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The Characteristics of Hydrogeological Parameters of Unconsolidated Sediments in the Nakdong River Delta of Busan City, Korea

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ABSTRACT

This study dealt with the characteristics and the interrelations of hydrogeological parameters such as hydraulic conductivity, dispersivity and effective porosity of unconsolidated sediments for providing the basic data necessary for the planning of the management and preservation of groundwater quality in the Nakdong River Delta of Busan City, Korea. Groundwater quality in this area has been deteriorated due to seawater intrusion, agricultural fertilizer and pesticide, industrial wastewater, and contaminated river water. The physical properties (grain size distribution, sediment type, sorting) and aquifer parameters (hydraulic conductivity, effective porosity, longitudinal dispersivity) were determined from grain size analysis, laboratory permeability test and column tracer test. Among 36 samples, there were 18 Sand (S), 7 Gravelly Sand (gS), 5 Silty Sand (zS), 5 Muddy Sand (mS), and 1 Sandy Silt (sZ). Hydraulic conductivity was determined through a falling head test, and ranged from 9.2×10^{-5} to 2.9×10^{-2} cm/sec (0.08 to 25.6 m/day). From breakthrough curves, dispersivity was calculated to be 0.35~3.92 cm. Also, effective porosity and average linear velocity were obtained through the column tracer test, and their values were 0.04~0.46 and 1.06E-04~6.49E-02 cm/sec, respectively. Statistical methods were used to understand the interrelations among aquifer parameters of hydraulic conductivity, effective porosity and dispersivity. The relation between dispersivity and hydraulic conductivity or effective porosity considered the sample length, because dispersivity was affected by experimental scale. The relations between dispersivity and hydraulic conductivity or effective porosity were all in inverse proportion for all long and short samples. The reason was because dispersivity was in inverse proportion to the groundwater velocity in case of steady hydrodynamic dispersion coefficient, and groundwater velocity was in proportion to the hydraulic conductivity or effective porosity. This study also elucidated that longitudinal dispersivity was dependent on the scale of column tracer test, and all hydrogeological parameters were low to high values due to the sand quantity of sediments. It is expected that the hydrogeological parameter data of sediments will be very useful for the planning of groundwater management and preservation in the Nakdong River Delta of Busan City, Korea.

Key words : Unconsolidated sediments, Grain size, Hydraulic conductivity, Dispersivity, Effective porosity

1. Introduction

The coastal area is the center of people residence, industrial and economic activities in the world. Busan is the representative city developed at the coastal area in Korea. New York, San Francisco, and Los Angeles of America, London and Liverpool of England, Sydney and Melbourne of Australia, Tokyo and Osaka of Japan, Singapore, and Hong Kong are also very large cities in the coastal area. In Korea, the largest delta is developed in the west side of Busan City which is located at the downstream of the Nakdong River. The large-scale economic, industrial, and agricultural activities have been carried out in the Nakdong River Delta. Gimhae International Airport, Myongji Free Economic Zone, Noksan National Industrial Complex, Hwajeon General Industrial Complex and greenhouses of tomatoes and

vegetables were established in the delta area.

Groundwater quality in this area has been deteriorated due to seawater intrusion, agricultural fertilizer and pesticide, industrial wastewater, and contaminated river water (Chung et al., 2014). The groundwater cannot be used for agricultural or industrial uses as well as dinking purpose. Nevertheless, the study of groundwater contamination in this area is still in the beginning stage. The main chemical components of groundwater contamination are Na, Cl, SO_4, NO_3, and Br including the heavy metals of Fe, As, Mn, Zn, and Al (Chung et al., 2016).

Groundwater management and remediation should be performed for the improvement of groundwater quality in the Nakdong River Delta, because many people live at this area, and an Eco-Delta City and a new international airport are going to be constructed here. The basic groundwater data are necessary for groundwater management and preservation in the delta area. Accurate hydrogeological data are very essential for the understanding of groundwater flow, potentiometric surface of groundwater and advection-dispersion of contaminants.

Hydraulic conductivity and effective porosity are considered as the most significant properties in the groundwater hydrology, but it is difficult to determine the accurate values because of the heterogeneity of geological materials and experimental conditions (Gohardoust et al., 2017). Accu-

rate estimation of the hydraulic conductivity and effective porosity are substantial to the analysis of the magnitude of water exchange and contaminant transport between groundwater and surface water, and to solve a number of relevant geotechnical problems such as groundwater seepage from tunnel, land subsidence and landslide (Boadu 2000; Chen et al., 2008; Landon et al., 2001). Dispersivity is necessary to determine the mechanical dispersion in the process of contaminants transport through porous media, and it can be determined by a laboratory column tracer test (Singh, 2002).

The main objectives of this study were (1) to determine the hydrogeological parameters such as hydraulic conductivity, dispersivity and effective porosity of unconsolidated sediments for providing the basic data necessary for the management and preservation of groundwater quality in the Nakdong River Delta, and (2) to understand the hydrogeological characteristics of the sediments, and the interrelation of hydrogeologic parameters. Thus, the undisturbed sediments were collected, and three types of parameters such as hydraulic conductivity, effective porosity and dispersivity were determined by falling head permeameter and column tracer tests.

2. Hydrogeological setting

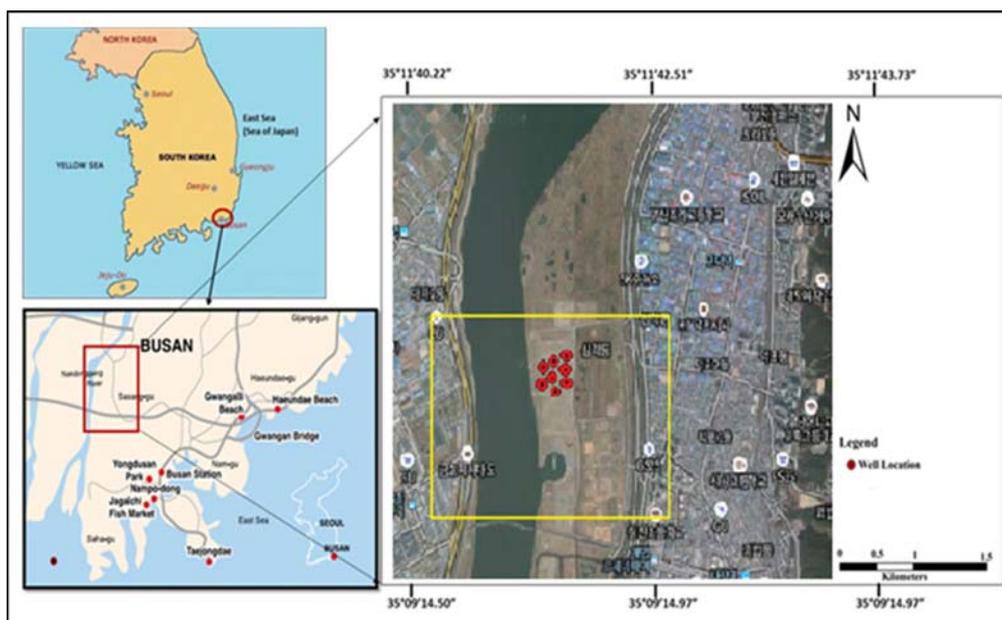The study area is located at the downstream of the Nak-

