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Assignment of the Groundwater Level at the Leachate Collection Pipe for the Waste Landfill Groundwater Simulation: Combination of the Two Dimensional Saturated - Unsaturated Vertical and Horizontal Groundwater Flow Model

by

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Abstract

The landfill construction has caused many negative impacts on the surrounding environment, particularly groundwater. Evaluation of the function of the leachate collection pipe at the landfill site is indispensable for managing the landfill operation. 3D groundwater flow simulation may be applicable but it requires much capacity of computer and time consumption comparing with 2D groundwater flow simulation due to the huge calculations. Therefore, the 2D horizontal groundwater flow simulation ($2D_h$) was carried out. However, the most difficulty is the assignment of the groundwater head at the leachate collection pipe buried for leachate drainage. Therefore, in the present paper the 2D vertical model ($2D_v$) was applied to calculate the change of groundwater table above the leachate collection pipe. This paper paid attention to examine the validation of the assignment of the leachate collection pipe boundary by applying the results of the $2D_v$. The $2D_h$ was coupled with the rainwater recharge model to solve the partial differential equation of groundwater flow. Finite difference method and iterative successive over relaxation were applied. The drainage volume of leachate collection was summed up in the whole landfill site and compared with the average volume of treated waste water. The study demonstrated that the groundwater level at the vicinity of the drainage pipe in the $2D_v$ analysis is reasonably assigned for the $2D_h$.

Keywords: Landfill, Leachate collection pipe, Drainage rate, Saturated-unsaturated two-dimensional vertical model ($2D_v$), Two-dimensional horizontal model ($2D_h$)

1. Introduction

During the past several decades, computer simulation models for analyzing flow of

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groundwater have played an increasingly important role in the evaluation of alternative approaches to groundwater development and management. The underlying philosophy of the simulation approach is that an understanding of the basic laws of physics and an accurate description of the specific system under study will enable an accurate quantitative understanding of cause and effect relationships. This quantitative understanding of these relationships enables forecasts to be made for any defined set of conditions. Even though model results (if developed competently and objectively) are imprecise, they represent the best decision making information at the time the results are made [1].

The partial differential equation of groundwater flow was solved by many researchers. Several numerical models are available for simulating the movement of water in variably saturated porous media [2) 3)]. Even few researchers have applied other models such as Johnson *et al.* [4] to simulate the drainage discharge. However, applying the results of the $2D_v$ to simulate the leachate collection pipe and its drainage rate is very rare at the large region. To estimate the function of the leachate collection pipe system, the present paper applied the numerical simulation to the specific site having faults, sheet walls, and leachate collection pipe. The $2D_v$ is applied to unsaturated-saturated zone including different permeabilities.

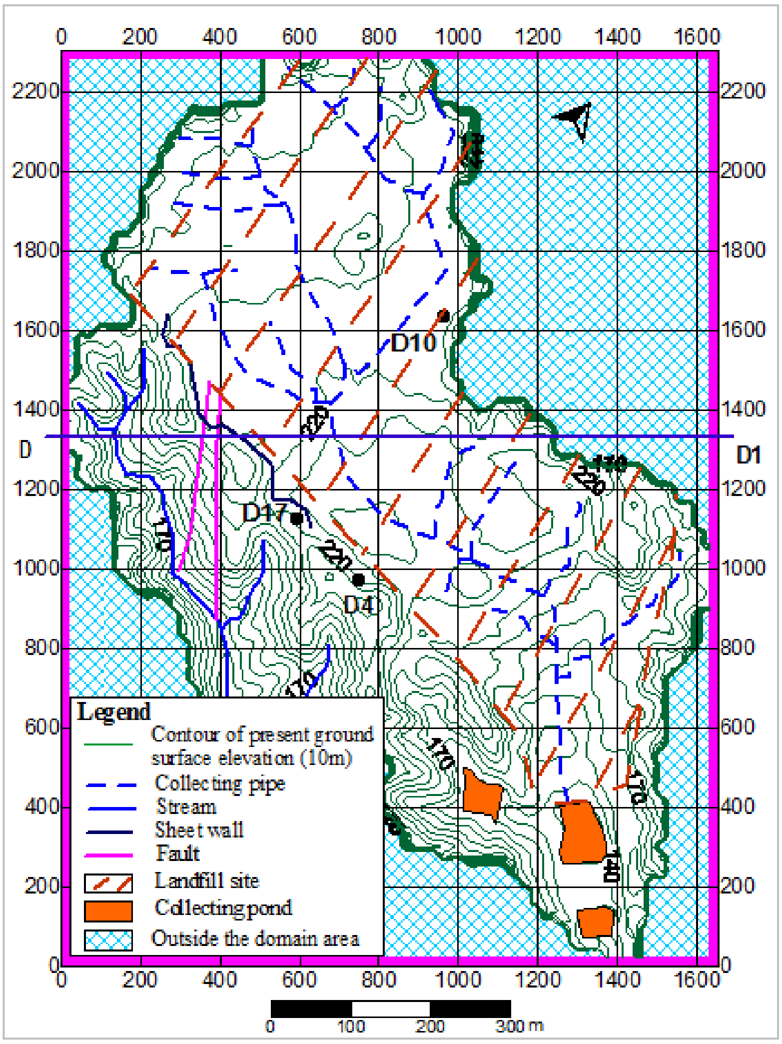

Fig.1 Study location.

