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Effect of Soil - Structure Interaction Constitutive Models on Dynamic Response of Multi-Story Buildings

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Abstract

The choice of an adequate soil constitutive model in a dynamic soil-structure interaction (SSI) problem has always been a challenge. Linear-elastic and elastic-perfectly plastic Mohr-Coulomb models are implemented in commercial software and extensively used in dynamic studies due to their ease of application. The objective of this paper is to assess the reliability of these two soil models in dynamic SSI finite element models. This is realised by comparing their structural dynamic responses with that of small strain hardening model, proven effective in dynamic analysis. Two - dimensional finite element models under plane strain conditions are generated by the use of PLAXIS software. The dynamic response of three concrete frame buildings of different slenderness ratios is evaluated when excited by a strong earthquake. The soil medium beneath the building structures is considered as a homogeneous half space with viscous boundary conditions at the truncated interface and is varying between loose, medium and dense sand. This paper demonstrated the inadequacy of the linear and Mohr-Coulomb models in capturing the real soil behaviour as their structural dynamic response is largely dissimilar to the small strain hardening behaviour.

Keywords: SSI, Linear-Elastic, Elastoplastic, Small Strain Hardening, Slenderness.

1 Introduction

Over the last few decades, strong earthquakes have caused severe damages to many building structures. Therefore, the need for realistic and adequate dynamic analyses has increased rapidly.

It is acknowledged that the soil-structure interaction (SSI) influences the seismic response of buildings [1-4]. Many parameters related to the soil have a major influence on the dynamic structural response in a SSI problem [5-8]. The choice of an appropriate soil constitutive model that is able to capture the real soil behavior is a significantly influencing geotechnical parameter. This has always been a challenge to engineers, since there is no available soil model that can perfectly depict the complex behavior of the soil under all conditions. Due to its simplicity in application, many studies are conducted based on Hook's law of linear elasticity or Coulomb's law of perfect plasticity in representing the soil behavior.

Studies have shown that when the earthquake input motion is weak or the soil medium is dense, the soil shear strains are small and it is then possible to apply the elastic-linear constitutive model. For sites undergoing medium to high soil shear strains, the elastic-plastic models can better illustrate the behavior [9-13]. High to very high soil strains result from the excitation of strong earthquakes on loose soil, so hardening models [14], nonlinear models[15-16] and hypoplastic models[17] shall be utilized.

In a seismic soil-structure problem, a finite part of the infinite soil domain (known as unbounded medium) has to be modeled to analyze the system soil-structure. The truncation of the soil should not affect the structural dynamic response. Therefore, energy-absorbing boundaries have to be assigned at the truncated boundaries to absorb the waves radiating from the structure. The "viscous boundaries" by (Lysmer and Kuhlemeyer)[18] can be easily achieved in most finite-element software.

The literature review has concluded the effectiveness of applying the hardening model based purely on the soil type and earthquake characteristics, disregarding the structure properties such as its slenderness. As known, the strain-hardening model enables a degradation of the soil stiffness with an increase level of strain. This necessitates the determination of many complicated parameters, especially the elastic moduli. However, elastic and Mohr-Coulomb soil models require less computational complexity as just a constant elastic modulus is required. For that reason, this work assesses the possibility of applying the linear and Mohr-Coulomb models to properly evaluate its adequacy in determining the dynamic structure response, while incorporating the building slenderness as well as the different soil types. A series of 2D plane strain finite element models under strong earthquake input motion are generated employing PLAXIS software.

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2 The Numerical Model Description

The analysis is performed by means of PLAXIS 2D dynamic finite element software in the time domain (version 2015)[19]. Three building structures of four, eight and twelve stories of 3.0 m story height are used to conduct this study (H= 12, 24 and 36 m respectively). The buildings are composed of concrete frames of three equally spaced bays and supported on raft foundation (B=12 m) (Figure 1.). They are resting on a single layer of homogeneous sandy soil of 120 m depth underlain by a rigid rock layer (Figure 2). An interface is defined between the foundation and the soil of interface strength reduction factor, R_{int}= 0.67. The effect of various types of soil (loose, medium and dense) on the structural dynamic response is examined when the soil behavior is idealized as linear, elastic- perfectly plastic and small strain hardening as well. For the elastic-plastic behavior, shear wave velocities of the different soil types (Vs) were assumed according to the 2000 International Building Code (IBC), then the shear modulus (G) and young's modulus (E) are calculated based on elastic equations, Eq.(1) and (2).

