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Reduction factors to evaluate acceleration demand of soil-foundation-structure systems

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ABSTRACT

The seismic acceleration loading of structures founded on compliant soil is investigated through numerical elastic time history analyses of coupled soil-foundation-structure (SFS) systems and appropriate reduction factors of acceleration demand for free-field to evaluate acceleration demand for the SFS systems are proposed. The proposed reduction factors are the division of the acceleration demand for the coupled SFS system over the acceleration demand for the free-field, and propose an alternative method to calculate the actual acceleration loading considering interaction effects. The advantages of the proposed methodology are i) its accuracy, as the reduction factors result from coupled SFS numerical finite element analyses and consider both inertial and kinematic interaction effects and ii) its practicality, as it can be applied by the user performing no finite element numerical analysis. Additionally, the presented methodology can be applied to systems with important mass (e.g. bridge structures). The proposed acceleration reduction factors are presented in terms of dimensionless engineering parameters such as soil to structure stiffness ratio and the structure's aspect ratio. The accuracy, efficiency, and practicality of the proposed methodology are highlighted through an application to a typical bridge structure. Because structures with surface foundations are examined, inertial interaction mainly affects the acceleration demand. Therefore, the proposed reduction factors clearly demonstrate and quantify the beneficial effect of damping on buildings and bridges, as the maximum average acceleration at the top of the actual SFS system can reduce to about 55–85% of the acceleration demand for the free-field motion.

1. Introduction

The earthquake acceleration loading of any structure depends on its *dynamic properties*, as well as on the *foundation motion* which is the input motion for the structure. To evaluate the seismic acceleration loading of structures having surface foundations, the available methods are the following:

i) Assume a *fixed-base structure* subjected to the *free-field* motion. In this case, SSI effects are totally ignored. Nevertheless, this methodology is conventionally used in seismic design practice.
ii) Assume a *flexible-base structure* subjected to *free-field motion*. In this way, inertial interaction effects are considered only on the system's dynamic properties (modification of fundamental period and damping), while the effects of inertial and kinematic interaction on foundation motion are ignored [e.g. [21]].
iii) Assume a *flexible-base structure* subjected to *foundation input motion* (*FIM*). FIM is different from the actual foundation motion, as it considers only kinematic interaction effects. More specifically, this framework considers inertial interaction effects only on the system's dynamic properties (modification of fundamental period and damping) and the effects of kinematic interaction are considered only on foundation motion. This approach is based on sub-structure method, which decomposes the soil-foundation-structure system into several subdomains [4,17]. Kinematic interaction effects are interpreted in the abovementioned methodology in an approximate manner from variations between free-field and foundation ground motion indices, neglecting inertial interaction because inertial interaction effects are concentrated in a narrow frequency range around the first-mode frequency [11]. However, foundation motion is affected by both inertial and kinematic interaction as stated also in Stewart et al. [22]. Additionally, the frequency range around the first mode mainly affects the acceleration demand, and consequently the response at foundation [10].
iv) Simulate the complete soil-foundation-system with continuum numerical simulations and calculate its response in one step with direct analysis. In this case, inertial and kinematic interaction effects are considered simultaneously [e.g. [24,7]]. This procedure is the

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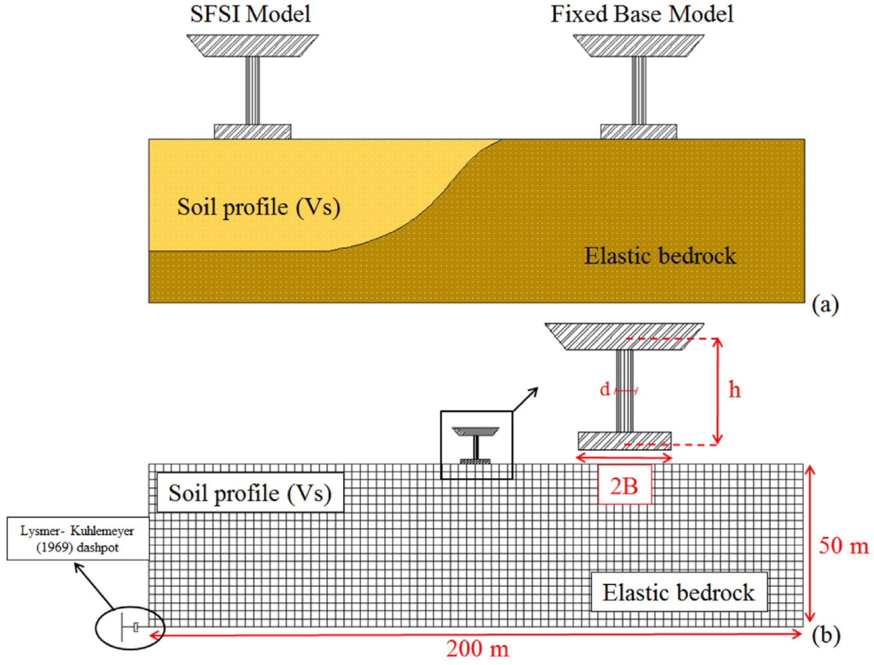

