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State-of-the-Art Review on Characterization of Porous Media using Wave Propagation

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Abstract: A number of studies have been made by using the concept of porous media in the areas of applied science and engineering mechanic (viz., acoustics, geomechanics, soil mechanics, rock mechanics), engineering (viz., petroleum engineering. bio-remediation, construction engineering), Geosciences (viz., hydrogeology, petroleum geology, geophysics) and material science. In this context, researchers have also characterized soilmass, which happens to a porous media using various methods. Moreover, many empirical correlations have been developed for the determination of various soil parameters. However, the use of wave propagation methods for the characterization of porous media like soils is comparatively a new area and has been a subject of interest among various researchers since last few decades. This paper gives a state-of-the-art review on characterization of porous media using the wave propagation technique with the theories and formulae given by various researchers. It is strongly believed that the present state-of-the-art review will give a clear understanding on wave propagation in porous media and will serve as a basic platform for various future studies which have not been given proper attention before.

Keywords: *Porous media, Waves, Attenuation, Porosity, Permeability*

1. Introduction

A porous media like soil and rock or even cement and ceramics is generally a solid matrix containing pores (voids) which are filled with a fluid (liquid or gas). Over the years, the concept of porous media has made its entry into many branches of science and engineering like engineering mechanic (viz., acoustics, geomechanics, soil mechanics, rock mechanics), engineering (viz., petroleum engineering, bio-remediation, construction engineering), Geoscience (viz., hydrogeology, petroleum geology, geophysics) and material science. Interestingly, flow through porous media has emerged as a separate field of study in the recent years. Moreover, it has generated a new branch of study called poromechanics, which involves the study of the deformation of the solid frame in a porous media. In this context, porous media characterization has become a very important point of research among scientists and engineers and especially in the field of soil and rock mechanics. Assessment of soil or rock properties are mainly done using conventional laboratory testing or by using various numerical models. However, the conventional laboratory tests are quite elaborate, cumbersome and time consuming. Similarly, the results from numerical models may not be accurate or represent the actual site conditions. Under these circumstances, wave propagation through the soil or rock seems to be a promising method for the characterization of these porous media. Biot used a model for the first time to describe the wave propagation in porous media, especially in saturated soils, which consist of two components: the grains which are called the skeleton and the pore fluid [1, 2]. Numbers of theoretical & numerical studies have been made thereafter on the basis of Biot's theory for acoustical characterization of porous media [3-7]. Some of the studies say that Biot's theory of wave propagation has some ambiguous facts about the local flow mechanism [3, 8-10]. In spite of that, Biot's theory is still widely used for the modelling of wave propagation through porous media and is the most dominating theory in this area of research [11]. In fact, some of the researchers have recently [12] extended the Biot's theory for the modelling of wave propagation in unsaturated media.

Many researchers have used the shear (S) and compression wave (P) for the characterization of porous media in terms of shear modulus, porosity, pore structure, permeability, clay content etc. [4,10, 13-18]. Also, some of the researchers have used stoneley wave for this purpose [19-20]. However, in this whole scenario of porous media characterization using seismic waves, the key parameter are mainly an attenuation factor/ coefficient, velocity dispersion and the characteristic frequency [4, 13-14, 20-22]. In this context, several researchers [11, 20-21, 23-29] have tried to model the attenuation factor numerically in a porous media by considering the various governing factors viz., wave frequency, permeability, porosity, clay content etc. Some of these researchers have found that the wave attenuation coefficient is linked to some peak value factor at central excitation frequency known as characteristic frequency. It is worth mentioning that, estimation of attenuation accurately in experiments is much difficult and more uncertain than simply measuring the wave velocity. Hence, many of the researchers have directly correlated wave velocity with various soil or rock properties like penetration no., shear strength, effective density, bearing capacity, void ratio, modulation of subgrade reaction, compression index, Poisson's ratio etc. [17-18, 30-31]. However, as mentioned above, many of the correlations mapping soil or rock properties in terms of wave velocities are blind of the factors like wave attenuation, frequency and velocity dispersion. Moreover, several other factors such as solidity of the porous media frame, confining pressure, degree of saturation, density of the medium, pore water pressure, fissures /cracks present in soil or rock mass needs to be taken into account when developing the models in porous media using wave propagation [7, 20, 32-37]. Keeping this in view, an attempt has been made in this paper to give a state-of-the-art review on the experimental and the theoretical work done previously on correlating seismic waves to porous media characteristics. Moreover, many of the researchers [24, 29, 38] have advocated in favour of further studies required for mapping of some soil permeability in porous media using seismic waves. They have emphasized more about the effects of fluids and pore water pressure on wave attenuation and wave velocity as well as the requirement of extensive experimental works for validation and accuracy of the numerical models. Keeping this in view, a separate section has been included in this paper related to the application of wave propagation method for study of soil permeability. It is strongly believed that the present study will give a clear understanding on wave propagation in porous media and will serve as a basic platform for various future studies which have not been given proper attention before.

