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Earthquake Analysis of Buried Structures and Pipelines Based on Rayleigh Wave Propagation

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ABSTRACT

In this paper, an interface 3D-beam element is presented for the linear dynamic analysis of buried, or pile, structures under a seismic ground motion represented by R-wave propagation. The formulation of the element is based on the assumption that the ground is a viscoelastic continuum, which can be represented by a 2-parameter soil model of the Winkler and the shear type (Pasternak model). The formulation takes into account the effects of shear deformation and a constant axial force of the beam. The stiffness matrix and the load vector of the interface element are stated in the complex domain as depending on the frequency and damping properties of the soil. It is stated that the load vector is a function of the ground deformation. An example of a pipeline is presented for demonstration purposes.

INTRODUCTION

Buried, or underground, structures are commonly encountered in practice as tunnels, structural foundation units, piles and pipelines, etc., which may stand alone or as parts of land and offshore structural systems. Analysis of underground structures differs from that of superstructures because of interaction with the surrounding soil-medium. This interaction is a well-known phenomenon, and for the solution, the finite element (FE) method is commonly used (Manolis and Beskos, 1997). This analysis technique is very general and appropriate if a fine mesh is used. The analytical solution of this problem is rather tedious and limited to some simple structure-soil configurations (Militano and Rajapakse, 1999; Makris, 1994). One other alternative is to use the finite difference method (Juhasova, 1991), which may also have limited applications. Thus, a simple but reasonable analysis procedure for underground structures can be more attractive and practical. In the FE analysis, this may be achieved by using the concept of a soil-structure interface element, in which the contribution of the soil is implemented. In the literature, available members of this kind are mostly for special-purpose applications (Novak and Aboul-Ella, 1978; Song and Wolf, 1994). In the current paper, an interface 3D beam-element formulation, suitable for the modeling of a buried (underground) structural system or a part of it, is presented in general for the response analysis to earthquake excitations. The surrounding or underlying soil medium of a structural member is assumed to be a viscoelastic continuum, represented by the Voigt (Kelvin) model (Japanese Society of Civil Engineers, 1997; Ishihara, 1996; and Novak et al., 1978). For the interaction, the soil deformations are assumed to follow the Pasternak model—deformations of both Winkler- and shear-type (Selvadurai, 1979). Since earthquake analysis is involved in this paper, it is well known that the destructive seismic ground motion is due to the Rayleigh wave propagation (Bolt, 1970, 1993). The largest amplitudes in an earthquake record following the P- and S-waves identify the Rayleigh wave (R-wave). Their amplitudes are highest at the ground surface and die away gradually with the depth of the ground. The R-wave propagation produces an elliptical g round-motion trajectory that introduces an additional earthquake loading term on members.

Development of an interface soil-beam element has been a subject worked on for a long time. Formulation of a 2D beam resting on an elastic foundation has been well established (Miranda and Nair, 1966; Selvadurai, 1979; and Ting, 1982). The stiffness matrix and the consistent force vector of a 2D beam on a Winkler-type foundation were presented by Ting and Mockry (1984), who used the exact lateral displacement. Yokoyama (1991) presented a finite element formulation of a 2D Timoshenko beam resting on the Pasternak soil model while Karadeniz (1999) presented a 3D formulation, for the static and eigenvalue analyses. These elements are inappropriate in the dynamic response analysis since the soil model used cannot characterize dynamic soil-properties adequately. This paper is an extension of a 3D-interface beam element presented by Karadeniz (1999) for the dynamic-response analysis under seismic ground-motion in general. It is assumed that the soil medium is a linear viscoelastic continuum and the seismic ground-displacements are available analytically from the free-field (without structure) solution of the R-wave equation. For the completeness of the paper, some basic differential equations of the beam theory, used in the formulation of the interface element, are summarized below.

DIFFERENTIAL EQUATIONS OF CLASSICAL BEAM THEORY

After a deformation state under a distributed external loading (q_y and q_z) in the local y and z coordinates, the internal force components of an infinitesimal 3D beam element are shown in Fig. 1. The displacement components in the local y and z coordinates are, respectively, u_y and u_z. For a Timoshenko beam, the derivatives of these displacements with respect to x are stated as:

$$\frac{du_y}{dx} = \gamma_y + \theta_z \quad \text{and} \quad \frac{du_z}{dx} = \gamma_z - \theta_y \tag{1}$$

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