Artificial Groundwater Recharge Using Underground Piping Method

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ABSTRACT / Recently, rapid industrialization, urbanization and higher living standards accelerate to increase groundwater consumption resulting in continuously dropping groundwater elevations. To maintain enough groundwater volume without dropping groundwater elevations, the proper groundwater recharge is necessary. The groundwater recharge can be classified into two categories which are natural recharge and artificial recharge. Even though the natural recharge through by direct infiltration from the rainfall is desirable, the artificial groundwater recharge is necessary when the increment of groundwater consumption exceeds natural recharge rate. Well method and scattering method are utilized as artificial recharging methods. Even though the well method was more frequently used rather than scattering method, a severe disadvantage ,which is the reduction of the void of soil surface, is indicated in the well method. Recently, the underground piping method, which is a scattering method, is receiving increasing attention as a proper recharging method. The method is indirectly to supply water to the underground using an underground piping system. Therefore, the void of soil surface is not severely reduced and better infiltration rate can be achieved.

In this paper, the artificial groundwater recharge using underground piping method is investigated through experiments and numerical analysis. The influence of the groundwater by underground piping method is evaluated through comparing recharging heights. Good agreements between experiments and numerical analysis are obtained and the artificial groundwater recharge by underground piping method is well tested and verified.

1. Introduction

Groundwater, which makes up about 14% of the earth's fresh water and amounts to appro-

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ximately 4 million km^3, moves through the openings that exist within the natural materials forming the earth's surface[15]. Groungwater has always been one of the most important sources of water supply. Virtually all parts of the earth are underlain by water, and wells have been constructed throughout recorded history to provide a water supply when surface water was not readily available. Recently, rapid industrialization, urbanization and higher living standards accelerate to increase groundwater consumption. The increment of groundwater consumption has substantially exceeded natural recharge rates, resulting in continuously dropping groundwater elevations.

The severe low flows in the dry season can be resulted from the drop of the groundwater elevations. Also, the drop of the groundwater elevations can cause degradation of the quality of surface water. Therefore, it is very important to forecast the variation of water environment such as groundwater elevations, water quantity and water quality, and to provide effective solutions for reducing disadvantages by the change of water environment. Especially, to maintain natural groundwater elevations without dropping groundwater elevations, recently artificial groundwater recharge methods have been used as an effective solution even though more effective recharging techniques need to be developed.

The research about groundwater recharge has been conducted by several hydraulic and hydrologic researchers in the world. Latinopoulos[10] obtained the analytical solution of groundwater recharge. It is frequently applied for preliminary evaluation for the effect of groundwater recharge. He concluded that water storage and runoff in the soil water zone were mainly depending upon soil characteristics and recharged durations. Herrling[7] conducted the research for the possibility of recharging groundwater with the high water of streams in valleys of the glacial period. A time dependent, two dimensional finite element model has been employed. Khan and Mawdsley[9] investigated the effects by land use changes which affect the hydrologic characteristics of the basin and hence the recharge to the groundwater. A non–linear, conceptional, explicit soil moisture accounting model was applied. Wheater et. al.[18] conducted the research for dynamic processes of soil water movement under vegetation which can be significantly affected by changes in land use. In the research, the concept of a single field capacity to represent a dynamic soil water profile is shown and the implications for the estimated effects of land use change were discussed. Rushton[16] investigated how aquifer demands were supplied either from groundwater storage or from recharge. The limited ability of the aquifer to transmit potential recharge and the importance of local dewatering around pumped wells were shown in the research. Bhattacharjee[1] studied the potential groundwater yield by evaluating the increment in groundwater reserve and checking the specific yield of the aquifer by pumping tests. Schmidtke et. al.[17] developed an extended Kalman filter model for characterizing minimum variance estimates of the piezometric heads and coefficients defining an unconfined aquifer subject to artificial recharge. Guvanasen and Volker[6] investigated the contaminant movement in an unconfined aquifer from a long strip recharge basin through experiments in a sand–filled flume. Also, they compared speed of movement of the contaminant front and the thickness of the mixing zone as well as increment in the free surface level.

The groundwater recharge can be classified into two categories which are natural recharge and artificial recharge. The natural recharge is mainly conducted by direct infiltration from the rain. Well method and scattering method were first utilized as artificial recharging methods. The well method is more frequently used rather than scattering method. However, in the well method the void of soil surface is reduced by physical and chemical processes during recharging. The physical process is caused by movement of suspended material and the chemical process is caused by oxidization or combustion of the material. Consequently, the reduction of the void causes drop of the groundwater table. Recently, the underground piping method, which is a scattering method, is receiving increasing attention as a proper recharging method. The method is to supply water indirectly to the underground using underground piping system. Therefore, the void of soil surface is not severely reduced and better infiltration rate can be achieved.

Essentially, the underground piping method is initiated as a part of the structure for purifying waste water. The capillary force near the pipe is major force to be used for underground recharge. Even though the possibility of the underground recharge by underground piping method is shown in the literature, the influence of the ground water by underground recharging is not well analyzed. Therefore, in this paper the influence of the ground water by underground piping method is investigated through indoor experiments and numerical analysis.

2. Underground Piping Method

2.1 Description of Soil Water Zone

Soil water zone is located in the upper part in the underground and it has a function of a filtering system when rainfall and/or the stored surface water infiltrate directly to the underground. Because of the function of a filtering system, the superior quality of groundwater is achieved. A tipical soil water zone is shown in Figure 2.1. As shown in the figure, the zone consists of three components of soil, air and moisture.

