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The porosity of saturated shallow sediments from seismic compressional and shear wave velocities

Osman Uyanık *

Süleyman Demirel University, Earthquake and Geotechnical Research Center, Isparta, 32260, Turkey

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ABSTRACT

This study devises a new analytical relationship to determine the porosity of water-saturated soils at shallow depth using seismic compressional and shear wave velocities. Seismic refraction surveys together with soil sample collection were performed in selected areas containing water-saturated clay–silt, sand and gravely soils. Classification of clay–silt, sand and gravel dense soils provided the coefficient of experimental equation between the data sets, namely, Poisson's ratio, shear modulus and porosity values. This study presents a new analytical relationship between Poisson's ratio and shear modulus values, which are obtained from seismic velocities and porosity values of water-saturated material computed from water content and grain densities, which are determined by laboratory analysis of disturbed samples. The analytical relationship between data sets indicates that when the shear modulus of water-saturated loose soil increases, porosity decreases logarithmically. If shear modulus increases in dense or solid saturated soils, porosity decreases linearly.

1. Introduction

Determination of porosity in soils is an important step in resolving leakage problems, determining permeability and revealing water outflow at the base of dams and in fracture rocks and in solving consolidation problems at the foundations of structures. Seismic velocities have been used in previous research projects to address such problems (e.g. Dadashpour et al., 2009; Bozcu et al., 2007; Soupios et al., 2006; Tezcan et al., 2006; Soupios et al., 2005; Karastathis et al., 2002; Al-Hamoud and Tanash, 2000; Savvaidis et al., 1999; Dutta, 1984). Many researchers have investigated empirical or analytical relationships between *in-situ* experiments and porosity. Porosity is one of several factors affecting the propagation of seismic waves in soils; major factors include:

a. Lithological properties of soil (grain sizes, shape, type, distribution, amount, compaction, consolidation and binding)
b. Physical properties (porosity, permeability, density, anisotropy, saturation degree, solid–liquid interference, pressure and temperature)
c. Elastic properties (shear modulus (G), bulk modulus (K), Young modulus (E), Poisson's ratio (μ) and Lamé constant (λ)).

Any change in the lithological properties of soil also affects seismic wave velocities. For instance, seismic wave velocities depend upon the amount of compaction and consolidation of a soil. The higher the compaction rate the higher the velocities of both shear waves (S-waves) and compressional waves (P-waves). These relationships have been the subject of many previous studies, some of which outlined here. Pickett (1963) showed that the ratio of compressional (P) to shear (S) wave velocities could serve as a lithological indicator.

The velocity of seismic waves changes according to the physical properties of soils; the seismic wave velocity in dense soil is higher than that in loose soil (Uyanık and Ulugergerli, 2008). Increasing soil density indicates higher soil compaction. P-wave velocity is utilized in identifying lithology, porosity and pore fluids. S-wave velocity is utilized for mineral identification, determining soil porosity and for identifying fluids. The ratio of P- and S-wave velocities (V_p/V_s) may help in fluid type identification, especially water or gas reservoirs. The V_p/V_s ratio is more sensitive to the type of fluid than P-wave or S-wave velocities alone (Uyanik, 2010). Seismic P-wave velocity shows a significant decrease when the saturating fluid water is replaced by gas (Wyllie et al., 1956, 1958). As shear deformation cannot be sustained in liquids or gases ($G=0$), S-waves will not propagate at all in liquid and gas materials. However, P-waves can be propagated in all materials. On the other hand, P-wave velocities in liquid material are higher than in gas material. Therefore, the V_p/V_s ratio in liquid material will be higher than that in gas material.

Porosity is the ratio of volume of voids to the total volume of soil. Porosity depends on the origin of soil, on the degree of uniformity of grain-size distribution, on the water content, and; largely, on the shape of grains. In addition to the porosity value varies between 0 and 1, depending on the properties of soil.

In the theory of elasticity, Poisson's ratio is defined as the ratio of lateral strain to axial strain, or the measurement of transverse strain (shortening) and longitudinal strain (lengthening) resulting from a

* Tel.: +90 246 211 13 59; fax: +90 246 237 08 59.
E-mail address: uyanik@mmf.sdu.edu.tr.

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change in the normal stress of a soil sample under compression. Poisson's ratio has a value between 0 and 0.5, depending on the level of saturation of the soils with water or gas materials. A negative Poisson's ratio can occur only in the anisotropic materials (Love, 1927). A Poisson's ratio of 0.5 corresponds to water showing no volume change during loading. Within this range of variation of Poisson's ratio, researchers came to certain conclusions about porosity and saturated soil. These conclusions state that: melting at pores increases Poisson's ratio (Mann and Fatt, 1960); porosity decreases while Poisson's ratio increases (Koefoed et al., 1963); for saturated soils, Poisson's ratio is 0.45 and greater (Bowles, 1982); the ratio is close to 0.5 for high bulk modulus (low compressibility) of water-saturated soils (Bishop and Hight, 1977); it is above 0.49 for clayey water-saturated shallow sediments (Stuempel et al., 1984). On the other hand, Poisson's ratio and V_p/V_s ratio are approximately 0.1 (Gregory, 1976) and 1.5 (Tatham, 1982), respectively, for sediments saturated with gas. Watkins et al. (1972) proposed an empirical relationship between the compression wave velocity (80–2700 m/s) measured at site for surface soils and shallow sediments having different lithology and porosity (0.2–0.8). Salem (2000) obtained a linear relationship between Poisson's ratio and porosity, by calculating porosity from the relationship identified by Watkins et al. (1972) and calculating Poisson's ratio from the compressional and shear wave velocities obtained from seismic refraction studies performed at a site with shallow sediments in the center of glaciers in northern Germany. Hardin and Black (1968), and Hardin and Drnevich (1972) established experimental relationships between void ratio and shear modulus. Ohkubo and Terasaki (1976) indicated the relationship between shear wave velocity, density, porosity and elastic modulus. In addition to the empirical relationships between porosity and seismic velocities in soils, there are also certain analytical or empirical relations in rocks (e.g. Gassmann, 1951; Nur, 1969; Gardner et al., 1974; Toksoz et al., 1976; Nur and Wang, 1989; Wang, 1997; Dvorkin and Walls, 2000).

