Journal of Applied Geophysics 105 (2014) 185–190

Contents lists available at ScienceDirect

Journal of Applied Geophysics

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

Porosity estimation based on seismic wave velocity at shallow depths

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ARTICLE INFO

Article history:
Received 19 November 2013
Accepted 25 March 2014
Available online 2 April 2014

Keywords:
Compressional wave velocity
Error norm
Theoretical method
Porosity
Sensitivity
Shear wave velocity

ABSTRACT

Seismic wave velocity and porosity are used for the estimation of dynamic behaviors in the Earth, including seismicity and liquefaction. To increase the resolution of subsurface observations, seismic wave velocity and porosity can be combined in a compound method. To this end, in this paper, we utilize and rearrange the Wood, Gassmann, and Foti methods — three techniques commonly used to estimate porosity based on seismic wave velocity at shallow depths. Seismic wave velocity is obtained by a field velocity probe using the horizontal transmission technique. Porosity calculated using the Gassmann method shows the highest reliability considering observed porosity criteria. The sensitivities of each method are compared using the error norm. Results show that the Gassmann method has low sensitivity for calculating porosity, whereas the Wood and Foti methods have high sensitivity. Consequently, the Gassmann method is recommended for estimating porosity at shallow depths when using measured elastic wave velocity.

1. Introduction

The dynamic stresses associated with faulting cause seismicity and liquefaction deep within the Earth, which can often result in substantial damage at the surface. Observing changes in fault characteristics and behavior is necessary in order to monitor dynamic stress regimes and thus take measures to protect surface infrastructure. Seismic wave velocity has been widely applied to the investigation of subsurface geology and to improving our general understanding of fault behavior. For example, Zhang et al. (2009) documented the gathering of seismic data and receiver function imagery in order to define large-scale crustal structures, and Zang et al. (2009) used compressional and shear wave velocities to investigate plate tectonic processes involved in continental extension. Xu et al. (2010) and Sanchez-Valle et al. (2011) used similar seismic techniques to observe small-scale (local) geological phenomena, and Stroup et al. (2009) used porosity and permeability as indices for predicting microearthquakes on the basis of a one-dimensional poroelastic model. Porosity is considered in this study because it is one of the essential parameters that controls the compressibility, relative density, and natural state of soil.

The resolution achieved in estimating certain geological characteristics of the Earth may be improved by analyzing seismic wave velocity and porosity together. Several researchers have attempted to determine the porosity of particular soil types based on the theory of wave propagation, albeit with several assumptions (e.g., Foti et al. 2002; Yoon and Lee, 2010). Consideration of wave-based porosity has great potential for improving the resolution of subsurface observations. This paper focuses on several methods for deducing the porosity of soil by considering seismic wave velocity. The basic theories illustrating the relationship between seismic wave velocity and porosity are discussed, and an experimental method for obtaining seismic wave velocity is introduced. Finally, the reliability of each theory is discussed on the basis of the error norm technique. Laboratory testing of samples at shallow depths (approximately 0 – 20 m) is performed as a consolidation test to obtain highly reliable porosity measurements that are compared against our experimental data.

1.1. Seismic wave velocity and porosity

The three methods discussed in this study to obtain porosity through analysis of the seismic wave velocity are the Wood method, the Gassmann method, and the Foti method. Details regarding these methods are provided below.

2. Wood method

A fluid-saturated medium is affected by internal stress, generated fluid behavior, and external stress imposed by overburden load. Early work by Biot (1956a,b) suggested that seismic waves may propagate in porous elastic media that contain compressible viscous fluid. The relationship between stresses and strains caused by wave propagation is controlled by the compressibility, pore-water content and pressure, porosity, and elastic moduli (bulk, constrained, and shear moduli) of saturated soil. This theory (Biot, 1956a,b) has been widely applied in geophysics for analyzing seismic waves; however, an earlier study by Wood (1949) proposed the theory of wave propagation, which results in deformation of pore volume, pore-fluid volume, and solid volume

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http://dx.doi.org/10.1016/j.jappgeo.2014.03.018

