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NON-DESTRUCTIVE MEASUREMENTS OF FINE SEDIMENT INFILTRATION MASSES IN LABORATORY EXPERIMENTS

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ABSTRACT

Fine sediment infiltration into interstices of a riverbed has been investigated intensively in both laboratory and field experiments given its high impact on riverine ecology. The clogged pores influence the exchange between surface water and ground water, alter interstitial habitats for benthic organisms and also the reproduction habitats of gravel-spawning fish. So far, most laboratory investigations measured sediment infiltration masses using destructive methods, which allow only for the assessment of fine sediment infiltration masses at the end of experiments but not to investigate the dynamic behavior of clogging processes.
In this study a non-destructive method based on Gamma Ray Attenuation (GRA) is presented to measure fine sediment infiltration masses in laboratory experiments. Therefore, preliminary box experiments and flume experiments were conducted to proof the concept of the measuring technique and to tests its repeatability. To test the feasibility of GRA, a comparison to previously weighted infiltration masses was conducted yielding in deviations within a range of 1.5% to 4.8%, while the repeatability of the flume experiments yielded deviations between 3.7% and 5.6%. These promising results show the high potential of the GRA method for future experiments dealing with the phenomena of sediment infiltration and accumulation, especially in relation to the dynamic behavior of clogging processes.

Keywords: fine sediment infiltration and accumulation, clogging, gamma ray attenuation, laboratory experiments

1 INTRODUCTION

The investigations of fine sediment infiltration and accumulation, or simply clogging, have a long historical record in both field (Beschta and Jackson, 1979; Frostick et al. 1984; Zimmermann and LaPointe, 2005; Evans and Wilcox, 2014) and laboratory research (Einstein, 1968; Schaelchli 1993; Wooster et al. 2008; Gibson et al. 2009; Herrero et al. 2015;, Dudill et al. 2017) because of its high impact on river ecology. Fine sediments that intrude the interstices of the gravel bed lead to a reduction of the pore size and subsequently to a reduction of the hydraulic conductivity (Sear et al. 2008). This also reduces the hyporheic exchange processes, limits the supply of dissolved oxygen to interstitial habitats affecting benthic organisms (e.g. Gayraud & Philippe, 2003) and also the reproduction of gravel-spawning fish species (e.g. Noack et al. 2017).

The process of fine sediment infiltration and accumulation is characterized by a high degree of complexity because of the numerous involved parameter and multiple interacting processes. The rate of infiltrating material and its spatial and temporal heterogeneity is related to the supply of sediments to the gravel bed (Sear et al. 2008), the transport type in terms of suspended and bed load (Carling, 1984), the local hydraulics (Einstein, 1968), the dimensions of the interstices of the sediment framework (Frostick et al., 1984), scour and fill sequences during hydrological events (Kondolf et al. 2014) and river morphology (Zimmermann and LaPointe, 2005). In addition, interstitial processes in the riverbed play an important role such as the interstitial flow field that can lead to interstitial transport processes and further distribution of infiltrated fine sediments (Blois et al. 2012).

Next to the complex processes, adequate measuring techniques represent a challenge for the investigation of fine sediment infiltration and accumulation. Especially the measurements of infiltration masses and their infiltration depth in combination with identical initial conditions constitutes a major difficulty in flume studies as almost all applied measuring techniques are so far destructive and thus imply a new riverbed construction for subsequent experiments. However, related to stratification and sediment packing, it is hardly possible to provide fully identical initial conditions. Accordingly, this leads to complications in comparing obtained results of different simulation runs. In addition, destructive measuring techniques allow only for the assessment of fine sediment infiltration masses at the end of experiments but not to investigate the dynamic behavior of clogging processes.

This study presents the feasibility test of the Gamma Ray Attenuation (GRA) method for non-destructive measurements of infiltration masses that allows additionally to obtain a high resolution vertical profile of infiltrated sediments. Therefore, preliminary experiments were conducted to optimize operational parameters and to test the accuracy of the GRA-method in determining fine sediment infiltration masses. Afterwards, the gained knowledge was applied to set up flume experiments for testing the repeatability of fine sediment infiltration experiments, which represent a fundamental precondition to study in future the impact of different hydraulic and sedimentary boundary conditions or the dynamics behind the infiltration process.

2 MATERIAL AND METHODS

In general, GRA is a robust method to detect physical properties of materials. Among other applications, this technique is commonly used for determining soil sample's bulk density, porosity and soil water content (Baytaş & Akbal 2002, Beckers et al. 2018). Basically, the GRA method is based on Beer-Lambert Law (Equation 1), which relates the attenuation of gamma radiation intensity to the properties of the penetrated media.

$$I = I_0 \cdot e^{-\rho\mu x} \quad [1]$$

where I, I_0 are the gamma intensity/number of quants before and after passing the absorbing material respectively, ρ is the bulk density and μ and x are the mass attenuation coefficient and the net thickness of the absorbing material. The general setup of GRA measurements includes a gamma source, a source collimator to concentrate the emitted gamma quants and a detecting collimator in front of a scintillator to count the received gamma quants after passing the penetrated material. In this study, the radioactive source was Cesium Cs137 with a radioactive decay energy of 661 KeV, while the scintillator consisted of Sodium Iodide doped with Thallium (NaI(TI)).

To test the feasibility of GRA for detecting sediment infiltration masses, several preliminary tests were required to optimize the experimental setup, including mainly the distance between source and detector, the collimator size and the measuring time. Therefore, a simplified experimental setup was used consisting of a box (length=width=0.082 m, height = 0.25 m) filled with a central cubic packing of spheres (d_{sp} = 40 mm) to represent a simplified riverbed with large pores. Distance between source and detector was 0.19 m and the collimator size was 7.0 mm. Afterwards, the box is filled with water and a known weighted mass of sediments that represent the fine sediment infiltration mass. Figure 1 illustrates the experimental setup.

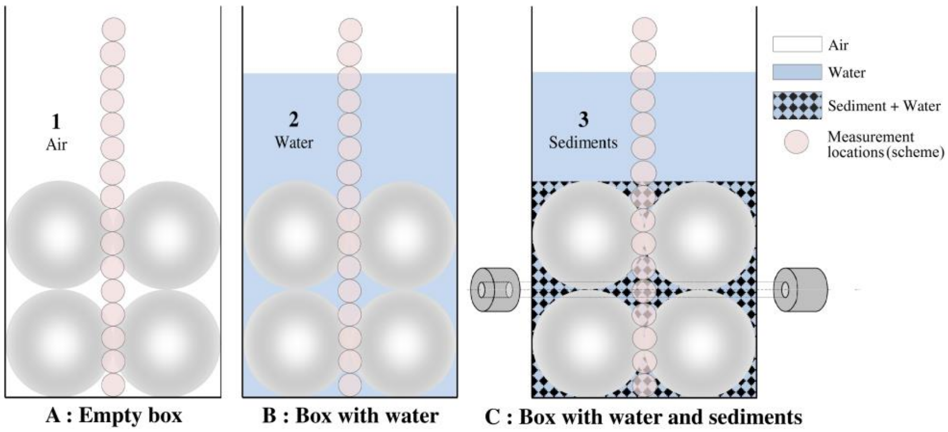

Figure 1. Experimental setup of the preliminary box experiments to measure fine sediment infiltration masses. The smaller circles represent the vertical positions of the GRA measurements.

Given the different absorbing materials (air/spheres/walls, water, sediments), the measuring procedure consists of three measurements at the same position: M1) empty box with spheres to detect the background attenuation given to air, box walls and spheres, M2) filled box with water and spheres to determine the total pore space between the spheres and M3) filled box with water, spheres and infiltrated sediments.

It is important to note that the GRA method allows only for integrative detections of net horizontal thicknesses of each material type and cannot horizontally resolve their distribution. Hence, the result is a net thickness of each material type for each horizontal measurement of a vertical profile. Finally, to obtain the net horizontal thickness of infiltrated sediments in a horizontal measurement layer, the water content of M3 is subtracted from the total pore space (M2). This procedure is done for multiple horizontal layers resulting in a vertical profile of sediment infiltration masses. Considering additionally the sediment density, the volume of each measurement layer and assuming a uniform distribution of sediment in horizontal axis, the infiltrated sediment mass can be calculated. The sum of all layers represents the total mass of infiltrated fine sediments.

Subsequently, the findings of the box measurements were transferred to a laboratory flume with a more complex bed configuration. The recirculating flume has a length of 8.0 m, a width of 0.25 m and a height of 0.30 m. A feeding machine allowed for a continuous supply of fine sediments with adjustable supply rates. The idealized riverbed consisted of table tennis balls in a rhombohedral packing arrangement. The distance between source and detector collimator was 0.49 m given to mounted frames on both sides for the automated vertical traversal to move the GRA device. The same collimator size of 7.0 mm was used for the flume experiments while the measuring time for one horizontal measurement was increased from 45 s to 240 s in order to reduce the statistical error effects.

The proposed setup has several advantages compared to natural gravel-matrices that have been used so far for sediment infiltration and accumulation experiments. Firstly, the simplified geometries with variable but known bed characteristics (particle sizes, pore sizes, porosity etc.) allow for a detailed examination of the distinct contributions of the different processes involved in sediment infiltration and accumulation. Secondly, for several experimental runs with the same bed configuration, identical initial conditions by simply flushing the infiltrated particles out of the simplified bed can be guaranteed. Thirdly, different bed configurations can be produced easily and quickly to investigate the effect of various packings on the infiltration and accumulation processes (future experiments).

Figure 2 show a cross-sectional view and Figure 3 a longitudinal view of the flume setup.

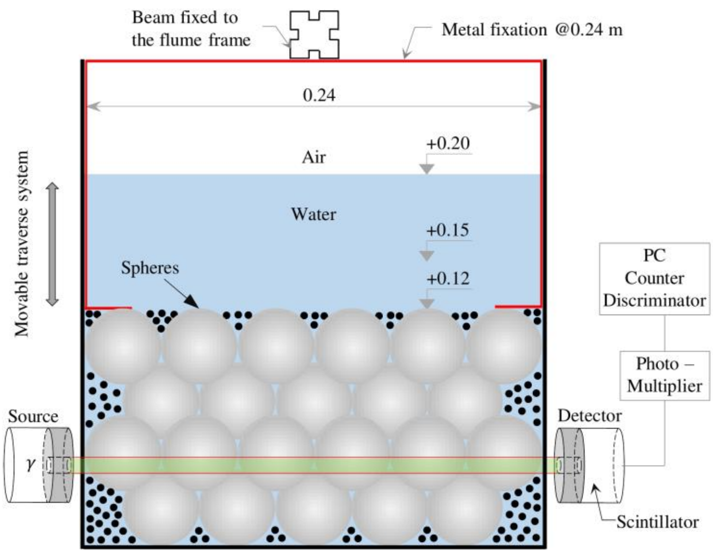

Figure 2. Cross-sectional view of the experimental setup of the flume for fine sediment infiltration experiments.

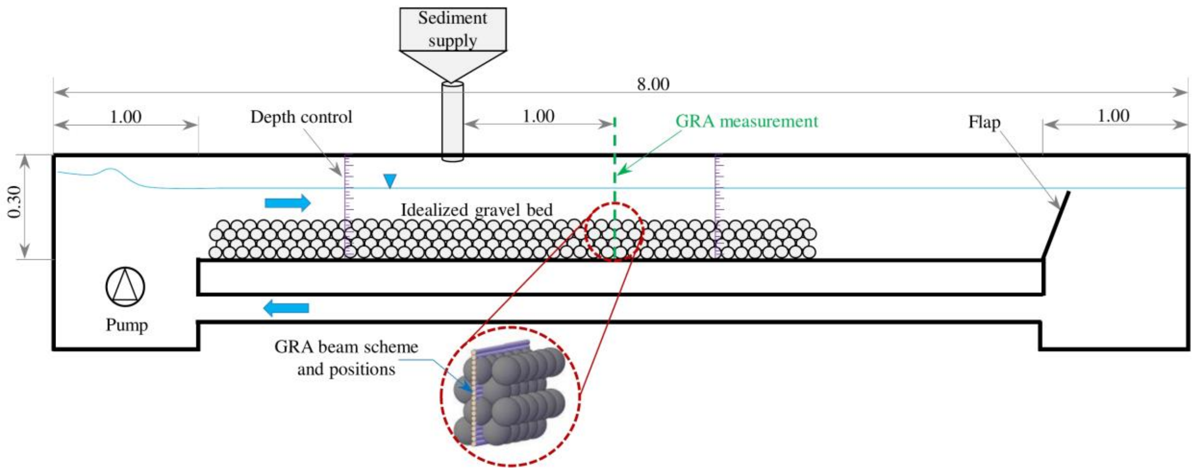

Figure 3. Longitudinal view of the experimental flume setup for fine sediment infiltration experiments.

3 RESULTS AND DISCUSSION

3.1 Preliminary box experiments

One objective of the box experiments was to optimize the experimental setup, e.g. the selection of a suitable collimator size and its related measuring times to achieve reliable count rates (Mayar et al. 2018). However, the main objective was to proof the measuring concept by comparing the measured fine sediment infiltration masses with the GRA method to the previously weighted masses. Figure 4 shows the results of the three required GRA measurements (M1-M3) for two different infiltration materials (d_{S1} = 1.0 - 1.8 mm and d_{S2} = 2.0 - 3.5 mm).

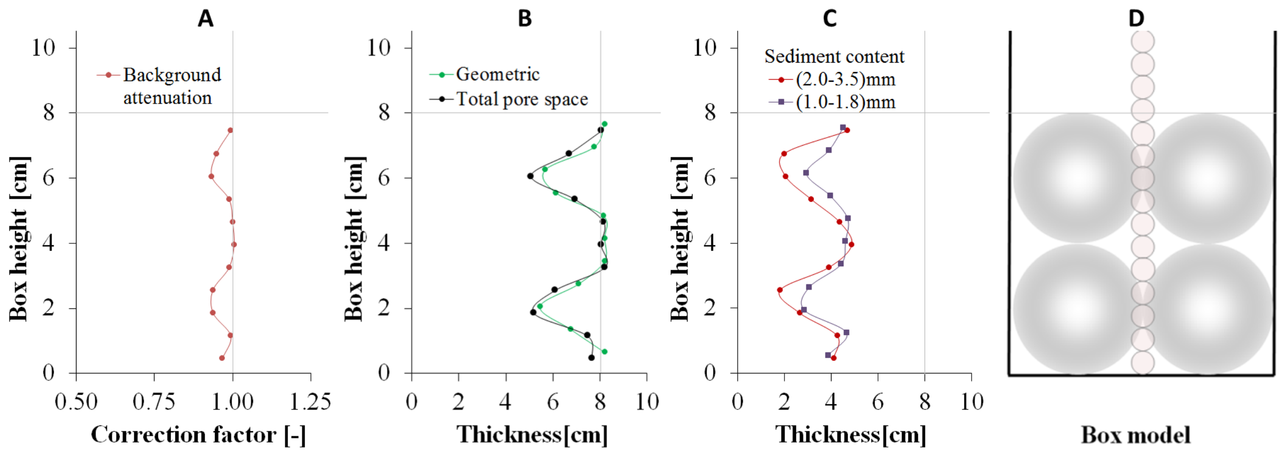

Figure 4. (A) Vertical profile of the background attenuation, (B) vertical profile of the total pore space, (C) vertical profile of infiltrated sediment masses, (D) 2D view of the box model with measurement locations.

The correction factor obtained from the first measurement (M1) in Figure 4A considers the attenuation of the spheres and box walls only.This vertical profile represents slightly the shape of the spheres. In Figure 4B the total pore space (based on M2) is visualized representing well the expected shape of the spheres. The comparison to a geometric analyses (black line) shows a satisfying agreement. Figure 4C includes the measured net thicknesses of infiltrated sediments for both infiltration materials. As expected, the vertical profile follows the shape of the spheres. Additionally, it can be observed that the finer material shows slightly a higher infiltration masses compared to the coarser infiltration material. Table 1 shows the comparison of measured to the previously gravimetrically determined masses. The deviation are from -1.1% for the coarser material and 4.8% for the finer material. Considering the statistical error of 3%, which originates from the random variation of emitted gamma quants of the gamma source due to its radioactive decay, the results can be interpreted to be in an acceptable range. Longer measuring times or larger collimator size could improve the results. However, the latter leads also to a loss in the resolution of the vertical profile.

Table 1. Comparison of GRA measured and previously weighted masses.

	d_{S1} = 1.0 - 1.8 mm	d_{S2} = 2.0 - 3.5 mm
weighted mass [g]	359.1	359.72
measured mass [g]	376.3	355.8
absolute deviation [g]	17.2	3.92
relative deviation [%]	4.8	-1.1

3.2 Flume experiments

The overall objective of the flume experiments in future will be to study on the one hand the influence of varying hydraulic and sedimentary boundary conditions and on the other hand the dynamic behavior of the infiltration processes. However, in this study the required repeatability tests are presented (Nourollah, 2019). Therefore, two repeatability tests (R1, R2) were conducted with two runs for each repeatability test. The hydraulic and sedimentary boundary conditions are listed in Table 2, while Figure 5 shows the vertical profiles of the net thicknesses of infiltrated sediments together with the thickness of the total pore space, which is identical for both repeatability tests given the same packing of spheres. The right drawing in Figure 5 shows the measuring locations along the vertical axis.

Table 2. Boundary conditions for the flume experiments to the repeatability of sediment infiltration and accumulation.

	particle size [mm]	supply rate [kg/min]	supply time [min]	discharge [l/s]	depth [m]	Fr [-]	supplied mass [kg]	No. of experiments
Test R1	1.0 - 1.8	1.4	14.3	15	0.08	0.79	20	2
Test R2	2.0 - 3.5	3.7	5.4	15	0.08	0.79	20	2