In Japan the landfills have been constructed with high technology and good standard at present. A major part of waste landfill is residue from incinerators or incombustible portion of crushed waste. The landfills used before 1970's when the incineration became popular, contain waste which did not undergo intermediate treatment. In other words, the landfill was just a dumping site [5)]. From 1970 to 1980's, the landfills contain both intact waste and incineration residue [6)]. Therefore, waste with high organic content such as food waste remains in such old landfills, causing offensive odor and foul leachate and deteriorating the impression of the landfills. Moreover, the first guidelines for the landfill facilities were published in 1979. The characteristics of waste depose at the landfill sites in Japan had been drastically changed, i.e. from unprocessed municipal solid waste (MSW) to incinerator residue and noncombustible MSW. In 1988, the new landfill guidelines were promulgated providing the standard values for facility and equipment as well as the new design criteria of leachate treatment facilities [7)].

Figure 1 shows A. landfill which is located in B. City, Japan and selected as case study. This landfill was inaugurated in 1970's. The maximum area of the landfill is 100 hectares. The planned landfill volume is about 20 million cubic meters. The function of this landfill is to dispose the final domestic waste. The main components of waste for burying are construction and demolition waste, glasses, ceramic, domestic materials, incinerated ash, and very small amount of disaster materials which contain organic materials.

The domain boundaries have been assigned as the zero groundwater flux boundary conditions because the calculation domain is determined considering the hydrological watershed. Inside the domain area, there are three waste water collecting ponds which are regarded as the impermeable boundaries. A concrete sheet wall system was constructed in order to prevent the leakage of the leachate of the landfill. The topography outside the landfill site presents the deep slope of ground surface. Understanding of the behavior of groundwater flow is the most important in order to make the landfill "safety" with the surrounding environment. Particularly, the effect of the leachate collection pipe is crucial to prevent the leak of the polluted water to the neighboring environment. Therefore, the evaluation of the leachate collection pipe function at the old landfill sites is indispensable. The life time of the landfill operation almost depends on the function of the leachate collection pipe. If the leachate collection pipe does not work, the waste water will overflow and make environment contaminated.

The main objectives of this study are: (1) to explain how to apply the $2D_v$ results to the $2D_h$, (2) to calculate the drainage rate of leachate collection pipe, (3) to demonstrate the validity of the model results, (4) to estimate the effects of the leachate collection pipe on the drainage rate.

2. Development of Theory

The 3D groundwater flow model can be applied to evaluate the function of the leachate collection pipe at the landfill sites. Because of the huge calculations the 3D groundwater flow simulation requires severely the capacity of computer and time consumption but not any personal computer can be used. To reduce these requirements, the 2D groundwater flow model is applicable. However, in the $2D_h$, groundwater simulation at the leachate collection pipe system at the landfill site is thorny for the researchers. Moreover, the groundwater table above the leachate collection pipe is not measured. Therefore, it is very difficult to assign the leachate collection pipe boundary. In order to overcome these difficulties, the authors attempted to simulate groundwater table and drainage rate of the leachate collection pipe by simulation of the $2D_v$. Then, the result of the $2D_v$ is applied to the $2D_h$. In this section, the authors explain the equations of groundwater flow as well as the model process in detail.

2.1 2D vertical groundwater flow equation

The following equations are given for the two-dimensional case in the vertical plane for the groundwater flow [8]:

$$(C_w + \beta S_0)\frac{\partial p}{\partial t} = \frac{\partial}{\partial x}\left\{k(p)\frac{\partial p}{\partial x}\right\} + \frac{\partial}{\partial z}\left\{k(p)\left(\frac{\partial p}{\partial z}+1\right)\right\} \tag{1}$$

$$C_w = \frac{\alpha m(\theta_s - \theta_r)\theta_e^{1/m}\left(1-\theta_e^{1/m}\right)}{1-m} \tag{2}$$

$$k(p) = \theta_e^{1/2}\left\{1-\left(1-\theta_e^{1/m}\right)^m\right\}^2 k_s \tag{3}$$

$$\theta_e = \frac{\theta-\theta_r}{\theta-\theta_s} = \left[\frac{1}{1+\left(1+\alpha|p|\right)^n}\right]^m \tag{4}$$

where $p(x,z,t)$[L]is pore pressure head (further it will be called as pressure head); k[LT^{-1}] is permeability in isotropic media, k is a function of the pressure head. In other words, k depends on water content of the porous media. s and r indicate saturated and residual values of soil water content (θ), respectively. α, n, m are the van Genuchten's coefficients [9]. S_0[L^{-1}] is specific storage coefficient. β is a switch number given by 0 or 1 for unsaturated or saturated condition.

