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Use Constant-Head Injection Test for In-Situ Estimation of Hydraulic Conductivity in Gravel Bed Rivers

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Synopsis

In order to get more comprehensive understanding of hyporheic exchange in gravel bed rivers, we use modified Constant Head Injection Test method and developed a set of portable equipment to conduct field survey of hydraulic conductivity. Equipment includes a micro water pump powered by portable electricity generator, a manually driven permeameter made by steel pipe, measuring cylinder, and several accessories. Problems were detected during the trial in Tenryu River and Koshibu River and improvements were made afterwards.

Keywords: CHIT, hydraulic conductivity, *in-situ* measurement

1. Introduction

For the last two decades the number of studies focused on hyporheic zone has been significantly increased (Boulton et al., 2010；Roberson and wood, 2010). The hyporheic zone is defined as an active ecotone between the river flow and the underlying groundwater where water flows through the substrate (Boulton et al., 1998). Other definitions depicted hyporheic zone from chemical and biological aspects respectively (Williams, 1989; White, 1993).

The ecological importance of the hyporheic zone has been recognized and documented since 1953 (Orghidan, 1953; 1959). Perhaps the most well-known ecological function of hyporheic exchange (surface water interact with subsurface water) is the supply of oxygen into the substrate and the consumption of oxygen within. For instance, Fig. 1 shows some fish species spawning their eggs in several centimeters' depth into sediment and these eggs will live on the dissolved oxygen entrained by the downwelling flow. Whitman and Clark (1982) found that the oxygen rate tended to decrease with the deeper interstitial, he proposed that respiration of organic sediments carried by the spate or infusion of low oxygen could be the possible reasons. Moreover, the mixing of ground water and surface water could result in cooling water coming out from the upwelling zone which provide a refuge for aquatic organisms and hyporheos in hot summertime (Hester and Doyle et al., 2009). The interaction between groundwater and surface water in the hyporheic zone can also significantly influences nutrient regimes in riparian environments, which creates an ecotone with unique ecological conditions (Brunke and Gonser, 1997).

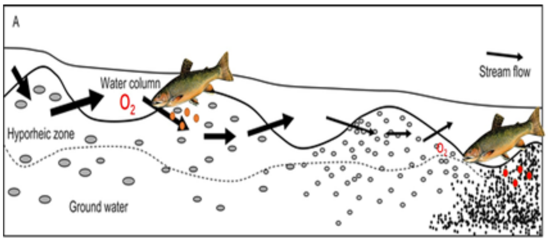


Fig. 1 Schematic view of salmon fish spawning red in gravel bed river (Andrew J. Boulton et al, 2010 and adapted).

The hyporheic exchange is largely controlled by hydraulic conductivity (Cardenas and Zlotnik, 2003). However, the natural riverbed hydraulic conductivity either showed static or homogeneity, it is rather dynamic and could be great heterogeneity. A main reason could be fine sediment intrusion (Malcolm et al., 2010). To study the natural evolution of K is important for scientist and river managers to better understand the complexity of hyporheic exchange.

The decrease of K within the top layer of sediment could be possibly caused by 1) hyporheic flow 2) biological activity 3) gas bubble nucleation (Song et al., 2007). Nowinski (2011) examined the evolution of K in a point bar within a year in an artificial meandering channel using 53 groups of mini piezometers, he concluded that the changing of K is because of the fine sediment movement and clogging the interstitial of sediment. While in natural rivers it is difficult to use such kind of method because the unsteady flow conditions and time and resources are continuously needed in the field.

In order to better manage or restoring the river ecosystem it is essential to acquire in-situ hydraulic conductivity data for the simulation and modeling of the K using computer could be far from the actual value.

Here we focus on in-stream technic rather than modeling and laboratory-based methods. For our purposes are to use a portable set of equipment to quickly estimate general in-situ riverbed hydraulic conductivity and to get dense data to cover as much area as we can to get a picture view of the hydraulic conductivity distribution map at the reach scale. Hopefully to lean about the spacial and temporal changing pattern of the near bed K and more importantly, why and what will cause the K change and how to manage with engineering methods, in order to have better ecological function or water purification ability.

Usually it is difficult to directly measure the streambed hydraulic conductivity, due to it is usually beneath the riverbed and submerged by stream water, especially for the in-situ estimation or in relative larger spatial scale and intensity survey. Especially for the hard gravel bed rivers, the cobbles could easily make the pipe (permeameter) tip and body deformed. The traditional ways to investigate the riverbed hydraulic conductivity such as standard slug test, grain-size analysis and observation wells are both time and resource-consuming procedure.

