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A centrifuge-based experimental verification of Soil-Structure Interaction effects

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ABSTRACT

A series of prototype dynamic centrifuge experiments is carried out to investigate the influence of soil properties and structural parameters on the Soil Structure Interaction (SSI) effect. Established analytical models are herein experimentally verified, and are proven accurate in estimating the system's natural frequency characteristics. It is observed that period elongation is strongly correlated to the relative superstructure-foundation stiffness. Although the present study deals exclusively with the small-strain near-linear range, the experimental response indicates occurrence of nonlinearity. The identified damping results remarkably larger than its analytical estimate and proves highly strain-dependent, raising questions on the reliability of existing analytical methods in capturing the actual dissipation mechanisms. An extended experimental dataset is formed under realistic stress and strain soil conditions, and is implemented, for the first time, for verification of existing analytical models offering valuable insight into the theory and serving as a benchmark for engineering practice.

1. Introduction

The interaction between the superstructure, the foundation and the subjacent soil has been proven to substantially influence the dynamic response of structures and is usually referred to as Soil Structure Interaction (*SSI*), or Soil Foundation Structure Interaction (*SFSI*). This phenomenon is relevant across a range of disciplines, ranging from geotechnical and earthquake engineering all the way to marine and offshore structures. The deformability of the supporting soil affects the global dynamic response by introducing translational and rotational degrees of freedom to the system foundation, thereby resulting in increase of the fundamental period of the overall system, as well as energy dissipation through wave radiation and hysteretic behavior of the soil [1]. SSI effects can be categorized into inertial interaction effects, kinematic interaction effects and soil-foundation flexibility effects [2].

The SSI phenomenon has been a point of academic interest in soil dynamics and earthquake engineering for more than forty years. From the inceptive work of Veletsos and Verbic [3] and the analytical formulations of Gazetas [4,5], to the recent experimental and analytical works of Anastasopoulos [6–8] the understanding of the complexity of this phenomenon continues to evolve. SSI effects have traditionally been considered as beneficial to the dynamic response of structures. In this context, their omission is assumed to lie on the safe side and, thus, many seismic design codes (ATC-3, NEHRP-97) suggest their omission. In design practice SSI effects are only considered for highly sensitive structures founded on sensitive ground. According to Mylonakis and Gazetas [9] this tendency reflects the simplifying assumptions adopted by the actual design provisions for the estimation of seismic demand.

According to the same authors however, existence of seismic records of larger spectral values at the longer period-range indicates the possibility for increased seismic demand owing to the SSI effect. Furthermore, in the case of stiff structures, the period elongation effect results in higher seismic demand. Period lengthening further increases displacement demand and consequently the structural ductility demand. This can be critical for slender structures in terms of serviceability and second order effects. Lastly, the period shift due to SSI could lead to resonance effects with detrimental implications, when the fundamental frequency of the soil-structure system approaches the frequency peak of the excitation, or the eigenfrequency of the soil. In all aforementioned cases, negligence of SSI effects is not to the side of safety.

The present work aims to shed light on the understanding of the SSI phenomenon through a parametric experimental study conducted in a centrifuge facility. The main focus is put on the linear, or rather near-linear, range of the response in order to study the influence of various soil and structural parameters on the modal characteristics of the

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Abbreviations: FS_v, Foundation Safety Factor against vertical loads; PLR, Period Lengthening Ratio; SDR, System Damping Ratio; IDR, Identified Damping Ratio

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Nomenclature

Geometric parameters

B	width of a rectangular footing or diameter of a cylindrical footing
D	depth of embedment
h	height of the column
H	effective height of the equivalent SDOF model

Material properties parameters

G_o	shear modulus of soil
v	Poisson's ratio of soil
ρ	density of soil

Foundation impedance parameters

K_c	static stiffness of the SDOF model, assuming fixed base conditions
K	static stiffness referred to the foundation base
C	radiation dashpot coefficient

