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Probabilistic Analysis of Soil-Structure Interaction Effects on Seismic Performance per ASCE/SEI 7-10 Guidelines

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ABSTRACT

This study investigates the impact of uncertainties in soil properties, particularly the stochastic variations in shear modulus (G) and Poisson's ratio (ν), on the period lengthening ratio ($\tilde{T}/T$) and base-shear reduction ($\frac{\Delta V}{V}$) of structures, considering soil-structure interaction (SSI) according to ASCE/SEI 7-10 guidelines. The motivation behind this research is to enhance the understanding and prediction of how uncertainties in soil properties affect the seismic response of structures, aiming at improving building design and safety. This research was conducted using a Monte Carlo simulation approach, generating 500,000 random values for G and ν to evaluate the variations (mean ± standard deviation) in the period lengthening ratio of the soil-foundation-structure system and base-shear reduction. The obtained results indicate that incorporating stochastic variations in the soil properties more accurately reflects the complexity and inherent uncertainty of the soil properties. Specifically, uncertainties in the shear modulus (G) significantly affect the fundamental period, base-shear reduction, and foundation damping. Conversely, the Poisson's ratio (ν) appears to be an inert factor. These findings have implications for seismic-design practices, suggesting that a deterministic approach might not capture critical aspects of material variability, thus contributing to uncertainties in structural response. This study provides critical insights into the role of soil properties in the dynamic response of structures, contributing to the development of more resilient designs and improving seismic risk management strategies.

Keywords: Period lengthening ratio, Monte Carlo simulations, Soil-structure interaction, Shear modulus, Poisson ratio, Stochastic analysis, Seismic design.

INTRODUCTION

In the mid-19th century, soil-structure interaction (SSI) analysis began to emerge, albeit tentatively, as a focus for improving building performance against seismic risk, with the aim of reducing human losses and structural damage. Initially, SSI was considered a minor factor in seismic analyses (Buitrago Goyez, 2017). However, its importance grew significantly with the emergence of massive and rigid structures, such as large industrial facilities and nuclear-power plants built on soft soils (Kausel, 2010; Demir & Livaoglu, 2023).

In experimental research, SSI provision has received substantial attention, with methods ranging from simple to highly sophisticated (Zhan et al., 2024). Simplified models continue to play a significant role in soil dynamics and geotechnical engineering (Dobry, 2014; Bapir et al., 2023) due to their suitability for reducing computational and data management-efforts (Guellil et al., 2017). On the other hand, these models provide a straightforward approach that allows engineers to address a multitude of practical issues related to SSI without resorting to complex or specialized methods (Worku, 2014). As SSI became a necessity, the civil engineering community established a series of standards and seismic-design codes to guide engineers, such as ATC 3-06, ASCE/SEI 7-10, ASCE/SEI 7-16 and FEMA P-1050 provisions (ASCE, 2016; FEMA, 2015).

The implementation of SSI in the seismic analysis of structures involves two main approaches: (i) the mono-step procedure (direct method), which considers SSI by modelling a partial soil domain around the structure; and (ii) the multi-step procedure (sub-structure method), which involves evaluating the seismic motion and dynamic stiffness of the foundation separately and then combining these parameters in the dynamic analysis of the structure (Guellil et al., 2020; NIST, 2012).

The fundamental period is a crucial parameter for controlling a structure's dynamic properties and is used in the estimation of seismic forces on buildings (Xiong et al., 2016). Most studies focusing on the impact of SSI on the dynamic response of structures during seismic shaking have reported that SSI extends the fundamental period of structures (Ada & Ayvaz, 2019; Khalil et al., 2007; Zaicenco & Alkaz, 2007; Stewart et al., 1999). A study published by Mercado et al. (2020) highlighted the significant influence of the structure’s geometric configuration and dynamic soil properties on the period lengthening ratio ($\tilde{T}/T$) of structures.

Previous studies have aimed to understand the behaviour of structures under dynamic loads and to produce reliable results (El Janous et al., 2024). Nevertheless, it is evident that various factors and parameters can alter the seismic performance of buildings when they experience seismic activity. A thorough review of the literature reveals that the relationships between the soil-structure interaction (SSI) and parameters such as the shear modulus (G) and Poisson's ratio (ν) have not been extensively explored. Thus, this study investigates the impact of these parameters on the seismic performance of buildings subjected to seismic loadings.

This research aims to analyze the impact of uncertainties in soil properties, specifically the random variations in shear modulus (G) and Poisson's ratio (ν), on the period lengthening ratio ($\tilde{T}/T$) and the reduction of base shear, while considering SSI for two soil types, D and E.

Analogical Modelling of the SSI Effects

In this research, the single degree of freedom (SDOF) system served as a representative of real structures (Fig. 1 (a)). This system is fundamental for understanding the dynamics of complex structures and is used to represent the first mode response of a structural system (El Janous et al., 2024; Cairo, 2022; Homaei, 2021).