In order to quicker and use less resources to get intensive information of riverbed hydraulic conductivity in the field, we use modified Constant Head Injection Test (CHIT) method and beforehand-made spread sheet to estimate the in-situ riverbed hydraulic conductivity and capable to get the result almost immediately. This method fits better for large scale and intensively survey of the gravel bed river especially with low accessibility.

CHIT method

For sub-meter scale we assume

Kh=Kv=K

$K=Q/2\pi LPy$ (Cardenas, 2003) and (Cho, 2000)

Where:

Kh is horizontal hydraulic conductivity

Kv is vertical hydraulic conductivity

K is the general hydraulic conductivity

Q is the stabilized injection rate

L: screened length

P: shape factor (dimensionless coefficient)

y: distance between stream stage and the desired water level in the permeameter

$$\boldsymbol{P}=\frac{1.1}{\ln((l+L)/r_w)}+\frac{\mathrm{A}+\mathrm{B}\ln[b-(l+L)/r_w]}{L/r_w}$$

Where: A and B are dimensionless coefficients that were originally in graphic form. These coefficients were approximated by Van Rooy (1988) (details in Butler, 1998).

The constant head injection test is standard tool used by many soil and civil engineers. While the original idea is for measuring the low K value media, for example, silt and clay. We use the modified CHIT method developed by Cardenas and Zlotnik to measure the higher K value rivers such as gravel bed rivers. Using the modified CHIT theory, we only need to measure the Q and y in the field, other values are given. By using a spreadsheet, the K value can be calculated in the field.

The purposes of this report are to show the instrumentation, field process and data analysis for using the CHIT method to study the gravel bed rivers in Japan and also try to identify the aquifer thickness b’s impact on the calculation result of K. For the development of the theory please refer the following papers (Bouwer and Rice, 1976; Dagan, 1978; Cardenas and Zlotnik, 2003).

2. Methodology

The permeameter was designed for relative high K value riverbed materials such as gravel and sandy rivers. The total length of the pipe is 1220mm (1200+20mm inside the cap), the inner diameter of the pipe is 45 mm, the outer diameter is 50mm, the thickness of the pipe wall is 2.5mm. The tip of the instrument is a solid cone which the height is 75mm and the circumference is 50mm. The cone is made of solid steel. The bottom part of the pipe is the hole area, the length is 200mm. Diameter of all the holes is 5mm, the vertical distance between two holes is 40mm and the lateral distance is 15mm. There are 110 holes in total, 10(vertical row) ×11(lateral row).

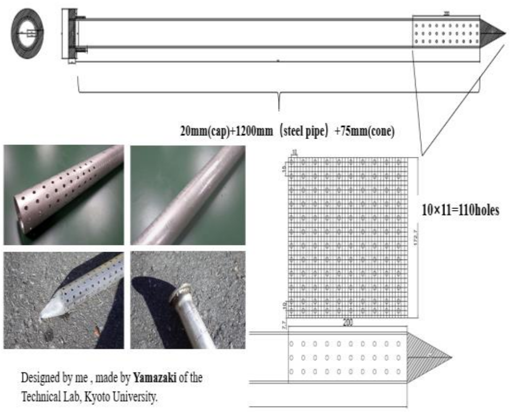


Fig. 2 Design of the permeameter

Stream water was collected in a bucket (without much suspended load, which could clog the hole area and streambed sediment), then pumped into the permeameter by a micro water pump which can adjust the discharge manually in order to keep a constant water level in the top of the permeameter. As the water level attained the designed height y and was steady (e.g. for 10s to several minutes), pull out the pipe into a volume cylinder, as the same time start the timer, thus the injection rate Q can be measured.

During the pre-test we found that funnel is unnecessary because as the water level goes up it can flow out from the interstitial of the funnel and pipe, instead we just keep a constant water level same as the top edge of the pipe.

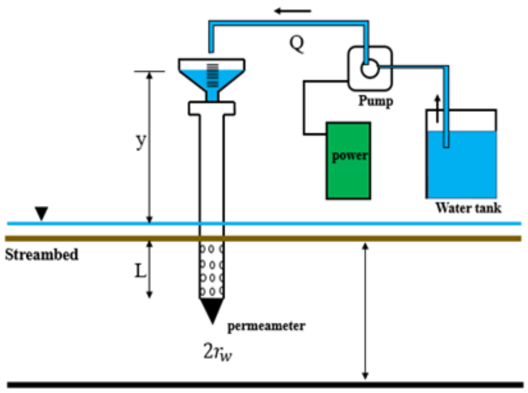


Fig. 3 Illustrate of Instrumentation

Known test geometry, injection rate Q and operational head y, K can be easily calculated.

