Application of Ultrasound Waves in Determining the Degree of Saturation for Porous Media

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https://doi.org/10.29227/IM-2026-02-02-009

Submission date: *2026-10-04* | Review date: *2026-24-04*

Abstract

Velocity of ultrasound waves through the porosity media is determining of physical-mechanical properties these medium. The presence and movement of water in porous media are determined porosity thereby medium, system of cracks and fractures. This is turn the basis of methods for determining the properties of the environment based on changes in velocity of the ultrasound (longitudinal) waves (v_p). Water content (varying degree of saturation) in rocks, these features significantly affects. The object of this article is to present specific results for the application of ultrasound wave transition through the porous medium and their change as a result of different water content in this environment, thus evaulate the impact of changes in water content – saturation – on the transition rate of ultrasound (longitudinal) waves in laboratory specimens. Measurement was practise on the sandstones from Hubová – Ivachnová (Slovakia). Velocity of propagation longitudinal – ultrasound waves oneself measure on the dry samples and then on the saturate samples after various time (after 15 minutes; 30 minutes; 1 hour; 2 hours; 4 hours and 24 hours). Exam was execution on the samples with cylinder form. Exams were accomplish in the laboratory, a savior that velocity of ultrasound waves is higger than in the in - situ conditions. Cause is various ruptures, cracks in the rocks, which are in the massif. On the other side, presence ground water in massif influence velocity of ultrasound waves. Velocity of ultrasound waves is higger in the saturation rocks than in the dry rocks. This fact be needed take into the account.

Keywords: *porous media, saturation, ultrasound (US) waves, velocity*

1. Introduction

The water content in a porous environment, as well as in any other material in general, to a large extent affects the physical and mechanical properties of the material - the environment. The presence and movement of water in a porous environment are conditioned by the porosity of this environment, the system of cracks and fractures (depending on their occurrence). Water has an impact on the bulk density of the investigated porous environment, its swelling, but its impact is of course also significant in terms of plant supply at individual developmental stages and, last but not least, the water content in the soil aeration zone represents one of the sources of water reserves in soils.

The impact of the water content in a porous environment, as well as in rocks, which also represent an extreme case of a porous environment, must be taken into account when building geotechnical and especially hydrotechnical structures, in hydromelioration and environmental measures. Few engineering structures are as closely linked to the natural environment as hydrotechnical structures, especially dams and protective dikes [1]. This results primarily from their function, i.e. creating conditions for the redistribution of flows in time and space, and also their significant function in flood protection. Their connection with water – flows in riverbeds, precipitation, groundwater and seepage water puts them in a position of extreme dependence on knowledge of the natural environment. It is not only knowledge of hydrological data, but also geological, hydrogeological and geotechnical foundations, the morphology of the territory, its climate, etc. And perfect knowledge of these natural conditions is practically unrealistic, because it is a constantly changing process, moreover complicated by the random nature of development (e.g. hydrological conditions). These facts point to the fact that the most sensitive area of hydrotechnical structures is generally the contact of the subsoil with the structure itself. It is therefore important to know as many input parameters as possible when building hydraulic structures, and the effect of water content - saturation - is certainly one of the most important factors that affects the physical and mechanical parameters of rocks (e.g. modulus of elasticity E, shear strength, compressibility, permeability in the horizontal and vertical directions, porosity, bulk density). Places where the impact of water can be negative are landfills, especially during floods. Therefore, it is important to choose a suitable location when building a landfill, which is subject to environmental impact assessment. Since individual classes of landfills differ in terms of construction (construction), it is necessary to pay particular attention to the requirements for sealing the landfill. Waste must be sealed with a geological barrier (of appropriate characteristics) or artificial sealing, the parameters of which are defined by the STN standard. From a water management point of view, the main risk resulting from the existence of landfills is the seepage of polluted landfill water into the subsoil and groundwater. Surface recipients may also be at risk if pollution continues to migrate [2].