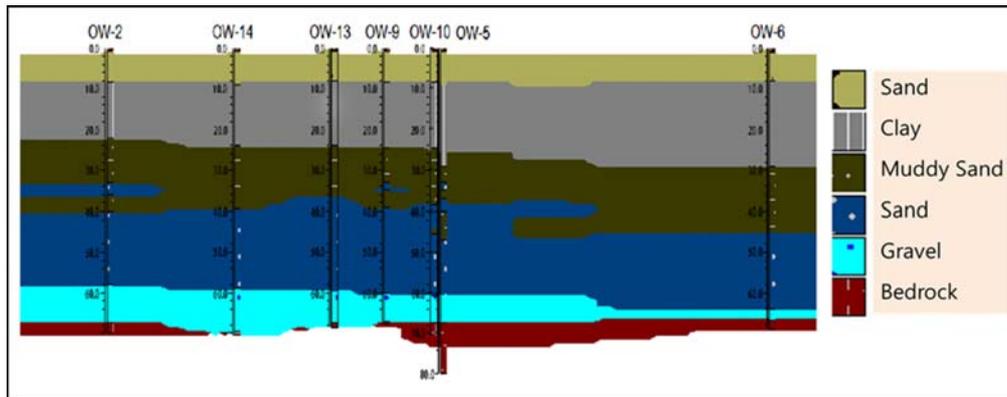**Fig. 1.** Location map of the study area.

Fig. 2. Geological cross section of the study area.

dong River in the Gangseo-gu of the Busan Metropolitan City, Korea (Fig. 1). The length of the Nakdong River is 525 km, and the total watershed area is 24,000 km². The river has eight main tributaries. The river flows from Andong City, Gyongbuk Province to the Busan Metropolitan City, Gyongnam Province, and it is finally connected to the South Sea of Korea. During the monsoon season of summer, flood event frequently occurs in the study area, and many sediments and organic materials deposit in the river banks. The delta deposits are about 60~90 m deep, and composed of backfill, muddy sand, clay, muddy sand, sand and gravel in sequence (Chung et al., 2015; Won et al., 2015). The thickness of upper muddy sand layer is ranged from 5 to 10 m, clay layer from 10 to 30 m, lower muddy sand from 10 to 15 m, sand layer from 20 to 25 m, and gravel layer from 5 to 10 m, respectively (Fig. 2).

The delta sediments was deposited from the Tertiary Period of the Cenozoic Era, and they were also eroded during the time of the deposition due to sea-level change (Yoo et al. 2014). Thus, it is estimated that most of the sediments was deposited in the Quaternary period. The upper muddy sand took place in the Holocene period. The basal gravel bed indicates an unconformity between delta sediments and bedrock. The bedrock consists of hornblende granite formed in the Cretaceous period of the Mesozoic Era (KIGAM, 1983). Thus, it is estimated that the gravel layer was deposited from the Tertiary Period. The upper muddy sand layer is relatively soft and loose, but lower pure clay layer is stiff and dense. The study area forms two types of aquifers on a basis of clay layer, i.e., an unconfined aquifer of muddy sand layer and a confined aquifer of sand-gravel layer. The

salinity of confined aquifer is 26~28 ‰, and that of unconfined aquifer is 0.6~1.0 ‰ (Chung et al., 2015).

The industrial complex sites are located beside the Nakdong River as well as at the upstream of the river. Some of the factories are also managed around the study area. Rice paddies and greenhouses of fruits and vegetables are managed in the delta. Many houses, roads, and airport are also located at the deltaic region. Accordingly, some contaminants such as nitrate, phosphate and some inorganic and organic materials have come into the Nakdong River and groundwater of the Nakdong Delta. The mouth of the Nakdong River is connected toward the South Sea of Korea, and the seawater is intruding the river and the coastal groundwater.

3. Materials and methods

The parameters of hydraulic conductivity, effective porosity and dispersivity are very important to enhance the understanding of the hydrogeological properties of the geological materials. In this study, grain size analysis, permeability test and tracer test of sediments in the Nakdong River Delta were carried out to produce the hydraulic conductivity, effective porosity and dispersivity of the sediments.

3.1. Grain size analysis
36 sediment samples of the Nakdong River Delta were used for grain size analysis. 6% H_2O_2 solution and 10% HCl solution were used to eliminate the organics and carbonates, respectively. After eliminating the organics and

carbonates, the sediments were washed three times to get rid of salt in the sediments using the distilled water. The pretreated sediments were graded into two parts by the 4Φ (0.0625 mm) sieve. Sediments (sand or gravel) over 4Φ were analyzed by a Ro-Tap Sieve Shaker, and classified into 1Φ interval. The sediment (silt or clay) less than 4Φ were analyzed by Automatic Grain Size Analyzer (Malvern: Mastersizer Micro) after dispersing with 50 ml of 2% Sodium Hexam-etaphosphate solution, and they were classified into 1Φ interval.

3.2. Permeability test

Hydraulic conductivities of sediments were produced using a falling head permeameter. Falling head test is a common laboratory method to determine the hydraulic con-ductivity for the medium to fine grained sediments or soils. Falling head permeameter consists of a column of sediment sample and a standpipe providing water, and measures the volume of water passing through the sample. The hydraulic conductivity of the sample was calculated as the following equation (Fodor et al., 2011).

$$K = \frac{A_c \cdot L}{A_s \cdot t} \ln\left(\frac{h_0}{h_t}\right) \tag{1}$$

where L is sample length, A_s is cross section area of sam-ple, A_c is cross section area of the standpipe, t is the total time of water flow though the sample, h_0 and h_t are the ini-tial and final water levels in the standpipe above the same water head reference.

3.3. Column tracer test

One-dimensional column test is very useful to determine the longitudinal dispersion coefficient and average linear velocity of an unconsolidated porous medium. Recently, longitudinal and transverse dispersivities could be determined by the laboratory image analysis using sodium fluorescein as tracer (Citarella et al., 2015), and by laboratory column test using CO2, N2, and O2 gas tracers in the soil contaminated with VOC or petroleum (Hibi et al., 2012). The longitudinal dispersivity was also determined by self-potential signals in the electrodes into the sand sample, and this method had a good result as traditional concentration method (Straface and De Biase, 2013).

In this study, 36 samples (23 long samples and 13 short samples) were used for the column test using sodium bro-mide (NaBr) tracer. The length of long samples was from 32 cm to 39.5 cm, and short sample was from 17.4 cm to 22.8 cm, respectively. Bromide concentration was mea-sured by bromide electrode of pH/ISE Meter (Model: Istek pH-250L). Breakthrough curves were produced on basis of the relative concentrations of tracer (a concentration at the specific time (C(t) over the initial concentration (C_0)) versus the elapsed times (t) for all samples. Column tracer test was simultaneously carried out with the permeameter test of hydraulic conductivity, using the undisturbed sediment sam-ples. The tracer test needed the elapsed time from 10 minutes to 4.44 days according to samples. Although the experimen-tal time was short for pure sand or gravelly sand samples, it was very long for sand samples bearing mud or silt.