3. Field Survey and Result

Photo 1 First trial in Tenryu river

The first trial was conducted in the upstream of Tenryu river on Oct 29th, 2018 as showed in photo 1. The riverbed is characterized by coarse materials and newly deposited sediment. K value was expected to be very high. At first, we tried to measure the hydraulic conductivity of the top 20-30cm layer of the riverbed. While when stream water was pumped into the pipe it just went down into the very loose sediment instantly, which means the K was too high for this instrument to measure. As we hammered the pipe into the 80cm depth, the water table inside the pipe was steadily kept by adjusting the micro water pump, Q was measured by a volume cylinder. As calculated, K=0.01429 cm/s= 12.35m/day.

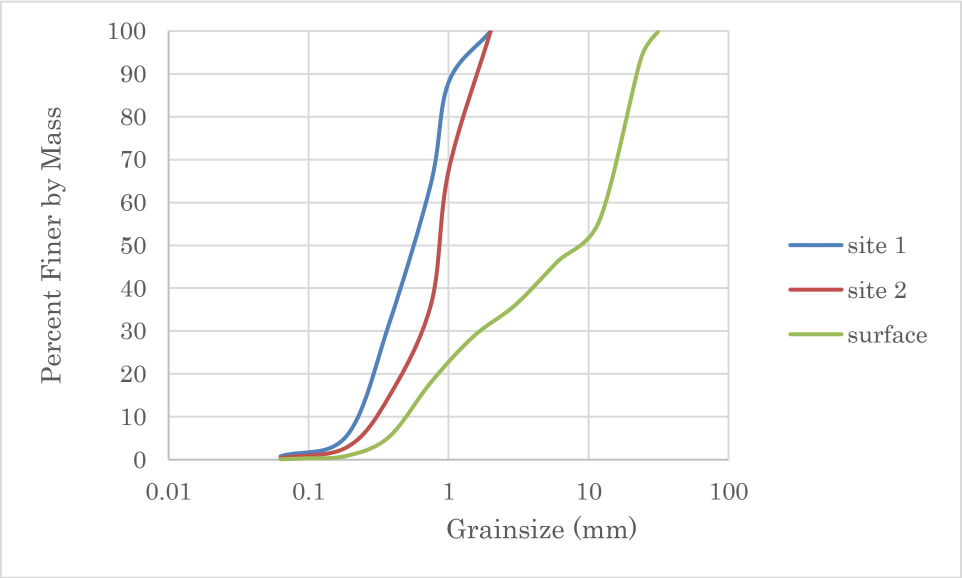
We conducted a second trial in Koshibu River on January 23rd, during low flow conditions. Study site is located downstream of Koshibu dam, during low flow seasons the dam stores water and supply to an off-channel hydropower station. The dam releases about $1m^3/s$ discharge as an environmental flow to the downstream channel. A sediment bypass tunnel was built and operated from 2016 in order to discharge the sediment from upstream of Koshibu dam (Auel et al., 2017). The tunnel was operated and discharge large amount of sediment to downstream channel during last summer high flow events, thus the riverbed and newly deposited gravel bar tend to have larger interstitial spaces therefore high hydraulic conductivity at least within the top layer. Same with Tenryu River, the hydraulic conductivity of top layer was too high for this instrument, we can only measure the 50cm depth K. Study site 1 is located about 2000m downstream of Koshibu dam, in the field we measured that y=50cm l=45cm, and Q=80.53323cm3/s, with assumed aquifer thickness is 500cm, we calculated K=0.0189 cm/s=16.30m/day, which is less than the normal range of K in gravel and sandy rivers, see figure 5 (Freeze and Cherry, 1979). That is probably because the fine sediment intrusion from the ground water aquifer, to specify the reason need more knowledge of groundwater fluctuation data around this area.

Site 2 was selected just the opposite site of site 1 in order to check the heterogeneity of the hydraulic conductivity between neighboring bars. In site 2 hydraulic conductivity in 50cm depth was calculated 0.04456 cm/s, which equals to 38.50m/day, about twice times that of site 1. We also collected sediment samples that infiltrated into the pipe trough the holes from the two measuring sites and one bag of surface sediment sample. Samples were brought back to laboratory and standard sieving method was conducted after completely dry up. Table 1 shows the sample measured and based on the results, grainsize distribution curves were generated (table 2). From the table we can see the percentage of particle size under medium and fine sand (0.25-0.5mm) in site 1 (31.6%) is much higher than site 2 (14.7%) and surface sample (5.3%), which could explain why K measured in site 1 is smaller than the K in site 2. In addition, during the test particle size under 0.063 wasn’t taken into account, further study should emphasis the influence of fine material on hydraulic conductivity (e.g. to learn the quantitative relationship between fine sediment that infiltrated into the interstitial of riverbed and the decrease of K).