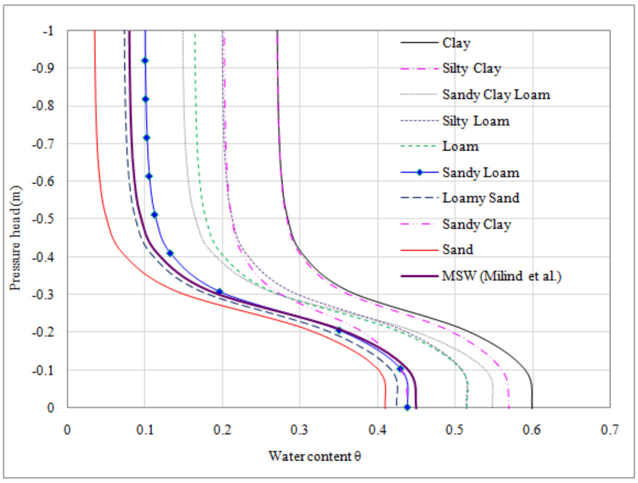

Fig.2 Mean van Genuchten parameters for 9 textural classes (modified from Hodnett *et al.*[10]).

Table 1 Van Genuchten's coefficients.

Van Genuchten's coefficients	
θ_r	0.118
θ_s	0.445
n	2.0
m	0.5
α	0.000491m^{-1}

Figure 2 shows the relationship of water content and pressure head for the different soil types by Hodnett *et al.*[10]. The van Genuchten's coefficients in **Table 1** are assumed for the landfill material which is taken from Hodnett *et al.*[10] as the dot blue line in **Fig.2**. The brown line shows the van Genuchten's coefficients for MSW by Milind *et al.* [11]. The dot blue and brown lines present the insignificant difference. Comparison of **Table 1** and **Fig.2** demonstrated that the waste material property is seemly similar to sandy loam.

2.2 2D horizontal groundwater flow equation

Isotropic and heterogeneous two dimensional horizontal groundwater flow equation assuming constant water density can be described by partial differential equation as Eq.(5):

$$n_e \frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(kb\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(kb\frac{\partial h}{\partial y}\right) + Ra(x,y,t) \tag{5}$$

where, $h(x,y,t)$[L] is elevation of groundwater table, $Ra(x,y,t)$[LT^{-1}] is the recharge rate which is calculated from rainfall, rainwater interception and potential evapotranspiration [12)]. Note that b[L] is $b=h(x,y,t)-z(x,y)$, $z(x,y)$[L] is elevation of bedrock. n_e is effective porosity.

2.3 Flow chart of numerical simulation

The groundwater flow simulation was conducted for the unconfined aquifer. The evaluation of the function of the leachate collection pipe is indispensable at the landfill site. The difficulty of the assignment of the leachate collection pipe boundary in the $2D_h$ was solved by the application of the results of the $2D_v$. The $2D_v$ was applied to unsaturated - saturated cross section D-D1 (**Fig.1**). In the present paper, the mathematical model was employed to make a quantitative analysis.

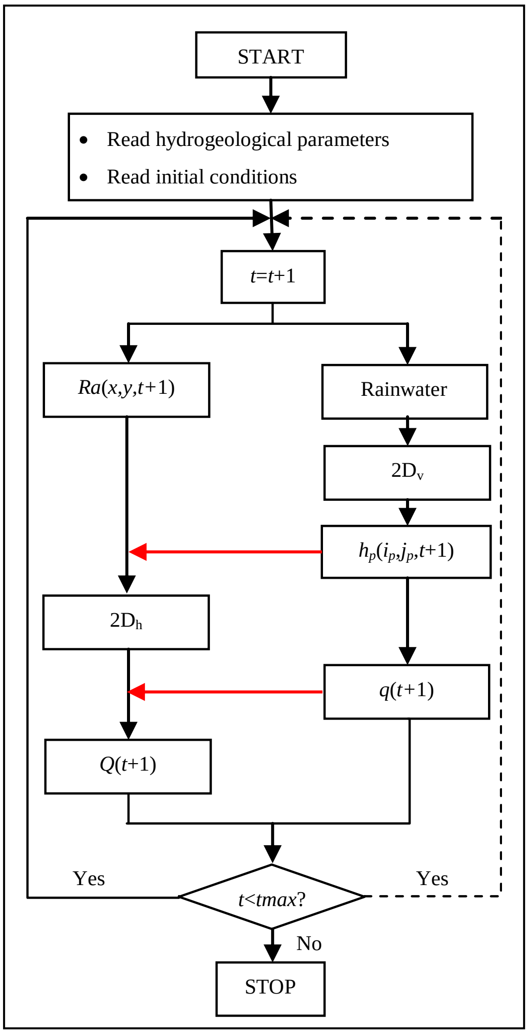

Fig.3 Simulation flow chart.

