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Effects of variability in soil properties on the seismic performance of CBF buildings

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ABSTRACT

Numerous studies have been conducted on the seismic performance of concentrically braced frames (CBF), which represent one of the most used seismic force-resisting systems in steel buildings in North America. Most of these studies have assumed a rigid foundation, even when considering soil-structure interaction to determine the footing's demand and the performance of the superstructure. Meanwhile, there is significant uncertainty in soil properties, such as soil stiffness and bearing strength, even for the same soil (e.g., site class D), owing to its inherent heterogeneity. Therefore, there is a need to understand better the influence of variability in soil properties on the performance of CBF buildings.

In order to investigate the influence of different soil models and the associated assumptions for soil behaviours on the performance of CBF buildings with an X-bracing configuration, a parametric study is carried out for two archetype office buildings with 1 and 2 storeys. These archetypes are located in Vancouver, Canada, on a Class D site. These buildings are designed per the 2020 National Building Code and the 2019 editions of the Canadian steel and concrete design standards. An advanced numerical model, including brace buckling and fracture, gusset plate connections, beam-to-column connections, and P-Delta effects, is developed in OpenSees. The soil and foundation are modelled using a Beam-on-Nonlinear-Winkler-Foundation (BNWF) approach. The results of this study show the significance of considering the uncertainty of soil properties in numerical analysis.

Keywords: CBF, Soil-foundation-structure interaction, Soil uncertainty, Nonlinear analysis, BNWF approach

INTRODUCTION

Concentrically braced frames (CBFs) are commonly used as the seismic force-resisting system in low-rise steel buildings in North America. Several studies have been carried out on the seismic response of CBF buildings; however, in the majority of these investigations, the effects of soil and foundation are overlooked, e.g., [1–3]. There are few studies that take into account the soil-foundation-structure interaction (SFSI) when evaluating the seismic performance of CBF buildings, e.g., [4–7]. Wichman et al. [4] studied 12 short-period CBF archetype buildings with foundations designed per the US code. They showed that incorporating soil and foundation effects altered the predominant behaviour of the buildings, with the braces remaining mainly elastic while the footings rocked on the soil underneath. Koboevic and Murugananthan [5,6] studied 3-storey CBF buildings with Canadian not capacity-protected (NCP) and capacity-protected (CP) footings on soft and stiff soils located in moderate and high seismic zones. They demonstrated that the incorporation of SFSI reduced the moment demand on both types of foundations but to a much greater extent on NCP foundations. Madani et al. [7] studied 2- and 5- storey CBF office buildings on both soil classes C and E with Canadian capacity-protected (CP) footing. Owing to the large dimension of the required footing, they found a minimal impact of the soil and foundation on CP foundation seismic demand. Though these studies examined the effects of soil and foundation, the possible variability in soil properties was not considered.

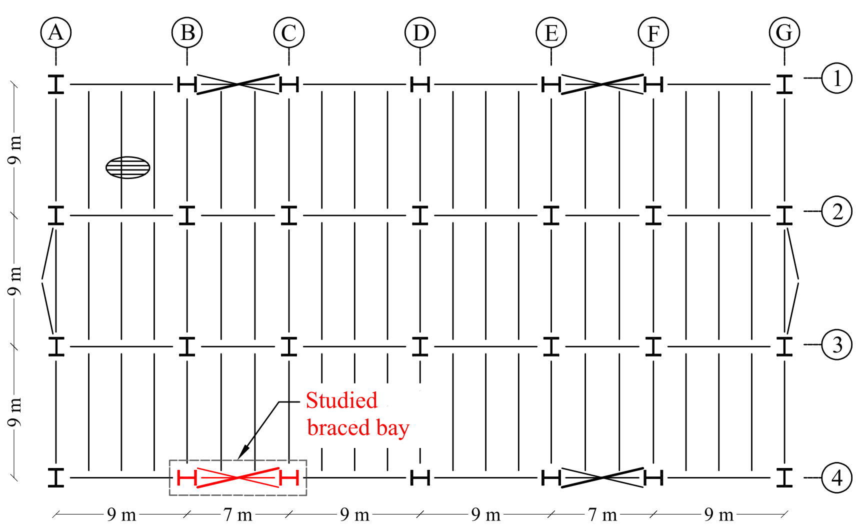
Since the properties of soil, such as stiffness and strength, are highly variable and often difficult to determine accurately, it is crucial to consider the uncertainty associated with soil properties in numerical analysis when considering SFSI [8–10]. Ignoring this variability can lead to unrealistic predictions of the building's seismic response and performance.

