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The Effect of Diffusion on the Sedimentation Rate of Soil Microparticles

Milan Gombos ¹, Andrej Tall ¹, Branislav Kandra ¹, Dana Pavelkova ¹

¹Institute of Hydrology, Slovak Academy of Sciences in Bratislava, Dúbravská cesta 9, 841 04 Bratislava, Slovakia

pavelkova@uh.savba.sk

Abstract. The submitted paper presents the results of the experiment aimed at quantifying the effect of diffusion on the sedimentation rate of soil microparticles of different fractions. The goal of the experiment was to specify the determination of the texture composition of soils. The textural composition of the soil gives basic information about its hydrophysical properties. Standard methods for determination of granulometric soil composition are based on sedimentation methods. Measuring errors occur in the measurement of the soil microparticle rate, which are usually made of clay particles. Their source is the effect of diffusion. In the settling process with the gradual formation of the colloidal dispersion system, the deposition rate decreases. The rate of sedimentation of the dispersion particles approaches the rate of the mean diffusion feed in the opposite direction. Gradually, the state of dynamic sedimentation equilibrium occurs. The dispersion ratio was in dispersed system formed by clay soil particles from the Senne site. The dispersed medium was distilled water. Grain analyzes were performed by a laser diffraction method on a Mastersizer 2000 from MALVERN Instruments. The soil microparticles' rates were measured on the basis of the time and the path of particles with diameter d (90). The output of the experiment is the diffusion coefficient, diffusion average feed and sedimentation rate for soil particles of different sizes. The results of the work show that with size of sedimented soil particles, the effect of diffusion increased. On this basis, it is possible to verify the lower limit of the results of grain size analyzes based on the sedimentation method. The results of the work show that the reduction of the size of the settled soil particles increases the effect of diffusion. On this basis, it is possible to quantify the lower limit of the results of grain size analyzes based on the sedimentation method and the particle size at which dynamic sedimentation equilibrium occurs.

1. Introduction

In hydrogeological research, soil microparticles are a matter of particular interest. They are usually made of clay particles with a high proportion of clay minerals. Clay particles are defined as particles $\leq 2 \mu\text{m}$. Soils with a high proportion of clay particles ($> 45\%$) are called clay.

The aim of the experiment was to measure the deposition rate of the various fractions of soil microparticles separated during sedimentation, to identify the lower limit of the Stokes equation. The next goal was to quantify the effect of diffusion on the sedimentation rate and to create a dynamic balance of the formed colloidal dispersion. Granulometric method of sedimentation analysis was applied. The dispersion ratio was formed in the dispersion system from clay soil particles from the Senné site in the East Slovakian Lowland (ESL). The dispersed medium was distilled water. Grain analyzes



were performed by a laser diffraction method on a Mastersizer 2000 from MALVERN Instruments. The soil microparticles' speeds were measured on the basis of the time and the passed path of particles with diameter d (90). Knowledge of these properties is essential for the exploration and numerical simulation of the heavy soils water regime [1], [2], [3]. For these reasons, it is necessary to know the proportion of soil microparticles in the soil.

Until now, standard laboratory procedures based on rate measurements using the sedimentation method are analysed using the Stokes equation. The disadvantage of these processes is the fact that with the reduction of the sedimenting particles the dispersing system passes into a colloidal state. The results are affected by diffusion, and so the Stokes law is limited from below. In recent years, a method based on the principle of laser diffraction can be used to measure the size and rate of deposition of microparticles [4], [5], [6].

The authors of the paper are based on the hypothesis that can be used to identify the particle size interval between the lower limit of the Stokes law and the sedimentation equilibrium. It is assumed that, at this interval, the effect of diffusion begins to manifest itself most clearly. Formally it is possible to express it as a particle diameter interval $D(P) \in < D(P)_{min}, D(P)_{max} >$, where $D(P)_{min}$ is the diameter of grains „ D “ with the probability of occurrence „ P “ when a dynamic sedimentation equilibrium occurs. D_{max} is the diameter of grains „ D “ with the probability of occurrence of „ P “ when the Stokes law ceases to apply.