2. Porous media

As mentioned, a porous media is a material having minute interstices through which fluid may pass. Some examples of porous media are soil, rocks, an aquifer, sponge, zeolite, ceramic, biological material like wood, etc. The flow of fluid through porous media is mainly governed by the geometry of pore space and the spatial arrangement of the grains. The pore spaces of sizes in the order of 10^{-4} to 10^{-2} m are associated with structural pores, whereas, the porous matrix contains the smaller pore sizes in the range of 10^{-7} to10^{-5}m [39]. A porous media can be categorized as a (i) Saturated porous media (ii) Unsaturated porous media (iii) Consolidated porous media or a (iv)Unconsolidated porous media. In another way, depending upon the frame type, a porous media can be classified as a (i) Rigid frame porous media (ii) Limp frame porous media or a (iii) Elastic frame porous media [11]. In a rigid frame porous media, pores are prismatic with fixed cross-sectional shape, but of variable pore size distribution. The limp model assumes that the stiffness of the solid phase is zero, but takes into account its inertial effects and the motion of the solid phase is considered in this model. In an elastic frame porous media, wave propagation involves coupled solid and fluid waves. While polymeric foams are common examples of elastic frame porous materials, metal foams and soft fibrous layers are examples of rigid and limp frame materials, respectively.

The important characteristics of a porous media includes its pore network, air and water permeability, degree of saturation, nature of consolidation, electrical conductivity and strength in relation to solid and pore structure. Various studies related to a porous medium can be one of the following types, i.e. (i) characterization of the nature of the solid surface and structure of the pore system (ii) studies of properties of solid plus fluid in condition like freezing of fluids within porous media (iii) fluid flow characteristics through porous media or (iv) deformation study of the solid frame known as "poromechanics" [40]. Some of the studies made related to various aspects of porous media are establishment of soil, water characteristic curve, pore pressure effects, estimation of the pore structure by tomographic technique and the recent one with wave fields in porous media.

3. Porous media characterization using wave propagation

The acoustical characteristics are dependent on the basic properties of the porous media. Hence, if it could possible to relate these properties with each other then it will result in a direct method of assessment in porous media. The acoustical method seems to be a more promising method of soil or rock profiling because of its non-destructive in nature [29]. As mentioned earlier, the credit goes to Biot who for the first time introduced wave propagation in porous media. Biots proposed an equation in case of saturated porous media, which relates the soil parameters like density, porosity, permeability and fluid viscosity with the P wave in terms of characteristic frequency.

$$fc = \frac{b}{2\pi\rho} \qquad (1)$$

Where, b is the coefficient related to Darcy's coefficient of permeability k, as follows

$$b = \mu\beta^2/\mathrm{k} \qquad (2)$$

Later in 1962, Biot modified his equation as follows:

$$K\ (m^2) = \frac{\eta\phi}{f_c\rho} \qquad (3)$$

Later, on the basis of Biot's equations many researchers have studied the properties of soils and rocks using its acoustic response. The modified formulae, as proposed by different researchers are summarized in Table. 1.