The aim of this study is to investigate a new analytical relationship between porosity to Poisson's ratio and shear modulus for water-saturated shallow sediment soils. In order to control the accuracy of this relationship and to calculate the coefficient of relationship, the data were gathered from geotechnical reports prepared in different cities of Turkey (Fig. 1) (Ertunç et al., 2001; Türker et al., 1996, 1998; and Uyanık, 1995). These reports consist of seismic refraction results, vertical electrical sounding (VES) surveys and borehole observations, and laboratory experiments on soil mechanics. The results obtained from these studies were interpreted and geotechnical cross-sections were drawn. It can be seen in the cross-sections that layers show variations in lateral and vertical directions, and consist of soils with fine sand to sandy gravel range and silty clay. These soils have different grain sizes (Fig. 2). In many of the study areas, the groundwater level varies between 1.5 m and 16 m. The data used in this study were gathered from water-saturated soils beneath the groundwater level. These data consist of P- and S-wave velocities, Poisson's ratio, shear modulus, porosity, bulk density and grain density, water content and soil type of water-saturated soils. The values for Poisson's ratio and shear modulus were calculated from P- and S-wave velocities. The porosity values were obtained from the values of water content and grain density of the soils in the study areas. Firstly, all the data are classified according to soil type and Poisson's ratio (Fig. 3) for water-saturated shallow soils (Table 2).

Secondly, this study identified a new analytical relationship between the soil porosity, with shear modulus and Poisson's ratio for water-saturated shallow soils. This study used theoretical equation of bulk modulus of linear elastic theory related to Poisson's ratio and shear modulus and mechanically expressed bulk modulus related to compressional stress and volumetric deformation. Finally, the coefficient of the analytical relationship between the porosity with shear modulus and Poisson's ratio is determined using the classified data and a non-linear regression analysis technique. The correlation coefficient between porosities calculated from Poisson's ratio–shear modulus containing seismic velocities and from water content-grain density is approximately 98%.

2. Method

Ishihara (1970) developed a simple relationship to determine the Poisson's ratio of water-saturated soils, using porosity and shear modulus parameters. The present study, by following that simplified method, used seismic velocities to estimate the porosity of water-saturated undrained soils. The aim of the study was to estimate the porosity of water-saturated undrained soils without obtaining samples or disturbing the natural situation of soils, by using a non-destructive seismic refraction method to determine the seismic wave velocities. The development of the analytical relationship derived for this purpose is given in detail in the following sections.

In linear elastic theory, the bulk modulus (K) dependency on shear modulus (G) and Poisson's ratio (μ) is expressed via Eq. (1):

$$K = 2G(1+\mu)/[3(1-2\mu)]. \tag{1}$$

The shear modulus (G) in Eq. (1) is related with shear wave velocity (V_s), density (γ_n) and gravitational acceleration (g) as shown in Eq. (2):

$$G = \gamma_n V_s^2 / g. \tag{2}$$

The term γ_n in Eq. (2) may also be calculated from the compressional-wave velocity (V_p). The empirical relationship between γ_n (kg/m^3) and V_p (m/s) for soils was given by Tezcan et al. (2006) as follows:

$$\begin{aligned} \gamma_n &= 0.2V_p + 1800 \quad \text{for hard clay, mudstone, etc.} \\ \gamma_n &= 0.2V_p + 1700 \quad \text{for gravel, dense sand} \\ \gamma_n &= 0.2V_p + 1600 \quad \text{for clay, sand, etc.} \end{aligned}$$

Lastly, Poisson's ratio (μ) is related to V_s and V_p as shown in Eq. (3):

$$\mu = [(V_p/V_s)^2 - 2] / [2(V_p/V_s)^2 - 2]. \tag{3}$$

Bulk modulus in Eq. (1) is also expressed mechanically using Eq. (4), below:

$$K = \sigma / \varepsilon \tag{4}$$

where σ is the compressional stress and ε the volumetric deformation.

Shear waves do not propagate through liquid and gas materials, while they do propagate through solid materials. Consequently, shear waves and shear modulus are not affected by drainage conditions. However, P-waves are affected by soil deformation in drained or undrained conditions, since they can propagate through liquid and gas materials. In consequence, bulk modulus is also affected. In this case, if a compressional stress is applied to an undrained, water-saturated soil element, this stress has two components. One component is the effective vertical stress (σ') transmitted through the soil skeleton and the other is pore water pressure (u) transmitted through water in soil pores. Hence, the vertical stress (σ) is given by the following equation

$$\sigma = \sigma' + u. \tag{5}$$

According to Eq. (4), the bulk modulus of soil grains (K_h) describes the volumetric compression of the soil skeleton (V) by a small amount (ΔV_h), according to effective stress (Eq. (6))

$$K_h = \sigma' / [\Delta V_h / (1-\phi)V]. \tag{6}$$

Effective vertical stress is obtained by Eq. (7) below:

$$\sigma' = K_h[\Delta V_h / (1-\phi)V]. \tag{7}$$