Figure 3 shows the flow chart of the numerical simulation. The dash arrow indicates the “do-loop” of the $2D_v$. The most important component is simultaneous numerical integration and conventional assignment of groundwater table above the pipe. The permeability of faults has not analyzed yet. Therefore, it was assumed equal to the permeability of the aquifer. Besides, the sheet walls were simulated with low permeability. The comparison of observed and calculated values is necessary to make the model more precise.

Simulation of the $2D_v$ is aimed in order to obtain the groundwater table above the leachate collection pipe ($h_p(i_p,j_p,t)$) and the drainage rate ($q(t)$). $h_p(i_p,j_p,t)$ was simulated separately by solving Eq.(1). The calculated result of $h_p(i_p,j_p,t)$ from the $2D_v$ was applied to assign the leachate collection pipe boundary in the $2D_h$ of the landfill site for each time step. The rainfall was applied to the surface boundary of the $2D_v$ calculation domain. The $2D_h$ will calculate the drainage rate ($Q(t)$) in the whole simulated region. t+1 means next time step.

3. Numerical Model

The transient groundwater flow by Eqs.(1) and (5) is solved by an implicit finite difference method using an iterative successive over relaxation technique.

In the $2D_h$, the maximums of length and width of the selected area are 2,305m and 1,650m, respectively. The model domain is divided into irregular discretized grid system for x and y directions. The grid size is gradually changed from 2m to 10m [13]. The bedrock elevation is 80m above sea level. The time interval is 1 hour. In the groundwater flow model, the extinction depth was set 1.5m to allow the water uptake by trees. Additional evapotranspiration from the groundwater table will not occur on the groundwater table if the groundwater table is deeper than the extinction depth [12].

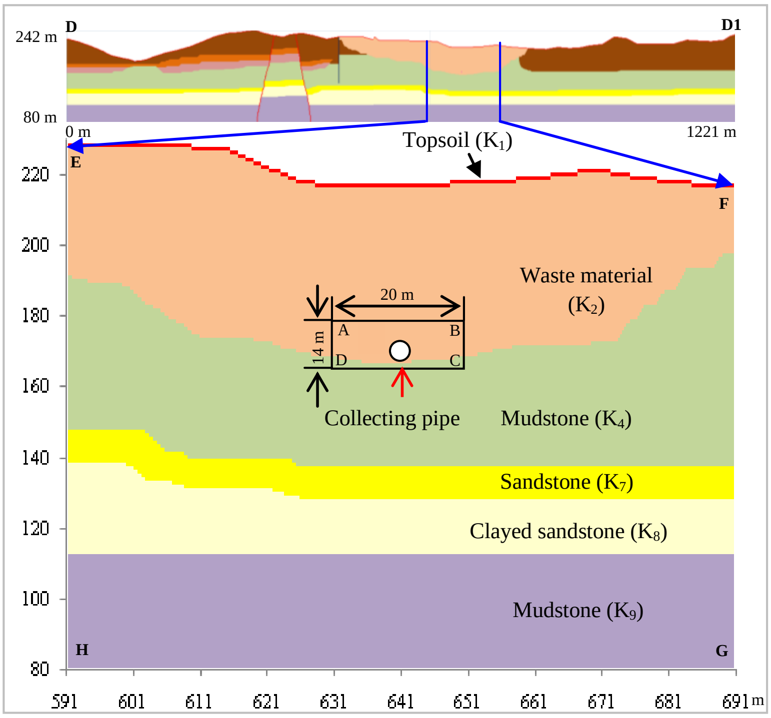

Fig.4 Geological conditions at cross section D-D1.

As mentioned previously, assignment of the groundwater table above the leachate collection pipe and the related drainage rate are crucial for the horizontal groundwater flow simulation. The $2D_v$ simulated for the cross section D-D1 in **Fig.1**. **Figure 4** illustrates its geological conditions and the leachate collection pipe location. EFGH and ABCD will be used to explain in the section 4.2. At the right side of the leachate collection pipe, the thickness of waste material is thinner than that of the left side. Below waste material, there is a mudstone layer which has smaller permeability. The figure also shows the permeability values of K_1, K_2, K_4, K_7, K_8 and K_9.