Furthermore, incorporating the uncertainty in soil properties into the numerical analysis can help to understand better the range of possible outcomes to minimize the potential impact of uncertainties to ensure the safety and reliability of designed buildings. Numerous studies considered soil and foundation effects along with the uncertainty of soil characteristics for buildings other than CBFs, e.g., [11–13]. Jin and Sarkani [11] used surrogate MDOF systems to study the effects of soil uncertainty on the response of buildings. They showed that variations in soil properties could have a significant effect on the response of the structure. Zhongcheng and Zhongxian [12] studied the effects of uncertainty in shear wave velocity and Poisson's ratio for a reactor structure. They concluded that the variation in the shear wave velocity had a greater impact on the system's response than Poisson's ratio. Raychowdhury [9] investigated the effects of soil properties uncertainty on the response of low-rise moment-resisting frame buildings. It was concluded that the storey drift was the most influenced quantity among all studied outcomes. Moghaddasi et al. [10] studied the effects of variability in system parameters and soil properties along with uncertainties in ground motion characteristics on the seismic response of surrogate SDOF buildings. The findings demonstrate the risk of using the structural response from simplified methods that neglect SFSI and the nonlinearity of members. The research conducted by Akhoondi and Behnamfar [13] showed that the probability of collapse due to incorporating uncertainties in soil properties and SFSI is higher in low-rise buildings compared to high-rise buildings.

Because the inclusion of SFSI for low-rise buildings with Canadian NCP foundations, along with consideration for the uncertainty in soil properties and variability in ground motion records, may potentially have a significant impact on the seismic response of buildings, the aim of this study is to examine how variation in soil properties affects the performance of X-braced CBF buildings. To achieve this, two office buildings with 1 and 2 storeys located in Vancouver, Canada, were selected as archetypes, both located on a Class D site. These buildings were designed according to the 2020 National Building Code (NBC 2020 [14]) and the 2019 Canadian steel (CSA S16-19 [15]) and concrete (CSA A23.3-19 [16]) design standards. An advanced numerical model using OpenSees [17] is developed to account for various factors, including brace buckling and fracture, gusset plate connections, beam-to-column connections, and P-Delta effects. The Beam-on-Nonlinear-Winkler-Foundation (BNWF) method is employed to model the soil and foundation. A set of 20 historical ground motions matching the soil site condition and design spectrum is selected to perform the time-history analysis, and the results of this analysis are presented in terms of the relative significance of different soil properties.

BUILDING DESIGN

This study investigated 1- and 2-storey office buildings in Vancouver, Canada, with the seismic category *SC4* that were designed on Site Class D (180m/s $\leq V_{s30} \leq$ 360m/s). A moderately ductile X-type tension-compression CBFs with a ductility reduction factor (R_d) of 3 and an overstrength factor (R_o) of 1.3 is the lateral force-resisting system in the east-west (E-W) loading direction. The members of CBF and gravity frames were designed in accordance with NBC 2020 and CSA S16-19. Design spectral accelerations for both buildings were on the plateau of the Canadian design spectrum resulting in the same base shear coefficient equal to 0.3. The equivalent lateral force procedure was used to calculate the seismic design forces. Figure 1 shows the plan view of all buildings and the elevation view of the two-storey archetype buildings.

