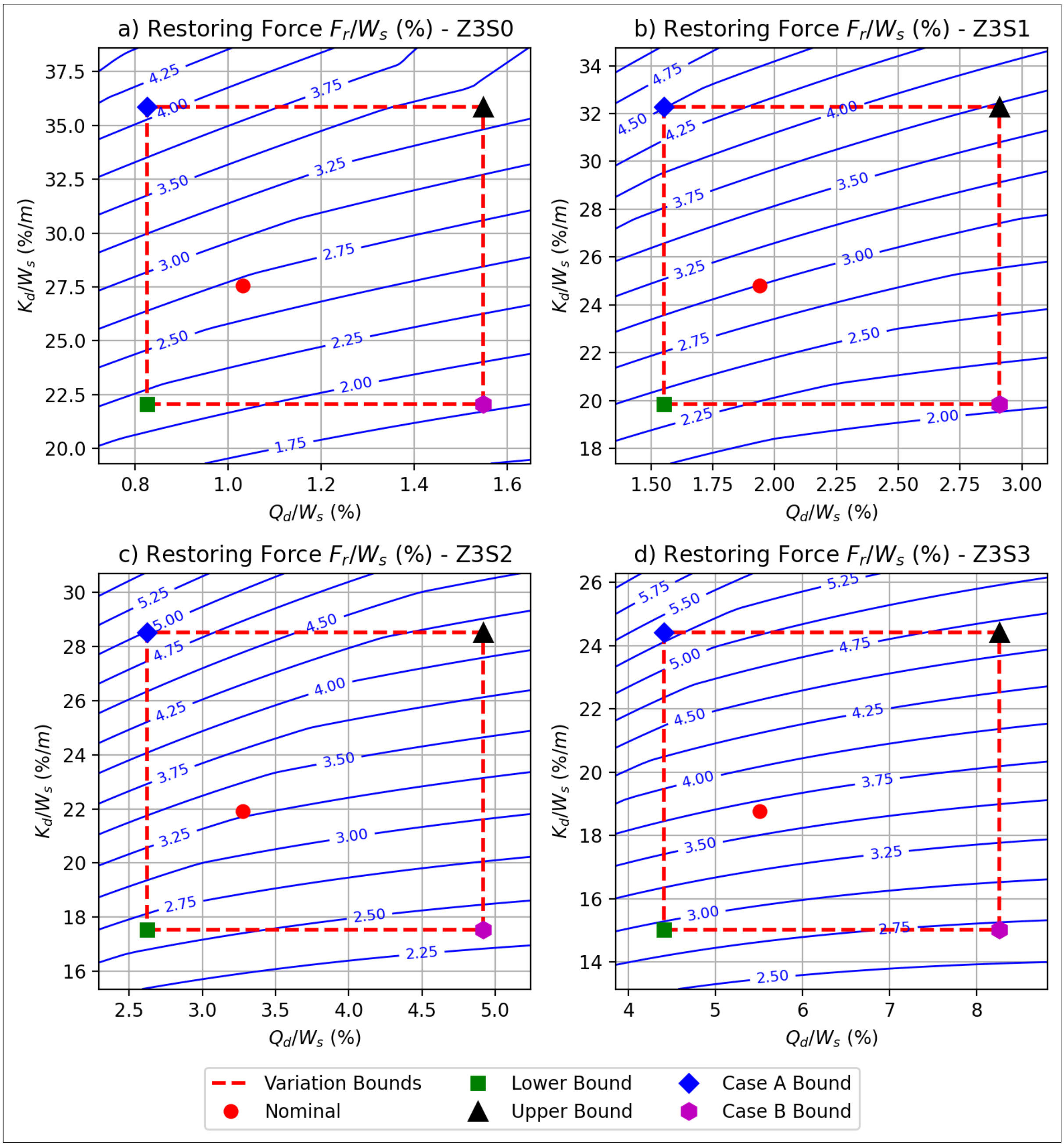

Fig. 13. Restoring force variations as a function of Q_d and K_d under seismic conditions for Zone 3 and across the four soil profiles.

