Analysis of transient response of saturated porous elastic soil under cyclic loading using element-free Galerkin method

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Saturated soil can be idealised as two-phase media comprising deformable soil skeleton and pore fluid. The transient response of the saturated soil is especially important to understand the deformations and the pore water pressures generated by ground motion. This response is a key factor to the analyses of buildings, machine foundation, offshore structures, wave propagation in geological medium due to blast or earthquake, and pile driving. A fluid-filled porous medium theory was proposed by Biot (1941) to analyze this transient response. Most of the transient response problems are solved by numerical methods such as finite element method (FEM) and finite difference method (FDM) in conjunction with appropriate time integration schemes. Typical FEM methods were proposed by Sandhu and Wilson (1969), Ghaboussi and Wilson (1972, 1973), Ghaboussi and Dikman (1978), Prevost (1982), Zeinkiewicz et al. (1977), Zeinkiewicz (1980) and Zeinkiewicz and Shiomi (1984). However, it is difficult for FEM to analyze the problems associated with moving boundary. A meshless method is an effective alternative.

This paper will study the transient response of seabed under wave loading using meshless element-free Galerkin method (EFGM). The wave-induced transient response has its own characteristics: first, wave loading is applied on the surface of seabed through water pressure. If shallow water is concerned, this wave loading still has energy to produce impact on the seabed. When water wave propagates over seabed, a cyclic pressure will exert on the surface of seabed, thus causing pore fluid in the seabed to flow and seabed to deform. Transient fluctuation of pore water pressure generates the transient reduction of effective stress, and thus seabed may lose its strength momentarily during a cyclic wave. Second, water over the seabed and pore water in seabed interact each other. The soil of the seabed has an effect on the wave train. This interaction also makes the water-seabed interface complicated. Furthermore, an object placed on the seabed may move along the seabed surface. This is a moving boundary problem.

Several publications are available for the wave-induced pore pressures and effective stresses analysis. Most of these are based on Biot_s consolidation theory (1941). The approaches can be roughly classified into two categories: analytical approaches and numerical methods. Among analytical approaches, Yamamoto et al. (1978) and Madsen (1978) considered compressible pore fluid in a porous seabed of infinite thickness subjected to a two-dimensional wave. Their final governing equation, for saturated isotropic soils, was a sixth-order linear differential equation. Later Okusa (1985) reduced the order of the governing equation to fourth order. However, they assumed periodic variables in time domain and in space, and thus the solution is not general. As the governing equations are generally difficult to solve analytically for finite soil thickness, Thomas (1988) developed a semi-analytical one-dimensional finite element procedure to simulate the waveinduced stresses and pore water pressures. He also assumed that all variables are harmonic. His formulation was tremendously complicated. Among numerical algorithms, FEM and FDM were main tools. Although they are successful in many problems, some difficulties remain in the treatment of mesh distortion associated with moving boundary conditions. Recently developed meshless methods could overcome these disadvantages because meshless methods do not use any element. On this meaning, meshless methods are attractive for the transient analysis of wave-induced seabed responses.

A two-dimensional transient problem under wave-induced load has essential and natural boundaries that are periodic in time and in space. The periodic temporal boundary conditions are easily implemented in numerical procedures. However, a special procedure is required for the implementation of boundary conditions with periodicity in space. This paper will develop a variational approach to treat periodic temporal and spatial boundary conditions, which are common boundaries in those transient problems under cyclic loading. Meshless methods are recently developed numerical techniques. EFGM proposed by Belytschko et al. (1994) is a successful meshless technique that requires only nodes to discretize a problem domain. Its shape functions are constructed by moving least-square (MLS) approximants (Lancaster and Salkauskas, 1981). Other forms of meshless methods include reproducing kernel particle method (Liu et al., 1995), h _ p clouds (Duarte and Oden, 1996), the partition of unity (Babuska and Melenk, 1997), smooth particle hydrodynamics (Monaghan, 1988), and radial point interpolation method (Wang and Liu, 2002).

This paper presents a meshless element-free Galerkin procedure to solve the transient response of fluidsaturated porous elastic soil under cyclic loading. The EFGM is firstly applied to a one-dimensional problem. This is a typical temporally periodic problem to investigate the transient response of a fully saturated, elastic and isotropic porous soil layer subjected to sinusoidal surface loading. A two-dimensional wave-induced transient problem for a seabed with finite thickness is studied when subjected to a progressive wave. This problem includes both temporal and spatial periodic boundary conditions. A moving boundary problem is also designed to check the capability of the current procedure. This paper is organised as follows. First, brief descriptions of MLS approximants are presented. Then, governing equations for fluid-saturated elastic–porous medium are described. Periodic temporal and spatial boundary conditions are incorporated into the variational formulations. The numerical implementation for above variational formulations is presented. Finally, examples are used to assess the performance of the current procedure.

Moving least-square approximation

MLS method is employed in the EFGM to approximate a function uð_xxÞ with u_hð_xxÞ, where uð_xxÞ is the actual function and u_hð_xÞ is its approximation. The approximation consists of three components: a basis, usually a polynomial; a weight function associated with each node; and a set of coefficients that depend on node position. The weight function is non-zero only over a small sub-domain around the node. This nonzero domain is called compact support or domain of influence. The overlap of the nodal domains of influence defines a nodal connectivity.

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