The soil water zone can be categorized into two separate zones which are capillary zone and suspended zone. In the capillary zone, the suction pressure is balanced with statistical water pressure. In the suspended zone, the water content is almost constant as shown in the figure.

The water in the zones is directly supplied by rainfall and/or the stored surface water. The supplied moisture is usually remained in the recharging zones in the underground without evaporating to the air or pumping out through wells. The soil water zone is also known

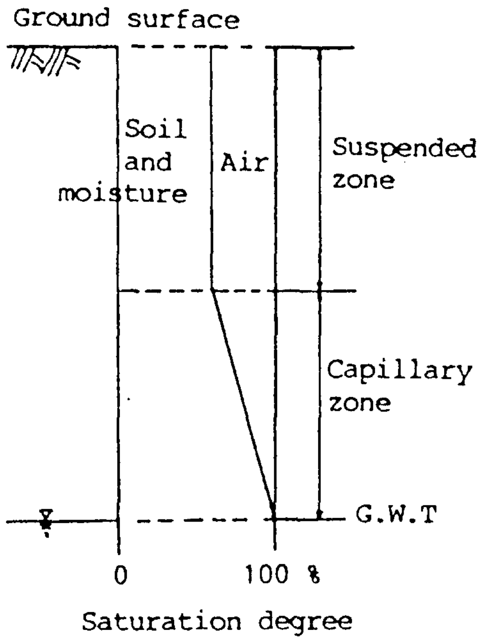

Fig. 2.1 A typical soil water zone

as an unsaturated zone because the air is located with water in the zone. The existing of the air indicates main difference between unsaturated and saturated zones. On the other hand, the water in the saturated zone is moved by surface tension which is cohesive force between water and air.

2.2 Structure of Underground Piping

Underground piping method is an artificial recharging method used to recharge water to the underground by supplying water artificially. The typical cross section of the artificial recharge by underground piping method is shown in Figure 2.2. The water supplied by underground piping method is first stored in the trench shown in the figure and then scattered

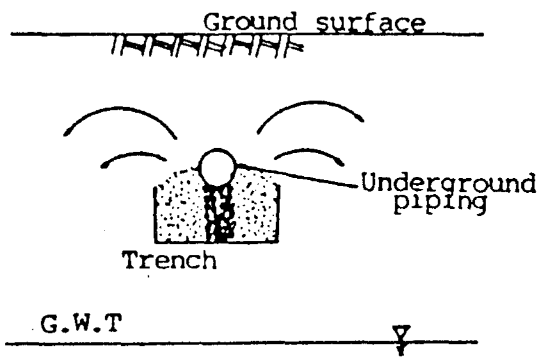

Fig. 2.2 A typical cross section of artificial recharge by underground piping

upward by capillary force, or infiltrated downward by capillary force and/or gravity force. The water infiltrated to the soil water zone is purified by a function of a filtering system in soil water zone.

3. Infiltration Processes in the Unsaturated Zone

3.1 Infiltration Equations

The unsaturated zone is differentiated from the saturated zone by existence of air. However, the unsaturated zone can be easily changed to the saturated zone through raising groundwater table. Therefore, it is necessary to introduce infiltration equations which can be used to the saturated and unsaturated zones. In the saturated zone, infiltration equation can be obtained using Darcy Law. The equation is written as follows.

$$q = -k_o(\triangle\psi + \triangle z) \tag{3.1}$$

where, q : apparent velocity

k_o: saturated infiltration coefficient

ψ: capillary potential

z: gravity potential

In the unsaturated zone, the water movement is different from that in the saturated zone because of the existence of the air. The infiltration paths in the unsaturated zone are interrupted by the mixing processes of air and water. Generally, without very low water content the flow of the groundwater can be considered as a laminar flow. In the laminar flow, the infiltration equation is written as follows.

$$q = -k(\theta)(\triangle\psi + \triangle z) \tag{3.2}$$

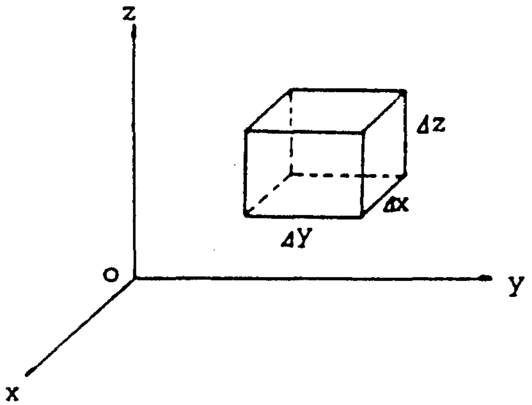

Fig 3.1 A sketch of a soil element

where, $k(\theta)$: unsaturated permeability coefficient

θ : water content

Equation 3.2 indicates that the reduction of cross sectional area in underground flow paths, which can be indicated by interrupting infiltration paths, can be written as the reduction of the permeability coefficients. Generally, it is known that θ can be replaced with ψ. Two relationships between θ and ψ, one is applied in dry condition and another is applied in the wet condition, are used. Therefore, unsaturated peameability coefficient ($k(\theta)$) can be replaced with $k(\psi)$. In the Figure 3.1, the equation of mass conservation of water between time $\triangle t$ can be written as a following equation.