3.4. Effective Porosity

Porosity is one of the most important properties in porous media. The pore space can be divided into an intercon-nected space that allows fluid to flow, and a disconnected space that is unavailable for fluid flow. Two types of poros-ity can be defined as volumetric porosity and effective porosity. Volumetric porosity is the ratio of all pore spaces to the bulk volume in a porous medium. Effective porosity is the ratio of interconnected void spaces with respect to the bulk volume. For a large-sized material such as sand or gravel, effective porosity is close to volumetric porosity. On the other hands, for a small sized material of mud, silt or clay, the large difference is reported between effective porosity and total porosity (Todd and Mays, 2005). Effec-tive porosity can be determined by the direct method of a laboratory or in-situ experiment, the inverse modeling of a specific groundwater basins, or electrical resistivity pros-pecting (Taheri Tizro et al., 2012; Whitman and Yeboah-Forson, 2015).

In this study, effective porosity was calculated using the ratio between flow rate and average linear velocity during the column tracer test. The equation is

$$n_e = \frac{q}{v_a} \tag{2}$$

where n_e is effective porosity, q is flow rate (cm/sec), v_a is average linear velocity (cm/sec).

4. Discussion and Results

4.1. Grain size distribution

The grain size distribution of a porous medium has a major effect on its hydrogeological properties such as porosity, hydraulic conductivity and dispersivity. Mixtures of different grain size at various proportions result in different void-solid ratios in the medium. Grain size is the most fundamental property of sediment particles, affecting their entrainment, transport and deposition of contaminants. Thus, grain size analysis provides the evidences regarding to the sediment provenance, transport history and depositional conditions (Folk, 1954).

Sediment types of samples were classified according to the triangular classification of Folk (Folk, 1966), and statistical values of mean and sorting were calculated by the fol-

Table 1. Results of grain size analysis

Sample No. / Depth(m)	Grain Size (%)				Mean (Ø)	Sorting (Ø)	Sediment Type
	Gravel	Sand	Silt	Clay			
OW-8 40.5~41	0.00	93.64	5.00	1.36	2.91	1.17	S
OW-8 55~56	0.00	98.58	1.17	0.25	1.78	0.82	S
OW-9 31~31.5	0.00	75.99	13.83	10.19	3.81	2.58	mS
OW-9 32~32.5	0.18	73.30	16.85	9.67	3.36	2.81	(g)mS
OW-9 34~34.5	0.00	97.09	2.18	0.74	2.06	1.09	S
OW-9 34.5~35	0.00	95.93	3.57	0.49	2.32	1.01	S
OW-9 35.5~36	0.00	82.75	11.44	5.80	3.80	1.92	mS
OW-9 39~39.5	0.00	89.98	6.09	3.92	2.32	2.00	mS
OW-9 40~40.5	0.00	85.10	11.04	3.86	3.11	1.87	zS
OW-9 42~42.5	0.00	80.80	12.14	7.06	3.09	2.45	mS
OW-9 49~49.5	1.58	97.13	1.06	0.23	1.27	0.92	(g)S
OW-9 50~50.5	2.63	91.10	4.54	1.74	1.80	1.69	(g)S
OW-9 51~51,5	5.19	93.08	1.32	0.41	1.55	1.11	(g)S
OW-9 52~52,5	0.00	97.72	1.78	0.50	1.87	0.91	S
OW-9 53~53.5	0.04	92.54	5.87	1.56	2.10	1.49	(g)S
OW-9 54~54.5	0.00	96.83	2.76	0.41	1.82	0.95	S
OW-9 55~55.5	0.00	93.07	5.06	1.87	2.64	1.42	S
OW-9 57~57.5	0.00	98.70	0.98	0.32	1.46	0.79	S
OW-9 58~58.5	0.00	93.49	5.19	1.32	2.09	1.38	S
OW-9 59~59.5	0.15	98.42	1.23	0.20	1.66	0.77	(g)S
OW-10 31~31.5	0.00	96.67	2.71	0.63	2.71	0.89	S
OW-10 40.5~41	0.00	66.53	19.90	13.56	4.30	2.82	mS
OW-11 31~31.5	0.00	93.06	5.62	1.32	2.42	1.33	S
OW-11 31.5~32	0.00	93.06	5.62	1.32	2.42	1.33	S
OW-11 40~40,5	0.00	88.76	8.00	3.25	2.47	1.87	zS
OW-11 55~56	0.00	94.31	4.43	1.26	1.79	1.38	S
OW-12 40~40.5	0.00	94.67	4.10	1.24	2.10	1.31	S
OW-12 52~53	0.28	97.18	2.11	0.43	1.85	0.95	(g)S
OW-13 39.5~40	0.00	91.64	5.65	2.71	2.30	1.72	S
OW-14 33.5~34	0.00	30.81	47.91	21.27	5.84	2.83	sZ
OW-14 51~52	0.00	89.10	8.02	2.88	2.85	1.67	zS
OW-15 34~34.5	0.00	96.37	2.94	0.69	2.38	1.06	S
OW-15 40~40.5	0.00	88.86	7.66	3.48	2.56	1.91	zS
OW-15 52~52.5	0.00	97.44	2.13	0.44	2.29	0.89	S

Remarks G : gravel, S : sand, M : mud, Z : silt
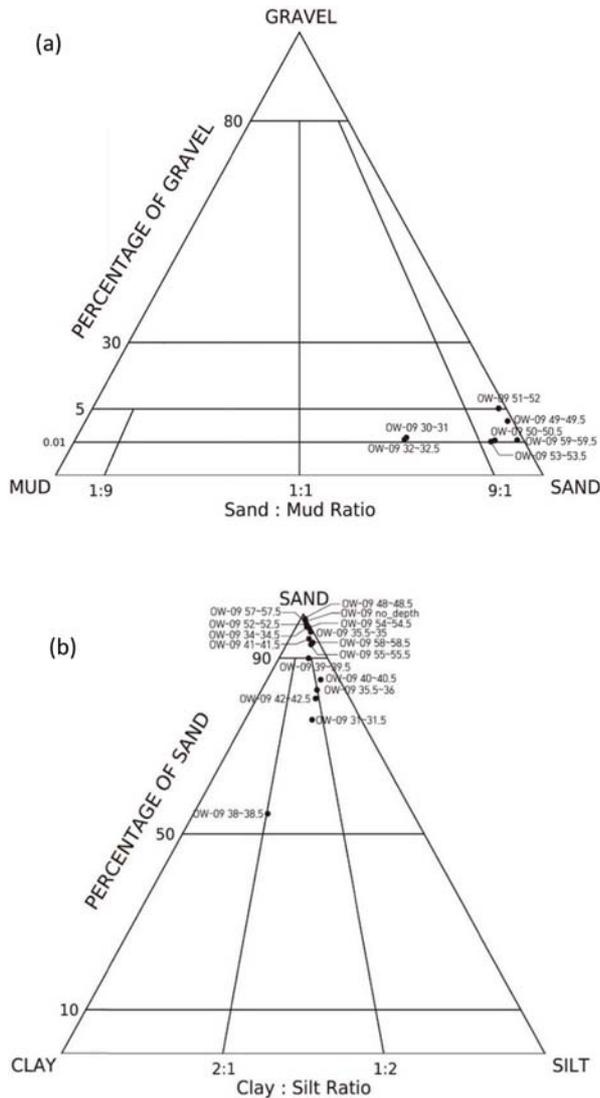
Fig. 3. Triangular classification (a) Gravel-Mud-Sand, (b) Sand-Clay-Silt of OW-9.