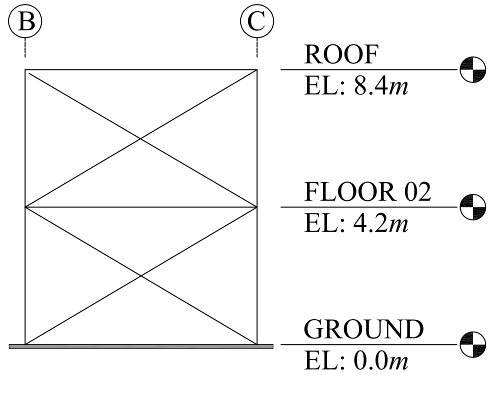


a)

<u>Note</u>:
Gravity Loads
1. Roof Loading
   Dead = 1.4 kPa
   Snow = 1.8 kPa
   Live = 1.0 kPa
2. Floor Loading
   Dead = 2.8 kPa
   Partition = 0.5 kPa
   Live = 3.6 kPa

Exterior Wall = 1.5 kPa

Seismic Design Parameters
Importance Category Normal
Importance Factor = 1.0
R_d = 3.0, R_o = 1.3
Seismic Category *SC4*
Vancouver, Canada
(49.261° N, 123.114° W)



b)

Figure 1 Studied CBF buildings: (a) typical plan view; (b) elevation view of the 2-storey CBF

The braces were selected from compact square hollow structural sections (HSSs), which met the slenderness ratio requirements of CSA S16-19 ($70 \leq KL/r \leq 200$). To accommodate brace end rotation, the gusset plate connections were designed with a $2t_p$ linear offset, where t_p refers to the thickness of the gusset plate. For the design of the beams and columns, the capacity design requirements of CSA S16-19 were followed, taking into account the probable tensile and compressive resistance of the braces. An additional moment of 20 percent of the nominal plastic moment of the column section is added to the forces from the capacity design for the columns. Sections selected for brace, beam, and column members for the braced frames of all buildings are provided in Table 1.

Table 1 Section sizes of CBFs and footing dimensions[4]

Building	Storey	Braces	Beams	Columns	Footing sizes[1] (m)	
					Soft soil	Stiff soil
1-storey	1	HSS 76 × 76 × 6.4	W410 × 39	W250 × 45	12.5*1.0*0.8	12.5*1.3*1.0
2-storey	2	HSS 89 × 89 × 4.8	W410 × 39	W310 × 79	14.6*3.4*0.8	13.6*3.8*0.9
	1	HSS 102 × 102 × 7.9	W410 × 60	W310 × 79		

1. Length*Width*Depth

Two typical soil site classes were considered in this study. The properties of the stiff soil and the soft soil representative of site class D were specifically chosen to be near those characterizing the site classes C and D and site classes D and E boundaries, respectively. The site with stiff soil had a shear wave velocity (V_{s30}) value of 354 m/s, while the site with soft soil had a V_{s30} of 183 m/s. According to the Canadian concrete design standard (CSA A23.3-19), CP foundations must be able to withstand factored gravity loads and the probable capacity of the SFRS system. Meanwhile, NCP foundations are designed to handle factored gravity loads plus the greater of 75% of the nominal moment capacity of the system and the overturning moment corresponding to R_dR_o = 2.0. However, in both cases, the designed moment need not be greater than the overturning moment corresponding to R_dR_o = 1.0. Moreover, stability against overturning, bearing resistance, sliding capacity of the footing, and the impact of footing rotation on building drift must be considered in designing Canadian foundations. In this study, the CSA A23.3-19 commentary's general method was used to calculate the footing rotation's contribution to the overall drift of the building. Table 1 provides the final foundation sizes.