The aim of the work was to quantify the influence of diffusion on the deposition rate of soil microparticles of different fractions.

2. Methods

The basis of the experiment was the exact determination of the texture composition of soils. The textural composition of the soil gives basic information about its hydrophysical properties. Standard methods for grading soil composition are based on sedimentation methods. During measuring of the rate of soil microparticle, which are usually formed of clay particles, errors of measurements occur. Their source is the effect of diffusion. In the settling process with the gradual formation of the colloidal dispersion system, the deposition rate decreases. The rate of sedimentation of the dispersion particles approaches the rate of the mean diffusion feed in the opposite direction. Gradually, the state of dynamic sedimentation equilibrium occurs. The dispersion ratio was formed in the dispersion system from clay soil particles from the Senné site in the East Slovakian Lowland (ESL).

The theoretical foundations are based on the Navier-Stokes equation (1). That for spherical particles is defined in the form:

$$u = \frac{2}{9} \frac{(\rho - \rho_0) \cdot r^2 \cdot g}{\eta_0} \quad [\text{m}^2 \cdot \text{s}^{-1}] \quad (1)$$

This relationship applies to spherical shape particles that are much larger than the environmental molecules, provided they have a smooth surface without electrical charge and are moving at low speeds in the laminar flow area for a small Reynolds number ($\text{Re} < 0.5$). In the calculations of the sedimentation rate of soil particles, the greatest deviations from the reality occur mainly due to the non-observation of the condition of the spherical shape and the size of the particles in the smoothness of their shape and in the small particles due to the diffusion. The process of settling in the dispersion system takes place until the dynamic equilibrium of the system occurs. In sedimentation equilibrium the rate of sedimentation of the dispersed particles equals the rate of diffusion thereof in the opposite direction. This is particularly evident in colloidal dispersions. In coarse dispersions, diffusion is undetectable. Analytical dispersions do not produce measurable sedimentation. In colloidal solutions, the diffusion coefficient decreases with

increasing particle size and rises with increasing temperature. If the coefficient f is known, so the diffusion coefficient D can be calculated according to Einstein equation (2):

$$D = \frac{k_B \cdot T}{f} \quad [\text{m}^2 \cdot \text{s}^{-1}] \quad (2)$$

where k_B is the Boltzman constant and T is the absolute temperature.

Numerically represents the substance amount of difunctional substance that passes through the unit area per unit of time at the unit concentration gradient. The equation for expressing the diffusion coefficient D (3) as a function of the dimension of the spherical particle is in the form:

$$D = \frac{k_B \cdot T}{6 \cdot \pi \cdot \eta_0 \cdot r} \quad (3)$$

The colloidal particles in the dispersion system perform Brown's motion, so it is possible to measure only the quadratic mean of the displacement of the particles (mean displacement Δ) at the same consecutive time intervals. The relation between the diffusion coefficient D and the mean displacement Δ expresses the Einstein-Smoluchow equation (4) in the form:

$$\bar{\Delta} = \sqrt{2 \cdot D \cdot \tau} \quad (4)$$

Where τ is the period over which the particle diffuses to distance Δ .

For measurements based on laser diffraction analysis, the particle size distribution of certain size in the dispersion expressed in % of volume. Numerically, this is the same value as expressed in % of weight. Outputs from laser diffraction measurements in the form of particle sizes of a certain size allow for the calculation of the rate of movement of a microparticle of a certain size. In the actual process, samples of the suspension (colloid) for laser diffraction are taken from the two elevations H_1 and H_2 (Figure 1) from the dispersion system at selected time intervals. For each high level, dependence is sought (5), (6):

$$D(P)^{H_1} = f(t)^{H_1} \quad (5)$$

$$D(P)^{H_2} = f(t)^{H_2} \quad (6)$$

Where $D(P)^{H_1}$ and $D(P)^{H_2}$ are a function of time. These are particle sizes with a D -diameter and a probability of occurrence of P which at different times t passes through the sampling level H_1 and H_2 .