lowing equations (Folk, 1954; Folk, 1966) :

$$\Phi = -log_2 D \tag{3}$$

$$\bar{x} = \frac{\Sigma fm}{n} \tag{4}$$

$$\sigma = \sqrt{\frac{\Sigma f(m-\bar{x})^2}{100}} \tag{5}$$

where Φ is logarithmic grain size, $\bar{x}$ is mean of grain size, σ is sorting, D is grain diameter (mm), f is percentile weight of grain size, and m is a median value (Φ scale) of grain size.

All sediment samples were collected from the confined

aquifer below the pure clay layer. Table 1 gives the results of grain size analysis for the samples in the study area. Fig. 3 and Fig. 4 show the triangular classifications of Gravel-Mud-Sand and Sand-Clay-Silt for OW-9, respectively.

All sediment types with exception OW-14 (33.5~34.0 m depth) belonged to sand types bearing a certain amount of gravel, silt, or mud. Most of samples ranged from 1.5 to 3.0 in the mean diameter of Φ scale. The mean diameter of OW-14 (33.5~34.0 m depth) was the largest Φ scale value, i.e., 5.84. Most of samples ranged from 1.0 to 2.0 in the sorting of Φ scale, and it indicated poorly sorted. The sorting values of 5 samples varied from 2.0 to 3.0, and the samples were very poorly sorted. Poorly sorted sediments generally showed the low hydraulic conductivities.

4.2. Hydraulic conductivity

36 samples were used to determine the hydraulic conductivities. The length of samples ranged from 17.4 to 39.5 cm, and the diameter of samples is all 91.56 cm. The sediment samples were collected in the undisturbed state using the Standard Penetration Test (SPT) hammer and thin wall tubes.

Table 2 summarizes the hydraulic conductivities of 36 samples using the falling-head permeameter. Most of the samples (35 samples) belonged to the sand types of S (Sand), gS (Gravelly Sand), mS (Muddy Sand), and ZS (Silty Sand). 18 samples of S type, 7 samples of gS, 5 samples of mS, and 5 samples of ZS showed the hydraulic conductivities of 0.25 to 17.57 m/day (2.90E-04~1.70E-02 cm/sec), 8.94 to 25.6 m/day (1.00E-02~2.90E-02 cm/sec), and 0.02 to 1.85 m/day (1.90E-5~2.10E-03 cm/sec), and 0.11 to 6.63 m/day (1.30E-04~7.70E-03 cm/sec), respectively. Only one sample of sZ (Sandy Silt) showed the hydraulic conductivities of 0.08 m/day (9.20E-05 cm/sec). Gravelly Sand (gS) sediments gave the highest hydraulic conductivities, and a Sandy Silt (sZ) sediment rendered the lowest hydraulic conductivity. Thus, sand sediments represented higher hydraulic conductivities, and silt sediment exhibited the lowest hydraulic conductivities.

4.3. Mass transport of contaminants

Hydrodynamic dispersion includes the mechanical dispersion and the molecular diffusion. Mechanical dispersion happens during the process that contaminants move through

Table 2. Hydraulic conductivities of sediments using a falling-head permeameter

Sample No./ Depth (m)	Sample Length (cm)	Sample area (cm³)	K (cm/sec)	K (m/day)
OW-8 40.5~41	37.8	91.56	3.1E-03	2.64
OW-8 55~55.5	35	91.56	6.7E-03	5.76
OW-8 55.5~56	38.1	91.56	2.0E-03	1.75
OW-9 31~31.5	34.5	91.56	1.9E-05	0.02
OW-9 32~32.5	32.3	91.56	3.4E-04	0.29
OW-9 34~34.5	21.7	91.56	1.5E-02	12.61
OW-9 34.5~35	23	91.56	1.5E-02	12.79
OW-9 35.5~36	39.3	91.56	2.6E-04	0.22
OW-9 39~39.5	37.8	91.56	1.5E-03	1.27
OW-9 40~40.5	36.6	91.56	1.3E-04	0.11
OW-9 42~42.5	20.3	91.56	2.1E-03	1.85
OW-9 49~49.5	22	91.56	1.7E-02	14.27
OW-9 50~50.5	32.7	91.56	1.0E-02	8.94
OW-9 51~51,5	21.3	91.56	1.6E-02	17.57
OW-9 52~52,5	21.3	91.56	1.7E-02	14.64
OW-9 53~53.5	26	91.56	1.6E-02	13.54
OW-9 54~54.5	35.6	91.56	1.2E-02	10.39
OW-9 55~55.5	20.4	91.56	2.5E-03	2.18
OW-9 57~57.5	38.7	91.56	1.8E-02	15.93
OW-9 58~58.5	17.4	91.56	2.0E-02	17.05
OW-9 59~59.5	35	91.56	2.8E-02	24.16
OW-11 31~31.5	38.2	91.56	1.2E-03	1.04
OW-11 31.5~32	38.9	91.56	1.0E-02	8.71
OW-11 40~40,5	22.8	91.56	1.2E-03	1.01
OW-11 55~55.5	38.3	91.56	8.0E-03	6.91
Ow-11 55.5~56	37.6	91.56	1.2E-02	10.35
OW-12 40~40.5	22	91.56	2.9E-04	0.25
OW-12 52~52.5	36	91.56	2.9E-02	25.06
OW-12 52.5~53	22.8	91.56	2.1E-02	17.83
OW-13 39.5~40	35.2	91.56	3.9E-04	0.34
OW-14 33.5~34	38.2	91.56	9.2E-05	0.08
OW-14 51~51,5	35.9	91.56	7.7E-03	6.63
OW-14 51.5~52	39.5	91.56	1.5E-04	0.13
OW-15 34~34.5	22.5	91.56	2.1E-03	1.86
OW-15 40~40.5	39.1	91.56	1.1E-03	0.96
OW-15 52~52.5	37.6	91.56	1.9E-02	16.79

the porous media. Molecular diffusion is the process by which solutes move from the areas of higher chemical potentials to the areas of lower chemical potentials (Fetter, 2001). Molecular diffusion is described by Fick's Laws. Advection is the process by which dissolved solutes are carried along with the flowing groundwater.