As shown in Fig. 1(b), the model represents the structure with a mass *m* attached to the soil by springs and dashpots located at height h up to the foundation, allowing the structure to experience free motions in two directions (Kumar et al., 2014). The structure is connected to the foundation by a rigid bar. The foundation rests on the ground and interacts with the soil *via* impedance functions, which are defined as the reactions exerted by the soil on the foundation. The soil-foundation interaction is modelled using discrete components consisting of springs and viscous dashpots. For the displacements, u_g was considered for the ground displacement, u_0 for the displacement due to horizontal translation, $h\theta$ for the displacement due to rocking, and *u* for the displacement due to structural distortion (Cairo, 2022).This model is commonly adopted to account for inertial SSI (Guellil et al., 2020; Maravas et al., 2014) and is widely used in modern codes (FEMA, 2015; ASCE, 2016).

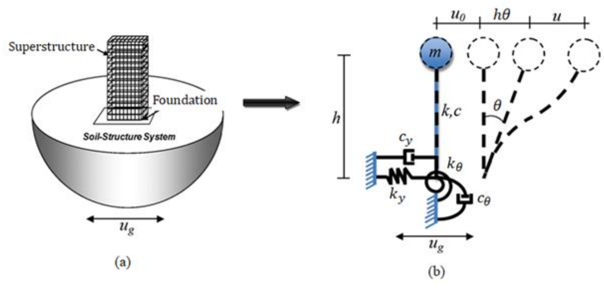

Figure (1): Modeling of SSI: (a) Schematic view of SSI system, (b) Equivalent SDOF system

The fundamental period of a building-type structure was calculated using Equation (1) proposed by Veletsos and Nair (1975), which takes into account the flexibility of the foundation.

$$\frac{\tilde{T}}{T} = \sqrt{1 + \frac{k}{k_y} + \frac{kh^2}{k_\theta}} \quad (1)$$

where $\tilde{T}$ and T represent the flexible and fixed fundamental periods of the structure, respectively; k_y and k_θ symbolize the translational and rotational rigidities of the foundation, respectively; h and k denote the total height and the flexural stiffness of the structure at a rigid base, respectively.

FEMA (2005) and ASCE (2005) requirements indicated the same equation, with the FEMA provisions notably overestimating the response (Vivek & Raychowdhury, 2017). Previous investigations have noted that most formulae related to the fundamental period of flexible-base structures were developed for systems with a single degree of freedom (SDOF) (Sadek et al., 2020). However, Equation (1) can also be applied in multi-storey framed structures (MDOF systems), where the fundamental mode of vibration is dominant, using the height h as the height of the centre of mass for the primary mode.

The foundation damping ($\tilde{\beta}$) results from both the structural viscous damping (β) and the effective viscous damping of the soil-foundation interaction system ($\tilde{\beta}_0$), as described by Equation (2) given by Veletsos and Nair (1975):

$$\tilde{\beta} = \tilde{\beta}_0 + \frac{\beta}{(\frac{\tilde{T}}{T})^3} \quad (2)$$

The translational stiffness (k_y) and rotational stiffness (k_θ) of the soil are computed as follows:

$$k_y = \frac{8}{2-\nu} GR_h \quad (3)$$

$$k_\theta = \frac{8}{3(1-\nu)} GR_\theta^3 \alpha_\theta \quad (4)$$

To illustrate the inherent variability of soil properties (shear modulus and Poisson's ratio) in the base-shear reduction $\frac{\Delta V}{V}$ considering soil-structure interaction, the provisions of the American standards ASCE/SEI 7-10 and FEMA (750) code provisions were explored in this study. To account for the effects of soil-structure interaction, the determined base shear (V) must be adjusted to $\tilde{V}$, as shown in Equation (5):

$$\tilde{V} = V - \Delta V \quad (5)$$

The reduction (ΔV) shall be computed as follows and must not exceed 0.3 V, as depicted in Equation(6):

$$\Delta V = \left[C_s - \tilde{C_s}\left(\frac{0.05}{\tilde{\beta}}\right)^{0.4}\right]\overline{W} \leq 0.3V \quad (6)$$

where Cs is the seismic-design coefficient computed using the fixed-base fundamental period of vibration (T).

$\tilde{C_s}$ is the value of Cs computed using the fundamental period of vibration ($\tilde{T}$) for a flexibly supported structure, as specified in ASCE/SEI 7-10. $\tilde{\beta}$ is the fraction of critical damping for the structure-foundation system. $\overline{W}$ is the effective seismic weight of the structure, which shall be taken as 0.7W, except for structures where the effective seismic weight is concentrated at a single level, in which case it shall be taken as W. $\tilde{T}$ is the effective period, given as follows:

$$\tilde{T} = T\sqrt{1 + \frac{k}{k_y} + \frac{kh^2}{k_\theta}} \quad (7)$$

The seismic-response coefficient corresponding to the fixed-base period T is given by (for an elastic response and a building with normal occupancy):