In these equations, researchers have incorporated various factors like tortuosity, cracks, pore diameter, frequency range etc. in Biot's equation. Although, Biot's theory was originally developed for saturated media, later other researchers extended it for unsaturated soil as well.

Table.1 *List of modified Biot's Equation by Previous Researchers*

Eq.No.	Proposed Equation	Reference
4	$K_{(m^2)} = \frac{\rho\eta}{2\pi(\rho m - \rho_f{}^2)f_r} \cdot \frac{v_0}{v_\infty}$	[4]
5	$f_{c(Hz)} = \frac{\emptyset . g}{2.\pi.k}$	[16]
6	$Q^{-1} = \left\{\frac{1}{(r_1 - r_2)} . I_n \frac{A_2}{A_1}\right\} . \frac{C}{\pi . f}$	
7	$f_r = k_s \frac{\varepsilon^3}{\eta}$	[41]
8	$f_{r(Hz)} = \frac{\eta\emptyset}{2\pi\alpha_\infty \rho_f k}$	[42]
9	$K = \frac{\eta \rho_w d_p{}^2 g}{32\mu}$	[43]
10	$K_{i(m^2)} = \frac{d^2\emptyset^3}{72\alpha_\infty{}^2(1-\emptyset)^2}$	[44]
11	$\alpha_\infty = 1 - 0.5\left(1 - \frac{1}{\emptyset}\right)$	

Yavuz et al. [32] found good results by replacing the density and compressibility terms with modified values for a water-air mixture in unsaturated soils. Geertsma and Smit [45] in their study compared the Biot's and Squirt flow mechanism and concluded that the Biot's theory yields good results at macroscopic level, but it does not include the dynamic effect of capillary fluid and neglects the dissipation caused by local flow on elastic wave propagation. Hence, Biot's theory can well describe the attenuation in saturated sand, but for the saturated silt and for the smaller soil particles the squirt flow mechanism needs to be considered [35, 46]. It can be mentioned here that in squirt model, the grains of a porous material are themselves allowed to have porosity in the form of micro cracks and the resulting flow from crack to pore is called "squirt flow" [5]. Later, several researchers [46-48] did their studies on combined Biot/squirt (BISQ) model relating compression velocity and attenuation to the elastic constants of the drained skeleton and of the solid phase, porosity, permeability, saturation, fluid viscosity and compressibility, and the characteristic squirt-flow length.

Seismic waves, mainly the S and P waves are used for the characterization of porous media. P wave is capable of travelling through both the solid matrix as well as the fluid passing through it. However, S wave is capable of travelling only through the solid matrix. Apart from the fast P waves, Biot found another P wave in his study which is comparatively slower than the other wave. This wave is diffusive in nature, which attains high attenuation at lower frequency. This slow P wave depends upon the volume ratio of soil grains and pore voids [16]. Hence the information regarding the porosity and hydraulic conductivity of porous media can be estimated with higher accuracy by using slow P wave. Researchers [49-50] have worked on the detection of Biot's slow wave in natural rocks and they concluded that the amplitude of this slow wave depends on the permeability of the sample and the pore fluid viscosity. However, it is mentioned that the detection of slow P wave is difficult under normal condition, but it can be easily seen in rock with permeability ranging upto 200 mD (milli-darcy) by using the shock tube apparatus. Apart from the P and S wave some of the researchers [20, 51] have used Stonley waves in their study. A Stoneley wave is a high- amplitude surface wave (or interface wave) that typically propagates along a solid-solid interface. When found at a liquid-solid interface, this wave is referred to as a Scholte wave. It is learnt that Stoneley waves in permeable boreholes are diagnostic of formation permeability because their propagation is affected by the dynamic fluid flow at the borehole wall. It is found that low and medium frequency Stoneley waves are very sensitive to the permeability of the fractures and can be used to assess the permeability from in-situ logging data, if the fracture porosity and zone thickness can be measured.

