A Probe for Measuring 3D Groundwater Velocity without a Borehole

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1. Introduction

Recently, there has been a growing demand for the investigation of groundwater flow velocity for the purpose of the maintenance of dykes or reservoir for irrigation. In well technique measurement, a Heat Pulse Flowmeter (HPF) with four channels and electrical conductivity detectors placed inside the well provides centimeter scale readings for depth profile velocities[1)]. Besides, the point velocity probe (PVP) rapidly measures direction and magnitude of the water velocity vector to within 9% and 8 degrees at the centimeter scale in porous media without need of calibration[2)]. Similarly, an automated on-line groundwater velocity probe measures flow velocity within a screened well. It uses a flushed semi-permeable gas chamber with a gas tracer, the tracer diffusion period determines groundwater velocity[3)]. Besides, a cost-effective in situ method for precisely measuring groundwater flow velocity based on groundwater-induced cooling was also presented using closed circulation of heated fluid, the experiment established the functional relationship between temperature differences and groundwater velocity[4)]. In response to this need, a power-free, inexpensive, and time-efficient measurement probe has been developed[5)]. This novelty probe is called Paper Disk Groundwater Velocimeter (PDGVs). In 2016, the PDGVs sensor paper was enhanced, resulting in a single dot with a 3 mm diameter positioned at the center of the paper. This improved sensor’s paper resulted in an alignment curve of the relationship between Darcy flow velocity and tailing lengths of giving period 5 and 60 minutes for ranged velocity of 0.3 cm/min -1.5 cm/min[6)]. Furthermore, existing devices can measure groundwater flow in three dimensions. However, the devices still need boreholes to be measured[7)]. If no borehole is needed for measurement, the measurement of the groundwater flow in dyke or reservoir will be much easier. For this reason, we developed a new small device with absence of boreholes which can measure 3-dimensional groundwater flow velocity and direction.

2. Methods

2.1. Micro-paper disk groundwater velocimeter

The Micro Paper Disk Groundwater Velocimeters (M-PDGVs) were invented based on the principle of the paper disk groundwater velocimeter[6)]. The M-PDGVs have two types, vertical 2D and horizontal 2D. These types consist of 1000 mm extension rod along with paper disk of 29 mm x 10 mm size and 2 mm diameter dot for vertical 2D type, and 10 mm x 10 mm size with 1 mm diameter dot for horizontal 2D type. The ability of these micro types to measure the two directions of the flow both vertical and horizontal directions.

2.2. Experiment methods

The purpose is to verify horizontal and vertical velocity and direction with M-PDGVs. A water tank filled with quartz sand (d_{50} = 0.5 mm) was used for calibration of the Micro-PDGVs (Figure 2). Using a peristatic pump, groundwater flow was generated in the sand tank. The horizontal 2D type setting velocity ranged from 0 cm/min – 0.12 cm/min with changing horizontal flow direction stepwise from 130 deg to 220 degrees over a measurement period of 60 minutes. However, the vertical 2D type measurement condition was undertaken for 15 minutes period with the measured velocity ranged from 0 cm/min – 0.1 cm/min and vertical inclination from -45 to 45 degrees as omnidirectional and inclinational tests. These experiments were conducted 5 times for each condition.

2.3. Analysis methods

In the analysis phase, the first step involved the original paper solely with dot ink, which was subsequently eluted after the probe was submerged into the soil. Thereafter, the dot generated a tailing that aligned with the water flow directions over a certain period. The dot and tailing length were analyzed with an open-source image analysis software, Image-J, after scanning the paper. Channel separation for the experiment included the Red, Green, and Blue (RGB) colors. The brightness, specifically a value of 105 in the red channels, was used for dot detection and the brightness of blue channels and red channel were used for tailing detection.

The following flowchart illustrates the mechanism. The ideal ink tailings area, shown in Fig. 4 a), was close to an ellipse. Therefore, in order to assess the quality of the ink tailings, the ratio of the area of the ellipse to the area of the ink tailings was calculated, with its maximum Feret diameter D_{Fmax} as the major diameter and its minimum Feret diameter D_{Fmin} as the minor diameter. For a, the ratio of the approximate ellipse area to the ink tailings area was 0.9, and for b, in contrast, the ratio was 0.7. The quality of tailing length Q is calculated using the area of the ink tailing A and ellipsoid area A' as below (1) and (2).

$$Q = \frac{A}{A'} \tag{1}$$

$$A' = \frac{\pi}{4} D_{Fmax}\ D_{Fmin} \tag{2}$$

The length of the tailing by the eluted ink from the printed dot was identified from the scanned color image of the paper disk using blue and red channel based on machine classification. The longitudinal red channel's brightness distributions of the tailings of ink were used to estimate groundwater flow velocity. The brightness distributions were acquired using the multiple thresholds of the red channel. When the brightness of the red channel is correlated to the concentration of the ink on the paper, the relationships between concentration of the ink on the paper and brightness of the red channel (B_R) are written as (3).