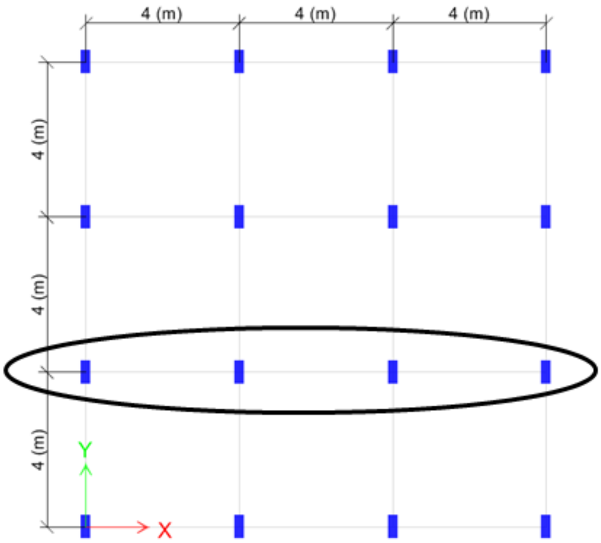


Fig. 1. Plan view of an intermediate frame columns layout

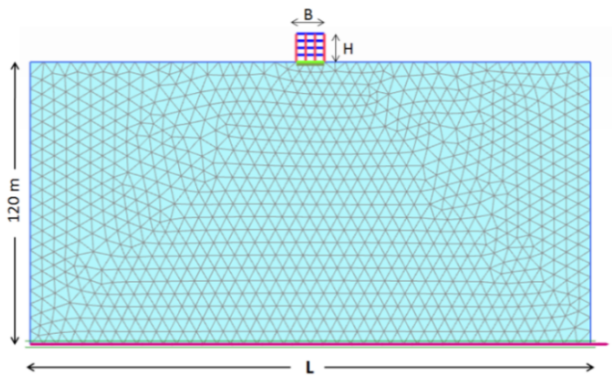


Fig. 2. Two dimensional finite element model of the soil -structure interaction system.

$$G= \rho\,(Vs)^2 \quad (1)$$

$$E= G\,(1+2\nu) \quad (2)$$

Where ρ is the soil density and ν is the Poisson's ratio.

The mechanical properties are summarized in Table 1.

Table 1. Mechanical properties of Elastic and Elastoplastic soil.

Parameter	Symbol	Magnitude			Unit
		Loose sand	**Medium sand**	**Dense sand**	
Total unit weight	γ	17.5	19.5	20.5	KN/m^3
Young's modulus	E	44.6	323	5640	MPa
Shear modulus	G	17.84	124	2090	MPa
Poisson's ratio	ν	0.25	0.3	0.35	-
Angle of internal friction	ϕ	28	35	40	°
Dilatancy angle	ψ	3	5	8	-
Compression wave velocity	V_p	173.2	467.7	2082	m/s
Shear wave velocity	V_S	100	250	1000	m/s
Raleigh Damping	α β	0.05 0.00117	0.1198 0.00102	0.3626 0.000764	- -
Damping ratio	ζ	2	2	2	%

As for the hardening soil model with small-strain stiffness (HSS), validated empirical equations for sandy soil are employed to derive the different soil parameters in the absence of experimental data[20] (Table 2.).

Table 2. Mechanical properties of HSS small soil.

Parameter	Symbol	Magnitude			Unit
		Loose sand	**Medium sand**	**Dense sand**	
Total unit weight	γ	17.5	19.5	20.5	KN/m^3
Small strain stiffness	G_0^{ref}	70.2	94	125.28	MPa
Shear strain at $0.7G_0$	$\gamma_{0.7}$	$1.85.10^{-4}$	$1.5.10^{-4}$	$1.04.10^{-4}$	-
Poisson's ratio	ν_{ur}	0.2	0.2	0.2	-
Triaxial compression stiffnes	E_{50}^{ref}	9	30	57.6	MPa
Primary oedometer stiffness	E_{oed}^{ref}	9	30	57.6	MPa
Unloading/reloading stiffness	E_{ur}^{ref}	27	90	172.8	MPa
Reference pressure	P^{ref}	100	100	100	MPa
Rate of stress-dependency	m	0.65	0.543	0.4	-
Failure ratio	R_f	0.9	0.9	0.9	-
Stress ratio in primary compr.	K_0^{nc}	0.53	0.426	0.357	-

A strong earthquake input motion (Parkfield, California 2004) of magnitude 6, peak ground acceleration 0.3g, and 50 seconds duration is applied at the bedrock level. The truncated boundaries of the soil domain are provided with viscous boundaries of Lysmer type. They are placed far enough from the structure to ensure a good absorption of the radiating waves.

The numerical models are discretized into finite elements of mesh element size Δh Smaller or equal to one - eighth to one - fifth the ratio of shear wave velocity and the highest frequency of the earthquake input motion: $\Delta h \leq 1/8 - 1/5\ (V_s / f_{max})$[21].