$$C_s = \frac{2}{3}F_a S_s \leq \frac{2}{3}\frac{F_v S_1}{T} \quad (8)$$

where S_s is the mapped MCER spectral response acceleration parameter at short periods, as determined in accordance with Section 11.4.1 (ASCE/SEI 7-10). S_1 is the mapped MCER spectral response acceleration parameter at a period of 1s, as determined in accordance with Section 11.4.1 (ASCE/SEI 7-10). The coefficients F_a and F_v are the site amplification factors for the short-period and intermediate-period regions of the design .They are defined in Tables 11.4-1 and 11.4-2, respectively. For soil type D, F_a assumes a value of 1.6, while F_v takes a value of 2. Similarly, the seismic-response coefficient $\tilde{C_s}$ corresponding to the flexible-base period $\tilde{T}$ is determined from Equation (7).

The reduction in base shear due to SSI is given by Equation (9):

$$\frac{\Delta V}{V} = 0.7[1 - \frac{\tilde{C}_s}{C_s}\left(\frac{\beta}{\tilde{\beta}}\right)^{0.4}] \times 100\% \quad (9)$$

Building Considerations and Simulation Methodology

The Monte Carlo simulation is the well-known approach for addressing system uncertainties. This simulation method solves deterministic problems by using a multitude of random variables and statistical modeling to find adequate numerical functions in complex systems (Harrison, 2010). The algorithm begins by setting a maximum number of iterations N_{max} and a tolerance ε for the relative error. During the simulation, random values are generated, and the function of interest (the mean of the fundamental period ratio $(\tilde{T}/T)_{mean}$ and the base-shear reduction ($\frac{\Delta V}{V}$)) is evaluated. The sums and variances are updated iteratively. The process stops when the relative error $\frac{\sigma}{\mu\sqrt{N}}$ is less than ε or when N reaches N_{max}. This approach ensures efficient and accurate estimation, as highlighted by Rubinstein and Kroese (2016). The most commonly used probability distribution functions for estimating uncertainty in geotechnical properties are the uniform, normal, lognormal, gamma, and exponential distributions (Joughin, 2023). The lognormal distribution is often used to model data in various engineering fields due to its properties, such as non-negativity and skewness. Its hazard function, which initially increases and then decreases, makes it suitable for many engineering datasets (Bendriss & Harichane, 2024; Guellil et al., 2020).

A 6-storey building with a height of 18 m is considered in the current study. This building is founded on site soils classified as types D and E, according to the NEHRP classification system, with a maximum gravitational acceleration of $0.1g$.

A shear-wave velocity of 200 m/s and 150 m/s is assigned to site classes D and E, respectively. Poisson's ratios of 0.4 and an effective soil unit weight of 18 kN/m³ are assumed for both site classes. The characteristics of the site soils are summarized in Table 1. Monte Carlo simulations were used to explore the effects of uncertainties in soil properties (shear modulus and Poisson's ratio) on the fundamental period of the soil-foundation-structure system and the reduction in base shear. In the present investigation, the random values of G and ν were generated following a lognormal distribution, with specified mean values and coefficients of variation (Fig. 2(a), Fig. 3(a), Fig. 2(c), Fig. 3(c)). This was accomplished using the "*lognrnd*" function in MATLAB, which generates random samples based on the parameters of the lognormal distribution. The summary statistics of the generated data are presented in Tables 2, 3, 4. For each random value, and the period lengthening ratio of the soil-foundation-structure was calculated (Fig. 2(b), Fig. 3(b), Fig. 2(d), Fig. 3(d)). The mean and standard deviation values for each G and ν are then shown in Fig. 4.