The purpose of this article is to present partial results of the application of ultrasonic waves passing through a porous environment and their change as a result of different water content in this environment, i.e. to evaluate the impact of changes in water content – saturation – on the velocity of ultrasonic (longitudinal) waves passing through samples in laboratory conditions.

Laboratory experiments were performed on 19 samples, while a full assessment of the impact was possible only in 9 cases due to insufficient data or violation of sample consistency.

2. Theoretical background and methodology of measurement

Sources of dynamic forces acting on a material over time and changing their size and position are called excitation forces. These forces, which transmit energy, propagate in the form of various types of elastic (seismic) waves. In general, we distinguish 3

types of such seismic waves propagating in a material - a porous medium [3]. They are:

a) longitudinal waves, or longitudinal, bulk;

b) transverse waves, or transverse, equiluminal;

c) surface, or Rayleigh waves.

Whereas ultrasonic waves belong to the group of longitudinal waves.

The propagation velocity of elastic waves in a porous medium depends on the propagation velocity of seismic waves in their solid part (skeleton), on the porosity and on the propagation velocity of seismic waves in the pore filling. In general, the velocityof seismic waves in a medium with high porosity is lower than in a medium with low porosity and that in a water-filled medium the propagation velocity of waves is higher than in the same but non-water-filled medium. The pressure to which the medium is or has been exposed is of great importance. An increase in pressure will cause a decrease in porosity and thus an increase in the propagation velocity of seismic waves [4].

From what has been mentioned so far, it is evident that for determining the degree of saturation of a porous medium, it is possible to use a method based on the application of the passage of ultrasonic waves through the medium. This method can also be used to determine other physical and mechanical properties of a porous medium (Young's modulus of elasticity E, Poisson's number v, shear modulus of elasticity G, applicable in hydrotechnical practice). In general, this is a principle of measuring and evaluating the velocity of passage of seismic (longitudinal or ultrasonic) waves through a certain sample with parallel surfaces.

Field or in situ methods include seismic methods [5]. Seismic methods use seismic equipment - a set of devices used to process and register a seismic signal. The main part of the seismic equipment is a geophone and its task is to convert the mechanical oscillation of particles of the earth's surface caused by the arrival of a seismic wave from the excitation point into an electrical signal. According to the location of the excitation point and geophones, we can distinguish between areal and linear geophone locations. In foreign literature [4], geophone location methods are often mentioned, such as cross-hole (a charge is placed in one borehole and a recording device is in the other borehole), down-hole and up-hole (using one borehole, an excitation point on the surface and a recording device in the borehole or an excitation point in the borehole and a recording device on the surface). From the point of view of applicability in hydrological research, laboratory methods are more interesting.

In general, indirect methods are used, which are based on measuring vibrations (natural vibration methods and forced vibration methods – resonant and non-resonant methods), and on measuring wave propagation – acoustic methods (continuous wave propagation methods and pulse dynamic methods – ultrasonic methods).

A great advantage of ultrasonic measurements is their non-destructiveness, i.e. the possibility of repeating the test without disturbing the sample. (This fact of non-destructive methods is especially important when studying changes in the physical and mechanical properties of rocks over time). Ultrasound is a longitudinal mechanical wave with a frequency greater than 20 kHz (various types of ultrasonic measuring instruments measure in the range of 20 kHz to 500 kHz).

Using ultrasonic methods, we can obtain the following properties of the examined rock samples:

- propagation velocity of ultrasonic waves;
- dynamic modulus of elasticity and dynamic Poisson's ratio;
- strength, density and others.

The ultrasonic method used is based on measuring the time required for waves to pass through the sample.

The measurement procedure was as follows. A sample of precise geometric shape (cube, cube, cylinder) was cleaned of impurities and dried in a dryer at a temperature of 105 °C for 24 hours. All samples were weighed after being removed from the dryer and the diameter and height were recorded. The bulk density was calculated from the measured parameters. Subsequently, after cooling the samples to laboratory temperature (+ 20 °C), a layer of gel was applied to two opposite sides, to which a transmitter and a sensor from an ultrasonic device were attached. The application of the gel layer is necessary to fill the air gaps at the sample-metal interface (ultrasonic sensor). An ultrasonic device UPV E 49 was used to perform the test – Fig. 1.