The length of the cross-section D-D1 is 1221m. The highest elevation is 242m. The grid sizes 1m x 1m for both directions. There are 9 layers in the calculated area. **Table 2** shows the values of permeability and other model parameters. The data was adopted from the measured data at the study site.

The present paper focuses on the groundwater flow surrounding of the leachate collection pipe in the $2D_v$. The leachate collection pipe was constructed inside the waste material to drain the leachate. The diameter of the leachate collection pipe is 1m. The pressure head of the leachate collection pipe was assigned equal to 0.0 m[14)] for the $2D_v$. Most of these layers were formed by mudstone. The sandstone layer is considered as an aquifer. The permeability of waste material seems to have a bit high value compared with the natural soil in the study area.

Table 2 Model parameters.

Model parameter	**Value (unit)**	**Note**
K_1	10^{-3} cm/s	Topsoil
K_2	$5x10^{-3}$ cm/s	Waste material
K_3	$3.6x10^{-4}$ cm/s	Tuff
K_4	$4x10^{-4}$ cm/s	Mudstone
K_5	$3x10^{-4}$ cm/s	Mudstone
K_6	$5.2x10^{-4}$ cm/s	Mudstone
K_7	$8x10^{-4}$ cm/s	Sandstone
K_8	$6x10^{-4}$ cm/s	Clayed sandstone
K_9	$3.5x10^{-4}$ cm/s	Mudstone
K_w	10^{-7} cm/s	Sheet walls
K_f	$8x10^{-3}$ cm/s	Faults
Runoff coefficient of landfill site	0.7	
Runoff coefficient of natural site	0.3	
Extinction depth	1.5 m	
Pipe	p = 0.0 m	Pressure head
n_e	0.25	
S_0	$2.5x10^{-3}$/cm	
Surface	$-k(p)\left(\frac{\partial p}{\partial z}+1\right)=-$ *Rainfall intensity*	

4. Model Results and Discussion

4.1 Recharge rate

The time dependent recharge rate is modeled by $Ra(x,y,t)$ in Eq. (5). Recharge rate is calculated by the rainwater recharge model[12]. The model includes the calculation of evapotranspiration and recharge of rainfall taking account the landuse factors which are related to the coefficient of surface runoff (rf). The runoff coefficients were selected according to the Guideline for surface runoff coefficients by the Ministry of Education, Culture, Sports, Science and Technology, Japan. **Figure 5** shows that the landfill cover is very hard. Therefore, in the study area, there are two types of landuse such as forest and landfill site where runoff coefficients are 0.3 and 0.7, respectively. The effect of rainwater interception was also considered by Tsutsumi *et al.*[12]. The hourly rainfall from 2003 to 2007 was available. The rainwater recharge model was applied with hourly time series. **Figure 6** shows the recharge rate calculated by the rainwater recharge model. The recharge rates at natural site and landfill site are 42% and 27% of rainwater, respectively. This demonstrates that at landfill site, the infiltration of rainwater is less than that of rainwater at natural site.

Fig.5 Landfill cover.

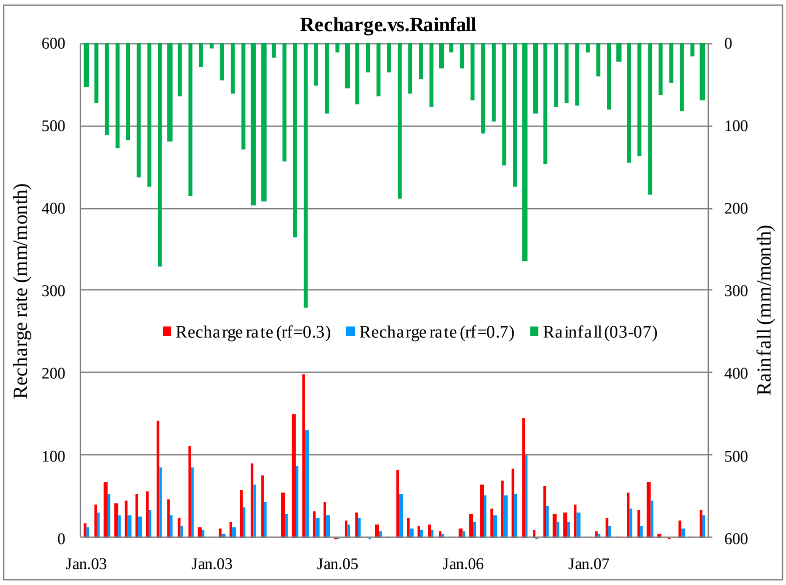

Fig.6 Rainfall and recharge rate.