NUMERICAL MODELLING

The archetype buildings were modelled analytically in 2D using OpenSees [17]. The seismic weight and gravity loads were calculated per NBC 2020. To account for P-Delta effects in the models, a steel CBF was linked with an equivalent gravity frame using axially rigid links. The effects of gravity framing on the overall response of buildings were considered, as discussed in Elkady and Lignos [18]. The second-order (P-Delta) effects were taken into account using the corotational transformation method in OpenSees. To replicate the inherent damping of the buildings, tangent stiffness proportional Rayleigh damping of 2% was specified in the first two modes. The fundamental periods obtained from modal analysis were 0.21 s (0.24 s) and 0.31 s (0.35 s) for base model 1-storey and 2-storey buildings on stiff (soft) soil. Figure 2 provides a summary of the modelling assumptions.

Modelling CBF and Gravity Frames

The braces of the CBF systems were modelled following the recommendations of Sen et al. [19] with 16 displacement-based nonlinear beam-column sub-elements with 4 integration points. Each brace cross-section was discretized into 128 fibres. The initial out-of-straightness was set to 0.2% of the effective length of the brace. The Steel02 material was assigned to the fibres with the probable yield stress (R_yF_y) of 460 MPa for rectangular hollow structural sections (with F_y = 350 MPa) as per CSA S16-19. The maximum strain range proposed by Sen et al. [19] was used to account for possible fracture in the braces. Hsiao et al. [20] suggested a method to model the gusset plate connection in order to accurately represent the behaviour of the braces during buckling and post-buckling, and this method was implemented here.