Various parameters affecting porous media characterization using the wave propagation as mentioned above can be categorized as the acoustical parameters (e.g., characteristic frequency, quality factor, amplitude, wave velocities, attenuation coefficient, damping ratio) or physical parameters (e.g., grain size, porosity, permeability, density, fluid viscosity, bulk modulus, clay content). However, the key parameter which bridges the relationship between the seismic response and physical properties of porous media is characteristic frequency. The characteristic frequency is the frequency at which the wave shows maximum attenuation. It can be noted that the attenuation of waves is expressed in terms of inverse quality factor (1/Q).

4. Acoustical parameters affecting wave propagation in porous media

One of the acoustical parameters, i.e. attenuation is the weakening of the strength of the waves or loss of wave energy with distance. Graphically, it shows the decay of wave amplitude with time and distance. When the seismic load is applied on a porous media in the form of S or P wave, the structure of porous media deforms as the wave passes through it. Due to the deformation, fluid pressure may build up in the pore spaces depending upon the amount and type of fluid present in the porous media. In some cases, pressure gradient develops across the boundary of two regions when they are close to each other. Due to this pressure gradient between two regions, the fluid flows from one region to another. This phenomenon of flow of fluid is termed as local flow, which is responsible for the dissipation of energy of the acoustical wave and causes attenuation and velocity dispersion of waves [12]. One major cause of elastic wave attenuation in heterogeneous porous media is wave-induced flow of the pore fluid between heterogeneities of various scales as found by the researchers [28]. It is stated that for frequencies below 1 kHz, the most important cause is the wave-induced flow between mesoscopic inhomogeneity, which is large, compared with the typical individual pore size but small compared to the wavelength. Moreover, the characteristic frequency much depends upon the wave attenuation in a porous media and hence the dispersion of waves which is the difference in wave velocities with frequencies. Based upon a series of experiments on the marine sediments ranging from coarse sand to clayey silt, Hamilton reached upon the conclusion that in viscoelastic model, pore water movement relative to mineral grains and pore water viscosity are the main causes of attenuation in soil. In case of linear viscoelastic or nearly elastic model, internal friction causes attenuation. Very similar to this, some researchers [45] have found that two possible causes of wave attenuation in porous media are the viscous pore fluid motion and the dry friction of soil grains. In sand, it is suggested that porosity could be the better parameter to relate the attenuation because it is better measure of the number of interparticle contact which affect wave attenuation. However, in case of fine silt and clays, attenuation along with the shear strength and dynamic rigidity are apparently related to cohesion between fine particles. In a stratified medium like a heterogeneous rock sample, porosity, saturation as well as the grain and frame moduli are listed as the main causes of wave attenuation [52]. However, for all these cases, attenuation decreases with increasing viscosity or decreasing permeability at low frequencies. It is stated that the attenuation coefficient of waves is much affected by the permeability [22, 46]. Researchers [46] have also found that peak attenuation, which occurs at the characteristic frequency shift towards the higher frequency region when permeability of the specimen decreases.

In further research, the attenuation factor is correlated with characteristic frequency which is associated to the inverse quality factor. The quality factor can be calculated using the following relationship as suggested by Hamilton.

$$Q^{-1} = \frac{aV}{\pi f - \frac{\alpha^2 V^2}{4\pi f}} \qquad (12)$$

Where, α is the attenuation coefficient representing wave attenuation which in turn depends upon the frequency (in case of compression wave) as follows:

$$\alpha_p = k_p f^{\dot{n}} \qquad (13)$$

Where, k_p is the attenuation factor which is constant for a particular type of porous media. This attenuation factor again can be calculated as follows:

$$k_p = 8686\pi\left(\frac{Q^{-1}}{V_r}\right) \qquad (14)$$

However, it is worth mentioning here that Eq.12 to Eq.14 are limited to frequency ranges of 3.5 to 100 kHz. For higher frequency range Biot's Equation can be used for wave attenuation calculation. As per studies by Pandit et al. [53] the quality factor can be calculated as follows:

$$Q^{-1} = -\left(\frac{1}{2\pi}\right)\left(\frac{\Delta W}{W}\right) \qquad (15)$$

