Computers and Geotechnics 75 (2016) 93–102

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

Numerical and analytical investigation of compressional wave propagation in saturated soils

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A R T I C L E   I N F O

Article history:
Received 30 August 2015
Received in revised form 23 January 2016
Accepted 25 January 2016

Keywords:
Hydro-mechanically coupling
Compressional wave propagation
Analytical solution
Finite element analysis
Vertical site response

A B S T R A C T

In geotechnical earthquake engineering, wave propagation plays a fundamental role in engineering applications related to the dynamic response of geotechnical structures and to site response analysis. However, current engineering practice is primarily concentrated on the investigation of shear wave propagation and the corresponding site response only to the horizontal components of the ground motion. Due to the repeated recent observations of strong vertical ground motions and compressional damage of engineering structures, there is an increasing need to carry out a comprehensive investigation of vertical site response and the associated compressional wave propagation, particularly when performing the seismic design for critical structures (e.g. nuclear power plants and high dams). Therefore, in this paper, the compressional wave propagation mechanism in saturated soils is investigated by employing hydro-mechanically (HM) coupled analytical and numerical methods. A HM analytical solution for compressional wave propagation is first studied based on Biot's theory, which shows the existence of two types of compressional waves (fast and slow waves) and indicates that their characteristics (i.e. wave dispersion and attenuation) are highly dependent on some key geotechnical and seismic parameters (i.e. the permeability, soil stiffness and loading frequency). The subsequent HM Finite Element (FE) study reproduces the duality of compressional waves and identifies the dominant permeability ranges for the existence of the two waves. In particular the existence of the slow compression wave is observed for a range of permeability and loading frequency that is relevant for geotechnical earthquake engineering applications. In order to account for the effects of soil permeability on compressional dynamic soil behaviour and soil properties (i.e. P-wave velocities and damping ratios), the coupled consolidation analysis is therefore recommended as the only tool capable of accurately simulating the dynamic response of geotechnical structures to vertical ground motion at intermediate transient states between undrained and drained conditions.

1. Introduction

1.1. Background

During an earthquake, the ground is subjected to simultaneous shaking in both the horizontal and vertical directions. However, it is common practice for geotechnical earthquake engineering problems to investigate the vertically propagating shear waves and assess the corresponding site response only to the horizontal components of the ground motion. This is based on the assumption that the effect of the vertical component of the ground motion, induced predominantly by vertically propagating compressional waves, is less significant, due to its smaller magnitude and higher frequency content compared to the horizontal ground motion component [31]. However, since 1990s, strong vertical ground motions have been repeatedly observed, leading to significant damage of engineering structures in the form of vertical compression [22,30,7,17,26]. In particular in the recent 2011 Christchurch earthquake, strong vertical ground motions were widely observed [17], which induced significant damage on crib retaining walls due to the contact loss of the crib units in the vertical direction [26]. Furthermore, the numerical investigations of the response of structures described in Kunnath et al. [16], show that neglecting the vertical ground motions in the seismic design of highway bridges and overcrossings may lead to failures due to bending moment capacity exceedance induced by strong vertical motions. Moreover, for the seismic design of critical structures (e.g. nuclear power plants, high dams), ground motion effects have to be taken into

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http://dx.doi.org/10.1016/j.compgeo.2016.01.019
0266-352X/

Notation (SI units)

c_1 and c_2 fast and slow wave velocities (m/s)
c_w wave velocity in the fluid (m/s)
D soil constrained modulus (kPa)
$D_{Undrained}$ and $D_{Drained}$ soil constrained modulus under the undrained and drained conditions (kPa)
E Young's modulus (kPa)
$f_{Undrained}$ and $f_{Drained}$ fundamental frequency of a soil layer subjected to vertical motions under the undrained and drained conditions (Hz)
g gravitational acceleration (m/s^2)
G_s specific gravity
H depth of a soil layer (m)
k permeability (m/s)
k wave number (m^{-1})
k^* complex wave number (m^{-1})
K_f bulk modulus of the pore fluid (kPa)
n material porosity
$R()$ and $I()$ real and imaginary parts of a complex number
t current time in any analysis (s)
v_r relative vertical displacement between the solid and pore fluid phases (m)
v_s and v_f vertical displacements of the solid skeleton and pore fluid (m)
v_s shear wave velocity (m/s)
v_p compressional wave velocity (m/s)
$v_{p_{Undrained}}$ and $v_{p_{Drained}}$ compressional wave velocity under the undrained and drained conditions (m/s)
z vertical distance in a soil layer from the coordinate origin (m)
δ amplitude decay employed by to quantify the wave attenuation in Bardet and Sayed [2]
ν Poisson's ratio
ξ material damping ratio
ξ_1 and ξ_2 damping ratios for fast and slow waves
ρ_s and ρ_f densities of the solid skeleton and pore fluid (g/cm^3)
ϕ a complex number representing different types of compressional waves
χ ratio between the effective soil constrained modulus and pore fluid bulk modulus
ω circular frequency of an input motion (rad/s)

