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Transient kinematic pile bending in two-layer soil

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ABSTRACT

The dynamic response of piles to seismic loading is explored by means of an extensive parametric study based on a properly calibrated Beam-on-Dynamic-Winkler-Foundation (BDWF) model. The investigated problem consists of a single vertical cylindrical pile, modelled as an Euler–Bernoulli beam, embedded in a subsoil consisting of two homogeneous viscoelastic layers of sharply different stiffness resting on a rigid stratum. The system is subjected to vertically propagating seismic *S* waves, in the form of a transient motion imposed on rock outcrop. Several accelerograms recorded in Italy are employed as input motions in the numerical analyses. The paper highlights the severity of kinematic pile bending in the vicinity of the interface separating the two soil layers. In addition to factors already investigated such as layer stiffness contrast, relative soil–pile stiffness, interface depth and intensity of ground excitation, the paper focuses on additional important factors, notably soil material damping, stiffness of Winkler springs and frequency content of earthquake excitation. Existing predictive equations for assessing kinematic pile bending at soil layer interfaces are revisited and new regression analyses are performed. A synthesis of findings in terms of a set of simple equations is provided. The use of these equations is discussed through examples.

1. Introduction

During the passage of seismic waves through soft deposits, embedded piles tend to deform in a different manner with respect to the surrounding soil. The difference between soil and pile motion depends on several factors, notably soil layering, pile–soil stiffness contrast, excitation frequency and kinematic constraints at the pile head and tip [1–4]. As curvatures are imposed to the pile body by the vibrating soil, bending and shearing will develop even in the absence of a superstructure. The associated pile bending moments are, thereby, referred to as “kinematic”, to be distinguished from those generated by loads acting at the pile head due to the dynamic response of the superstructure (so-called “inertial” moments). Kinematic and inertial bending moments constitute complementary aspects of a unique phenomenon known as soil–pile–structure interaction (SPSI). Reviews of the subject have been published, among others, by Novak [5], Pender [6] and Gazetas and Mylonakis [7].

Evidence from case histories – as documented by Mizuno [8] and other Japanese researchers [9–12] – or from recent experimental investigations on physical pile models in centrifuge and 1*g* earthquake simulators [13–18] have elucidated the important role of kinematic interaction in seismic response of pile foundations. Kinematic bending is significant (as compared to its inertial counterpart) particularly in correspondence to stiff pile caps and soil layer interfaces. The latter may explain the concentration of seismic demand at depths where inertial effects are negligible.

The accumulated evidence has generated significant interest in exploring theoretical and analytical aspects of the phenomenon and developing seismic regulations to incorporate it into design procedures [19–21].

Following the early work by Margason and Halloway [22], theoretical investigations of the problem began in the 1980s [1,23–27] and continued into the 1990s and beyond [2–4,28–31].

In 2005, a systematic research effort was initiated in Italy under the auspicious of the ReLUIS project (University Network of Seismic Engineering Laboratories), which has lead to a number of publications [32–43]. The main goal of the project was to produce engineering provisions to be incorporated into the new national seismic code [21], which is compulsory in Italy since July 2009.

1.1. Unresolved issues

At present, it appears that many aspects of kinematic pile bending are well understood, whilst others require further research and remain unresolved. *First*, most of the published results concentrate on flexible piles (i.e., piles whose lengths are greater than the so-called “active pile length” [44], embedded in

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