$$C = \alpha(255 - B_R) \qquad (0 \leq B_R \leq 255) \tag{3}$$

When the relationships between C and velocity v is written as

$$\frac{dC}{dx} = -\alpha\frac{dB_R}{dx} = -\frac{\beta(t)}{v}$$

then

$$v = \frac{\beta(t)}{\alpha}\left[\frac{dB_R}{dx}\right]^{-1} \tag{4}$$

Where: C: ink concentration on paper (g cm^{-2}), B_R: brightness of red channel (-), x: distance on paper (cm), α : coefficient (g cm^{-2}), β(t): coefficient (g cm^{-4} s)

Table 1 The details of the M-PDGVs vertical 2D and horizontal 2D types

Device Types	Materials	Dimensions
Vertical 2D	Paper	10 mm x 29 mm 2 mm diameter dot
	Sponge	29 mm x 6 mm x 10 mm
Horizontal 2D	Paper	10 mm x 10 mm 1 mm diameter dot
	Sponge	10 mm x 6 mm x 29 mm (2 units)

Table 2. The velocity and direction measured condition in the laboratory experiment for both the vertical 2D and horizontal 2D M-PDGVs.

Measurement Devices	Direction	Time (minute)	Mean Tank Velocity (cm/min)
Vertical 2D	Setting tilt (0°, 15°, 30°, 45°, -15°, -30° & -45°)	15	0 0.05 0.08 0.1 0.2
Horizontal 2D	Northward Orientation (-40°, -10°, 5°, 20° & 50°)	60	0 0.01 0.02 0.04 0.08 0.12

3. Results and Discussion

3.1. Vertical 2D measurement results

Fig. 5 illustrates the relationship between the tailing length of the vertical 2D type M-PDGV and the reciprocal of the ink brightness differential. This relationship is linear, with a high correlation coefficient (R2 = 0.9267). Fig. 6 depicts the errors in the vertical inclination direction at a velocity of 0.1 cm/min, within a range between -45 degrees and 45 degrees.

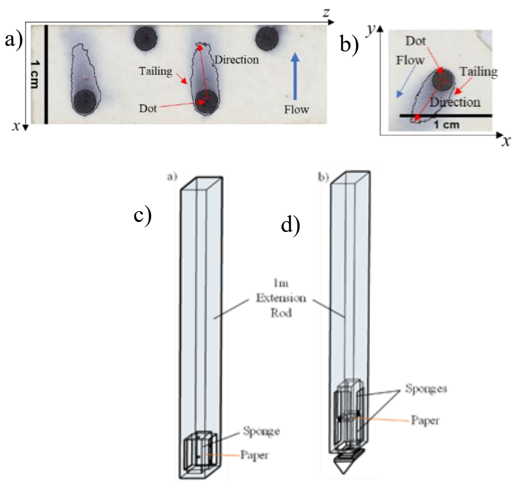

Fig 1. Two types of M-PDGVs: a) vertical 2D type and b) horizontal 2D type. The paper disk of M-PDGVs sensor after measurement is shown in c) vertical 2D type [tilt = 0°] and d) horizontal 2D type [direction = 220°] *x* axis and *y* axis are on the horizontal plane. z axis is vertical.

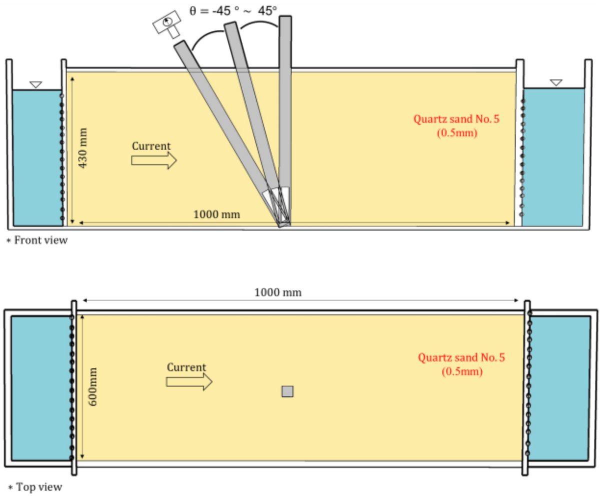

Fig 2. The water tank front and top view were used for vertical 2D and horizontal 2D M-PDGVs experiment.

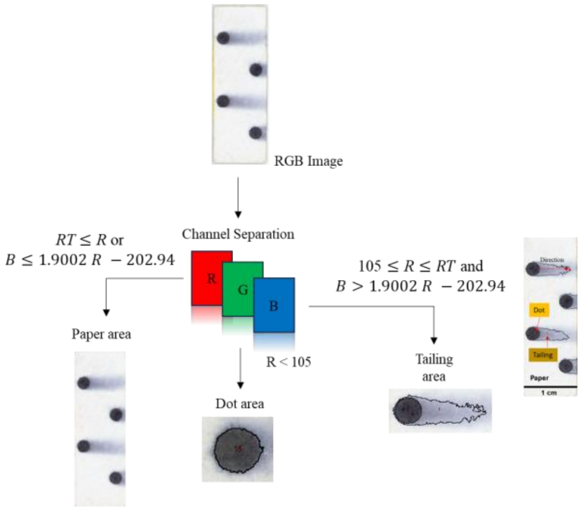

Fig 3. The channel separation analysis for the scanned paper dot and tailing, where the range of threshold *RT* at 175 – 215, the red channel *R* for dot detection 105 and the maximum brightness *B* 255.