The transport of a conservative solute in a one-dimensional system can be described by the advection-dispersion equation (Charbeneau, 2000) as

$$\frac{\partial C}{\partial t} = D_l \frac{\partial^2 C}{\partial l^2} - v_l \frac{\partial C}{\partial l} \tag{6}$$

where C is concentration of contaminants, t is travel time of contaminants, l is longitudinal distance from the contamination source, D_l is longitudinal hydrodynamic dispersion coefficient, and v_l is longitudinal average linear velocity.

The advection-dispersion equation may be solved analytically under different initial and boundary conditions (Ogata and Banks 1961).

$$\frac{C}{C_0} = \frac{1}{2} erfc\left(\frac{l - v_l t}{2\sqrt{D_l t}}\right) + \frac{1}{2} \exp\left(\frac{v_l x}{D_l}\right) erfc\left(\frac{l + v_l t}{2\sqrt{D_l t}}\right) \tag{7}$$

where $erfc(x)$ is complementary error function, C is contaminant concentration at (l, t), C_0 is initial concentration of contaminant, l is the distance from the contamination source, D_l is longitudinal hydrodynamic dispersion coefficient, and v_l is average linear velocity.

The value of complementary error function in the right second term of Eq. (7) is converged to zero because the numerator is much larger than denominator. Thus, 1-D advection diffusion equation can be expressed as,

$$\frac{C}{C_0} = \frac{1}{2} erfc\left(\frac{l - v_l t}{2\sqrt{D_l t}}\right) \tag{8}$$

where

$$erfc(x) = 1 - erf(x) \tag{9}$$

$$erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt \tag{10}$$

Solute transfer in porous media is dominated by mechanical dispersion and effective molecular diffusion. Thus, the longitudinal dispersion coefficient is represented by the following formula (Todd and Mays, 2005).

$$D_L = \alpha_L v_l + D^* \tag{11}$$

where D_l is longitudinal hydrodynamic dispersion coefficient, α_l is longitudinal dispersivity, v_l is longitudinal average linear velocity, and D^* is effective molecular diffusion coefficient.

When the flow rate of the contaminant is very small, the molecular diffusion predominantly represents longitudinal hydrodynamic dispersion, and $D_l = D^*$. However, the moving velocity of contaminants is not generally small in the subsurface, and the molecular diffusion is neglected in the hydrodynamic dispersion. Thus, longitudinal hydrodynamic dispersion coefficient is represented as $D_l = \alpha_l v$.

Concentration $\left(\frac{C}{C_0}\right)$ in Eq. (8) is represented by a breakthrough curve like

$$P(-\infty, x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^x e^{\frac{-t^2}{2}} dt \tag{12}$$

Probability distribution according to the distance in the normal distribution curve is

$$P(-\infty, x) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^x e^{\frac{-(t-\mu)^2}{2\sigma}} dt \tag{13}$$

When in Eq. (13) $\mu = 0$, $\sigma = 1$, i.e., the standard normal distribution curve, Eq. (12) and Eq. (13) become the same. According to Gelhar et al. (1979),

$$D_l = \frac{\sigma_x^2}{2t} \tag{14}$$

where σ_x^2 is the variance of contaminant travel distance, t is time to reach the distance x, D_l is longitudinal hydrodynamic dispersion coefficient.

Using groundwater velocity, Eq. (14) becomes

$$D_l = \frac{\sigma_x^2 v}{2x} \tag{15}$$

where v is average velocity of groundwater.

In case of normal distribution curve (Domenico and Schwarz, 1998),

$$D_l = \frac{1}{8t}(t_{0.84} - t_{0.16})^2 \tag{16}$$

Thus, longitudinal dispersivity is

$$\alpha_l = \frac{D_l}{v} \tag{17}$$

$$\alpha_l = \frac{1}{8tv}(t_{0.84} - t_{0.16})^2 \tag{18}$$

Average linear velocity is

$$v_a = \frac{x}{t_{0.5}} \tag{19}$$

Fig. 4 shows the breakthrough curves of representative samples. All parameters ($t_{0.16}$, $t_{0.50}$, $t_{0.84}$) necessary for the determination of actual velocity and dispersivity were obtained from the breakthrough curves. Using Eqs. (16), (18) and (19), the dispersion coefficient, dispersivity and actual velocity were calculated according to the relationship between elapsed time and the effluent tracer concentration normalized by initial tracer concentration
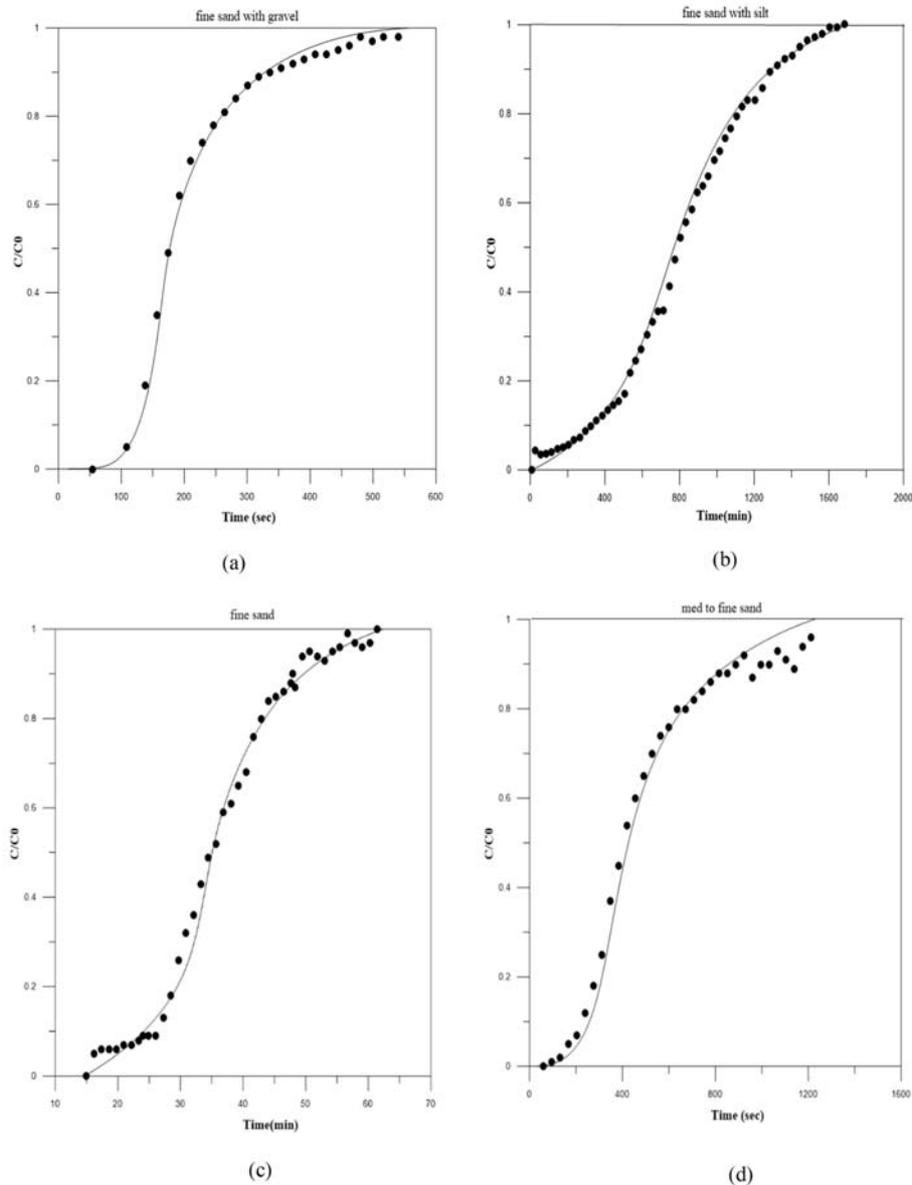
Fig. 4. Breakthrough curves of bromide solution for (a) OW-9 35.5~36 m, (b) OW-9 51~51.5 m, (c) OW-9 53~53.5 m (d) OW-11 55~56 m samples, respectively.

