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A laboratory method to determine the hydraulic conductivity of mountain forest soils using undisturbed soil samples

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SUMMARY

Determination of infiltration properties of soils under laboratory conditions necessitates the collection of soil samples in a way that maintains their natural physical properties. Mountain forest soils, containing rock fragments, root systems and a significant amount of organic matter, make it extremely difficult to test their hydraulic conductivity using both laboratory and field methods. A widely used technique of sampling by driving a cylinder into the ground in this type of soils causes damage to their structure resulting from the displacement of root systems and rock fragments as well as reduction of soil porosity. Thus, subsequent results contain an error that is difficult to estimate. The aim of the present research was: (1) to develop a laboratory method for testing the hydraulic conductivity of mountain forest soils, and in particular a method of collection of undisturbed soil samples, (2) to determine the influence of the applied method of collecting samples on the thickening of their peripheral layer and on elimination of increased infiltration at the boundary between the soil medium and the cylinder, (3) to determine the extent of the impact of the irregular shape of a sample on its hydraulic conductivity and (4) to develop an empirical method for determining the actual values of hydraulic conductivity, taking into account the error associated with the flow of water through samples with different shapes. The method of soil sampling consists in gradual formation of a cylindrical soil monolith and filling the free space between the monolith and the tri-cylindrical container with low-pressure assembly foam. This method ensures preservation of the natural physical properties of the examined samples and elimination of errors during the measurement of the hydraulic conductivity, caused by increased infiltration at the boundary between the soil medium and the cylinder. It was shown that the mean error of hydraulic conductivity determination, related to the irregular shape of samples, amounts to 11.57%. The error may be eliminated by the application of conversion coefficients.

1. Introduction

Hydraulic conductivity is one of the basic measures of the flow of water in the ground. Field and laboratory methods widely reported in the literature indicate the existence of numerous ways and instruments for measuring hydraulic conductivity (Ohte et al., 1989; Plagge et al., 1990; Ankeny et al., 1991; Hendrayanto et al., 1998; Youngs, 2001; Bagarello et al., 2004; Meadows et al., 2005; Lassabatère et al., 2006; Schindler and Müller, 2006; Peters and Durner, 2008; Price et al., 2008). Their use is usually dependent on the type of soil material being tested. Numerous studies show that the values of hydraulic conductivity determined by laboratory methods are rarely in accordance with the values of hydraulic conductivity determined by *in situ* measurements (Ankeny et al., 1991; Mohanty et al., 1994; Fallico et al., 2005; Price et al., 2010). This is due to the fact that both field and laboratory research is burdened with errors which may account for the differences in the obtained hydraulic conductivity values (Ankeny et al., 1991). The selection of an appropriate method usually depends upon a number of factors, such as accuracy, speed, and ease of measurement as well as costs (Lee et al., 1985). Field methods are generally time-consuming and costly (Wessolek et al., 1994; Iwanek, 2005). In turn, the collection and transport of samples may affect errors occurring during laboratory measurements in an unspecified manner (Fodor et al., 2011).

Determination of the hydraulic properties of soil under laboratory conditions requires the collection of undisturbed soil samples (Twardowski and Drożdżak, 2007). The method of sampling is of great importance due to the preservation of the natural pore system, rock fragments or roots. According to a study by Kucza (2007), disturbance of the natural structure of the samples

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obtained from the organic horizons of forest soil may have a large impact on the value of the hydraulic conductivity. In the litter horizon (Ol) these changes range from 3% to 15%, in the case of damage to the structure of the deeper horizons (Ofh, A), the changes in the hydraulic conductivity may reach up to 85%.

Mountain forest soils, most often containing rock fragments, numerous root systems and organic matter with varying degrees of decomposition, make it extremely difficult to examine hydraulic conductivity using both field and laboratory methods. In addition to a significant proportion of organic matter, forest soils contain a large number of macropores, particularly in the surface layer, as a result of the activity of soil fauna, and a high content of root systems (Bonell, 1993). Although macropores may constitute a relatively small share of the total porosity of the soil, they may have a disproportionate effect on their infiltration properties (Buttle and House, 1997) and on the transport of nutrients in the soil (Bormann and Klaassen, 2008).

Difficult terrain, associated with a high slope and limited access of water, often makes the *in situ* methods of testing the hydraulic conductivity of mountain forest soils difficult to apply (Hendrayanto et al., 1998). Under laboratory conditions, the largest errors in the measurement of the hydraulic conductivity of forest soils result from improper soil sampling techniques and small sizes of samples due to which the samples do not adequately represent the heterogeneity and macroporosity of soils. The most common way of soil sampling is by driving a cylinder into the ground, which in the case of forest soils may cause the displacement of root systems and rock fragments or destruction and compaction of channels present in the soil. The wrong sampling by uneven driving the cylinder into the ground creates gaps between the cylinder and the soil sample, thus leading to errors during measurements (Chappell and Lancaster, 2007).