The soil damping characteristics are modeled by Raleigh damping coefficients for all constitutive models, whereas a hysteretic damping is added for small strain hardening behavior.

The Raleigh coefficients of the different soil types are calculated by assuming a constant damping ratio of 2 % and by applying formulae that are implemented in the software [22]: $\omega_1 = \pi\, Vs/2D$; $\omega_2 = n\, \omega_1$; $n = \frac{\omega_s}{\omega_1}$ where, D: depth of the soil domain, ω_s: fundamental frequency of the seismic input motion, n: odd integer multiplier greater than the ratio between the fundamental frequency of the seismic input motion ω_s and the first natural frequency of the soil ω_1.

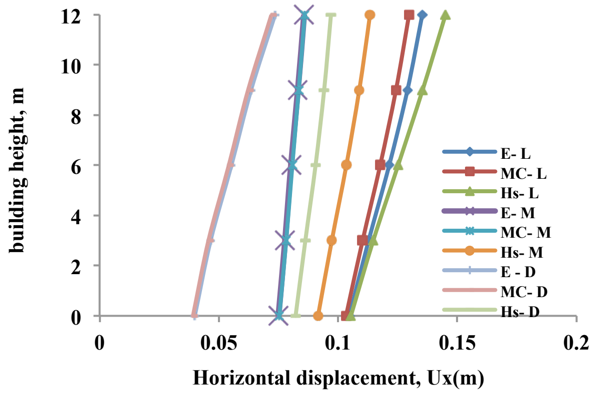
3 Results and Discussions

The dynamic response of the three buildings of different height (H) to width (B) ratios H/B =1, 2 and 3 is evaluated by examining the peak horizontal displacement (U_x) at the different story levels. The analysis is performed when linear (E), elastoplastic (MC)and small strain hardening (Hs) soil behaviors are considered for loose (L), medium (M) and dense (D) soil types.

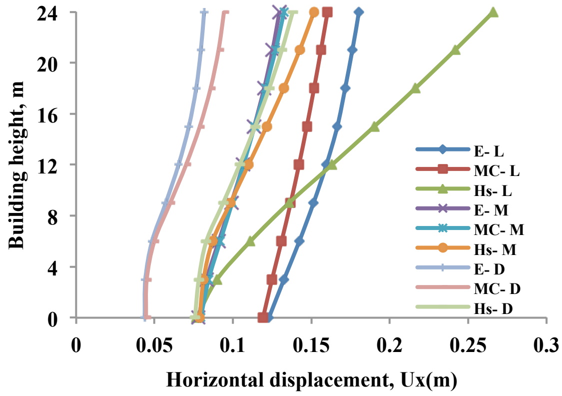
The dynamic analysis for the various considered buildings of different slenderness ratios and various soil types shows approximately similar results for both linear elastic and elastic perfectly plastic models. However, when compared to the small strain hardening behavior (HSS), the Mohr-Coulomb model (MC) displayed different horizontal displacements for the studied buildings for different soil types (Figure 3. (a), (b) and (c)). The maximum rate of variation of the displacements in percent between MC and HSS models are summarized in Table 3. The positive and negative values correspond to an increased and decreased percentage respectively.

Table 3. Rate of variation of displacement between MC and HSS models

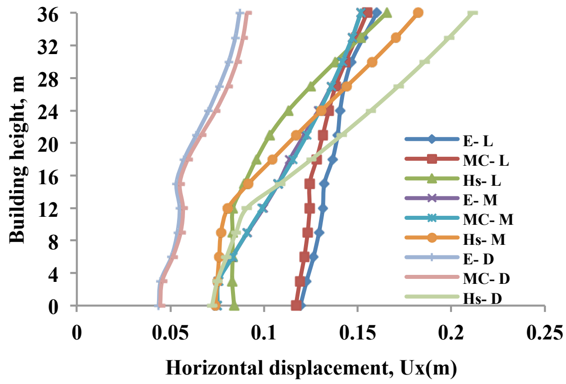
s	Loose	Medium	Dense
1	-10	-24	-52
2	55/-40	-13	-41
3	49	23/-16	-57



a)



b)

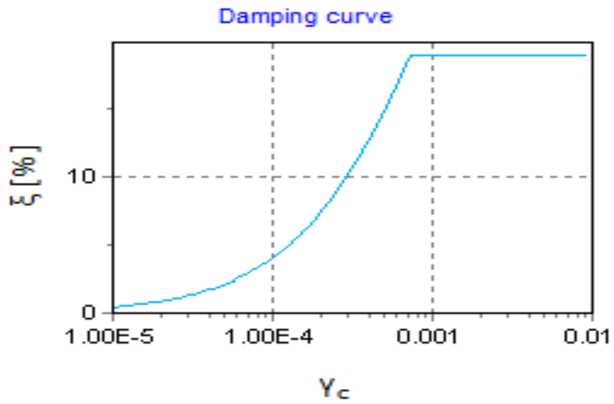


c)