Table 3 shows the longitudinal dispersion coefficients and dispersivities of all samples.

18 samples of Sand type, 7 samples of Gravelly Sand, 5 samples of Silty Sand, 5 samples of Muddy Sand and 1 sample of Sandy Silt showed the longitudinal dispersion coefficients of 4.47E-04~9.47E-02 cm^2/sec, 7.61E-03~7.51E-02 cm^2/sec, 3.10E-04~1.08E-01 cm^2/sec, 7.44E-04~1.13E-02 cm^2/sec, and 4.07E-04 cm^2/sec, respectively. Their dispersivities were 0.36~3.2 cm, 0.35~1.15 cm, 1.17~3.92 cm, 0.7~ 2.03 cm, and 1.73 cm, respectively. Silty Sands represented

the highest dispersivities and Gravelly Sands exhibited the lowest dispersivities, even though hydraulic conductivities of Gravelly Sands were larger than those of Silty Sands. The reason was because Gravelly Sand Types included short samples, and Silty Sand Types only consisted of long samples. Dispersivity showed the characteristics of scale dependence (Chen et al., 2008; Gelhar et al., 1979). The number of long samples was 23, and the length varied from 32 cm to 39.5 cm. The number of short sample was 13, and the length varied from 17.4 cm to 22.8 cm. Thus, it was

Table 3. Dispersivities obtained from breakthrough curves

Sample N0./ Depth (m)	Sample length (cm)	D_L (cm²/sec)	α_L (cm)
OW-8 40.5~41	37.8	4.47E-04	1.75
OW-8 55~55.5	35	3.78E-02	1.56
OW-8 55.5~56	38.1	1.33E-02	3.20
OW-9 31~31.5	34.5	7.44E-05	0.70
OW-9 32~32.5	32.3	5.05E-04	0.80
OW-9 34~34.5	21.7	7.59E-02	1.54
OW-9 34.5~35	23	4.42E-02	1.49
OW-9 35.5~36	39.3	1.68E-03	1.94
OW-9 39~39.5	37.8	8.24E-03	2.03
OW-9 40~40.5	36.6	3.10E-04	1.17
OW-9 42~42.5	20.3	1.13E-02	1.53
OW-9 49~49.5	22	2.58E-02	0.74
OW-9 50~50.5	32.7	7.61E-03	0.36
OW-9 51~51,5	21.3	7.51E-02	0.62
OW-9 52~52,5	21.3	1.91E-02	0.36
OW-9 53~53.5	26	7.03E-02	1.15
OW-9 54~54.5	35.6	6.46E-02	1.85
OW-9 55~55.5	20.4	2.76E-02	2.25
OW-9 57~57.5	38.7	5.90E-02	1.78
OW-9 58~58.5	17.4	8.11E-02	1.25
OW-9 59~59.5	35	6.33E-02	0.70
OW-11 31~31.5	38.2	3.38E-03	1.08
OW-11 31.5~32	38.9	4.26E-02	1.59
OW-11 40~40,5	22.8	2.62E-02	3.80
OW-11 55~55.5	38.3	1.33E-02	0.73
Ow-11 55.5~56	37.6	9.47E-02	2.57
OW-12 40~40.5	22	2.57E-03	1.67
OW-12 52~52.5	36	5.11E-02	1.05
OW-12 52.5~53	22.8	2.56E-02	0.35
OW-13 39.5~40	35.2	1.36E-03	1.09
OW-14 33.5~34	38.2	4.07E-04	1.73
OW-14 51~51,5	35.9	1.08E-01	3.26
OW-14 51.5~52	39.5	1.78E-03	3.92
OW-15 34~34.5	22.5	1.58E-02	1.57
OW-15 40~40.5	39.1	1.89E-02	2.60
OW-15 52~52.5	37.6	5.98E-02	1.29

Table 4. Effective porosities determined by the experiment

Sample No./ Depth (m)	q (cm/sec)	v_a (cm/sec)	n_e
OW-8 40.5~41	1.05E-03	2.55E-04	0.18
OW-8 55~55.5	2.70E-03	2.42E-02	0.11
OW-8 55.5~56	8.77E-04	4.15E-03	0.21
OW-9 31~31.5	2.52E-04	1.06E-04	0.04
OW-9 32~32.5	1.45E-04	6.29E-04	0.23
OW-9 34~34.5	1.26E-02	4.93E-02	0.25
OW-9 34.5~35	9.14E-03	2.97E-02	0.31
OW-9 35.5~36	9.50E-05	8.67E-04	0.11
OW-9 39~39.5	5.53E-04	4.06E-03	0.14
OW-9 40~40.5	5.41E-05	2.65E-04	0.20
OW-9 42~42.5	1.38E-03	7.38E-03	0.19
OW-9 49~49.5	1.58E-02	3.46E-02	0.46
OW-9 50~50.5	5.03E-03	2.10E-02	0.24
OW-9 51~51,5	1.57E-02	1.22E-01	0.17
OW-9 52~52,5	1.71E-02	5.33E-02	0.32
OW-9 53~53.5	1.14E-02	6.12E-02	0.19
OW-9 54~54.5	6.72E-03	3.49E-02	0.19
OW-9 55~55.5	2.15E-03	1.23E-02	0.18
OW-9 57~57.5	1.0E-02	3.31E-02	0.25
OW-9 58~58.5	3.0E-02	6.49E-02	0.41
OW-9 59~59.5	2.0E-02	9.07E-02	0.15
OW-11 31~31.5	4.65E-04	3.12E-03	0.14
OW-11 31.5~32	3.66E-03	2.68E-02	0.11
OW-11 40~40,5	7.47E-04	6.91E-03	0.25
OW-11 55~55.5	4.61E-03	1.82E-02	0.28
Ow-11 55.5~56	1.03E-02	3.69E-02	0.12
OW-12 40~40.5	1.82E-04	1.54E-03	0.45
OW-12 52~52.5	2.19E-02	4.86E-02	0.25
OW-12 52.5~53	1.81E-02	7.28E-02	0.17
OW-13 39.5~40	2.14E-04	1.25E-03	0.13
OW-14 33.5~34	3.08E-05	2.35E-04	0.16
OW-14 51~51,5	5.34E-03	3.31E-02	0.11
OW-14 51.5~52	5.01E-05	4.54E-04	0.13
OW-15 34~34.5	1.34E-03	1.00E-02	0.08
OW-15 40~40.5	5.60E-04	7.29E-03	0.16
OW-15 52~52.5	7.55E-03	4.62E-02	0.15

confirmed that the experimental scale was a more important factor to affect the dispersivity than hydraulic conductivity.