Where, W is the total energy of wave and ΔW, the loss of energy in one cycle passing through the porous media. In terms of attenuation coefficient α, the quality factor can be calculated as follows:

$$Q = \frac{2\pi}{[1 - exp(-2\alpha\lambda)]} \qquad (16)$$

Where, λ is the wavelength related to the speed, *c* and wave frequency *f* as follows:

$$\lambda = \frac{2\pi c}{f} \qquad (17)$$

In many studies it is common to see that wave velocity increases with increase in wave frequency, especially in case of coarse saturated sands [54]. The frequency effect is also associated with the wave attenuation in saturated media, as the attenuation coefficient depends on the wave frequency [11]. S and P wave attenuation in terms of inverse quality factor for different types of soils are studied by some of the researchers [55-56] which shows a clear-cut variation in wave attenuation with frequency as shown in (Fig.1).

In spite of the numbers of equations as suggested by different researchers, the acoustical parameters vary from media to media and are not certain and remain subjective [12, 29].

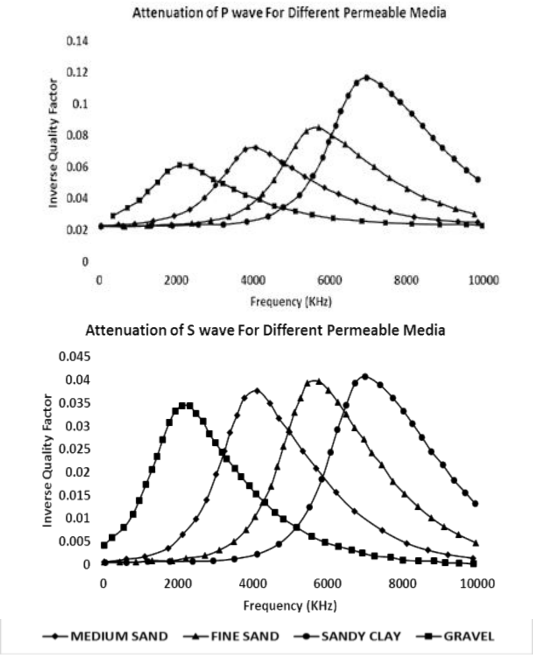

***Fig.1**. Variation of S and P waves attenuation with frequency (derived from [56])*

5. Physical parameters affecting wave propagation in porous media

The physical parameters related to porous media which affects the wave propagation can be categorized as the (i) elastic properties of the frame structure (ii) viscous properties of pore fluid and (iii) capillary pressure and effective permeability [57]. As already mentioned in the previous section, it mainly includes permeability, fluid viscosity, fluid density as well as the density of the porous material and the whole medium, confining pressure, pore pressure, effective stress, pore structure, micro cracks etc. [18, 20, 34, 36, 58]. Apart from these, degree of fracturing and weathering as well as the mineralogical composition may also greatly affect the wave propagation behaviour in porous media, especially in rocks. As such, the shear strength behaviour in a porous media using wave propagation method are greatly affected by the confining pressure, void ratio and grain size [34,58]. Though, some of the researchers have stated that the pore pressure has very low effect on wave velocity [7], researchers like Mavko [59] in their study found that with increase in pore pressure there is a decrease in wave velocity. This is because of the softening of elastic frame with higher pore pressure by opening of cracks and flaws, especially in case of rocks. Again, contrary to this, higher pore pressure may makes the pore fluid and air behave as less compressible which leads to a rise in wave velocity. This phenomenon seems to be more prominent in soils. However, velocity almost always increases with effective stress. In soil like clay, effective stress is not an important factor, but in case of silty soil the effective stress plays an important role for frequency greater than 10 KHz.