Fig. 1. Ultrasound device

Before measuring, it is necessary to set the specific length (height) of two opposite sides of the sample through which the longitudinal (ultrasonic) wave will pass on the device. The velocity v_p (m.s^{-1}) of the passage of ultrasonic waves between two opposite sides subsequently appeared on the device display. The result of the measurement was therefore the velocity of ultrasonic waves (m.s^{-1}).

The velocity of propagation of longitudinal waves was measured with dry samples and then after immersing them in water for various lengths of time (after 15 min., 30 min., 1 h., 2 h., 4 h. and 24 h.) - after drying the samples with a cloth. The results of the measured data are evaluated in table 1, table 2 and Fig. 2. – Fig. 5. The main aspect of the contribution is the determination of the degree of saturation (S_s). According to Hyánková et al. (1985), the degree of saturation is defined by the following relationship:

$$S_s = \frac{\rho - \rho_d}{\rho_w - n} \tag{1}$$

where ρ is the bulk density of the wet sample (kg.m^{-3});

ρ_d is the bulk density of the dry sample (kg.m^{-3});
ρ_w is the bulk density of water (kg.m^{-3});
n is the porosity.

The measurements were carried out on cylindrical samples with a diameter of approximately 5 cm and a height of 10 cm. According to the STN EN 72 1001 standard [7], the sandstones from the *Hubová – Ivachnová* site are light grayish-brown with coarse psamitic grain size, evenly grained, and contain macropores. The sample had a homogeneous texture

3. Results and discussion

Table 1 shows the measured ultrasonic wave propagation velocities for individual samples in the dry state and after periods of water saturation. The values of bulk density, respectively porosity, are also given here. In the table, the lowest and highest increases of ultrasonic wave velocity values of the samples are underlined and shown in italics. The minimum and maximum values of bulk density, respectively porosity, are also indicated.

Table 2 shows the values of porosity n and degree of saturation S_s and ultrasonic wave transmission velocities v_p for samples that did not break down after 24 hours. The results are given for 9 samples (*P 70a, P 71a, P 72a, P 72b, P 78a, P 79a, P 80, P 103, P 104*). The other samples decomposed after 24 hours of saturation in water and their use for further measurements was unrealistic. As can be seen from Fig. 2, the velocity of ultrasonic waves passing through the tested rock samples increases directly proportionally to the saturation time of these samples.

The velocity of ultrasonic waves (Table 1) has range from 987 m.s^{-1} (*P 84b*) to 4025 m.s^{-1} (*P 78a*) for dry samples (the average value is 2115 m.s^{-1}) and from 2258 m.s^{-1} (*P 71a*) to 4279 m.s^{-1} (*P 78a*) for samples saturated with water for 24 hours, with the average value being 3114 m.s^{-1}. The difference in ultrasonic wave velocities for dry samples is 3038 m.s^{-1}, and for saturated samples 2021 m.s^{-1}. The largest increase in ultrasonic wave velocity (704 m.s^{-1}, i.e. an increase of 37.52%) was recorded for sample *P 103*, the smallest (254 m.s^{-1}, i.e. an increase of 6.31%) for sample *P 78a*, while the average value of the increase in velocity due to saturation for 24 hours was 455 m.s^{-1} (i.e. an increase of 17.11%).

Tab. 1. Bulk density of dry samples (ρ_d) and velocity of ultrasound – longitudinal waves (v_p) for the dry and saturation samples (various time)