4.4. Effective porosity

Porosity is defined as the ratio of pore volume to bulk volume of porous media. The porosity is a measure of the storage capacity (pore volume) that is capable of holding fluids. It is static property that can be measured without flow. Effective porosity is expressed as a ratio of interconnected interstices to total volume of porous media (Todd and Mays, 2005). Effective porosity is not necessarily proportional to the volumetric porosity of porous media. Although clay has large porosity like sand or gravel, clay has very small effective porosity. Thus, sand mixed with clay or silt represents much smaller effective porosity than pure sand.
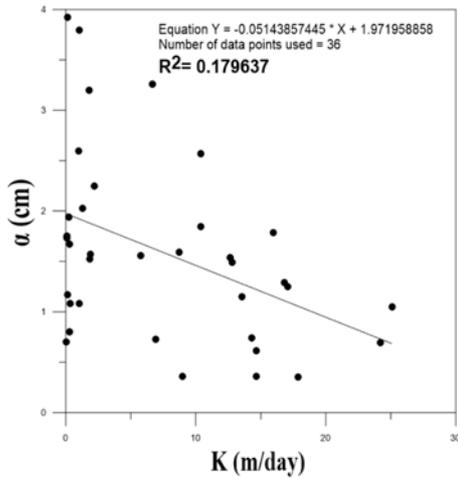
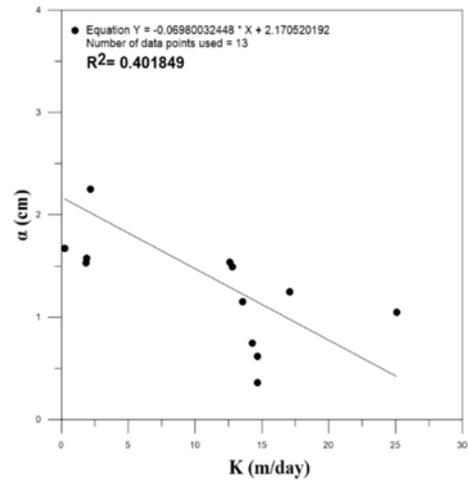**Fig. 5.** Comparison of dispersivity with hydraulic conductivity for 36 long and short samples.

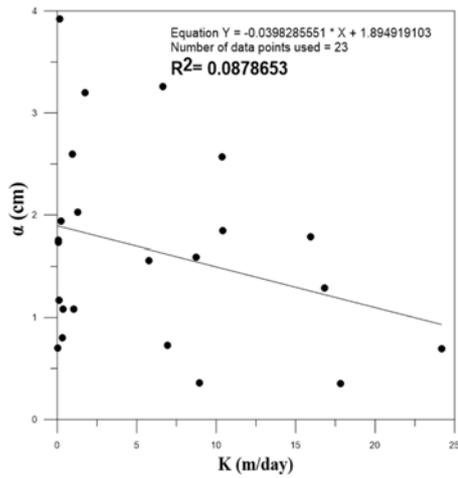**Fig. 7.** Comparison of dispersivity with hydraulic conductivity for 13 short samples.

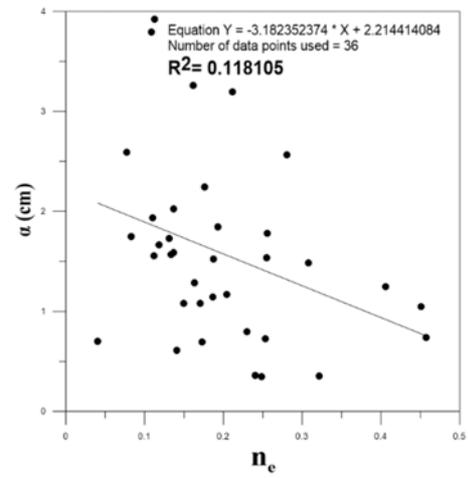**Fig. 6.** Comparison of dispersivity with hydraulic conductivity for 23 long samples.

Fig. 8. Comparison of dispersivity with effective porosity for 36 long and short samples.

Table 4 summarized the experimental results. 18 samples of Sand, 7 samples of Gravelly Sand, 5 samples of Silty Sand, 5 samples of Muddy Sand and 1 sample of Sandy Silt showed the effective porosities of 0.08~0.45, 0.15~0.46, 0.04~0.23, 0.11~0.25, and 0.16, respectively. Gravelly Sands represented the highest effective porosities and Muddy Sand exhibited the lowest effective porosities. The reason was because silt, clay or mud degraded the effective porosity of porous media. Sand, Gravelly Sand, Silty Sand, Muddy Sand and Sandy Silt showed the average linear velocity of 2.55E-4~6.49E-02, 2.10E-02~1.22E-01, 1.06E-04~7.38E-03, 2.65E-04~3.31E-02, and 2.35E-04 cm/sec, respectively. In average linear velocity, Gravelly Sands showed the highest

values, and Muddy Sands showed the lowest values.

4.5. Interrelations between hydrogeological parameters

Statistical methods were used to understand the relation between aquifer parameters of hydraulic conductivity, effective porosity and dispersivity. The relation between dispersivity and hydraulic conductivity or effective porosity considered the sample size, because dispersivity was affected by experimental scale. The lengths of long and short samples were from 32 to 39.5 cm, and from 17.4 to 22.8 cm, respectively. Fig. 5~Fig. 7 showed the relation between dispersivity and hydraulic conductivity for 36 all samples, 23 long samples and 13 short samples. Their relations were all

Table 5. The interrelations of aquifer parameters for 36 samples

| Correlation	Number of Samples	Correlation coefficient	Regression equation	Determination coefficient
α versus K for long and short samples	36	0.42	$Y = -0.05 \cdot X + 1.97$	0.18
α versus K for long samples	23	0.29	$Y = -0.04 \cdot X + 1.89$	0.088
α versus K for short samples	13	0.63	$Y = -0.07 \cdot X + 2.17$	0.40
α versus n_e for long and short samples	36	0.35	$Y = -3.18 \cdot X + 2.21$	0.12
α versus n_e for long samples	22	0.21	$Y = -3.13 \cdot X + 2.18$	0.045
α versus n_e for short samples	13	0.51	$Y = -3.45 \cdot X + 2.32$	0.26
n_e versus K for long and short samples	36	0.65	$Y = 0.01 \cdot X + 0.13$	0.42
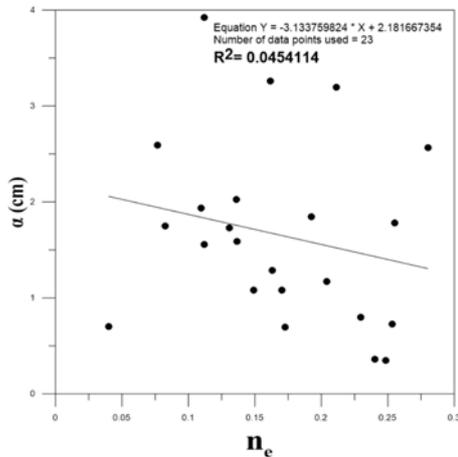
Fig. 9. Comparison of dispersivity with effective porosity for 23 long samples.
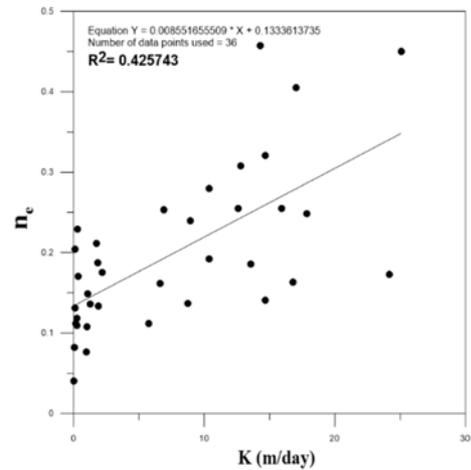