Similarly, in sand and gravels, effective stress needs to be considered properly for frequency more than 10 Hz [35]. Clay content and the degree of saturation are other important parameters affecting wave propagation in porous media. Paoletti found that, when clay content increases from 0 to 30% with constant porosity and water saturation it causes reduction of S wave velocity upto 12 % and shear modulus upto 50%. Similarly, when the degree of saturation varies from 0 to 100% with constant porosity and clay content, it causes a 5 % reduction in shear velocities. Researchers [60] have correlated attenuation coefficient with porosity and clay content as follows:

$$\alpha = 0.0315\emptyset + 0.241C - 0.132 \qquad (18)$$

Where, the attenuation coefficient α is in decibel per unit length of the medium (dB/cm) and was measured at 1 MHz frequency and 40 MPa confining pressure. It is found that the V_s and V_p are linearly related to porosity in the range 2 to 30% and to clay content in the range 1 to 50% [61]. It is also found that the effect of clay in reducing wave velocities is about 1/3.2 times as great as the effect of porosity for V_p and 1/2.6 times as great for V_s. Hence, it is concluded that V_s is more likely to get affected by the porosity and clay content than V_p. George in his study found the P wave velocity to be maximum at full saturation. This is due to the decreased compressibility of the soil matrix in the absence of air. The velocity quickly decreases when air is introduced into the sample, and then slightly recovers at lower moisture contents. This increase may be due to the increased stiffness of the soil matrix offered by increased capillary pressure. On the other hand, the S wave velocity increases with decrease in moisture content. This is consistent with the effect of density and the increase in shear modulus due to increasing effective stress. Based upon their numerical study on the properties of porous media affecting the wave velocities, it is found that the wave attenuation depends upon the media thickness, its stiffness and coefficient of permeability [62]. Wavelength of surface waves decreases with an increase in the thickness of porous media. Grain morphology also affects the wave velocities, as it is seen that the shear wave velocity in rounded sand particles is less as compared to that in angular particles [63]. Previous researchers [6, 64] have also found that the behaviour of attenuation as a function of frequency is governed by the distribution and shape of inhomogeneities. It has also been found by the previous researchers [64-65] that even for two rock mass with same porosity and saturation can have an elastic wave velocity difference of 2 Km/Sec and a difference in permeability by six orders. This is because of the pore structure has not been considered properly in many places while doing the acoustical profiling of porous media. In fact, some of the researcher [64] has pointed out that, though the Biot's theory of the acoustical study of saturated elastic media is well established and proved, but this theory ignored the effect of fracture and crack in natural rocks.

Apart from these acoustical and physical parameters as discussed above, there are some other factors which affect the wave amplitude in received signals. The parameters include driving pulse amplitude, coupling coefficient between transducers, holder and sample, transmission coefficient between transducers and sample and the sample length [66].

6. Wave velocity for porous media characterization

Apart from the complex equation which relates the acoustical properties with engineering properties of soil, many researchers [36, 67-68] have given simplified regression equation which relates seismic wave velocities with clay content, porosity, permeability, shear modulus, bulk modulus etc. They have measured S and P wave velocity in different kind of porous media like dry and water saturated sand [65], sandy silt and silty sand [23, 69], fine sand [23] sandstone [38, 50, 70] limestone [65, 64], dry and saturated carbonate rock [71] to relate it to other engineering properties. A summary of such relationships are presented in Table.2.