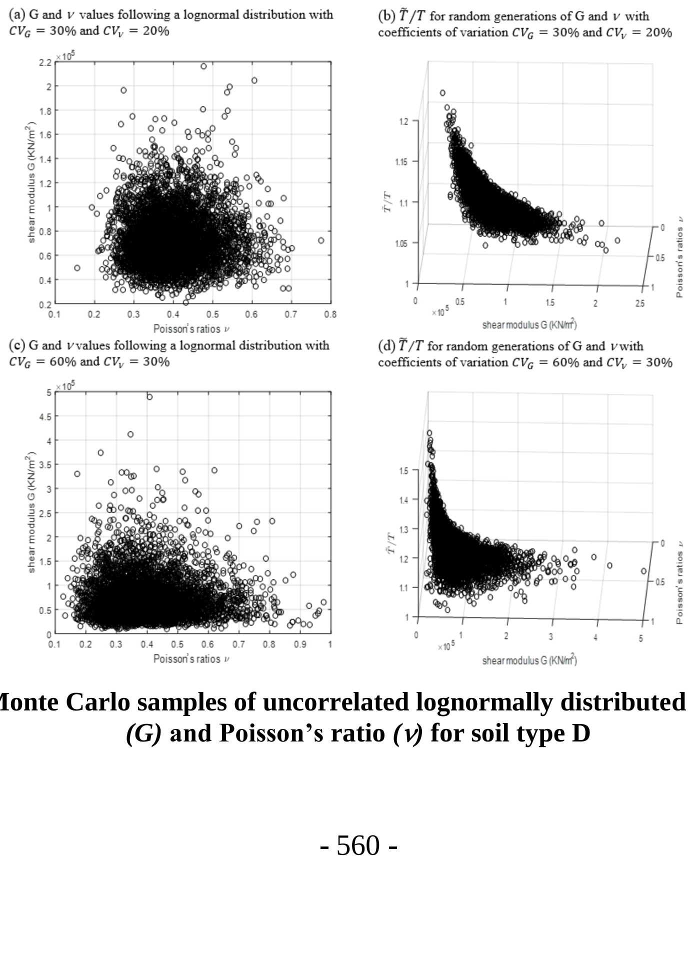

Figure (2): Monte Carlo samples of uncorrelated lognormally distributed shear modulus *(G)* and Poisson's ratio *(ν)* for soil type D

Table 1. Site soil data for types D and E: Classification according to the NEHRP code

Soil type	$v_s(m/s)$	$\gamma(kN/m^3)$	ν	$G(kN/m^2)$
D	200	18	0.4	72000
E	150	18	0.4	40500

v_s: shear-wave velocity, γ: soil-mass density,
ν: soil Poisson's ratio, G : soil shear modulus.

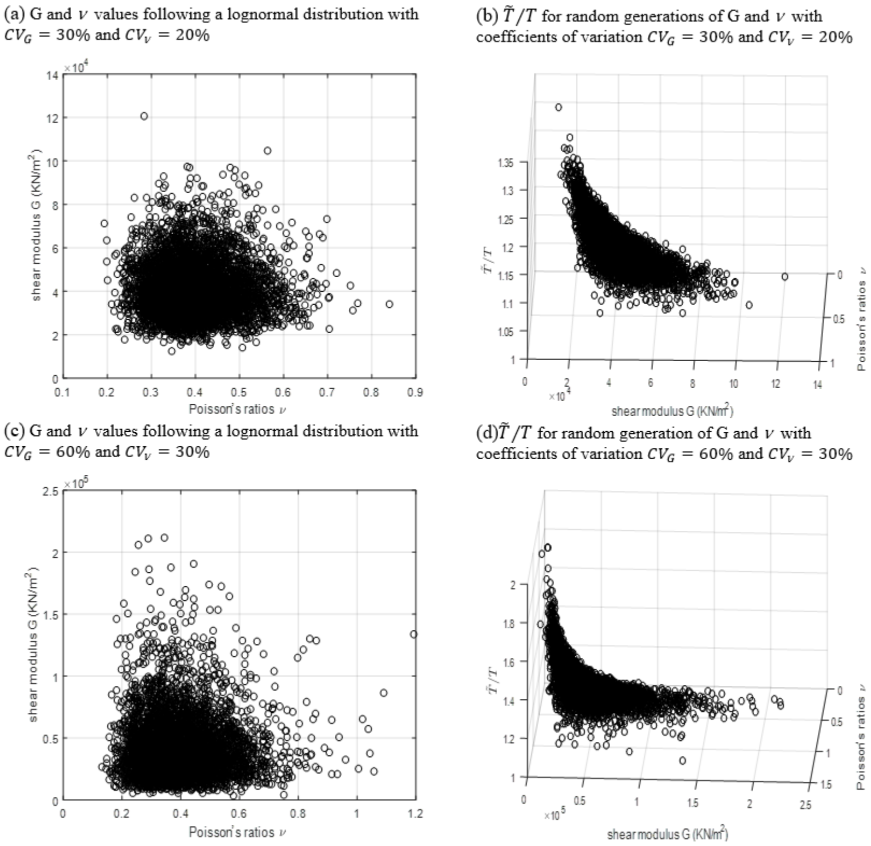

Figure (3): Monte Carlo samples of uncorrelated lognormally distributed shear modulus *(G)* and Poisson's ratio *(ν)* for soil type E

Table 2. Descriptive statistics of Monte Carlo simulation for shear modulus (G) for E-site soil type

	Coefficient of variation (%)									
	10	20	30	40	50	60	70	80	90	100
Minimum	24934	15698	9811	5644	4452	1997	1605	1155	571	720
Maximum	63375	102054	152127	249393	301248	729643	880053	985585	1229491	1351441
Range	38441	86356	142316	243749	296796	727646	878448	984430	1228920	1350721
Mean	40494	40493	40499	40485	40536	40502	40529	40536	40488	40493
Standard deviation	4047	8108	12142	16201	20243	24288	28455	32515	36364	40443
Kurtosis	3.17	3.68	4.59	5.98	7.91	11.99	17.25	22.25	30.15	35.27
Skewness	0.3	0.61	0.93	1.26	1.62	2.04	2.52	2.96	3.43	3.88

(a) $(\tilde{T}/T)_{mean}$ for soil type D (b) $(\tilde{T}/T)_{mean}$ for soil type E