Fig. 11. Comparison of effective porosity with hydraulic conductivity for 36 long and short samples.
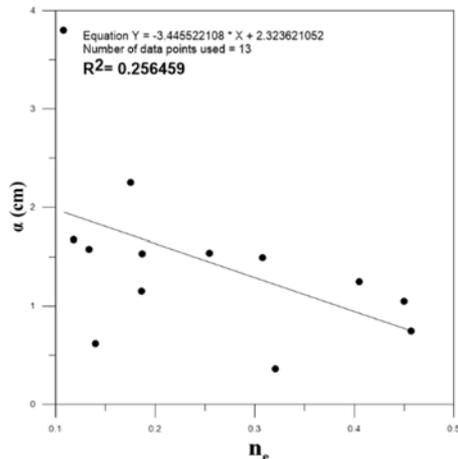

Fig. 10. Comparison of dispersivity with effective porosity for 13 short samples.

inversely proportional and the correlation coefficients were 0.42, 0.29, and 0.63, respectively (Table 5). Short samples rendered the largest correlation coefficient, because short samples consisted of sand or gravelly sand, and the number of samples are small. Otherwise, long samples included silty sands and muddy sands, and showed the smallest correlation coefficient.

Fig. 8~Fig. 10 showed the relation between dispersivity and effective porosity for 36 all samples, 23 long samples and 13 short samples, respectively. Their relation was also inversely proportional and the correlation coefficients were 0.35, 0.21, and 0.51, respectively (Table 5). Short samples also showed the largest correlation coefficient, and long samples represented the smallest correlation coefficient. The reason was the same as the relation between dispersivity and hydraulic conductivity.

The relations between dispersivity and hydraulic conductivity or effective porosity were all in inverse proportion. The reason was because dispersivity was in inverse proportion to the velocity of groundwater for the steady dispersion coefficients, and groundwater velocity was in proportion to the hydraulic conductivity or effective porosity. This study
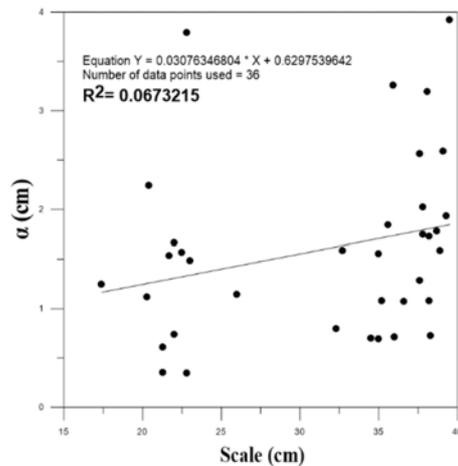
Fig. 12. Comparison of dispersivity with sample scale for 36 long and short samples.

also elucidated that effective porosity was in proportion to the hydraulic conductivity for 36 all samples in Fig. 11 and the correlation coefficient was 0.65 (Table 5).

Fig. 12 showed the relationship between the scales of all samples and longitudinal dispersivities from the laboratory tracer test. The result suggested that longitudinal dispersivity increased according to the experimental scale. This was in the agreement with the relationship presented by (Pickens and Grisak, 1981). This study showed that longitudinal dispersivity was dependent on the scale of column tracer test.

5. Conclusions

The large-scale economic, industrial, and agricultural activities have been carried out in the Nakdong River Delta. However, groundwater quality of this area has been deteriorated due to seawater intrusion, agricultural fertilizer and pesticide, industrial wastewater, and contaminated river water. The basic hydrogeological data are necessary for groundwater management and preservation in the delta area.

36 undisturbed sediment samples were used to determine the physical properties of grain size distribution, sediment type and sorting, and the hydrogeological parameters such as grain size, hydraulic conductivity, effective porosity, longitudinal dispersivity. All sediment types except OW-14 (33.5~34.0 m depth) belonged to sand bearing a certain amount of gravel, silt, or mud. Most of samples ranged

from 1.5 to 3.0 in the mean diameter of Φ scale. Hydraulic conductivity was determined through a falling head test, and ranged from 9.2×10^{-5} to 2.9×10^{-2} cm/sec (0.08 to 25.6 m/day). Gravelly Sand (gS) represented the highest hydraulic conductivities, and a Sandy Silt (sZ) sediment exhibited the lowest hydraulic conductivities.

Longitudinal dispersivities were calculated to be 0.35~ 3.92 cm from breakthrough curves obtained from a column tracer (NaBr) test. Silty Sands showed the highest dispersivities, and Gravelly Sands rendered the lowest dispersivities, even though hydraulic conductivities of Gravelly Sands were larger than Silty Sands. The reason was because Gravelly Sands included short samples, and Silty Sands consisted only of long samples. Dispersivity showed the characteristics of scale dependence. Also, effective porosity and average linear velocity were obtained through the column tracer test, and their values were 0.04~0.46 and 1.06E-04~6.49E-02 cm/sec, respectively. Gravelly Sands rendered the highest effective porosities and average linear velocities, and Muddy Sand gave the lowest effective porosities and average linear velocity.

The relations between dispersivity and hydraulic conductivity or effective porosity were all in inverse proportion. The reason was because dispersivity was in inverse proportion to the velocity of groundwater for the steady dispersion coefficients, and groundwater velocity was in proportion to the hydraulic conductivity or effective porosity. This study also showed that effective porosity was in proportion to the hydraulic conductivity for 36 all samples, and the correlation coefficient was 0.65

The relationship between sample scales and longitudinal dispersivities from the laboratory tracer test suggested that longitudinal dispersivity increased according to the experimental scale. This fact was in the agreement with the relationship presented by Pickens and Grisak (1981). Thus, longitudinal dispersivity was dependent on the scale of column test, and all hydrogeological parameters were low to high values due to the sand quantity of sediments. It is expected that the hydrogeological parameter data of sediments will be very useful for the planning of groundwater management and preservation in the Nakdong River Delta of Busan City, Korea.

Acknowledgements

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