Fig. 1. Finite element modelling of the soil-foundation-structure-systems studied, (a) description of the fixed base and SSI models and (b) numerical SSI model adopted in the present study [10].

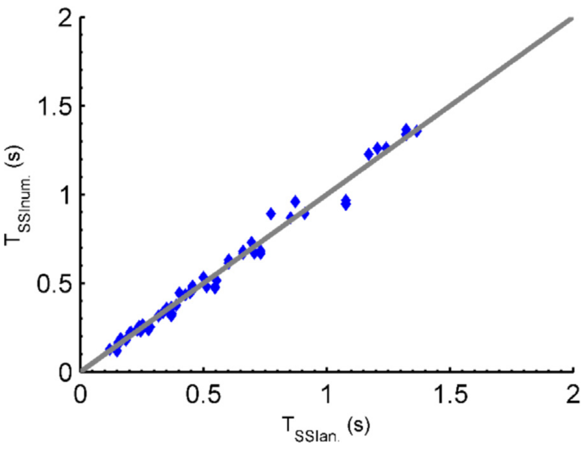

Fig. 2. Comparison between the FE-based ($T_{SSInum,}$) and analytical formulae of TSSI ($T_{SSIan.}$) for the selected SSI systems.

one adopted in the present paper.

Current design codes [17,4,5] treat the SSI using the sub-structure approach and appropriate foundation impedances [16,18,6], or via simplified discrete systems [14]. Therefore, they account for inertial or kinematic interaction separately and are unable to consider their combined effect. The present study aims at filling this gap by proposing a simple methodology for the evaluation of seismic acceleration demand for coupled soil-foundation-structure systems based on a comprehensive set of direct linear numerical analyses of coupled SFS systems subjected to earthquake motions at the base of the soil model (bedrock level). We propose appropriate reduction factors (RFs) to account for SSI in the seismic loading of soil-structure systems, by properly modifying the seismic loading of the simplest case of an SDOF structure which is fixed at its base and subjected to free field motion. The RFs describe the combined inertial and kinematic effects and can be very easily used in engineering practice for the estimation of seismic acceleration demand considering SSI effects in a single step.

2. Configuration and numerical modelling

To calculate the seismic acceleration demand of the studied SFS systems, we conducted 2D linear elastic time history analyses of coupled SFS systems using two-dimensional plane strain models in Opensees [15].

The superstructure is a single-degree-of-freedom structure (SDOF), the degree of freedom being the translational displacement of the structural mass, m_s. Single-degree-of-freedom structures are commonly used in SSI analyses because inertial interaction effects are most pronounced in the first mode [22]. The SDOF structure is characterized by its stiffness k_s, its mass m_s, its damping c_s and its height h. The structure is founded on a massless rigid surface foundation of width equal to 2B resting on the ground surface. Both the structure and the foundation are modelled with elastic beam column elements. A full connection is assumed between the foundation and the soil nodes. The entire superstructure's mass is lumped at the top of the superstructure without any contribution from the massless column. This SDOF can be interpreted as an equivalent representation of the fundamental mode of vibration of a multi-storey structure which is dominated by first-mode response or,

Table 1
Characteristics of the four distinct soil-foundation-structure systems [10].

V_s (m/s)	h (m)	2B (m)	m_s (mg)	T_{FIX} (s)	T_{SSI}/T_{FIX}	$h/T_{FIX} * V_s$	h/B
100/200/300/400	3	6	100/200/400/800	0.10–1.18	1.04–5.20	0.006–0.28	1
100/200/300/400	5	10	100/200/400/800	0.10–0.92	1.06–6.50	0.01–0.49	1
100/200/300/400	6	6	100/200/400/800	0.10–1.88	1.03–7.90	0.008–0.48	2
100/200/300/400	10	10	100/200/400/800	0.10–1.32	1.06–6.73	0.02–0.98	2