account for a very wide frequency range, with the compressional waves usually dominating the high-frequency limit. There is therefore a need for a more rigorous investigation of compressional wave propagation in geotechnical materials, which will ultimately assist the development of a better understanding of the site response due to vertical ground motion. In this paper, the compressional wave propagation mechanism in saturated soils is investigated, by employing a hydro-mechanically (HM) coupled analytical solution and an HM coupled Finite Element (FE) method. An analytical solution for compressional wave propagation, which is based on Biot's theory [4,5], is firstly employed to investigate the characteristics of the two types of compressional waves (fast and slow waves). The subsequent HM FE study reproduces the duality of compressional waves and identifies the dominant permeability ranges for the existence of the two waves. The predicted characteristics of the compressional waves (i.e. wave dispersion and attenuation) in different frequency ranges are further compared against the analytical solution to investigate the significance of the two types of waves in different conditions (i.e. undrained, drained or intermediate states).

1.2. Compressional wave propagation in saturated porous materials

The undrained approximation is a common assumption for analysing geotechnical earthquake engineering problems, which is of acceptable accuracy for relatively impermeable materials or/and under loading of relatively short duration. However, due to the complexity of dynamic soil behaviour and earthquake loading conditions, consolidation can occur in a soil profile during seismic loading, depending on the range of the dynamic loading duration and soil permeability. In that case, the undrained solution is insufficient for the accurate simulation of dynamic soil behaviour and a HM coupled analysis, which accounts for soil-pore fluid interaction effects, is required to investigate the seismic wave propagation mechanism.

The HM coupled theory concerning the elastic wave propagation in saturated porous materials was initially studied by Biot [4]. Based on the proposed formulation, three types of waves are introduced in saturated soil media under dynamic loading; two types of compressional waves and one type of shear wave. The two compressional waves are known as the fast wave and slow wave. In particular, the fast wave exists when the pore fluid and solid particles move in-phase under dynamic loading, while the slow wave is generated when there is an out-of-phase movement between pore fluid and solid phase (as shown in Fig. 1). It was pointed out by Biot [4] that the fast wave is the usually observed compressional body wave in earthquake engineering, known as a P-wave. On the other hand, the slow wave is highly dispersive and tends to attenuate at low loading frequencies and low permeabilities.

Since 1956, when the HM coupled dynamic theory of elastic wave propagation in saturated porous materials was proposed by Biot, the existence of the slow wave has been widely doubted by researchers. It was only in 1980, when Plona [23] proved experimentally for the first time the existence of slow waves propagating in saturated porous materials (using sintered glass spheres saturated with water). It should be noted that the material was subjected to an ultrasonic-frequency load (greater than 2000 Hz), in order to trigger the development of slow waves. After Plona [23], researchers started to extensively investigate the existence of the slow wave. Rasolofosaon [25] modified Plona's device and observed the slow wave in water-saturated porous plates made of artificially bonded natural sand grains. Nagy et al. [20] carried out similar experiments and observed the slow wave in natural rocks, which was the first time that the slow wave was experimentally observed in a natural material.

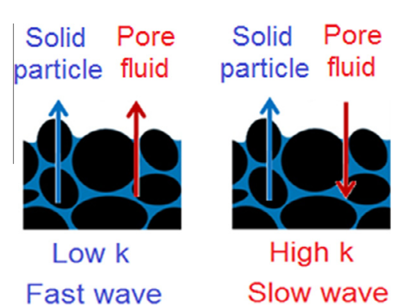

Fig. 1. A schematic graph for the fast and slow wave.