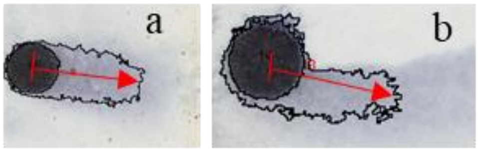

Fig 4. The quality of the ink tailing at vertical orientation [tilt = 0°]. a) tailing quality = 0.9, b) tailing quality = 0.7.

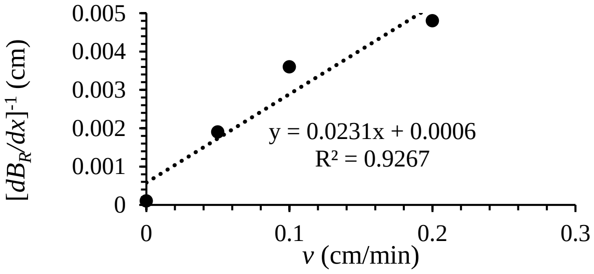

Fig 5. The calibration line of calculated tank (Darcy) velocity *v* and inverse of the derivative of brightness of red channel with respect to distance on the paper *x*; *t* =15 min.

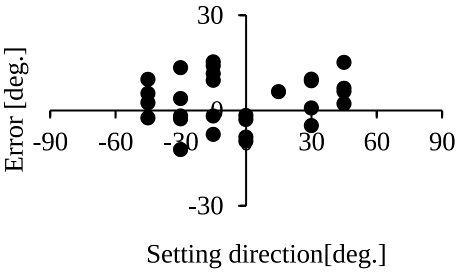

Fig 6. Relationship between setting direction and error direction of vertical 2D type at velocity = 0.1 cm/min

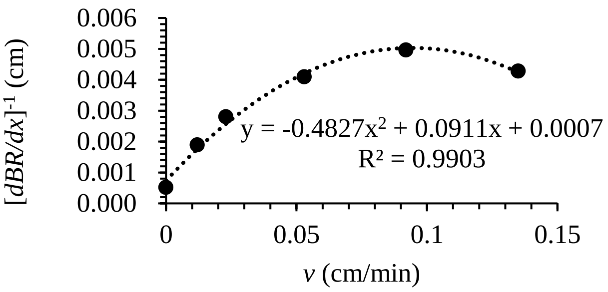

Fig 7. The calibration line of calculated tank (Darcy) velocity v and inverse of the derivative of brightness of red channel with respect to distance on the paper x; t =60 min

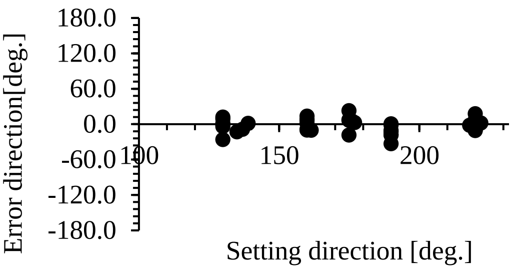

Fig 8. Relationship between setting direction and error direction of horizontal 2D type [direction = 130° – 220°].

Table 3 The omnidirectional and inclinational test results of horizontal 2D and vertical 2D groundwater flow directions measurements by M-PDGVs.

Type	Velocity [cm/min]	Time [mins]	SD [deg.]	RMSE [deg.]
Horizontal 2D	0.01 – 0.135	60	12.89	12.52
Vertical 2D	0.05 - 0.2	15	10.25	11.12

3.2. Horizontal 2D measurement results

Fig. 7 illustrates the regression curve of the horizontal groundwater flow and the measurement results. Since there is convex curve on the top, the upper limit of measurement is around 0.06 cm/min. Horizontal directions are shown in Fig. 8. Table 3 shows standard deviation (SD) and root mean square error (RSME) values for horizontal 2D and vertical 2D measurements. For horizontal 2D, the standard deviation measured was 12.89 degrees, showing a range of variability within -40 to 50 degrees based on horizontal orientation. The corresponding RSME is 12.52 degrees. As for vertical 2D device, the standard deviation of the vertical direction was 10.25 degrees and RSME was 11.12 degrees.

4. Conclusions

The set of groundwater velocity probes, M-PDGVs, which can measure three-dimensional groundwater flow velocity without a borehole was invented and evaluated. The velocity probes consistently showed linear responses to velocities ranging from 0 to 0.2 cm/min. In addition, both horizontal and vertical directional incline tests revealed that tailing tilt fitted alignment of the sensor inclination. This measurement emphasized the capability of M-PDGVs in detecting small-scale subsurface water movements. While the experiments were conducted in laboratory testing, the adaptability and precision of this probe suggest potential applications in such relevant field environments. This novelty is applicable in measuring groundwater flow in diverse environments were found to be challenging, including river embankment, ponds, tidal flat, wetland and micro-scale contamination areas.

References

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