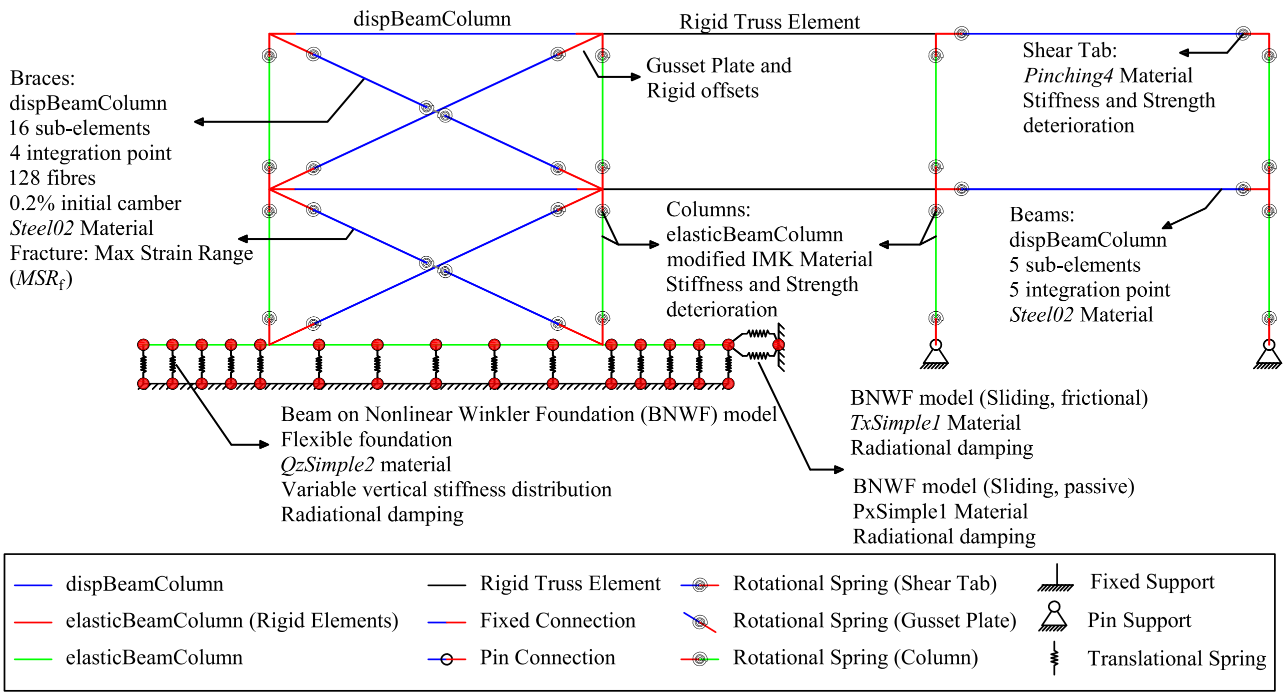


Figure 2 Analytical model of structure-foundation-soil system

Beams of both braced and gravity framing were modelled using 5 displacement-based sub-elements, and each sub-element had 5 integration points. Similar to brace elements, a Steel02 material is assigned to the fibres of these members. The columns were modelled using a concentrated plasticity model that incorporated elastic elements with springs at both ends, following the modified Ibarra-Medina-Krawinkler (IMK) deterioration model [21]. The reduction in the flexural capacity of the column and an increase in deterioration caused by axial forces from gravity loading were considered [22]. When relevant, the shear tab was modelled to consider the impact of the beam-to-column connection on the response of the building. Though at the design level earthquake, all members of the superstructure must remain elastic except the braces, as observed here, all possible sources of nonlinearity were considered in this study.

Soil-Foundation Modelling

To model the shallow foundation and the underlying soil, the substructure approach with the Beam on Nonlinear Winkler Foundation (BNWF) was utilized. This approach can represent various features, such as the flexibility of the footing, energy dissipation in soil, along with rocking and sliding of footing [23]. Elastic beam-column elements connected to vertical and horizontal springs were employed to model soil-foundation interaction. The vertical and horizontal zero-length springs were assigned the QzSimple2 and TxSimple1 materials, respectively, to account for bearing and frictional sliding resistance. The PxSimple1 material was also used to model the passive sliding resistance. The values of soil strength were calculated with established formulas in geotechnical engineering [24]. The stiffness values of the footing were determined by applying the formulas developed by Pais and Kausel [25] for foundations at the ground surface.

As stated previously, this study focuses on the impact of uncertainty in soil's mechanical characteristics on the performance of the building. These mechanical properties, such as strength and stiffness, depend on various soil parameters, including the friction angle (ϕ), cohesion (c), shear modulus adjusted for large strain levels (G), Poisson's ratio (ν), and unit weight (γ). Therefore, the variation and uncertainty of these parameters are considered for the assessment of the buildings' performance.

The lognormal distribution was used to describe the variation of soil parameters. The assumed median and coefficient of variation (COV) of these parameters are listed in Table 2. The median quantity of all soil parameters was extracted from Wichman et al. [4]. In addition to soil parameters, the concrete compressive strength of the footing was also another parameter investigated in this study. However, the correlation between parameters is neglected in this study. In the base model, the median of all random variables is used in numerical analysis.

Table 2 Median and coefficient of variations of studied parameters

#	Soil Parameter	Notation	Median		Coefficient of variation
			Stiff	**Soft**	
1	Friction angle	ϕ	40 deg	-	0.10 [8]
2	Cohesion	c	-	32 kPa	0.30 [13]
3	Normalized adjusted shear modulus	G/G_{max}	0.8	0.6	0.32 [8]
4	Poisson's ratio	ν	0.35	0.45	0.30 [12]
5	Unit weight	γ	19 kN/m^3	16 kN/m^3	0.06 [26]
6	Concrete compressive strength	f_c'	25 MPa	25 MPa	0.15 [27]

Ground motion selection and scaling

The ground motions were selected from the NGA-West2 Database [28] to represent the seismicity in the Vancouver region and correspond to the soil conditions present at the building sites. A set of 20 single horizontal component ground motion records was selected to account for record-to-record variability with a maximum of two ground motions per an event. The ground motions were scaled to match the design spectrum of Vancouver, Canada (49.261° N, 123.114° W). The scaling of records was carried out over 0.05 s to 2 s, employing the improved algorithm suggested by Baker and Lee [29]. The minimum and maximum allowable scale factors were set to 0.5 and 4, respectively. The spectral acceleration of selected and scaled ground motions, as well as the median of these records and the target spectrum, is illustrated in Figure 3. The selected ground motions had a moment magnitude range of M_W 6.5 to 7.6, a fault rupture distance (R_{rup}) of 10 km to 57 km, and an average shear wave velocity for the top 30 m of soil (V_{s30}) of 192 m/s to 345 m/s.