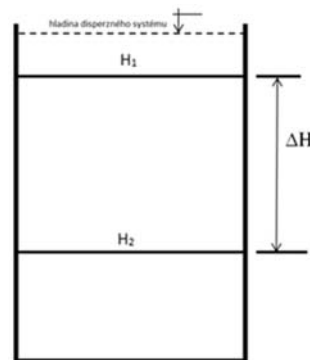


Figure 1. Scheme for the calculation of sedimentation rate and sampling for laser diffraction

It follows from equations (5) and (6) that, for the calculation of the rate, it is necessary to find the times t^{H_1}, t^{H_2} in which the left sides of the equations are equal, i.e. the particle under investigation has the same size and probability of occurrence at different heights. It is logical that such a situation occurs at different times from the beginning of sedimentation (7). Then it is valid

$$D(P)^{H_1} = D(P)^{H_2} \rightarrow \Delta t = f(t)^{H_2} - f(t)^{H_1} \rightarrow \text{rate } v = \frac{H_1 - H_2}{\Delta t} = \frac{\Delta H}{\Delta t} \quad (7)$$

For the expression of the right sides of equations (5) and (6), some form of analytical expression is preferred. Preferably, it is possible to use some interpolation method (linear, cubic), extrapolation respectively. Sometimes it is advantageous to divide the dependencies (5) and (6) into intersection intervals and then to express each dependence in the form of several equations.

The dispersed medium was distilled water. Grain analyzes were performed by a laser diffraction method on a Mastersizer 2000 from MALVERN Instruments. The soil microparticles' rates were measured on the basis of the time and the passed path of particles with diameter $d(90)$. The output of the experiment is the diffusion coefficient, diffusion average feed rate and sedimentation rate for soil particles of different sizes. The results of the work show that the impact of diffusion increases as the size of settled soil particles decreases. On this basis, it is possible to quantify the lower limit of the results of grain size analyzes based on the sedimentation method and the particle size at which dynamic sedimentation equilibrium occurs.

3. Results and discussions

In Figure 2 are graphically processed outputs of the particle size distribution of the studied heavy soil by the laser diffraction method at the monitored levels H_1 and H_2 . The starting point of the measurements was the homogeneous state of the suspension at time zero where the measurements were found to be almost identical grain curves at all three levels observed. At the time of pulling off the stirrer from the sedimentation cylinder, the soil particles began to sediment at different speeds, depending on their size. The measured soil particle sizes were in the range from about 550 μm to 0.1 μm , throughout the experiment. Figure 2 shows the measured grain profiles of the soil under investigation at ten selected time intervals. In the first phases of the experiment, the suspension state was close to a homogeneous state, when grain profiles at the three closely monitored heights were very similar. In the initial phases of the experiment, the most frequent particles from the range of 2.88 – 3.31 μm were at all sampling levels for 1 hour 20 min.

After this time in each of the three levels, the largest particle sizes at the same time were identified at different gradient intervals. At the end of the sixth day from the beginning of the experiment to the end, the most numerous particles were again from one grain interval (0.16 – 0.18 μm) at all levels. At the end of the experiment, almost all grading curves were measured at all three levels. In Figure 3 the lower validity of the Stokes law, i.e. about 0.2 μm . The state of the sedimentary equilibrium of the system was achieved in the colloidal dispersion system. In this dynamic equilibrium, the rate of sedimentation of the disperse particles is the same as the rate of diffusion in the opposite direction. In the state of sedimentary equilibrium, the particle size d in μm for $d(10)$, $d(50)$ and $d(90)$ were identified on the particle size distribution curve. Values are the direct output from the laser analyser measurements. The value $d(90)$ represents in this case the maximum or less diameter of the soil particle that is at the time of the measurement with a probability of 90% in the measured sample of the suspension. For the above probabilities, the following particle sizes were identified: $d(10) = 0.14 \mu\text{m}$, $d(50) = 0.19 \mu\text{m}$ and $d(90) = 0.27 \mu\text{m}$. The smallest particle identified in the dynamic equilibrium conditions of the formed dispersion system had a dimension of 0.113 μm .