Dynamic properties parameters

M	concentrated mass of the superstructure
f_c	eigenfrequency of the superstructure, assuming fixed base conditions
ω	circular frequency of the response
f	frequency of the response
f_D	damped frequency of the response
$\zeta_{radiation}$	radiation damping ratio of the soil
ζ_c	structural damping ratio
ζ_{mat}	material damping ratio, referred to the hysteretic action of the soil

Dissipated energy method parameters

$u(t)$	displacement response history of the equivalent SDOF system
$v(t)$	velocity response history of the equivalent SDOF system
$E_{kin}(t)$	kinetic Energy response history of the equivalent SDOF system
$E_{pot}(t)$	potential Energy response history of the equivalent SDOF system
$E_{tot}(t)$	total Energy response history of the equivalent SDOF system
E_D	dissipated Energy in one vibration cycle
ζ	estimated damping ratio of the system, based on the dissipated energy method

Subscripts

h	horizontal
r	rocking
sys	system soil, foundation and superstructure

structure-foundation-soil system. For the first time, a large amount of dynamic experiments consistently simulating realistic stress and strain soil conditions is carried out to verify established analytical models for prediction of soil stiffness and damping [4,5]. These formulations have so far been validated either numerically or experimentally through statically imposed loads, albeit failing to capture the dynamic characteristics of the SSI system [10]. A previously reported experimental study of small scale dynamic experiments has been limited to the1g gravitational level, failing to realistically simulate the stress and strain conditions of the soil [11,12]. A first preliminary insight to the problem treated herein was offered in [13]. In what follows, the state-of-the-art is broken down into the major thematic areas tied to this investigation, in an attempt to offer a comprehensive overview for the interested reader.

2. Fundamental concepts

In this section we describe the main benefits of centrifuge experimentation, as well as an overview of fundamental energy dissipation mechanisms that comprise the basis for the identification of the system damping.

2.1. Centrifuge modeling

The impedance of the soil is inextricably connected to the existing stress conditions. Thus, reproducing the large confining stresses that are observed even at relatively shallow foundation depths is crucial for the realistic modeling of soil-structure systems. As mentioned in [14], this stress-dependency is a key challenge in laboratory geotechnical modeling. The scaling of structural systems has long been studied and generally proven to provide meaningful results. A thorough work on the scaling of structural models under dynamic loading can be found in [15–17]. For geotechnical applications though, scaling of the stress distribution in the subsoil is non-trivial, while the behavior under the lower stress level of the scaled soil-profile cannot be reliably related to the prototype model. In this respect, centrifuge testing, which allows for one-to-one scaling of stress and strain distribution, becomes a powerful tool for geotechnical experiments. The adopted scaling laws for centrifuge experiments are described in [15–17], while scale effects associated to the underlying assumptions are outlined in [15,18]. These effects are found to bear negligible influence in the design of the present experiments.

2.2. Energy dissipation mechanisms

Despite the extensive research in the topic of soil dynamics, understanding of damping mechanisms remains primitive. Nevertheless, three main mechanisms of energy dissipation in SSI systems are broadly accepted. Firstly, radiation damping, which is highly frequency dependent, increases with the foundation width and embedment depth and is higher in case of deep homogeneous soil deposits [19]. Secondly, material or hysteretic damping, which is usually simulated as equivalent viscous damping, albeit unrealistic since the experimental experience indicates a strain-dependent hysteretic damping, especially for larger strains [20]. To incorporate hysteretic material damping and preserve causality, nonlinear frictional elements were derived by Meek and Wolf [21]. Finally, structural damping is usually modeled as equivalent viscous damping and assumed to be constant for each mode of vibration.

3. State-of-the-art in experimental SSI investigation

The significance of experimentation is ubiquitously recognized throughout engineering fields. Particularly in the domain of SSI, where numerous analytical and numerical models have been developed, experimental verification is necessary for proving these model reliable and actionable. According to [22], experimental studies on the dynamic response of foundation can be grouped in the three following categories: