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Improved geohydraulic characterization of river bed sediments based on freeze-core sampling – Development and evaluation of a new measurement approach

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SUMMARY

Prior to hydraulic engineering work, it is essential to know the geohydraulic properties of river bed sediments as precisely as possible in order to predict and minimize potential effects on adjacent aquifers. Many different methods are available, but all have limitations. Some destroy the natural sediment structure, others lack a small-scale resolution, and all fail to determine anisotropy. In this study, we present a new measuring approach to determine hydraulic conductivity (K) and anisotropy at a detailed scale. Frozen, undisturbed sediment samples taken with the freeze-core technique form the basis of our approach. Orientated core cutter samples are taken from the freeze-cores at different depths and examined by means of falling-head lab permeameter tests, in order to obtain detailed profiles of vertical and horizontal K values and anisotropy. The approach was tested with natural sediment samples from the bed of a channel near Potsdam, Germany, and with samples from an experimental container. For comparison and evaluation, hydraulic conductivities were also determined by means of in situ permeameter tests and empirically, on the basis of grain-size distribution (GSD). The results show a large discrepancy between the empirically determined hydraulic conductivities and the directly measured hydraulic conductivity with lab and in situ permeameter tests. We conclude that empirical methods based on GSD are not suitable for determining in situ conductivity of river bed sediments. Our new approach enables an improved geohydraulic characterization of river bed sediments including the determination of anisotropy.

1. Introduction

The hydraulic interaction of surface water and groundwater is of great importance regarding the resource management of water works using river bank filtration. Furthermore, detailed knowledge of the interaction process is necessary to assess the effects of hydraulic engineering on adjoining aquifers. Therefore, the structure and the geohydraulic properties of the river bed must be known as precisely as possible with regard to its role as a filter medium and its effect on water quality. River bed sediments often act as a filter which retains fine particles of the infiltrate. This causes shrinkage of pore volume and subsequently a consolidation of the filter layer alongside a reduction of hydraulic conductivity and possibly a development of a pronounced anisotropy (Schälchli, 1993). In this context, the hydraulic conductivity and the anisotropy of river bed sediments affect the hyporheic exchange (Salehin et al., 2004) and can be viewed as key variables of this process. There are a variety of methods to estimate the hydraulic properties of river bed sediments on different scales (cf. Kalbus et al., 2006; Rosenberry and LaBaugh, 2008).

Hazen (1893) formulated an empiric way to estimate the hydraulic conductivity K_g of sediments based on their grain-size distribution. For geotechnical and hydrogeological questions, this has become a standard method and can also be applied to river bed sediments. His approach has since been further developed by numerous authors to expand the applicability to different sediment compositions (e.g. Beyer, 1964; Köhler, 1965; Wittmann, 1981), but all methods have restricted application domains. With regard to K value determination, Tavenas and Ladd (1973) conducted a comparative testing program with 41 soil laboratories and came to the conclusion that the gradation test results show a large variability and low reproducibility between individual laboratories. They detected a difference of 20% for estimating d_{10}

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using identical sample material. Matthes et al. (2012) also observed considerable discrepancies in a cooperative program. The determined values for d_{10} of samples consisting mainly of sand varied by 112% amongst the individual testers. The difference was even more significant for silty, clayey specimens, the d_{50} difference being 203%. Especially precise grain-size distributions measured with sieve analysis of samples with a high percentage of fine fractions are more prone to error, as demonstrated by Matthes et al. (2012). The application boundaries of many methods, however, do not exclude such sediment compositions (cf. Hazen, 1893; Beyer, 1964). Uncertainties, which arise by determining the grain-size distribution also influence empirical methods applied to determine the hydraulic conductivity of sediment. This error propagation results in major inaccuracies. Furthermore, Matthes et al. (2012) found that the measurement uncertainty of gradation analysis increased the deviation error of calculated K_g values by several orders of magnitude. In addition, the original sediment structure is destroyed by sieving along with any disrupting mechanisms responsible for an increased hydraulic resistance. Cheng et al. (2013) investigated the influence of (oriented) stratification on the hydraulic properties of sediments. They noted that cross-bedding or other sediment compositions resulted in a significant difference in hydraulic conductivity for varying orientations even if the sediment was well-sorted. Biofilms can lead to a reduction of the hydraulic conductivity of river bed sediments, too (Nevo and Mitchell, 1967; Rinck-Pfeiffer, 2000). Due to the methodological approach by determining the grain-size distribution, the natural structure of the sediment and its natural bulk density is changed. Thus, no information of its initial conductivity in the original structure or the anisotropy can be obtained (Song et al., 2009).