$$\mathrm{div}\{\rho k(\triangle\psi+\triangle z)\}\triangle x\triangle y\triangle z\triangle t=\frac{\partial}{\partial t}(\rho\eta S\triangle x\triangle y\triangle Z)\triangle t \tag{3.3}$$

where, ρ :water density

η : void ratio

s : degree of saturation

In the underground flow, the volume change in the z direction is dominant compared to x, y directions. Therefore, with neglecting volume change in the x, y direction the right side of equation 3.3 can be rewritten as follows:

$$\frac{\partial}{\partial t}(\rho\eta s\triangle x\triangle y\triangle z)\triangle t=\{\rho\eta s\frac{\partial(\triangle z)}{\partial t}+\rho s\triangle z\frac{\partial\eta}{\partial t}+\eta s\triangle z\frac{\partial\rho}{\partial t}+\rho\eta\triangle z\frac{\partial s}{\partial t}\}\triangle x\triangle y\triangle t \tag{3.4}$$

Generally, it is assumed that the skeleton of soil particles and the volume of water is changed with linear relationship with respect to parameter variation. Because the change rates can be indicated using contraction coefficients, each term in the right side of equation 3.4 can be rewritten as equation 3.5 to equation 3.8 with contraction coefficients of α, β.

$$\rho\eta s\frac{\partial(\triangle z)}{\partial t}=\rho\eta s\frac{\partial(\triangle z)}{\partial p}\frac{\partial p}{\partial t}=\rho^2 g\eta s\triangle z\alpha\frac{\partial\psi}{\partial t} \tag{3.5}$$

$$\rho s\triangle z\frac{\partial\eta}{\partial t}=\rho s\triangle z\frac{\partial\eta}{\partial p}\frac{\partial p}{\partial t}=\rho^2 g(1-\eta)s\triangle z\alpha\frac{\partial\psi}{\partial t} \tag{3.6}$$

$$\eta s\triangle z\frac{\partial\rho}{\partial t}=\eta s\triangle z\frac{\partial\rho}{\partial p}\frac{\partial p}{\partial t}=\rho^2 g\eta s\triangle z\beta\frac{\partial\psi}{\partial t} \tag{3.7}$$

$$\rho\eta\triangle z\frac{\partial s}{\partial t}=\rho\eta\triangle z\frac{\partial s}{\partial\psi}\frac{\partial\psi}{\partial t} \tag{3.8}$$

where, p indicates water pressure which is written as $p=\rho g\psi$. Equation 3.5 and 3.6 is affected by the variation of skeleton of soil particles. On the other hand, equation 3.7 is affected by the variation of water volume. Equation 3.8 is related the variation of saturated degree and it can not be neglected in unsaturated soil water zones. However, in saturated soil water zones it can be neglected because the saturated degree is not changed with respect to time variation. With combining equation 3.5 to equation 3.8 equation 3.3 can be rewritten as follows:

$$\mathrm{div}\ \{\rho k(\triangle\psi+\triangle z)\} = \{\rho^2 g\, s(\alpha+\eta\beta)+\rho\eta\frac{\partial s}{\partial\psi}\}\frac{\partial\psi}{\partial t} \tag{3.9}$$

When the variation of skeleton of soil particles and water volume is very little, the first term in the right side in equation 3.9 can be neglected. Also, with assuming that ρ and η are constant in the unsaturated soil, the second term in the right in equation 3.9 can be changed as follows:

$$\rho\eta\frac{\partial s}{\partial\psi} = \rho\frac{\partial\eta s}{\partial\psi} = \rho\frac{\partial\theta}{\partial\psi} = \rho C(\psi) \tag{3.10}$$

Therefore, equation 3.9 can be rewritten as equation 3.11.

$$\mathrm{div}\ \{(k(\psi)(\triangle\psi+\triangle z)\} = C(\psi)\frac{\partial\psi}{\partial t} \tag{3.11}$$

Equation 3.12 is a infiltration equation in the saturated soil water zone. Through the comparison between equation 3.11 and equation 3.12, it is known that equation 3.11, which is an infiltration equation in unsaturated zones, can be applied in saturated zones. That is, equation 3.11 can be applied in both cases of saturated zone and unsaturated zone. Because the equation 3.11 has nonlinear characteristics, the solution of equation 3.11 can be obtained using the numerical analysis.

$$\mathrm{div}\ \{k_o(\triangle\psi+\triangle z)\} = C_o\frac{\partial\psi}{\partial t} \tag{3.12}$$

where, Ko:saturated permeability coefficient

Co :constant (Co $= \rho g(\alpha + \eta\beta)$)

3.2 Characteristics of Permeability Coefficient in Unsaturated Zones

As shown in the above chapter, it is necessary to investigate the characteristics of the unsaturated zone itself to analyze infiltration to the underground. Especially, the permeability coefficient in the unsaturated zones is an important parameter. Figure 3.2 shows the relationship between permeability coefficient and suction pressure head in the unsaturated zones. The permeability coefficient in the figure can be summarized as following equations.

$$K = Ko \quad \text{in which } \psi > \psi b$$
$$K = Ko\left(\frac{\psi_b}{\psi}\right)^n \quad \text{in which } \psi \leq \psi b \qquad (3.13)$$

where, ψ_b: bubble pressure

η : permeability coefficient

The bubble pressure head indicates the capillary force which causes the change of permeability coefficient. The force is greatly changed when bubbles in the void in the unsaturated zone are occured. Permeability coefficient is also affected by the diameter size and/or size distribution of soil particles. The coefficient is large in case of the bigger diameter size and constant size distribution of soil particles. That is, when a small size diameter and a wide range of size distribution of soil particles, the permeability coefficient is small.