4.2 Potential distribution

From the calculated pressure head, the potential distribution was obtained by adding the elevation of each grid point. Initial potential distribution is displayed in **Fig.7**. The initial condition was calculated from the groundwater table before the landfill was constructed. **Figures 8** and **9** show the potential distribution close to the leachate collection pipe after 7 months and 5 years, respectively. These figures are zoomed up to focus on the pipe location at the small part ABCD which is showed in **Fig.4**. The red lines show the border between mudstone and waste materials.

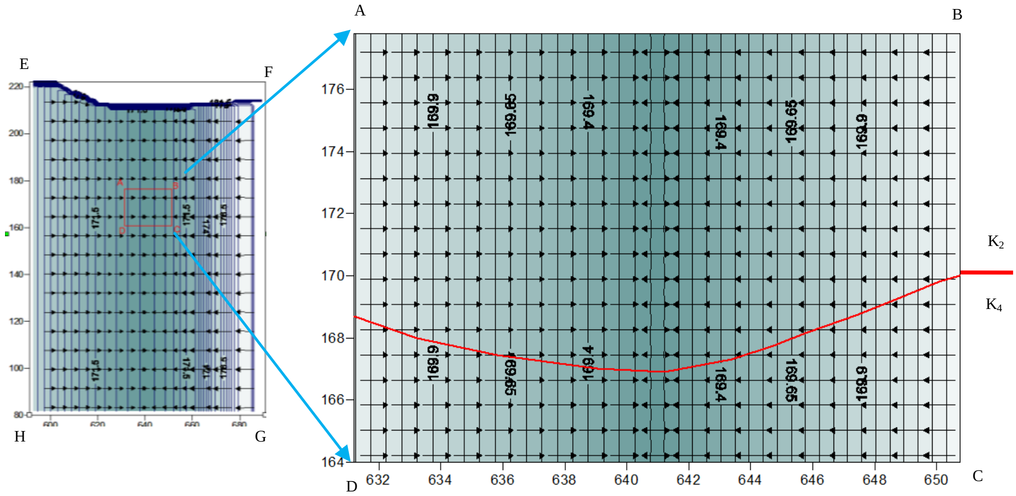

Fig.7 Initial potential distribution (m).

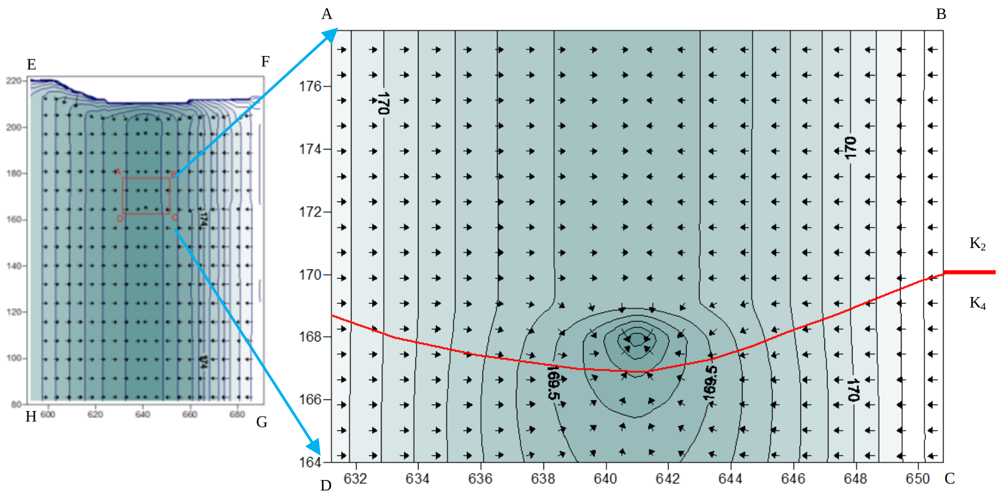

Fig.8 Potential distribution (m) and groundwater flow direction after 7 months.

At leachate collection pipe, pressure head was always set equal to 0.0 meter for the $2D_v$. Therefore, the figures show the smallest potential at the pipe location. It means that the groundwater is drained through the leachate collection pipe hence drawdown of groundwater table occurs. **Figure 8** shows that after 7 months, the potential distribution at the leachate collection pipe is lower than that of the vicinity. After 5 years, the shape of potential distribution surrounding the leachate collection pipe considerably changed from that of initial condition (**Fig.7** and **9**). However, the potential distribution around the leachate collection pipe did not change significantly after 7 months and 5 years.