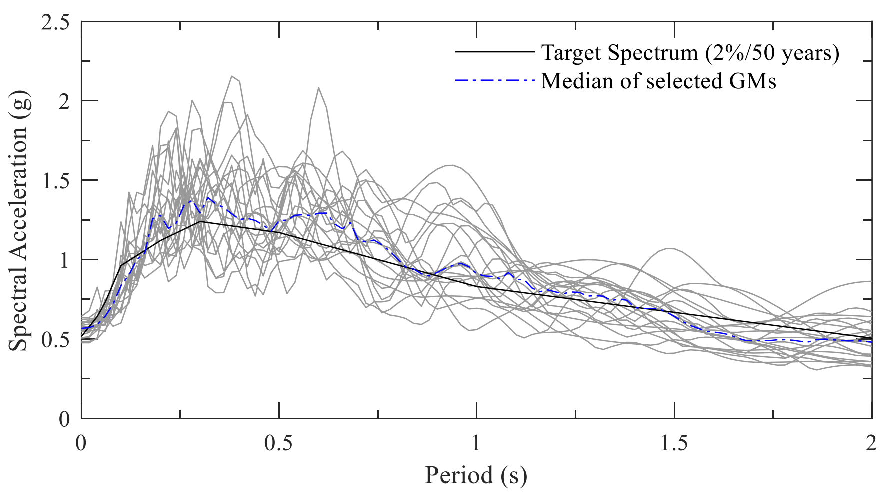


Figure 3 Selected ground motions scaled to design ground motion (2% in 50 years)

RESULTS AND DISCUSSION

The nonlinear response history analyses were performed on the 1- and 2- storey archetypes with NCP foundations on stiff and soft soil. To define realistic upper- and lower-bound values for the soil properties, the distributions described in the Soil-Foundation Modelling section are taken at the median ± two times the lognormal standard deviation (i.e., Median ± $2\sigma_{ln}$). In the following presentation of results, a lognormal distribution is fitted to the maximum of the outputs, and the median and dispersion values are calculated. As shown in Figure 4, the drift of gravity frames (overall drift) is the resultant of the CBF's drift relative to the foundation, the rotation of the footing, and the sliding of the footing. Figure 4 also illustrates the median value of the lognormal distribution fitted to contributors to the drift of 2-storey base models.