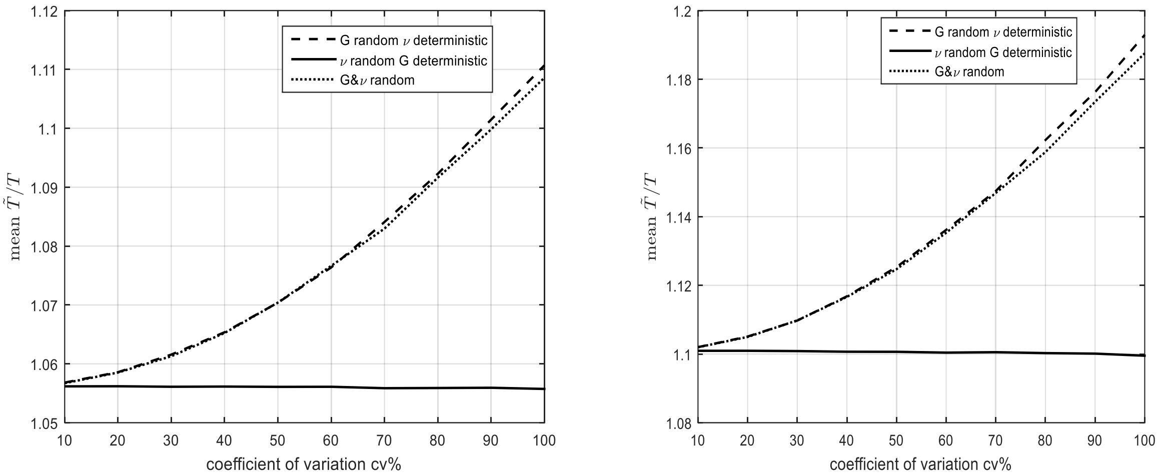

Figure (4): Mean of period-lengthening ratio $(\tilde{T}/T)_{mean}$ for random variations of shear modulus and Poisson's ratio: a) Soil type D; b) Soil type E

Table 3. Descriptive statistics of Monte Carlo simulation for shear modulus (G) for D-site soil type

	Coefficient of variation (%)									
	10	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
Minimum	45967	27065	17522	9702	7485	4572	3058	2240	950	1224
Maximum	114229	186547	252688	416512	613454	1041766	967608	1232580	1810485	2837833
Range	68262	159482	235166	406810	605969	1037194	964550	1230340	1809535	2836609
Mean	72008	71988	72003	71903	72066	71974	71958	71801	72051	72074
Standard deviation	7208	14413	21580	28762	36169	43187	50287	57073	64608	71937
Kurtosis	3.16	3.65	4.51	6.11	8.06	11.14	13.89	19.11	25.53	40.96
Skewness	0.30	0.61	0.92	1.28	1.63	2.03	2.38	2.84	3.30	3.98

Table 4. Descriptive statistics of Monte Carlo simulation for Poisson's ratio (ν) for D-and E-site soils

	Coefficient of variation (%)									
	10	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
Minimum	0.24	0.16	0.10	0.07	0.03	0.03	0.02	0.01	0.01	0.01
Maximum	0.65	1.01	1.47	2.77	4.19	4.40	5.66	6.89	10.88	25.96
Range	0.41	0.85	1.37	2.7	4.16	4.37	5.64	6.88	10.87	25.95
Mean	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Standard deviation	0.04	0.08	0.12	0.16	0.20	0.24	0.28	0.32	0.36	0.40
Kurtosis	3.17	3.70	4.63	5.95	8.07	10.59	14.87	19.33	31.99	69.85
Skewness	0.31	0.62	0.94	1.26	1.62	1.99	2.44	2.85	3.58	4.42

RESULTS AND DISCUSSION

Figs. 2b, 2d, and Figs. 3b, 3d provide valuable insights into the period lengthening ratio in response to changes in shear modulus (G) and Poisson's ratio (ν) for soil types D and E, respectively. For soil type D, the scatter in Fig. 2(a) illustrates a range from 0.2 to 0.9 for ν and from 0.02 to 0.24 MPa for G. Simultaneously, the resulting fundamental period lengthening ratio ($\tilde{T}/T$) spans from 1 to 1.20 as shown in Fig. 2(b), Conversely, when G exhibits a 60% variation and ν a 30% variation, the intervals widen to 0.02-0.45 MPa for G, 0.1-1.1 for ν (Fig. 2(c)), and 1.0-1.5 for $\tilde{T}/T$ (Fig. 2(d)). This variability emphasizes the significant impact of uncertainties in G and ν on the dynamic response of soil type D, suggesting a need for careful consideration in seismic design.