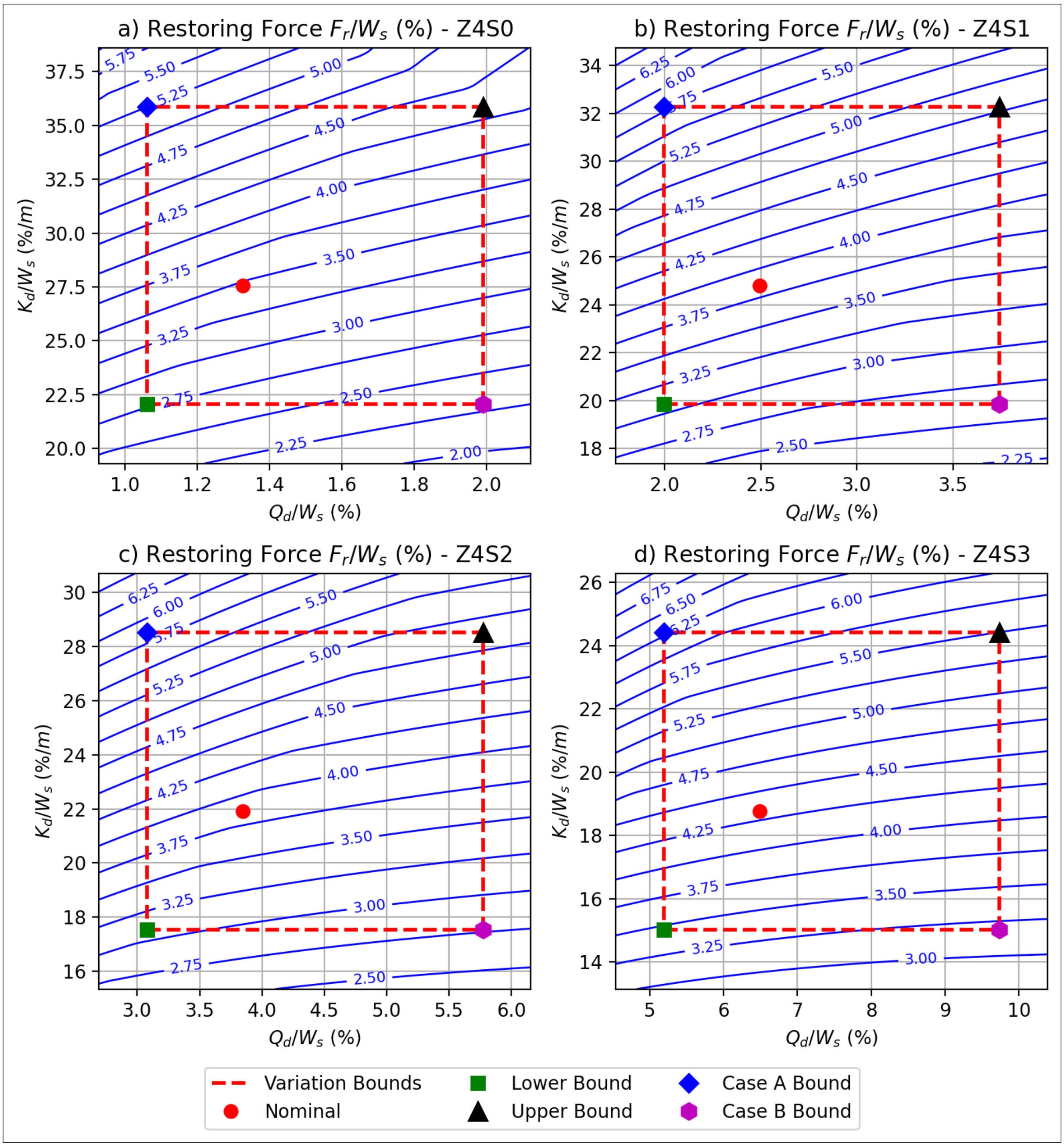

Fig. 14. Restoring force variations as a function of Q_d and K_d under seismic conditions for Zone 4 and across the four soil profiles.

CONCLUSIONS

This study comprehensively analyzed the behavior of seismic isolation systems under varying nonlinear properties and seismic conditions. The following key findings were derived:

- The effective damping (β_{eff}) demonstrates sensitivity to the variation of Q_d and K_d, increasing near the Case B Bound and decreasing near the Case A Bound. This highlights the influence of nonlinear property distribution on energy dissipation.
- Maximum displacement (D_M) decreases as Q_d and K_d approach the Case B Bound, and increases near the Case A Bound. Notably, for this response parameter, the Case A Bound is more critical than the Lower Bound.
- Base shear force behavior varies significantly with soil profiles. For flexible soil profiles (S2 and S3), the most critical base shear force is observed in the Upper Bound. Conversely, for stiffer soil profiles (S0 and S1), the Case A Bound governs the critical scenario.
- Across all analyzed scenarios, the Case B Bound consistently yields the lowest restoring force, representing the most

demanding condition to meet the minimum force criteria established by seismic code.

These findings emphasize the importance of accounting for variations in nonlinear isolator properties when designing seismic isolation systems. Moreover, they provide valuable insights into how soil conditions influence response parameters, offering a foundation for improving seismic design standards.

It is important to note that the observed results correspond to the cases analyzed in Section 3.2. For real-world projects with nominal values of Q_d and K_d different from those presented in this study, it is recommended to conduct an analysis across all four cases (Case A Bound, Case B Bound, Upper Bound and Lower Bound) to identify the most critical conditions for each response parameter of interest.

The current criteria, which is based on upper and lower bounds, may not account for the full variability in isolator properties and their influence on seismic response. This emphasizes the need for a comprehensive review and update of the code to ensure the safety and effectiveness of base-isolated buildings in earthquake-prone regions.

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