sample	**bulk density ρ_d kg.m^{-3})**	**porosity (%)**	**Velocity of US waves v_p (m.s^{-1})**							
			dry	**15 m.**	**30 m.**	**1 h.**	**2 h.**	**4 h.**	**24 h.**	**↑ velocity**
P 68b	2514,96	31,5	1660	1695	1803	1821	1861	1871	X	X
P 68c	2460,01	31,5	1574	1583	1643	1701	1740	1751	X	X
P 69b	2419,59	28,9	1325	1326	1428	1522	1538	1556	X	X
P 70a	2428,19	30,2	1823	2035	2143	2183	2200	2230	2340	517
P 70b	2425,96	30,2	2045	2045	2121	2140	2165	2181	X	X
P 71/2	2436,17	25	1900	1903	1924	1941	1960	2048	X	X
P 71a	2465,63	25	1810	1999	2013	2055	2077	2132	2258	448
P72 a	2549,47	3,1	3084	3125	3200	3298	3307	3335	3609	525
P 72b	2538,63	3,1	3069	3077	3302	3447	3457	3572	3594	525
P 73a	2461,25	26,7	1688	1783	1862	1865	1881	2031	X	X
P 76a	2470,3	20	1672	1805	1819	1849	1869	1910	X	X
P 78a	2606,27	2,4	*4025*	*4082*	*4111*	*4126*	*4126*	*4156*	*4279*	*254*
P 79a	2542,16	12	3789	3859	3970	4011	4039	4050	4096	307
P80	2514,16	15,9	2548	2548	2560	2603	2659	2705	2950	402
P 82a	2494,03	25,5	1999	2016	2023	2044	2048	2051	X	X
P 84	2410,09	30,1	1401	1431	1438	1446	1492	1508	X	X
P84b	*2397,61*	*32,1*	*987*	*997*	*1008*	*1202*	*1223*	*1226*	X	X
P 103	2540,99	16	1876	2287	2363	2399	2454	2550	2580	704
P 104	2453,47	29,5	1906	2052	2079	2091	2091	2145	2317	411
average	2480,47	22,8	2115	2192	2253	2302	2326	2369	3114	455

As for the bulk density (ρ_d), the values of individual samples increase with increasing velocity of ultrasonic waves through the samples – from 2397.61 kg.m^{-3} (sample *P 84 b*) to 2606.27 kg.m^{-3} (sample *P 78 a*), with the average value being 2472.26 kg.m^{-3}. The difference in bulk density values is 208.65 kg.m^{-3}. On the contrary, with increasing porosity value, the velocity of ultrasonic waves through the tested samples decreases. Porosity ranges from 2.4% (sample *P 78 a*) to 32.1% (sample *P 84 b*), with the average value being 22.85%. The measured data show the lowest recorded ultrasonic wave velocity (987 m.s^{-1}) for sample *P 84* with the highest porosity and the highest ultrasonic wave velocity (4279 m.s^{-1}) for sample *P 78* with the lowest porosity (Table 1).

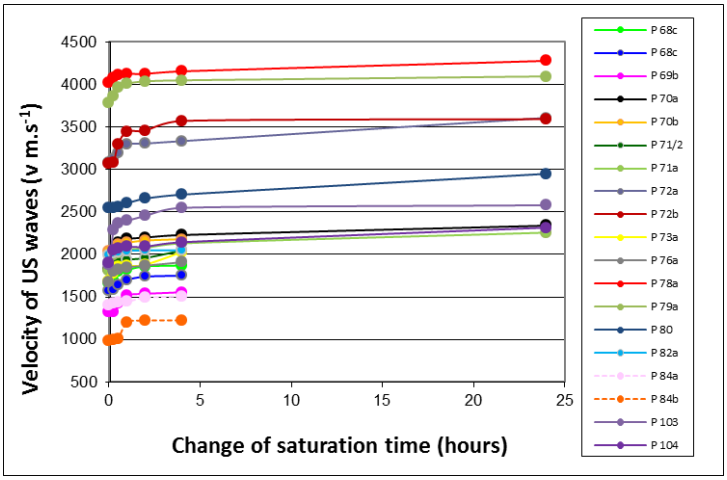

Fig. 2. Dependence velocity of ultrasound waves (v_p) by time of saturation

As can be seen from Table 2, the porosity value (n) of samples ranges from 2.4% (sample *P 78a*) to 30.2% (sample *P 70a*), i.e. the difference in the values samples is 27.8% and the average value is 17.15%. Sample *P 78a* also shows the highest bulk density (2606.27 kg.m^{-3}), on the other hand, the sample with the highest porosity (*P 70a*) does not show the lowest bulk density value (2428.19 kg.m^{-3}); the lowest value (2397.61 kg.m^{-3}) was recorded for sample *P 84b*, with a porosity of 30.1%, but this sample decomposed after 24 hours of water saturation.