Table 1 Sediment samples from Koshibu river

	Site 1 (from pipe)			Site 2 (from pipe)			Site 3 (surface)		
Sieve(mm)	Weight (g)	Percentage	cumulative	Weight (g)	Percentage	cumulative	Weight (g)	Percentage	cumulative
>31.5							64.5	6.3	100.0
16-31.5							387.3	37.8	93.7
8-16							99.6	9.7	55.9
4-8							103.1	10.1	46.2
2-4	52.8	12.0	100.0	63.8	32.6	100.0	75.7	7.4	36.1
1-2	103.1	23.4	88.0	60.9	31.1	67.4	109.3	10.7	28.7
0.5-1	145.0	33.0	64.6	42.2	21.6	36.3	131.1	12.8	18.1
0.25-0.5	114.4	26.0	31.6	23.1	11.8	14.7	44.7	4.4	5.3
0.125-0.25	21.1	4.8	5.6	4.9	2.5	2.9	60.	0.6	0.9
0.063-0.125	3.5	0.8	0.8	0.8	0.4	0.4	2.0	0.2	0.3
<0.063							1.2	0.1	0.1
total	439.9	100.0		195.7	100.0		1024.5	100.0	

Table 2 Grainsize distribution curve



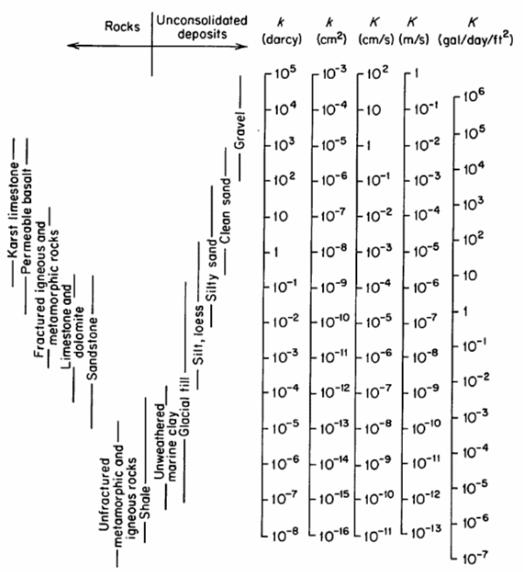


Fig. 4 Ranges of values of hydraulic conductivity and permeability for various geological materials (Freeze and Cherry, 1979).

4. Applicability

For both the first and second trial we do not have accurate b value which is the aquifer thickness, to know how calculated result K sensitive to b value change we use data from first and second experiment to test b depth under 7m. Before that we have tried to calculate K with b extreme conditions. As a result, as b ranged from 7m-100m, K only changed 1%, thus we were eager to know how K is sensitive to b under 7m.

We used the data source from the first trial and second trial. As b changed from minimum depth (that can be measured by this instrument) to 700cm, K changed from 0.006318cm/s to 0.006157cm/s, which equals to: 5.4588m/day to 5.3196m/day, means even without very accurate b value we still can use CHIT method to realize our purposes.

5. Discussion

Here we introduce a quick and mobile method for in-situ estimation of riverbed hydraulic conductivity, it aims not for very accurate determination of sediment column samples in small scales in the lab, instead, we use it mainly for intensive and reach scale survey, in order to knowledge general conditions of hydraulic conductivity in near bed layer or within geomorphic units such as sandbar and gravel bar. We have already modified the design of the permeameter in order to practice in possible high K rivers such as gravel bed rivers, however, during the field survey it seems that the apparatus still easily reaching the upper limitations for the rivers which has newly deposited gravel and sand tend to have much higher K than this instrument’s ability. Next step we want to increase the measurement ability of the permeameter for gravel bed rivers that have high

K. Another issue should be noticed is the strength of the pipe, after several trials because of the sledgehammer, the top and the tip of the permeameter had some deformation, we already contacted technical lab and reinforcement work had already be done.

For the next field survey, we plan to work within a small point bar in Katsura River, we also plan to use other method to measure K in same points in order to compare the results from different measuring methods.

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