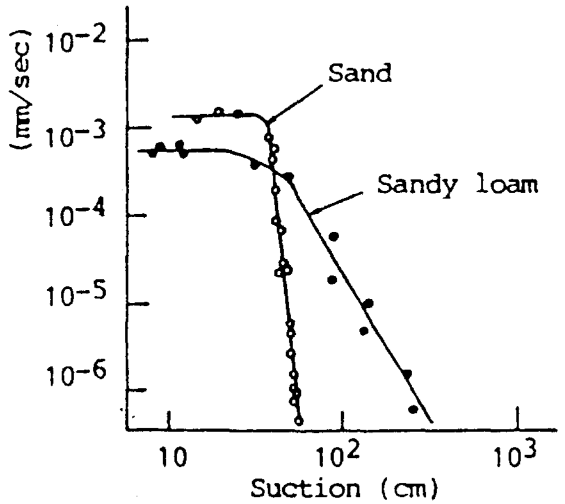

Fig. 3.2 Permeability coefficient of unsaturated soil

As indicated above, the permeability coefficient in the unsaturated zone is affected by bubbling pressure head. This is because the movement of the water is changed by bubbling pressure variation. The permeability coefficient is small when the degree of saturation is low and suction pressure is high. That is because the cross sectional area in the path is reduced as the air in the void interrupts the path of water in the unsaturated zone. On the other hand, the permeability coefficient is large when the degree of saturation is high. This is because the air content in the void is reduced as the suction pressure is reduced. That is, as the suction pressure near b is reduced, the air bubbles near the void in the unsaturated zones start to flow through the path and almost no air remains in the void. Therefore, the unsaturated zone is changed to the saturated zone.

4. Groundwater Recharge by Underground Piping Method

4.1 Experiments for Groungwater Recharge

4.1.1 Experimental Setup

As indicated in the previous chapter, the capillary force in the unsaturated zone is an important parameter. However, because the capillary force is affected by several defined and/or undefined factors, it is necessary to examine the phenomena of artificial groundwater recharge as well as capillary force using experimental facilities. In this paper, the experimental setup for recharging groundwater artificially by underground piping method is shown in Fig. 2.2. As shown in the figure, an experimental trench having length of 70 cm, width of 30 cm and depth of 60 cm is used. The dimensions of experimental facilities are shown in Table 4.1.

Table 4.1 Dimensions of experimental facilities.

	indoor experiment (cm)	field scale (cm)
width	3.0 (cm)	20.0 (cm)
height	2.5 (cm)	7.5 (cm)
water depth	1.0 (cm)	3.5 (cm)
soil thickness	26.0 (cm)	60.0 (cm)

In the experiment the interval between adjacent underground pipes were obtained by changing the interval of the movable walls. On the other hand, the groundwater levels were set to a fixed values through moving the trench upwards or downwards.

The water used for executing experiments was supplied from a water tank. Therefore, infiltration rate could be indirectly obtained by examining flow rate from the water tank. Drinking water was used as experimental water. The standard sand, which was obtained from Ju Mun Jin, was used as underground soil material. The particle size distribution was almost constant. The sand particles of diameter 0.30 mm to 0.42 mm occupied about 93% among experimental soil material. The specific gravity and void rate of experimental soil material were 2.65 and 47.6%, respectively. The permeability coefficient of the water (K) was 1.4×10^{-2} cm/sec.

The standard sand was selected as underground soil material because of two major advantages of stable phisical properties and easy handling compared to the other soil material. The schematic sketch of experimental conditions is shown in Fig. 4.1. Total 15 experiments in this paper were conducted for artificial groundwater recharge using underground piping

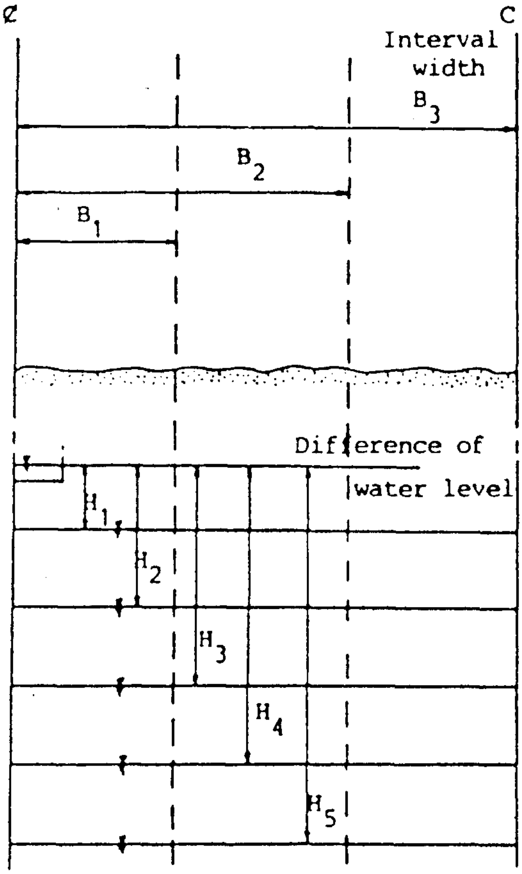

Fig. 4.1 Schematic sketch of Experimental conditions

method. Specifically, five cases of water difference between groundwater elevation and water elevation supplied through trench, which were 5, 10, 15, 20 and 25cm, were selected. Three cases of wall interval, which were 10, 20 and 30 cm, were also selected.