In situ permeameter tests, in contrast, enable the determination of the vertical conductivity K_v of river bed sediment in its original sediment structure (Landon et al., 2001). Song et al. (2009) drew a comparison between in situ permeameter tests and empirically calculated conductivities based on grain-size distribution. Their study showed a systematic variance between the different approaches. The calculated hydraulic conductivities based on empirical methods are considerably higher compared to the values of K_v determined from in situ permeameter tests. Landon et al. (2001) outline other in situ methods to determine the conductivity on a small and medium scale. The horizontal conductivity K_h of river beds can be estimated, for example, with slug and bail tests (Springer et al., 1999). The in situ vertical conductivity K_v can be ascertained if the exchange flow measured with a seepage meter is combined with the determined hydraulic potential distribution in the river bed (Fleckenstein et al., 2006). Only few methods allow the determination of the hydraulic anisotropy of river bed sediments. Systematic errors caused by scale-effects occur if different methods to quantify the vertical and horizontal hydraulic conductivity are combined regardless of their scale dependent application limits. Chen (2000) used in situ permeameter tests to detect the anisotropy of the river bed by adding bent infiltration pipes accompanying the usual infiltration pipes, to measure the horizontal conductivity K_h of the river bed. However, due to the experimental set-up, Chen's (2000) method to determine K_h is restricted to only one specific depth per measuring point. Also, a simultaneous measurement of K_v and K_h is only possible within a range of minor spatial displacement. Yet, in most cases the hydraulic properties of river beds are subject to pronounced spatial heterogeneity (Chapuis, 2012), which would cause further uncertainties, if the method were applied. In another measuring campaign he used the direct-push technology to gain additional depth-oriented information (Chen et al., 2008). This, however, also does not determine the anisotropy directly.

Our study shows a possible way to determine the in situ conductivity and anisotropy of river bed sediments on a small scale, which counteracts and minimizes the negative influence of observational errors and scale effects. The presented approach offers the possibility to determine the hydraulic conductivity of river bed sediments in vertically and horizontally orientated high-resolution. It is built on a series of consecutive experimental steps (Fig. 1) which conclude in a comprehensive understanding of the river bed and its geohydraulic properties. The introduced procedure starts with freeze-core sampling of the river bed (I). The freeze-core sampling technique allows undisturbed sampling of cohesionless sediments by freezing the sediment whilst preserving its original sediment structure. Undisturbed sediment samples can be taken up to a soil depth of 1.5 m. Freeze-core sampling of the river bed can be performed from a boat up to a water depth of 10 m. The next step is taking directionally orientated core cutter samples of different depths from the sediment samples (II). Both types, horizontal and vertical samples, were taken in close proximity to one another. On these samples, falling head permeameter tests under laboratory conditions were performed (III) and thereby the hydraulic conductivities were determined (IV). Based on the determined vertical and horizontal hydraulic conductivities the hydraulic anisotropy can be calculated (V).

To evaluate the performance of our new measuring approach, we compared the results with these of two established methods to determine the hydraulic conductivity of sediments, in situ permeameter tests and empirical methods based on grain-size distribution. Therefore, natural river bed sediment samples and samples taken out of an experimental container were used.

2. The new measurement approach

2.1. Freeze-core sampling

Conventional sampling techniques to extract water-saturated sands as well as unconsolidated silts and clays fail, if the cohesion of the sediment is very low. Whilst inserting and taking out the extraction device, the sample liquefies or is lost (Schreiner and

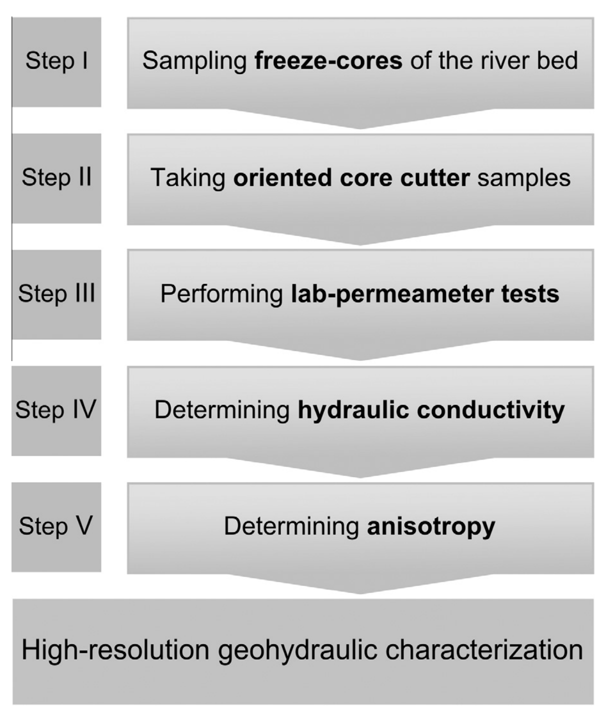

Fig. 1. Flow chart of our new approach to characterize the geohydraulic properties of river bed sediments presented in this study.