Similarly, for soil type E, Fig. 3(a) reveals a scatter ranging from 0.2 to 0.8 for ν and from 0.01 to 0.13 MPa for G. The corresponding fundamental period lengthening ratio ($\tilde{T}/T$) spans from 1.05 to 1.35 (Fig. 3(b)). In the case of increased variations (60% for G and 30% for ν), G and ν intervals broaden to 0.02-0.30 MPa and 0.1-1.1(Fig. 3(c)), respectively, resulting in a wider $\tilde{T}/T$ interval of 1.0-1.8(Fig. 3(d)). These findings suggest that soil type E is similarly sensitive to variations in G and ν, and the increased uncertainty amplifies the range of seismic parameters, influencing the fundamental period.

The outcomes underscore the need for a thorough understanding of the variations in G and ν for different soil types, as these uncertainties directly impact seismic parameters. Previous research has acknowledged the influence of G and ν on soil-structure interaction (Rama Rao et al., 2021; Shirgir et al., 2021). The broader context of these findings aligns with the recommendations of seismic-design practices, emphasizing the importance of accounting for material variability to enhance the reliability of seismic analyses (Zanini & Hofer, 2019; Vucetic & Dobry, 1991).

The impact of random variations in shear modulus (G) on statistical parameters, as illustrated in Fig. 4, provided crucial insights into the dynamic response of soil types D and E. Remarkably, the random fluctuations in G significantly influence the mean period lengthening ratio $(\tilde{T}/T)_{mean}$. For soil type D (Fig. 4(a)), the numerical values of $(\tilde{T}/T)_{mean}$ fluctuate within an interval of 1.056-1.11, underscoring the sensitivity of dynamic response to variations in G. Similarly, soil type E (Fig. 4(b)) exhibits variability in the mean period lengthening ratio $(\tilde{T}/T)_{mean}$ within the range of 1.10-1.19. The ratio $\tilde{T}/T$ depends on the effect of SSI and G parameter. Based on FEMA P-424 provisions (FEMA, 2010), the period of a 10-20 storey structure, with a vibration period of 1.5 s, reaches 1.64 ± 0.07 s under the effect of a variation coefficient of 80%.

These findings highlight the pivotal role played by the stochastic nature of G in shaping the seismic behaviour of soil types D and E. The variability observed in the mean period lengthening ratio $(\tilde{T}/T)_{mean}$ underscores the necessity for adopting a probabilistic framework in seismic design, acknowledging the uncertainties associated with material properties. These results align with previous research highlighting the importance of considering the probabilistic nature of soil properties in seismic analyses (Mirzaie et al., 2017; Gajan & Kayser, 2019). Practically, these findings extend to seismic-design practices, indicating that a deterministic approach may not adequately capture critical aspects of material variability, thereby contributing to uncertainties in structural response.

In the broader context of seismic engineering, these findings align with recommendations for incorporating probabilistic methodologies in seismic hazard and risk assessments (Lallawmawma & Sharma, 2023). The analysis of stochastic variations in shear modulus (G) and Poisson's ratio (ν), depicted in Fig. 5, offers significant insights into the dynamic response of structures embedded in soil types D and E. Variations in G exert a notable influence on $\frac{\Delta V}{V}$. For soil type D, $\frac{\Delta V}{V}$ decreased from 27.52% to 17.52%, underscoring the sensitivity of dynamic response to G variations (Fig. 5(a)). Similarly, soil type E (Fig. 5(b)) displayed variability in $\frac{\Delta V}{V}$, decreasing from 19.05% to 9.47%. Hence, the dynamic response, quantified by base-shear reduction, exhibited a change of 10% for soil type D and a change of 9.58% for soil type E due to the variations in G.

(a) Base-shear reduction $\frac{\Delta V}{V}$ (%) for soil type D (b) Base-shear reduction $\frac{\Delta V}{V}$ (%) for soil type E