The collection of samples for testing hydraulic conductivity under laboratory conditions should ensure:

1. Preservation of continuity of the sample with the surrounding soil.
2. Preservation of the natural residual system of the soil, i.e. the root systems and soil channels within and on the boundary of the sample.
3. Preservation of the natural porosity of the soil medium.
4. Preservation of main, vertical direction of infiltration of water flowing through the sample during testing.
5. Elimination of errors in the measurement of the hydraulic conductivity due to leakage at the boundary.

Therefore, the aim of the present research was: (1) to develop the laboratory method of examination of the hydraulic conductivity of mountain forest soils, in particular the method of collecting soil samples with intact structure, that would fulfil the above criteria, (2) to determine the influence of the applied method of collecting samples on the thickening of their peripheral layer and on elimination of increased infiltration at the boundary between the soil medium and the cylinder, (3) to determine the extent of the impact of the irregular shape of a sample on its hydraulic conductivity and (4) to develop an empirical method for determining the actual values of hydraulic conductivity, taking into account the error associated with the flow of water through samples with different shapes.

2. Materials and methods

2.1. The research area

In order to develop and test the method for testing the hydraulic conductivity of undisturbed soil samples, we selected 14 research plots located in the Beskid Makowski in south-central Poland (Fig. 1). Samples were obtained at an altitude of 550–800 m above sea level, from the horizons of mountain forest soils belonging to brown acid soils (PTG, 2008), formed out of weathered Magura sandstone. The research covered bioaccumulation horizons (A) developed under fir (*Abies alba* Mill.) and beech (*Fagus sylvatica* L.) forest stands as well as mineral horizons (B) lying directly below A horizons.

2.2. The method of collection of undisturbed soil samples

2.2.1. A container for collection of undisturbed soil samples

Fig. 2 presents a container for collecting undisturbed soil samples, which essentially consists of three cylinders having the same inner diameter, made of stainless steel, and two lids. Between the cylinders, there are angled spacers which preserve a gap between them. The cylinders are connected with a strong adhesive tape, adhering closely to the cylinder walls.

The two cylinders – the top and bottom ones – with a height h' of 30 mm, are used to protect the structure of the sample during its transport to the laboratory while the middle cylinder is intended for the sample itself. The height of the central cylinder h depends on the thickness of the horizon of soil from which the sample is obtained and amounts to 20–90 mm in the case of sampling from the horizons of mountain soil. It may be larger in the case of obtaining soil samples from non-stony soils.

During the development and testing of the method of collecting undisturbed soil samples, we used containers consisting of cylinders with a 150 mm internal diameter and the height of the central cylinder of 30, 40 and 60 mm.

2.2.2. Sampling the research material

The essence of collection of soil samples with undisturbed structure using the method proposed here involves gradual and precise formation of a soil monolith in a cylindrical shape (Fig. 3a). The formation of the monolith must be carried out with a sharp knife, trimming the protruding root systems with shears, and removing portions of rock fragments from the side surfaces (Fig. 3b and c). The monolith diameter should be about 20 mm smaller than the diameter of the container. After forming the monolith, its sides should be covered with a thin and flexible coating (silicone spray) to provide reinforcement of its outer surface. The formed and secured monolith should be covered with a previously prepared container in such a way that the lower and upper edge of the cylinder are located inside the soil horizon which will be subjected to the tests of hydraulic conductivity (Fig. 3d). Then, the gap between the monolith and the container should be filled with watertight filler in the form of low pressure assembly foam. The foam should be introduced using a four-nozzle, providing even and simultaneous distribution of the foam. The container should cover the soil monolith in such a way that the expanding foam can escape outside on both the upper and lower side of the container. This is particularly important for the collection of forest soil organic horizons, since no escape of the excess foam beyond the container may cause too much pressure of the filler onto the soil, and thus lead to its compaction. After drying of the filling material, the top surface of the monolith should be made even and the container should be closed with a steel cover. Then, the container should be cut off together with the monolith, its bottom surface should be made even and the bottom of the container should be covered with a lid.

This method also allows the collection of undisturbed soil samples formed on mountain slopes of varying gradients. Sampling on the slopes consists in the forming of the monolith in the manner described above except that the container should be placed on the monolith in a vertical direction in such a way that the soil