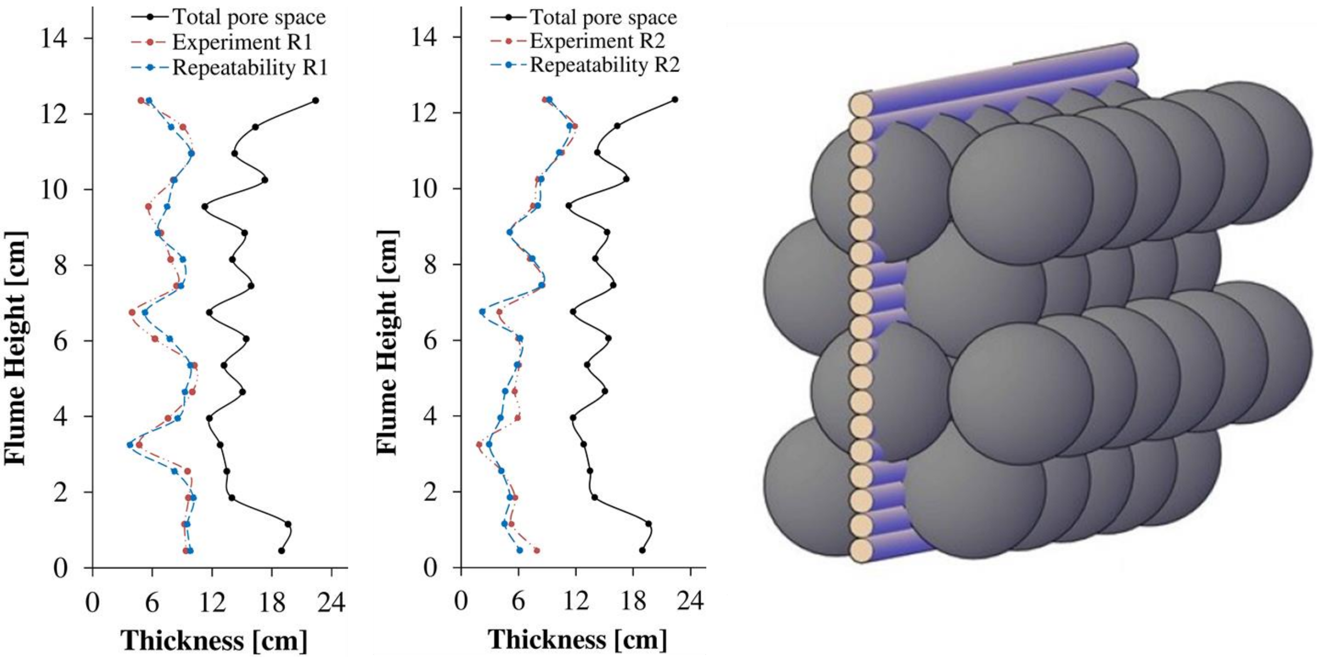

Figure 5. Vertical profiles of measured infiltration masses sediments for both repeatability tests R1 (left) and R2 (right).

The measured net thickness of the total pore space reflects the fluctuations along the vertical profile due to the shape of the spheres. The vertical profiles of the net thicknesses of infiltrated sediments are rather uniform, which is in contrast to the result of the preliminary box experiments. However, this can be explained because the GRA method does not allow for resolving the horizontal distribution. The uniform profile is a result of different packing and filling of pores within the flume.

Comparing both experiments with different particle sizes of the infiltrated material, it can be indicated that the finer material (1.0-1.8 mm) lead to higher thicknesses compared to the coarser material (2.0-3.5 mm), although the sediment supply rate is less. This is also confirmed by the higher total mass of infiltrated sediments (Table 3).

Table 3. Comparison of measured total infiltration masses for both repeatability tests.

	R1	R2
measured total mass (run 1)[g]	166.3	132.0
measured total mass (run 2) [g]	160.1	139.9
absolute deviation [g]	6.2	7.9
relative deviation [%]	3.7	5.6

The first repeatability test R1 shows a very high agreement between both experimental runs with a very low relative deviation of 3.7%, while the second repeatability test R2 shows a relative deviation of 5.6%.

The main potential sources of error are the statistical error given the variations of the radioactive decay of the gamma source and the exact positioning for each of the three required measurements. For the latter, an accuracy in the submillimeter range is required to reproduce identical results. Moreover, smaller variations in the sediment feeding machine were observed resulting in an additional uncertainty.

Considering these potential errors and the general complexity of the infiltration and accumulation processes, including all surface and subsurface processes, the measured infiltration masses provide promising results for future experiments dealing with fine sediment infiltration measurements. Especially because additional important parameters can be derived from the measurements such as water content or porosity that might be helpful in interpreting the outcomes.

For measuring the dynamic process of infiltration and accumulation, a compromise between required measuring time and collimator size have to be made because of the statistical error of the gamma source and its radioactive decay. The smaller the diameter the longer the measuring time to keep the statistical error in an acceptable range. However, too long measuring time lead to loss of temporal resolution. Therefore, our focus in terms of studying dynamic processes is currently set on single pore observations only.

4 CONCLUSIONS & OUTLOOK

This study presents the feasibility test of a non-destructive measuring technique (Gamma Ray Attenuation, GRA) for infiltration masses of fine sediments into a coarse simplified river bed. Based on preliminary experiments the principal functionality of the GRA method was proven before the gained knowledge was applied to flume experiments to test the repeatability of infiltration experiments.

For the preliminary experiments, the measured infiltration masses were compared to previously weighted masses leading to deviations between 1.5% and 4.8%, while the repeatability tests of the flume experiments yielded deviations between 3.7% and 5.6%. Considering the potential sources of errors, that include the variations of radioactive decay of the gamma source, the extra-high requirements on accurately positioning of the measuring system and the minor variations of the sediment supply given to our self-constructed sediment feeding machine, the results can be considered as promising, especially because it allows to observe the process without disturbing the riverbed and to obtain a vertical profile of the infiltration masses. Compared to destructive methods, that have been applied so far for these kind of experiments, the advantages of the GRA method become obvious. Especially because the non-destructive method allows for studying the dynamics of clogging processes. Hence, our future research will focus on experiments to study the dynamic behavior of clogging processes for different sedimentary and hydraulic conditions

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