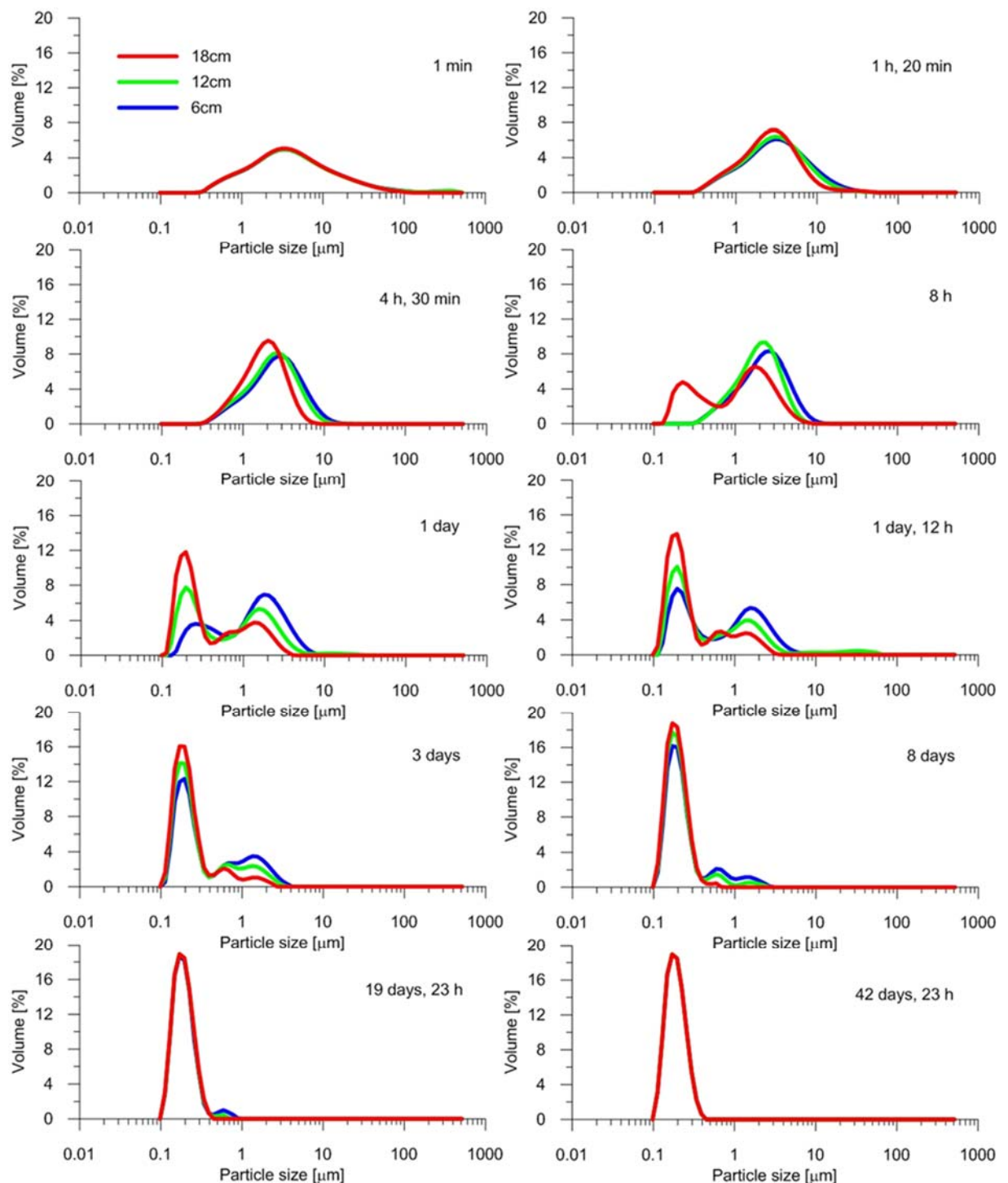


Figure 2. The particle size distribution of the studied soil at ten selected time intervals