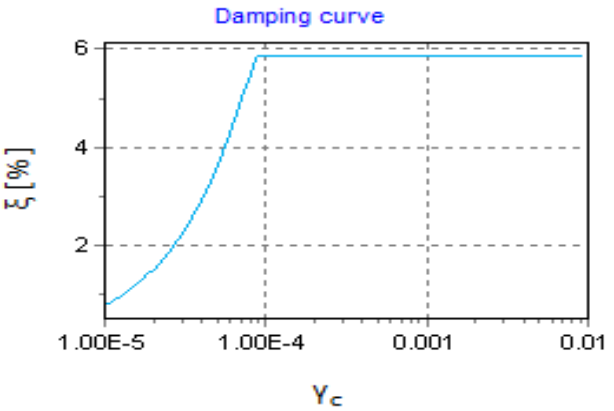
Fig. 3. Peak horizontal displacement of (a) four (b) eight and (c) twelve-storey buildings

The MC model represents the soil with a single Young's modulus value that is stress independent. Accordingly, the soil stiffness is calculated at the beginning of the analysis based on the starting stresses then remains constant till the end. The overestimated stiffness value in MC model with respect to the degrading strain-dependent stiffness in hardening behavior, justifies the decrease in results in MC model. The rate of variation in displacement values between both models depends on the soil type. For loose soil where the shear strains are high, the reduction in stiffness is more important than the medium and dense soil. As a result, the rate of variation is more pronounced in loose then medium and dense soil consecutively.

When subjected to cyclic loading, the HSS small behavior shows hysteretic damping. The larger the ratio of the small strain shear stiffness G_0 to the unloaded- reloaded shear modulus $G_{ur} = E_{ur}/2(1+\nu_{ur})$ leads to greater amount of hysteretic damping [23]. By calculating this ratio for the different soil types , the values obtained are: 6.24, 2.5 and 1.74 for loose, medium and dense soil respectively. This proves that the maximum damping ratio is the largest for loose soil and diminishes whenever the soil gets denser . However, the amount of the hysteretic damping varies depending on the amplitude of the strain cycles (γ_c). The variation of the damping ratio ζ function of the cyclic strain levels for the considered loose and dense soil is illustrated in Figure 4.(a) and (b) respectively. It clearly demonstrates that in this study, whenever the value of γ_c ranges between 10^{-5} and $1.5.10^{-4}$, the damping ratio for dense soil is greater than that for loose soil. The soil damping characteristics are therefore modeled by solely the Raleigh damping, similarly to the MC model. This justifies the decreasing displacement from loose to medium then dense soil in short building (S=1). However, at a higher cyclic strain value, the hysteretic damping ratio in loose soil is much higher than that in dense soil. The soil damping in loose soil incorporated a significant amount of hysteretic damping in addition to the Raleigh damping. Consequently, the structural displacements are the smallest at loose soil, and increases whenever the soil becomes denser. This explains the displacement contradictory trend observed at the higher building (S=3) and clarifies as well the larger displacements in loose soil in MC model where just Raleigh damping is considered.



a)



b)

Fig. 4. Damping ratio for different strain levels in case of (a) loose soil and (b) dense soil.

To conclude, the reliability of MC model in computing the structural dynamic response versus HSS hardening model is related to the soil and structure parameters. It is a function of complex interaction between the soil stiffness and the damping ratio, denoted by shear and cyclic strain respectively, and the structure slenderness ratio. The Mohr-Coulomb model demonstrated its inadequacy in this study in depicting the real soil behavior.

4 Conclusion

This study assessed the reliability of applying both linear-elastic and elastic-perfectly plastic soil models in soil-structure interaction problem. This was realized by evaluating and comparing the dynamic behavior for these constitutive models to the small strain hardening behavior. Therefore, the dynamic response of buildings of different heights was evaluated for various soil types when triggered by a strong earthquake. The obtained results show that:

- The Mohr-Coulomb model mostly underestimates the structural dynamic response due to an overvalued stress independent Young's modulus especially for loose soil.
- The Mohr-Coulomb behavior overestimates the results since just the frequency- dependent Raleigh damping insufficiently simulates the soil damping, whereas an additional hysteretic damping is incorporated in HSS small model.

The intricate interaction between the soil stiffness and damping parameters, and the structure slenderness ratio resulted in significant dissimilarity in behavior between Mohr- Coulomb and HSS hardening models. In this work, the linear-elastic and elastic-perfectly plastic soil models were proved inadequate in capturing the real soil behavior.

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