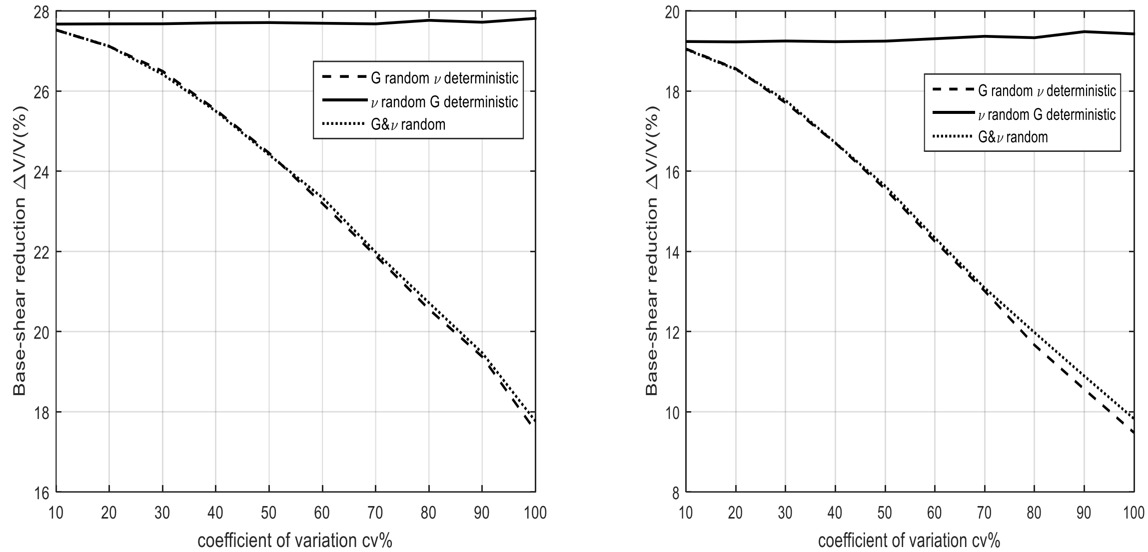

Figure (5): Base-shear reduction $\frac{\Delta V}{V}$ for random variations of shear modulus and Poisson's ratio: a) Soil type D; b) Soil type E

(a) Foundation damping factor $\tilde{\beta}$ for soil type D (b) Foundation damping factor $\tilde{\beta}$ for soil type E

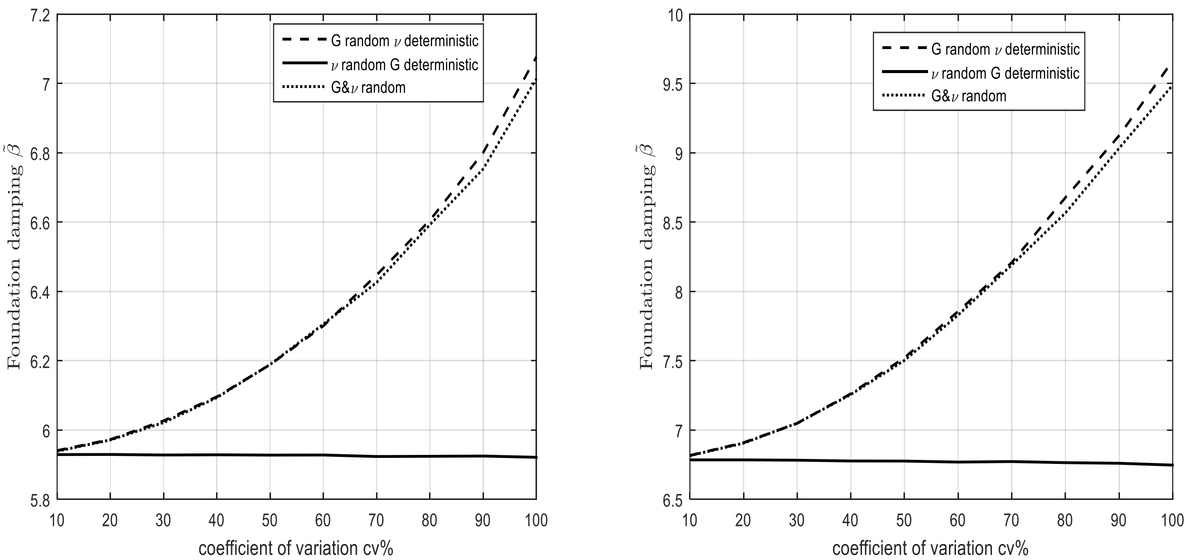

Figure (6): Foundation damping factor $\tilde{\beta}$ for random variations of shear modulus and Poisson's ratio a) Soil type D; b) Soil type E

When the shear modulus G varies randomly, it significantly alters the base shear response, making it highly sensitive to these fluctuations. This underscores the critical importance of considering the stochastic nature of G. Previous studies have indicated that variations in the structure's base shear depend on both structural stiffness and soil properties (El Janous et al., 2024; Ismail et al., 2020), highlighting the essential role of dynamic characteristics. Our findings are consistent with recent studies highlighting the substantial impact of

G on seismic response (Chanda et al., 2019), indicating its potential to induce significant changes in structural behaviour, particularly in seismically active regions (Pua et al., 2021).

In ASCE/SEI 7-10, it is recommended that the ratio $\frac{\Delta V}{V}$ should be less than 30% (Bapir et al., 2023). These findings indicate that random fluctuations in G can potentially affect compliance with ASCE/SEI 7-10 standards, particularly concerning the 30% limit for $\frac{\Delta V}{V}$. Therefore, incorporating these variations into the assessment and modeling of soil seismic behaviour is critical to ensure structural safety and adherence to design guidelines.

The findings depicted in Fig. 6 provide insights into the response of the foundation damping factor ($\tilde{\beta}$) to variations in shear modulus (G) for soil types D and E. Notably, the foundation damping factor appears relatively unaffected when G is treated as a deterministic component, exhibiting minimal fluctuation. However, when G is subject to random variation, the foundation damping factor becomes notably sensitive, highlighting the influence of the stochastic aspect of G.