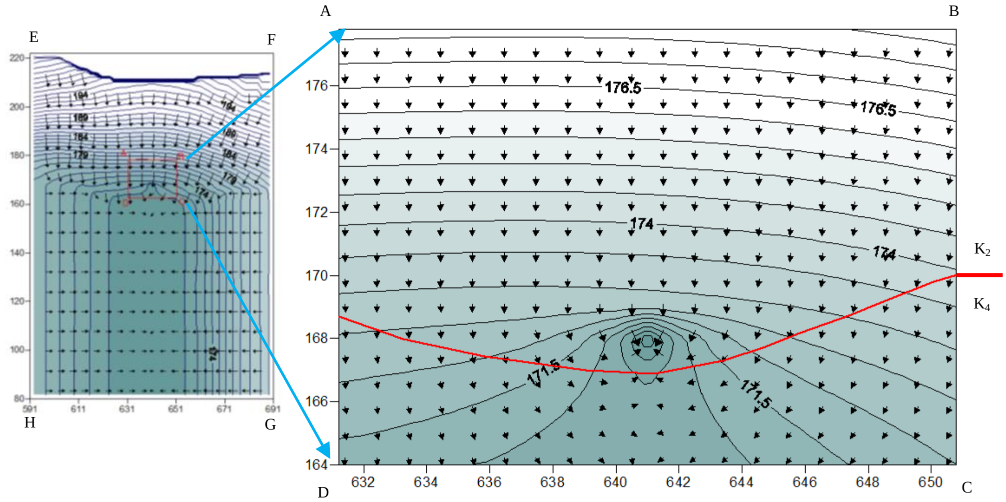

Fig.9 Potential distribution (m) and groundwater flow direction after 60 months.

4.3 Groundwater table above the leachate collection pipe

Figure 10 shows the groundwater table above the leachate collection pipe obtained by the 2D$_V$. To both directions of the leachate collection pipe, the groundwater table is significantly different. This happens depending on geological conditions (**Fig.4**).

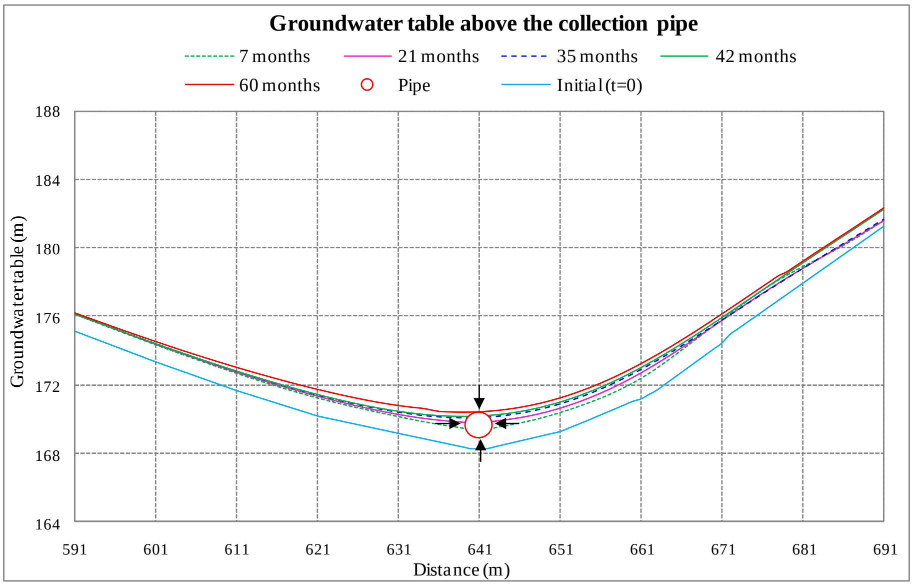

Fig.10 Groundwater table above the leachate collection pipe and flow direction.

The rainwater was captured and stored inside the waste material. Even though the pressure head of the leachate collection pipe was always set equal to 0.0 meter in the 2D$_V$, all of the leachate cannot be collected. Consequently, the groundwater table is maintained higher than the leachate collection pipe in the present simulation. The arrows indicate the groundwater flow direction.

4.4 Relationship of groundwater table and drainage rate

Figure 11 shows the plot of the groundwater table above the leachate collection pipe and drainage rate obtained by the $2D_v$. The rise of groundwater table induces the increase of drainage rate. As mentioned above, the groundwater tables at left and right side are asymmetric from each others. This may cause the difference of drainage rate in both sides.

However, **Fig.11** shows that the groundwater tables close to the leachate collection pipe seem to be symmetric within 1m distance in the both sides of the leachate collection pipe. The insignificant difference of the drainage rate can be neglected when the groundwater table at both sides is applied. By this reason, the authors applied the relationship of groundwater table above the pipe and drainage rate to the $2D_h$. When the groundwater table above the pipe ($h_p(i_p,j_p,t)$) is obtained by the $2D_v$, the drainage rate value was counted using the relationship of **Fig.11**. In other words, the drainage rate was taken from this figure according to the change of groundwater table. The drainage rate was summed up in the $2D_h$ to calculate along of the leachate collection pipe system in the whole landfill site. The results will be demonstrated in the section 4.6.