4.1.2 Experimental Results

The experimental results using above experimental conditions are shown in Fig. 4.2. In the figure recharge yield (㎤/min) indicates the infiltration rate at each experiment. The recharge height (mm/day) is calculated as the recharge yield per unit area in a day. As shown in the figure, when water difference between groundwater elevation and water elevation supplied to the trench is increased the recharge yield is also increased. Also, the

Table 4.2 Major characteristics of standard sand

specific weight	2.65
porosity	47.6%
permeability coefficient	1.4 x 10^{-2} cm/sec

recharge yield is nonlinearly increased according to the increment of wall intervals. However, the recharge yield has a limitation to the certain constant value even though water difference between groundwater elevation and water elevation supplied to the trench can be increased infinitely. This phenomena can be explained as the infiltration rate by capillary force has a limitation to the certain value. At the same time, the recharge height is increased by increasing water difference and/or wall intervals.

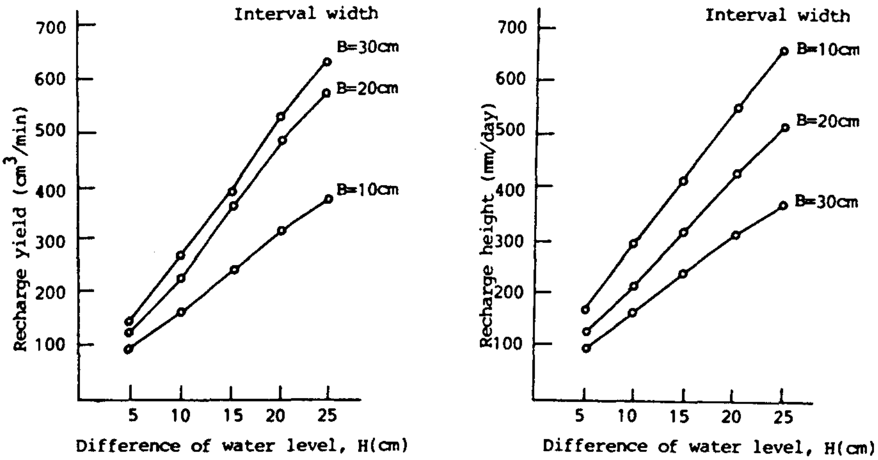

Fig. 4.2 Comparison of recharge yield and recharge height

4.2 Numerical Analysis

To verify the effect of groundwater recharge by artificial underground method, numerical analyses were conducted. As a proper solution method, the finite difference method is applied. The values of boundary conditions are obtained from experimental conditions. Recharge yields and/or recharge heights simulated by finite difference method were compared with experimental results.

4.2.1 Finite Difference Formulation

As shown in the previous chapter, the constant recharging rate per each experiment was used. Therefore, a steady infiltration equation is applied for the numerical analysis as a governing equation. The equation 3.11 can be rewritten as a following equation with neglecting a term of time variation.

$$\text{div}\ \{k(\psi)(\triangle\psi + \triangle z)\} = 0 \tag{4.1}$$

Considering two dimensional flow, equation 4.1 can be rewritten as follows:

$$\frac{\partial}{\partial X}\left[k(\psi)\frac{\partial \psi}{\partial X}\right] + \frac{\partial}{\partial z}\left[k(\psi)\frac{\partial \psi}{\partial z} + k(\psi)\right] = 0 \qquad (4.2)$$

where, $k(\psi)\frac{\partial \psi}{\partial X}$ and $k(\psi)\frac{\partial \psi}{\partial z} + k(\psi)$ indicate the velocity of x and z directions, respectively.

With considering very small element as shown in figure 4.3, the velocities of at block I, II, III and IV can be indicated as symbol V_I, V_{II}, V_{III} and V_{IV}.

Also, the permeability coefficient in the unsaturated zone can be indicated using symbol $K(\psi_I)$, $K(\psi_{II})$, $K(\psi_{III})$ and $K(\psi_{IV})$, respectively. The equation 4.2 can be rewritten as a following differtial equation.

$$\frac{1}{\triangle x_i}(V_I - V_{II}) + \frac{1}{\triangle z_j}(V_{III} - V_{IV}) = 0 \qquad (4.3)$$

where,

$$V_I = K_I \frac{\partial \psi}{\partial x} = k(\psi_I)\frac{2}{\triangle x_i + \triangle x_{i+,j}}(\psi_{i+1,j} - \psi_{i,j})$$

$$V_{II} = K_{II} \frac{\partial \psi}{\partial x} = k_I(\psi_I)\frac{2}{\triangle x_{I-1} + \triangle x_i}(\psi_{i,j} - \psi_{i-1,j}$$

$$V_{III} = K_{III} \frac{\partial \psi}{\partial x} + 1 = k(\psi_{III})\left\{\frac{2}{\triangle z_{j+1} + \triangle z_j}(\psi_{i,j+1} - \psi_{i,j}) + 1\right\}$$

$$V_{IV} = K_{IV} \frac{\partial \psi}{\partial z} + 1 = k(\psi_{IV})\left\{\frac{2}{\triangle z_j + \triangle z_{j-1}}(\psi_{i,j} - \psi_{i,j-1}) + 1\right\}$$

The equation 4.3 can be rewritten as following equation with variable values of $\triangle x$, $\triangle z$.