Table.2 *Summary of relationships correlating wave velocities to soil/rock properties*

Eq.No.	Proposed Equation	References
19	$V_{p\,(Km/s)} =$ 5.66-6.118Φ-3.53C+0.0007K	[14]
20	$G = G_o\left[\frac{(P_c - P)}{P_c}\right]^{f_c}$	[17]
21	$Q_{a(kPa)} = \frac{\gamma(V_s)^2 t}{n}$	[31]
22	$K_{s(kN/m^3)} = \frac{4\gamma V_s^{\,2}}{n}$	
23	$E_{(kN/m^2)} = \frac{(3\alpha - 4)G}{(\alpha - 1)}$	
24	$E_{k\,(kN/m^2)} = \frac{\gamma\left(V_p^{\,2} - 4V_s^{\,2}/3\right)}{g}$	
25	$V_{p\,(Km/s)} = -0.0218C - 0.0693\emptyset + 5.59$ $V_{s\,(Km/s)} = -6.0189C - 0.0491\emptyset + 3.52$	[61]
26	$V_{p\,(Km/s)} = -2.4C - 8.6\emptyset + 5.8$ $V_{s\,(Km/s)} = -2.1C - 6.3\emptyset + 3.7$	[66]
27	$(V_m)^{-1}{}_{(ft/s)} = \frac{\emptyset}{V_f} + \frac{(1-\emptyset)}{V_r}$	[72]
28	$V_{s\,(m/s)} = 128\,H^{0.28}$ for sand $V_{s\,(m/s)} = 116 + 4.65H$ for silt and clay	[73-74]
29	$V_{s\,(m/s)} = 77e^{-0.6}F_c^{\,0.05}$ $V_{s\,(m/s)} = 140PI^{-0.6}F_c^{\,0.05}$	[75]

7. Wave propagation for permeability study

Permeability in porous media like soil, rocks, sandstones, reservoir sediments, etc. are of great interest among the researchers. Many conventional formulae have been developed to estimate the soil permeability as listed in Table.3. Some of these formulae relate the water permeability (also known as hydraulic conductivity); whereas the others relate the air permeability (also known as intrinsic permeability) to various other parameters of the porous media. It can be mentioned here that the hydraulic conductivity is a property of both the soil and pore fluid and is mostly used for the study of ground water flow in porous media. On the other hand, intrinsic permeability depends only on the properties of the soil and is generally used in reservoir engineering where different fluids like oil, gas and water occurs and in aquifers where both fresh and saline water occurs. The relationship between the intrinsic permeability, K_i (m^2) and water permeability, K (m/s) is given as follows:

$$K_i = \frac{KY}{\eta} \qquad (30)$$

Where, γ is the volumetric weight of the fluid and η is the dynamic viscosity of the fluid. The intrinsic permeability is also expressed in milli-darcy (*mD*), where 1 Darcy is equal to 10^{-12} m^2.

It is seen that the actual permeability values are different than the calculated soil permeability from laboratory experiments. This may be due to the fact that, exact site conditions can't be simulated in the laboratory. In such a case, the wave propagation method seems to be a better option because of its non-destructive nature.

Table. 3*. Conventional equations as proposed in literature for estimation of soil permeability*

Eq. No.	Proposed Equation	Reference
31	$K_{i\,(m^2)} = \left[\emptyset\left(\frac{d_p}{2}\right)^2/8\right]e^{[2(\sigma log2)^2]}$	[4]
32	$K_{(m/s)} = \frac{\emptyset\,\rho_f\,\mathrm{g}\,d^2}{32\,\mu}$	[43]
33	$K_{(mD)} = \left(\frac{100\emptyset^{2.25}}{S_{wi}}\right)^2$	[72]
34	$K_{(m/day)} = \frac{g}{v}S_o\left(\frac{\emptyset - 0.13}{\sqrt[3]{1-\emptyset}}\right)^2 d_{10}{}^2$	[76]
35	$K_{(mD)} = K_s S_e{}^{2/n+\propto+2}$	[77]
36	$K_{(mD)} = \frac{0.136\emptyset^{4.4}}{S_{wi}{}^2}$	[78]
37	$K_{(mD)} = 8.4 \times 10^{-2} \times d^2\emptyset^{5.1}$	[79]
38	$K_{(mD)} = 10D_d{}^2\emptyset^{(3.64+m)}C^{-3.64}$	[80]
39	$K_{(cm/s)} = K_d \times d_{10}{}^2$	[81]
40	$K_{(Darcy)} = e^{12.8} \times \frac{GS^{1.057} \times \beta^{2.72}}{CM^{0.48} \times P^{1.41}}$	[82]

Keeping this in view, some of the researchers have studied the possible relationship between acoustical properties of porous media and its hydraulic conductivity. Biot's theory of wave propagation through saturated porous media can be used to estimate the permeability of the media like soil and rocks. Some researchers [13, 16] have found clear characteristic frequency for sandy soil and have correlated it to soil permeability using Biot's principle. Researchers have also found good relationships between V_s and the permeability in some types of rocks like sandstones [83].