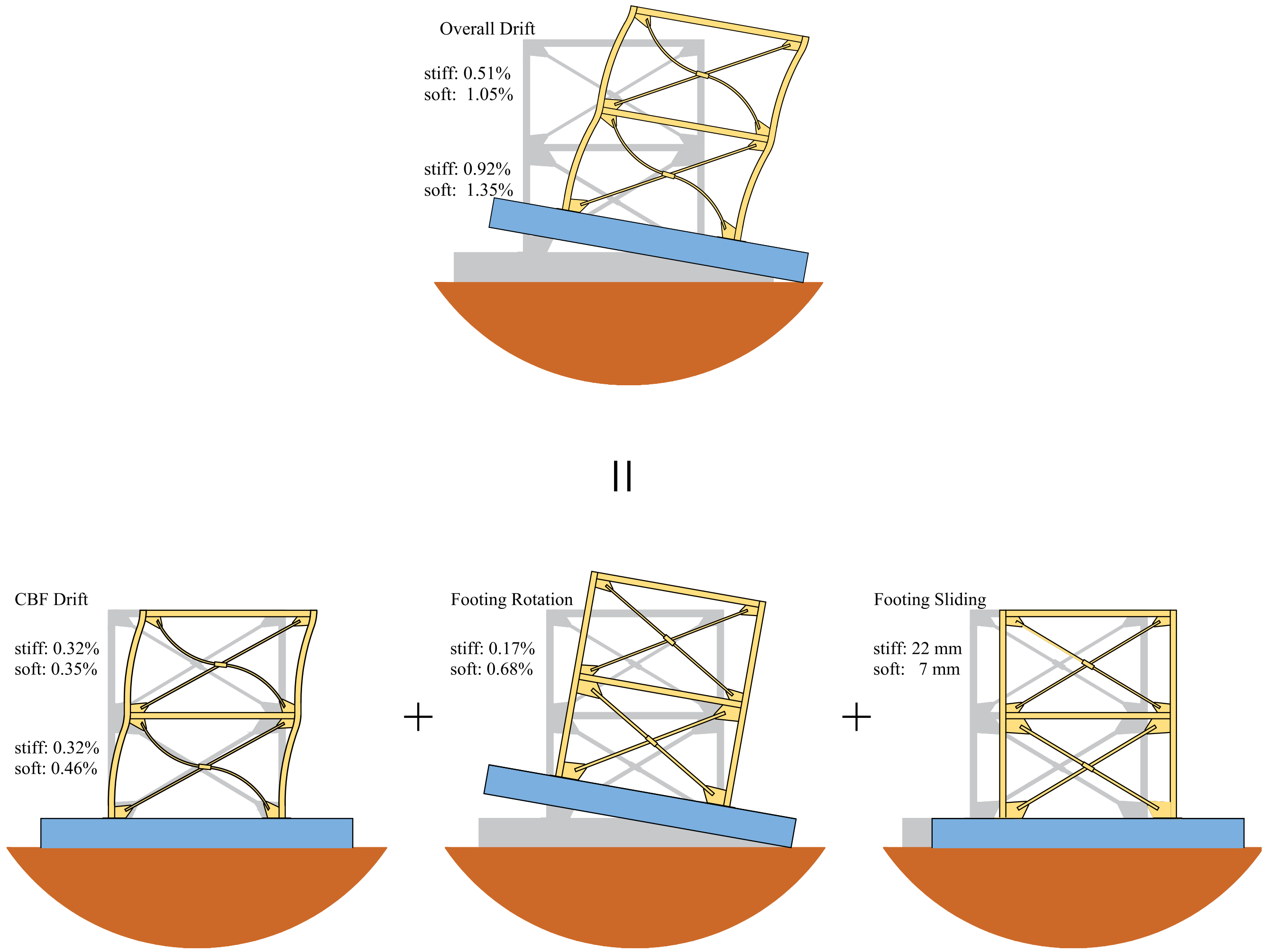


Figure 4 Median of the fitted lognormal distribution of the drift contributors for 2-storey base models

In Table 3, the drift results from the time-history analysis of buildings on soft soil are compared with the drift results of the base model at the lower (Median - $2\sigma_{ln}$) and upper (Median + $2\sigma_{ln}$) limit of each parameter. The black and blue values in the tables correspond to 1-storey and 2-storey archetypes, respectively. The results suggest that for 1-storey and 2-storey buildings on soft soil, using the lower limit of cohesion changes the primary contributor to drift from rotation to sliding. In addition, the change in the cohesion of soil has a more significant effect on the overall drift of the 1-storey building compared to the 2-storey building since the contribution of CBF drift is one-third (Figure 4) and one-tenth of the overall drift for the 2-storey and 1-storey base model archetypes, respectively.