$$\frac{1}{\triangle x_i}\left[k(\psi_I)\right]\frac{2(\psi_{i+1,j} - \psi_{i,j})}{\triangle x_i + \triangle x_{i+1}} - k(\psi_{II})\frac{2(\psi_{i,j} - \psi_{i-1,j})}{\triangle x_{i-1} + \triangle x_i}\Big]$$

$$+ \frac{1}{\triangle z_j}\Big[k(\psi_{III})\frac{2(\psi_{i,j+1} - \psi_{i,j}}{\triangle z_{j+1} + \triangle z_j}$$

$$- k(\psi_{IV})\frac{2(\psi_{i,j} - \psi_{i,j-1})}{\triangle z_j + \triangle z_{j-1}} + k(\psi_{III}) - k(\psi_{IV})\Big] = 0 \qquad (4.4)$$

The equation 4.4 can be rearranged as a function of i,j.

$$\psi_{i,j}\Big[\frac{1}{\triangle x_i}\left\{\frac{k(\psi_I)}{\triangle x_i + \triangle x_{i+1}} + \frac{k(\psi_{II})}{\triangle x_i + \triangle x_{i-1}}\right\} + \frac{1}{\triangle z_j}\Big\{\frac{k(\psi_{III})}{\triangle z_j + \triangle z_{j+1}}$$

$$+ \frac{k(\psi_{IV})}{\triangle z_j + \triangle z_{j-1}}\Big\}\Big] = \frac{k(\psi_I)}{\triangle x_i(\triangle x_i + \triangle x_{i+1})}\psi_{i+1,j}$$

$$+ \frac{k(\psi_{II})}{\triangle x_i(\triangle x_i + \delta x_{i-1})}\psi_{i-1,j} + \frac{k(\psi_{III})}{\triangle z_j(\triangle z_j + \triangle z_{j+1})}\psi_{i,j+1}$$

$$\psi_{i,j+1} + \frac{k(\psi_{IV})}{\triangle z_j(\triangle z_j + \triangle z_{j-1})} \psi_{i,j-1} + \frac{k(\psi_{III})}{2\triangle z_j} - \frac{k(\psi_{IV})}{2\triangle z_j} \qquad (4.5)$$

Equation 4.5 can be simplified as a following equation with 6 coefficients.

$$A\psi_{i,j} = B\psi_{i+1,j} + C\psi_{i-1,j} + D\psi_{i,j+1} + E\psi_{i,j-1} + F \qquad (4.6)$$

The equation 4.6 indicates that the middle value $\psi_{i,j}$ is obtained from the edge values, which are $\psi_{i+1,j}$, $\psi_{i-1,j}$, $\psi_{i,j+1}$ and $\psi_{i,j-1}$. In the numerical simulation, the unknown value $\psi_{i,j}$ can be obtained with boundary conditions and initial values as well as applying the above equation. As initial values, properly assumed values are given and then the unknown value at each point is adjusted by applying the finite difference equation using relaxation method. That is, the calculation at each time step continues till converged to the fixed value.

4.2.2 Boundary Conditions

The boundary conditions in the numerical analysis are very important. In the artificial groundwater recharge, upper boundary line is the surface of the soil and lower boundary line is groundwater elevation. It is assumed that the underground pipe is located with constant intervals. Therefore, the boundary at each side is considered as the centerline of the underground pipe. In this case, the existing soil water zone can be considered to be symmetric. Therefore, the numerical simulation can be done by analyzing the half of the zone with boundary conditions of no water flow. That is, the permeability coefficients of water are zero in the middle lines of the zones. The suction pressure head (ψ), which is a lower boundary line, is zero in the groundwater level. Therefore, the permeability coefficient (K) is zero. Because the surface of the soil as the upper boundary condition is impermeable, the permeability coefficient (K) is considered as zero. The summary of the boundary conditions is shown in the figure 4.4.

4.2.3 Comparison between experiment and numerical analysis

The recharge yields and recharge heights by the numerical analysis are compared with the results by experiments. The permeability coefficient $K(\psi)$ of 1.4×10^{-2} cm/sec, which is obtained by pilot test of standard test, was used in the numerical analysis. The capillary potential (ψ) and permeable coefficient (η) of 145 cm and 12.2 are used in the numerical analysis. Figure 4.5 shows the comparison between results from experiment and numerical analysis. As shown in the figure, the recharge heights simulated by numerical analysis are well agreed with the recharge height obtained from the experiments.

4.3 Recharge Yield by Underground Piping Method

The finite difference model developed in the previous chapter was applied to simulate recharge yield in the field soil. The underground material of sand soil was considered as the field soil. The permeability coefficient (K) of 5.4×10^{-3} cm/sec was utilized. The bubble pressure (ψ_b) and peameability coefficient (η) of −40 cm and 3.4 are used for field soil, respectively. The recharge heights simulated using the model developed in this paper are shown in Fig. 4.6. As shown in the figure, the recharge heights are increased by increasing water difference between groundwater elevation and water elevation supplied to the trench. The recharge heights are increased by increasing the intervals between underground pipes. It can be concluded that the recharge heights are greatly affected by groundwater levels in the