The fluctuation observed in the foundation damping factor for soil types D and E, ranging from 5.94% to 7.07% and from 6.82% to 9.66%, respectively, underscores the practical implications of random variation in G. These variations, influenced by the G fluctuation scale from 10% to 100%, highlight the necessity of considering G uncertainties in predicting foundation damping. A study by Wani et al. (2022) supported these observations, as they investigated the influence of soil properties on dynamic response, emphasizing the importance of incorporating uncertainties for robust seismic design.

Overall, the current investigation revealed that incorporating stochastic variations in soil parameters is essential to accurately represent the complexity and inherent uncertainty of soil geotechnical properties. Specifically, variations in the shear modulus (G) significantly impact the fundamental period, base-shear reduction, and foundation damping. In contrast, the Poisson's ratio (ν) has a negligible influence. These findings have important implications for seismic-design practices, indicating that a deterministic approach may overlook key aspects of material variability, thereby introducing uncertainties into the structural response.

CONCLUSIONS

This study examined the impact of the shear modulus *(G)* and Poisson's ratio *(ν)*, on the period lengthening ratio ($\tilde{T}/T$) and base-shear reduction $\frac{\Delta V}{V}$ on two soil types, D and E. Our findings revealed that the random values of the Poisson's ratio, generated following a lognormal distribution, had no significant effect on $\tilde{T}/T$, $\frac{\Delta V}{V}$, or the foundation damping $\tilde{\beta}$. Moreover, the random variation in soil properties, specifically the shear modulus, reduced $\frac{\Delta V}{V}$ by 10% under the effect of soil-structure interaction (SSI) for both soil types D and E, and also resulted in an increase in $\tilde{\beta}$. The foundation damping is more sensible to the variation in the shear modulus, or soil properties more generally, meaning high dissipated energy and implicating low $\frac{\Delta V}{V}$ values in soil type E compared to soil type D. Overall, it can be noted that the random variation in the shear modulus has a greater impact on the fundamental period lengthening ratio, base-shear reduction, and foundation damping for site class E compared to site class D. These findings have significant implications for seismic-design practices, suggesting that a deterministic approach may overlook crucial aspects of material variability, thereby introducing uncertainties into the structural response.

Inaccuracies in dynamic response estimates can arise due to certain limitations of the SDOF system, particularly its inability to account for irregular structural shapes and potential foundation damage during earthquakes. Further studies are required to explore advanced modeling techniques that more accurately simulate soil-structure interaction. Incorporating probabilistic approaches to account for soil variability is crucial. Additionally, investigating case studies of actual high-rise buildings and comparing their performance against predicted models could provide valuable insights for refining design codes and practices.

It is recommended to incorporate more refined seismic hazard assessments tailored to specific soil types and regions by integrating probabilistic seismic-hazard analysis with site-specific soil characteristics. Collaboration between geotechnical engineers, structural engineers, and seismologists should be fostered to gain cross-disciplinary insights and ensure a comprehensive understanding of soil-structure interaction effects.

It is advisable to conduct more in-depth studies to highlight the stochastic nature of soil properties in relation to the ASCE/SEI 7-10 guidelines.

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Abbreviation List

SSI: soil-structure interaction, SDOF: single degree of freedom, $\tilde{T}/T$: period lengthening ratio, $\frac{\Delta V}{V}$: base-shear reduction, $\tilde{T}$: effective period of the flexibly-supported structure, T: effective period of the fixed base, $\tilde{\beta}$: foundation damping, h: height of the structure, θ: rotation angle of the structure, k: stiffness of the structure, c: damping coefficient of the structure, k_y: translational stiffness of the soil in the horizontal direction, c_y: translational damping coefficient of the soil in the horizontal direction, k_θ: rotational stiffness of the soil, c_θ: rotational damping coefficient of the soil, u_g: ground displacement, v_s: shear-wave velocity, γ: soil-mass density, ν: soil Poisson's ratio, G: soil shear modulus, CV_ν: coefficient of variation of the soil Poisson's ratio, CV_G: coefficient of variation of the soil shear modulus, W: weight of the structure, $\overline{W}$: effective seismic weight of the structure, V: base shear for a fixed-base system, $\tilde{V}$: base shear due to SSI.

NOTATION

u_g : ground displacement
u_0 : displacement due to horizontal translation
$h\theta$: displacement due to rocking
u : displacement due to distortion of structure
h: height of the structure
θ: rotation angle
k : stiffness of the structure
c : damping coefficient of the structure
k_y : translational stiffness of the soil in the horizontal direction
c_y : translational damping coefficient of the soil in the horizontal direction
k_θ : rotational stiffness of the soil
c_θ : rotational damping coefficient of the soil
$\tilde{\beta}$: foundation damping
ν: soil Poisson's ratio
G : soil shear modulus.
$\frac{\Delta V}{V}$: base-shear reduction
$\tilde{T}/T$: period-lengthening ratio
$(\tilde{T}/T)_{mean}$: mean of period lengthening ratio
CV_ν: Coefficient of variation of the soil Poisson's ratio
CV_G : Coefficient of variation of the soil shear modulus.

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