Other researchers [22, 29] have correlated hydraulic data to attenuation coefficient or the inverse quality factor or dissipation factor of the wave as the attenuation coefficient is more affected by the permeability. In fact, some researchers have established relationships between the permeability and acoustical parameters as included in Table.1. However, it is learnt that the estimated permeability using wave propagation method including Biot's theory differs from the actual permeability of the porous medium. It is attributed to the squirt flow at the microscopic level [3, 8, 10]. Moreover, Biot's theory cannot be applied to estimate the permeability of rock in the low frequency range 1-100Hz [9, 84].

8. Concluding remarks

Many of the researchers have advocated in favour of the wave propagation method for porous media characterization. However, some results as available in the literature are contradictory and lack proper explanation. Moreover, in most of the theories, it was found that some or other sets of the acoustical or physical parameters are ignored, which otherwise play an important role in porous media characterization. Hence, it was required to synthesize the results from previous researchers as done in this present review that will serve as a basic platform for further development in this area. Establishment of individual empirical relationships for different group of porous media or inclusion of proper coefficient constant to take care of various affecting parameter seems to be a better option.

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Notations

α_∞ – Tortuosity factor
α – Attenuation coefficient
α_p – Wave attenuation for wave
A – Area of the sample
A_1, A_2 – Amplitude from receiver 1 and 2.
b – Coefficient related to Darcy's coefficient of permeability
β – Fraction porosity
c – Velocity of P wave in water
C – Volume Clay fraction/content
CM - Cementation factor
d – Diameter of soil grains
d_p – Diameter of pore void
e – Void ratio
E_k – Bulk modulus
E – Modulus of elasticity
ε – Aspect ratio
f – Frequency
f_c – Characteristic frequency
$\varnothing$ – Porosity
F_c – Percentage of clay and silt contents
g – Gravity
G_o – Shear modulus of solid material
G – Effective shear modulus
GS - Grain Size
H – Depth of sample
k_s – Bulk modulus of grains
K_i – Coefficient of intrinsic permeability
k_p – Attenuation factor
K_d – Permeability factor
K – Water permeability
λ – Wavelength
m – Inertia density of the rock grain
M_Z – Mean grain size
μ – Poisson's ratio
η – Dynamic viscosity of fluid
$\acute{\eta}$ – Exponent frequency
n – Factor of safety
ΔP – Logarithmic decrement
P_c – Percolation threshold
P_i – Inlet fluid pressure
P_o – Outlet fluid pressure
PI – Plasticity index
ρ – Bulk density of the sediments
ρ_f – Density of saturant fluid
ρ_w – Pore fluid density
Q^{-1} – Inverse quality factor of wave.
Q_a – Allowable bearing pressure
r_1, r_2 – Distances of amplitude from source
S_{wi} – Irreducible water saturation
S_o – Sorting index
t – Time
ΔT – Time period over which flow is measured
ν_0 – Low frequency
ν_∞ – High frequency
V_r – Phase velocity
V – Wave velocity
V_f – Wave velocity in saturating liquid
V_m – Wave measured velocity
V_r – Wave velocity in rock
V_p – Compressional wave velocity
V_s – Shear wave velocity
ν – Kinematic viscosity
ΔV – The volume of liquid flowed in time ΔT
W – Total energy of wave
ΔW – Loss of wave energy in one cycle
γ – Soil density
Y – Volumetric weight of fluid

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