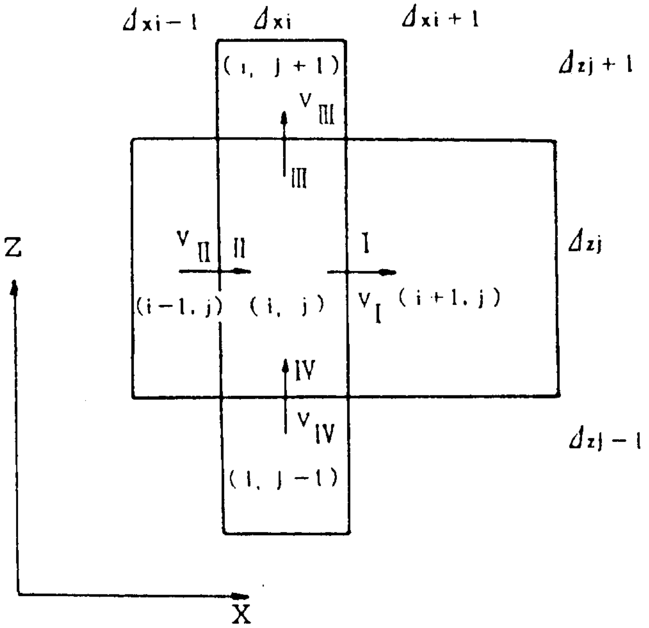

Fig 4.3 Schematic sketch of differential blocks

lower water difference between groundwater elevation and surface water elevation. However, the recharge heights are not affected by water differences in the higher water difference between groundwater elevation and surface water elevation. The recharge heights are almost constant when the difference between water levels is over 1m. Therefore, when the difference between water levels is over 1m in real application, the main consideration for calculating the recharge height should be intervals between underground pipes. Figure 4.7 indicates the relationship between the recharge height and the interval between underground pipes. As shown in the figure, the recharge height is slightly increased in the wide intervals.

Fig. 4.8 shows the distribution of water content in the soil around underground pipes. The