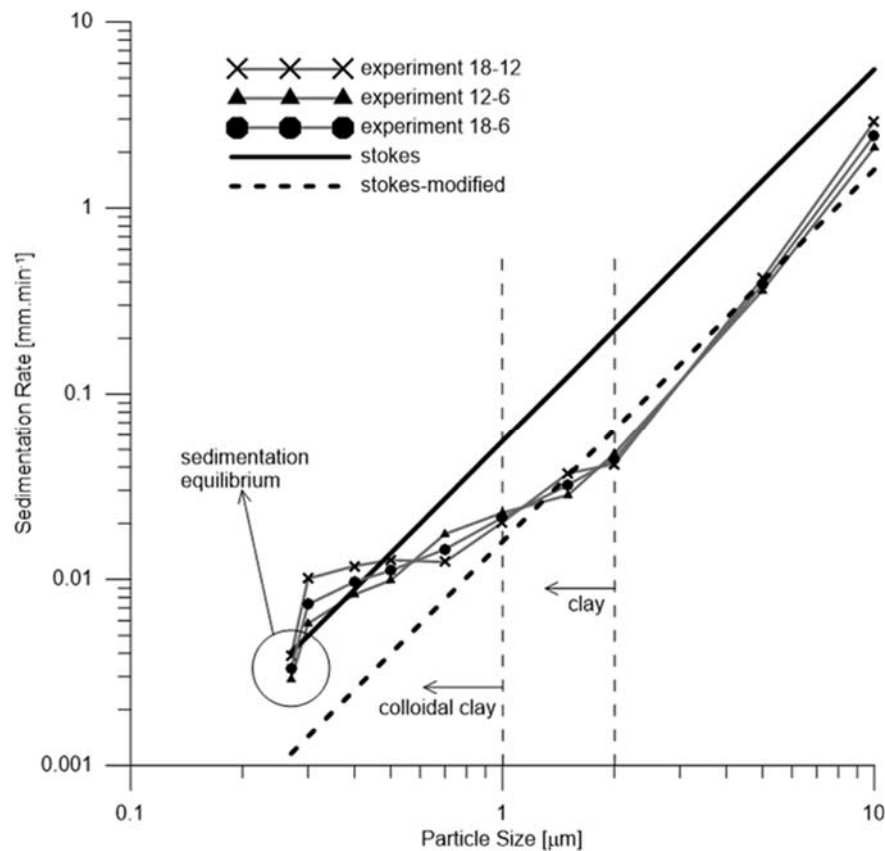


Figure 3. Measured sedimentation velocities and their comparison with computed by Stokes relationship (1)

Figure 4 shows the diffuse coefficient, mean displacement and sedimentation rates calculated for the different soil microparticle sizes. Diffuse coefficients were calculated according to (2), (3) and mean feed according to (4). The course of diffusion coefficient shows the effect of diffusion on deposition rate of colloidal dispersion soil microparticles. Diffuse mean feed gradually compensates for the sedimentation rate in the sedimentation process. With sufficiently small particles (in the experiment $d(90)=0.27\ \mu\text{m}$, $T=20^\circ\text{C}$) there is a dynamic sedimentation equilibrium of the disperse system.