In Table 3, the effects of normalized adjusted shear modulus are also significant on the drifts for the buildings on soft soil. With an increase (decrease) of the soil's shear modulus, the stiffness of soil springs increases (decreases), which results in a decrease (increase) in the footing sliding and rotation. Moreover, for the upper limit of G/G_{max}, since the footing's rotation is the primary contributor to the drift for both buildings, the decrease in the overall drift of the 1-storey building is greater because this building has a greater decrease in footing's rotation. The same trend is observed for Poisson's ratio in general. The upper limit of this parameter is limited to 0.5 in analysis, which is the maximum possible value for Poisson's ratio. Because of this limitation, though the influence of its upper limit is not significant, its lower limit has a significant impact on the performance of the 1-storey building. Referring to Table 3, the soil's unit weight has the smallest influence on the drift response. Moreover, the flexibility of footings arising from concrete compressive strength is relatively small for both buildings but more critical for the 1-storey building than for the 2-storey building.

Table 3 Changes in drift of each parameter compared to the base model for (1-storey / 2-storey) buildings on soft soil

Lower limit (Median - $2\sigma_{ln}$)				Parameter	Upper limit (Median + $2\sigma_{ln}$)			
Slid[1](%)	Rot[1](%)	CBF(%)	Overall(%)		Overall(%)	CBF(%)	Rot(%)	Slid(%)
214/261	-84/-30	-19/-41	-22/-3	c	2/-4	8/24	11/-15	-59/-34
24/102	22/16	-11/-3	17/13	G/G_{max}	-16/-9	12/34	-24/-17	-6/-38
4/10	23/4	-7/-4	18/-1	ν	-4/-3	0/8	-7/-4	2/6
5/7	2/5	-1/-3	3/2	γ	0/0	-2/4	-1/-6	-3/3
13/-2	9/3	2/2	8/3	f_c'	-7/-3	-1/2	-8/-4	-7/11

1. Slid: Footing's sliding; Rot: Footing's rotation

Table 4 shows that the response of the buildings on stiff soil is generally less sensitive to soil properties than for the buildings on soft soil. When the friction angle decreases, the footing's sliding increases, whereas the other contributors to overall drift experience a dramatic decrease. However, the overall drift still increases because the sliding of the footing is the primary contributor to overall drift for buildings on stiff soil. Table 4 also demonstrates that using the upper limit of friction angle decreases the footing's sliding and increases the footing's rotation, and this changes the primary contributor of drift for the 1-storey building. The variability in normalized adjusted shear modulus for buildings on stiff soil shows a trend similar to that observed for buildings on soft soil. Referring to Table 4, the soil Poisson's ratio and unit weight, as well as the concrete compressive strength, have negligible effects on the drift response of the buildings on stiff soil.

Table 4 Changes in drift of each parameter compared to the base model for (1-storey/ 2-storey) buildings on stiff soil

Lower limit (Median - $2\sigma_{ln}$)				Parameter	Upper limit (Median + $2\sigma_{ln}$)			
Slid(%)	Rot(%)	CBF(%)	Overall(%)		Overall(%)	CBF(%)	Rot(%)	Slid(%)
74/79	-61/-53	-14/-22	34/25	ϕ	9/5	31/86	184/52	-59/-79
27/22	-11/-8	-6/-8	15/6	G/G_{max}	-4/-4	7/9	15/0	-14/-17
3/1	2/1	-1/-1	2/1	ν	-1/0	1/1	-1/-2	-2/0
2/3	-2/-1	0/-1	1/1	γ	0/-1	0/1	1/1	0/-5
3/-1	8/8	-1/0	2/2	f_c'	0/1	1/0	-7/-9	0/5

CONCLUSIONS

This study evaluated the influence of variation in soil properties on the response of short-period CBF buildings designed according to the Canadian provisions for not capacity-protected foundations. The results of this study suggest that changing the values of random variables could alter the main contributor of drift from one mode to another (e.g., from foundation rotation to sliding or vice versa). This suggests a need for a comprehensive study where the impacts of variation of all random variables simultaneously on the performance of short-period CBF buildings are investigated. Additionally, it was concluded that uncertainty in cohesion, normalized adjusted shear modulus, and Poisson's ratio of soil have the greatest effect on the drift response of buildings on soft soil, whereas friction angle and normalized adjusted shear modulus of soil were the most impactful parameters on the drift response of buildings on stiff soil.

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