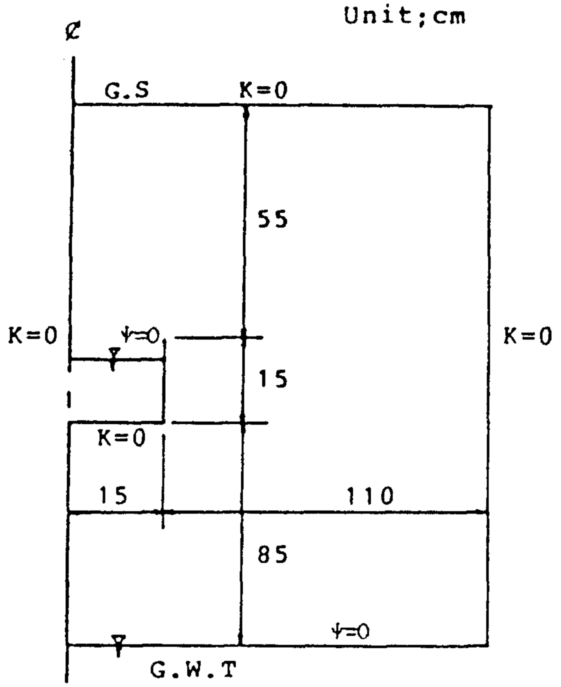

Fig. 4.4 Boundary conditions used in the experiment

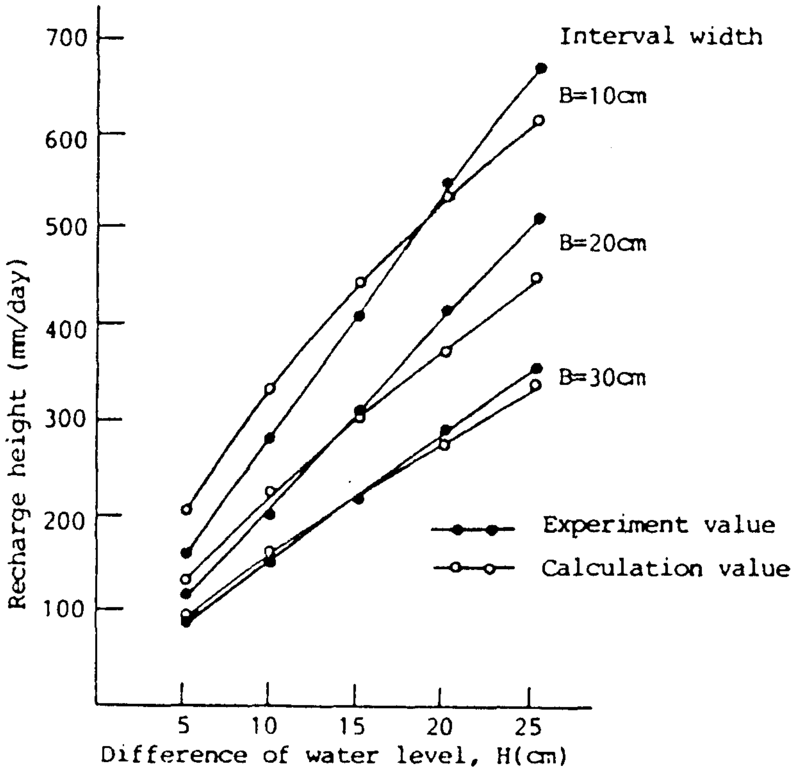

Fig 4.5 The comparison between experiment and numerical analysis

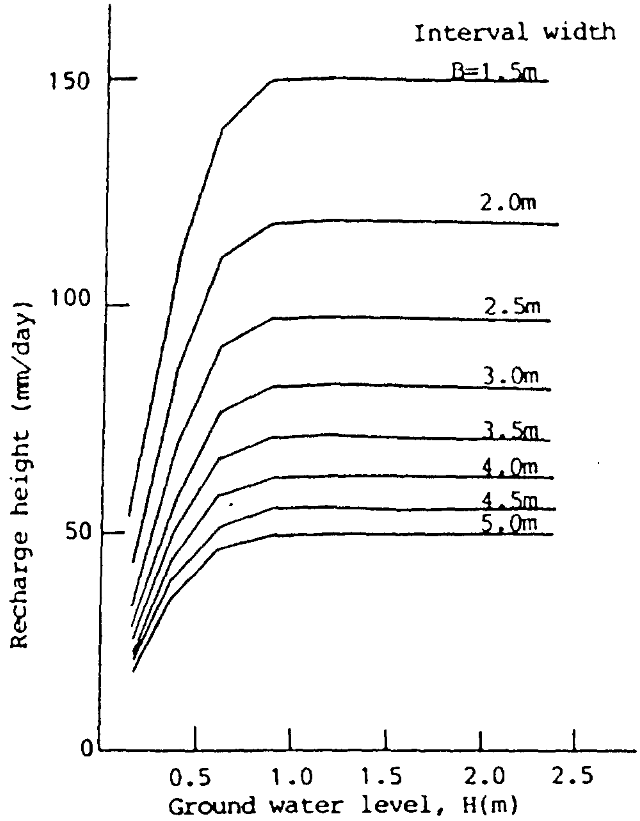

Fig. 4.6 The result of numerical analysis in a field

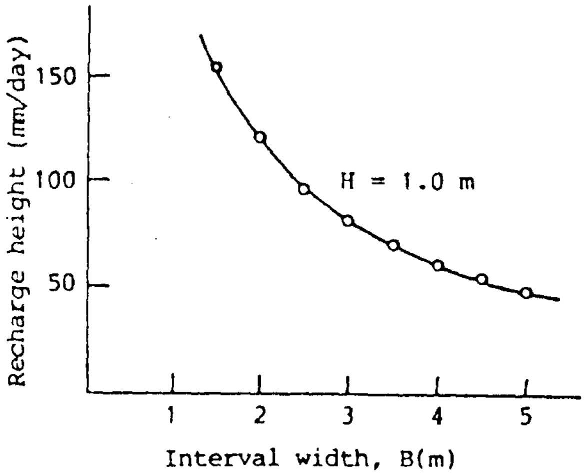

Fig. 4.7 The relation between pipe intervals and recharge heights

equation 3.13 was used for calculating the water content from the distribution of capillary force. As shown in the figure, the rise of water content is mainly affected by artificial recharge supplied from underground pipes.

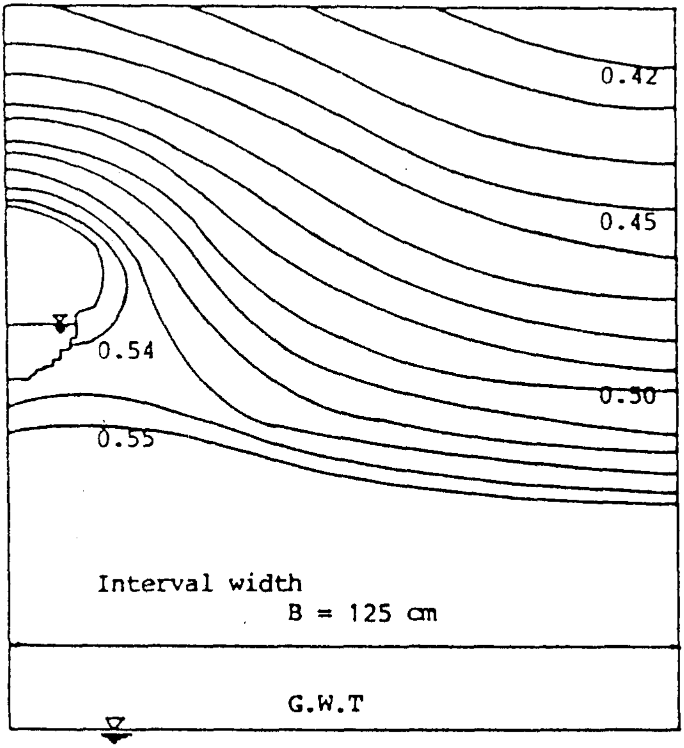

Fig.4.8 A distribution of moisture content of soil around underground piping.

5. Conclusion

To maintain enough groundwater volume without dropping groundwater elevations, the proper groundwater recharge is necessary. The groundwater recharge can be classified into two categories which are natural recharge and artificial recharge. Even though the natural recharge through direct infiltration from the rain is desirable, the artificial groundwater recharge is necessary when the increment of groundwater consumption exceeds natural recharge rate.

In this paper, as an artificial groundwater recharging method the underground piping method, which is to supply water indirectly to the underground using an underground piping system, is investigated throughout experiments and numerical analysis. The influence of the groundwater by underground piping method is evaluated by comparing recharging heights. Good agreements between experiments and numerical analysis are obtained and the artificial groundwater recharge by underground piping method is well tested and verified.

Generally, when water difference between groundwater elevation and water elevation supplied to the trench is increased the recharge yield is also increased. Also, the recharge yield is nonlinearly increased with a limitation to the certain constant value according to the increment of intervals between pipes. In the field application, the recharge heights are almost constant when the difference between water levels is over 1m. Therefore, when the difference between water levels is over 1m, the main consideration for calculating the recharge height should be intervals between underground pipes.

The water content distribution diagram shows the larger water content around underground pipes compared to the other parts. Therefore, using underground piping method the artificial groundwater recharge can be well achieved.

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