A sedimentation experiment was made with soil microparticles. Soil microparticles were collected at ESL, in heavy soils in Senné depression. The experiment lasted for 42 days and 23 hours. It was confirmed that the most pronounced effect of diffusion on sedimentation is expressed in the interval between the low validity of the Stokes Law and the dynamic sedimentary equilibrium $D(P) \in < D(P)_{min}, D(P)_{max} >$. The scientific contribution of the experiment lies in refining the current laboratory procedures for texture determination. Figure 4 shows the relationship between mean diffusion rate and microparticle deposition.

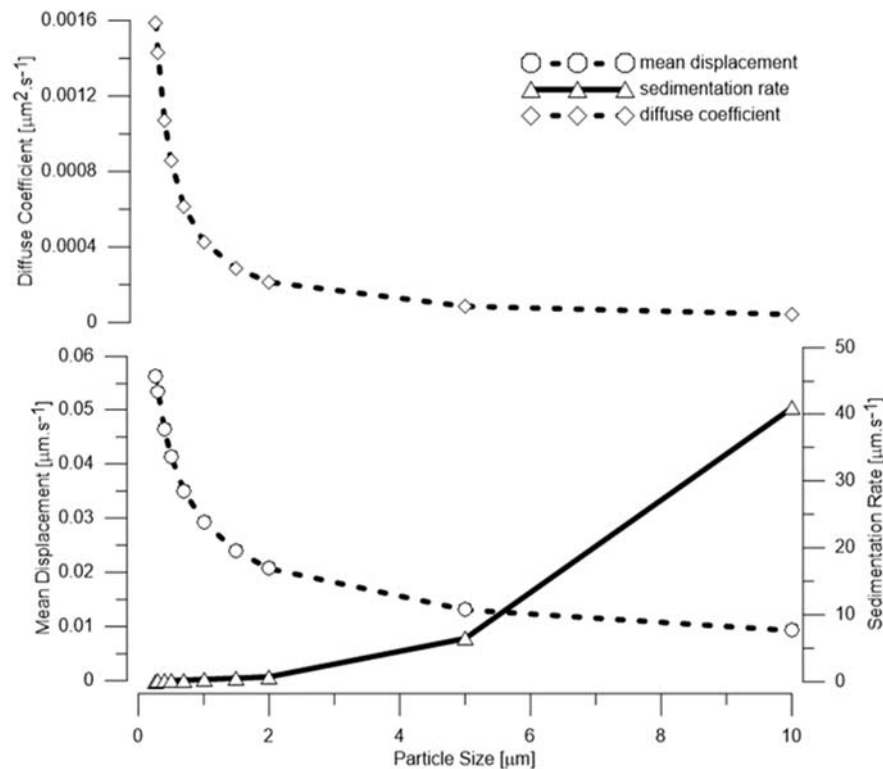


Figure 4. Diffusion coefficient, diffusion mean feed and sedimentation rate for colloidal soil microparticles

4. Conclusions

The aim of the experiment was to measure the deposition rate of the various fraction of soil microparticles separated during sedimentation, to identify the lower limit of the Stokes equation and to quantify the effect of diffusion on the sedimentation rate in the process of creating the dynamic equilibrium of the formed colloidal dispersion. Granulometric method of sedimentation analysis was applied. The dispersion ratio was formed in the dispersion system by clay soil particles from the Senné site in the East Slovakian Lowland (ESL). The dispersed medium was distilled water. Grain analyzes were performed by a laser diffraction method on a Mastersizer 2000 from MALVERN Instruments. The soil microparticles' rates were measured on the basis of the time and the passed path of particles with diameter $d(90)$. A nonlinear interval was defined in which texture identification procedures on non-dimensional methods should be used. The results of the experiment showed that under experimental conditions the validity of Stokes equation (1) ended with the deposition of particles $d(90) \leq 2 \mu\text{m}$. Further reduction of the sedimentation particles results in a colloidal dispersion system in which the diffusion effect of the particle movement in water increases. In the experiment, the dynamic sedimentation equilibrium occurred at $d(90) = 0.27 \mu\text{m}$.

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