Tab. 2. Comparison values of porosity n and degree of saturation S_s

sample	porosity n (%)	degree of saturation (%)	velocity of US waves after 24 hours (m.s^{-1})
P 70a	*30,2*	*4,08*	2340
P 71a	25	3,17	2258
P 72a	3,1	1,68	3609
P 72b	3,1	1,83	3594
P 78a	*2,4*	*1,14*	4279
P 79a	12	1,81	4096
P 80	15,9	2,98	2950
P 103	16	2,03	2580
P 104	29,5	3,49	*2317*
aver.	17,15	2,77	3113

As for the degree of saturation S_s, the value ranges from 1.14 (sample *P 78a*) to 4.08 (sample *P 70a*), i.e. the difference in the values of the samples is 2.94 and the average value is 2.77. According to Fig. 3, degree of saturation S_s value increases with the decreasing value of the ultrasonic wave velocity v_p. The lowest (1.14) degree of saturation S_s value is recorded for sample *P 78a*, at which the value of the ultrasonic wave velocity is 4279 m.s^{-1}. The highest (4.08) degree of saturation S_s value was recorded for sample *P 70a* with the value of the ultrasonic wave velocity of 2340 m.s^{-1}. However, this value was not the lowest, it was recorded for sample *P 71a* (2258 m.s^{-1}).

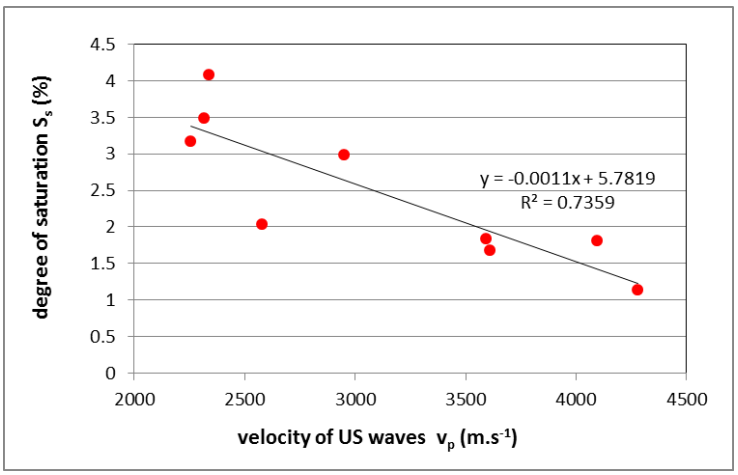

Fig. 3. Dependence velocity of ultrasound waves and (v_p) degree of saturation (S_s)

Fig. 4 shows a decreasing trend in the porosity value (n) with increasing ultrasonic wave velocity v_p through the samples. The lowest porosity value n (2.4%) is recorded for sample *P 78a*, which shows the highest ultrasonic wave velocity v_p (4279 m.s^{-1}). The highest porosity value n is recorded for sample *P 70a* (30.2%), which does not show the lowest ultrasonic wave velocity v_p (2340 m.s^{-1}). The lowest ultrasonic wave velocity v_p is assigned to sample *P 71a* (2258 m.s^{-1}) with a porosity value n of 25%.