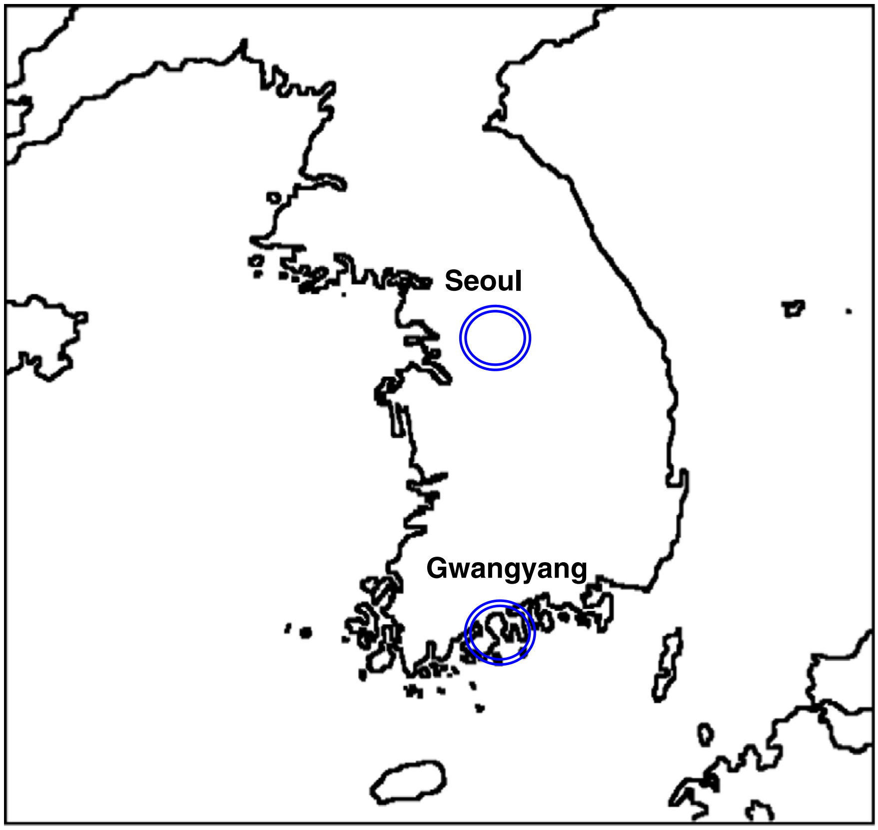

Fig. 1. Location of testing site.

(Salem, 2001). Expressions for these volume changes are reorganized into compressibilities, that is, the reciprocals of elastic moduli, with Wood (1949) stating that compressibility is related to the compressional wave and porosity as shown in Eq. (1). However, Wood (1949) recommends that the shear modulus should also be taken into account for saturated media with various grain sizes. Thus, Eq. (2) is suggested:

$$V_P = \left[\frac{1}{\{n\cdot\rho_f+\rho_s\cdot(1-n)\}\cdot\{n\cdot\beta_f+\beta_s\cdot(1-n)\}}\right]^{0.5} \tag{1}$$

$$V_P = \left[\frac{\left(\frac{1}{n\cdot\beta_f}\right)+\beta_s\cdot(1-n)+\left(4\cdot\frac{G}{3}\right)}{[n\cdot\rho_f+\rho_s\cdot(1-n)]}\right]^{0.5} \tag{2}$$

where, β_f and β_s denote the compressibilities of fluid and soil, respectively. ρ_f and ρ_s represent the densities of fluid and soil, respectively. V_P, n, and G denote the compressional wave velocity, porosity, and shear modulus, respectively. Eq. (2) implies that the porosity of a medium is related to compressional (*P*) wave and shear (*S*) wave seismic velocities (V_P and V_S, respectively), given that the shear modulus is a function of soil density and shear wave velocity (i.e., $G = \rho_s \times V_S$). Eq. (2) can be rearranged to yield porosity, as shown in Eq. (3):

$$n_{Wood} = \frac{\left(3\cdot\beta_f\cdot\beta_s+4\cdot\beta_f\cdot G-3\cdot\beta_f\cdot {V_P}^2\cdot\rho_s\right)}{\left(6\cdot\beta_f\cdot\beta_s-6\cdot\beta_f\cdot {V_P}^2\cdot\rho_s+6\cdot\beta_f\cdot {V_P}^2\cdot\rho_f\right)} + \left[\frac{\left(9\cdot{\beta_f}^2\cdot{\beta_s}^2+16\cdot{\beta_f}^2\cdot G^2+36\cdot\beta_f\cdot\beta_s+24\cdot{\beta_f}^2\cdot\beta_s\cdot G+9\cdot{\beta_f}^2\cdot{V_P}^4\cdot{\rho_s}^2\right)}{\left(6\cdot\beta_f\cdot\beta_s-6\cdot\beta_f\cdot {V_P}^2\cdot\rho_s+6\cdot\beta_f\cdot {V_P}^2\cdot\rho_f\right)} + \frac{\left(36\cdot\beta_f\cdot{V_P}^2\cdot\rho_f-36\cdot\beta_f\cdot{V_P}^2-18\cdot{\beta_f}^2\cdot\beta_s\cdot{V_P}^2\cdot\rho_s-24\cdot{\beta_f}^2\cdot G\cdot{V_P}^2\cdot{\rho_s}^2\right)}{\left(6\cdot\beta_f\cdot\beta_s-6\cdot\beta_f\cdot {V_P}^2\cdot\rho_s+6\cdot\beta_f\cdot {V_P}^2\cdot\rho_f\right)}\right]^{0.5} \tag{3}$$

3. Gassmann method

The work of Gassmann (1951), which is translated by Berryman (1999), also investigated wave propagation by using bulk and shear moduli in saturated isotropic porous media, with the additional consideration of a monomineralic medium. This theory concerns a low-frequency range of wave propagation, and the chemical interaction between porous media and fluid is assumed to be negligible. Gassmann

Table 1
Geotechnical properties of testing site.

Depth [m]	Liquid limit, LL (%)	Plastic limit, PL (%)	Plasticity index, PI (%)	Specific gravity, Gs	USCS	Compression index, Cc
16	36.4	24.5	11.9	2.61	ML	0.30
20	40.3	25.4	14.9	2.63	ML	0.19