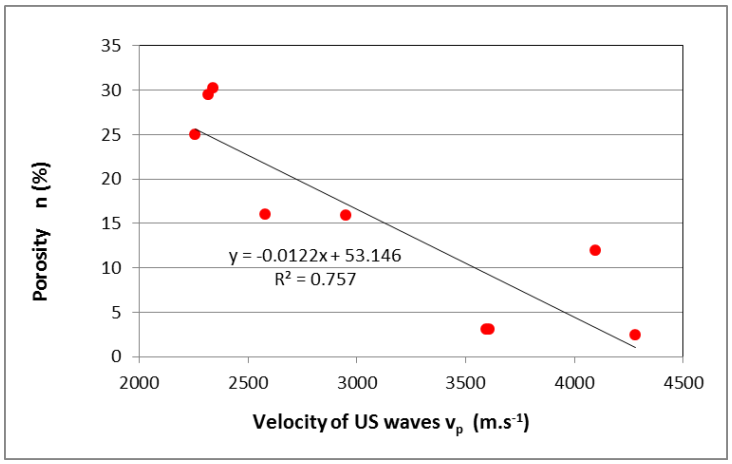

Fig. 4. Dependence of velocity of ultrasound waves and (v_p) and porosity (n)

The above facts lead to the mutual ratio of the values of the degree of saturation S_s and porosity n, shown in Fig. 5.

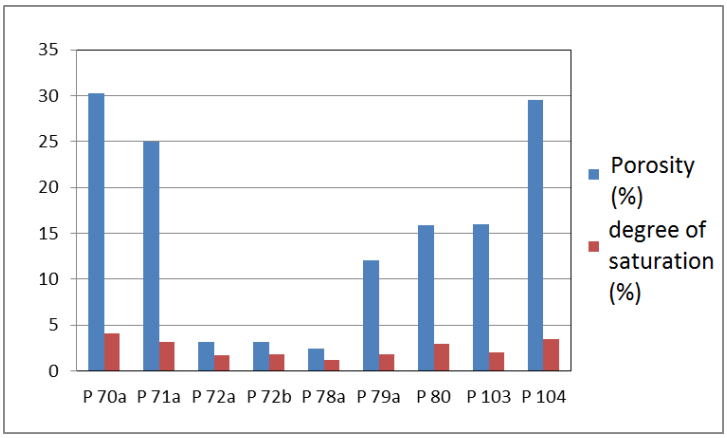

Fig. 5. Dependence between values of porosity n and degree of saturation S_s

4. Conclusion

Tests carried out led to the following conclusions for the studied samples:

1) results show that with an increase ultrasonic wave velocity value of the tested samples, value of the bulk density also increases - cause is a more compact structure (i.e. higher bulk density and associated lower porosity), i.e. with an increase in the bulk density by 8.70%, velocity of ultrasonic waves through the samples increases by 307.80%

2) increase in the velocity of ultrasonic waves value through the samples due to an increase in the saturation values of the samples - cause is filling pores of the rock with water, through which ultrasonic waves propagate faster than in air, i.e. an increase in the velocity of ultrasonic waves by 17.11% in 24 hours;

3) increase of degree of saturation S_s value of the examined samples with a decreasing velocity value of the ultrasonic waves (Fig. 3);

4) decrease in the porosity value n with increasing velocity value of ultrasonic waves v_p through samples (Fig. 4).

With increasing velocity of ultrasonic waves through rocks, the value of dynamic modulus of elasticity and informative compressive strength will also increase [5, 6].

Experiments on samples were carried out in the laboratory, i.e. that ultrasonic wave velocity in field tests would have a lower value than in the laboratory due to the occurrence of cracks, fractures, etc. This fact is opposed by the fact that different groundwater content in the geological environment affects velocity of ultrasonic waves during measurement. For this reason, ultrasonic wave velocity of dried samples in laboratory conditions will be lower than in field conditions. This fact must be taken into account in various geological and construction tasks, i.e. in the study of physical and mechanical properties of water-saturated and unsaturated rock environments, especially in assessing the tightness of landfills. Ultrasonic methods can provide a good alternative to the existing monitoring system for monitoring the tightness of landfills. On a similar principle, ultrasonic methods can also be used in investigating the tightness of injection screens in the bedrock of dams.

The mechanical properties of rock massifs are usually different from the properties of rock material. Compared to laboratory values, rock massifs show 10 times lower strength and 20 times lower ductility, compared to laboratory values [8].

Acknowledgments

This paper was prepared with the support of the project No. VEGA 2/0028/23.

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