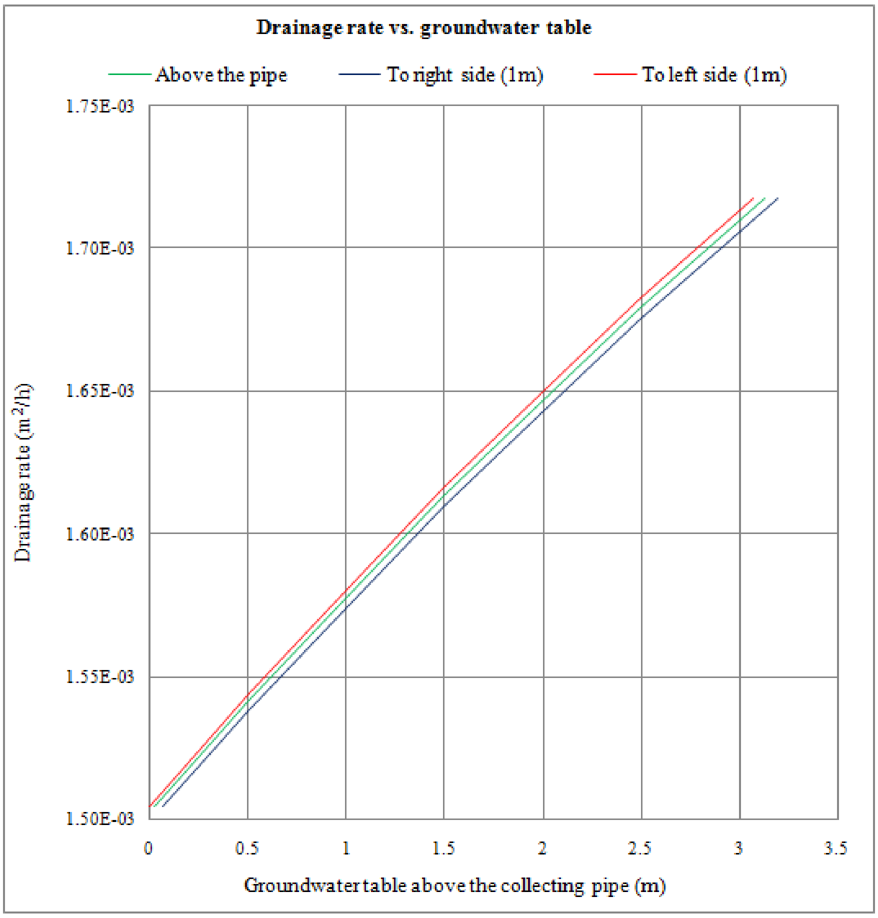

Fig.11 Groundwater table above the leachate collection pipe and drainage rate.

4.5 Observed and calculated value in the $2D_h$

In order to verify the accuracy of the models quantitatively, the observed and calculated groundwater tables were compared for the period from 2005 to 2007. Three observation wells in the study area were used to verify the accuracy.

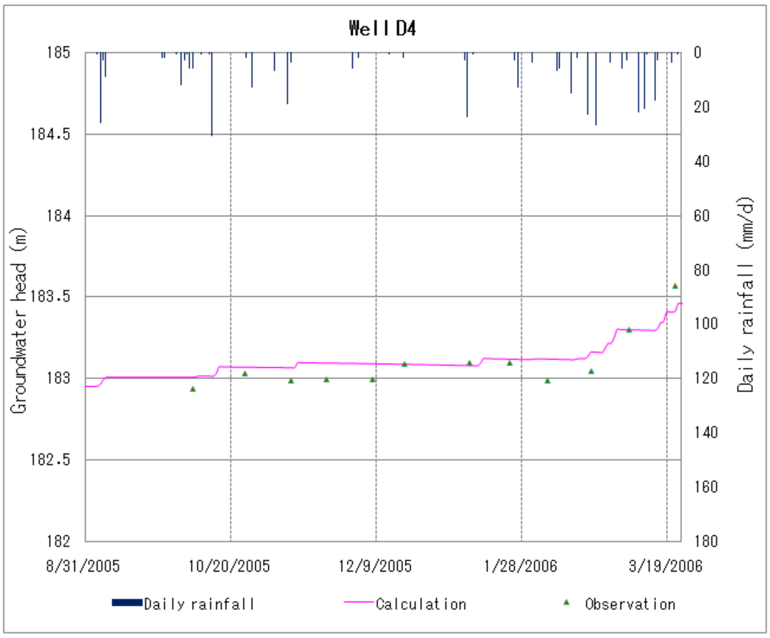

Fig.12 Observed and calculated groundwater at well D4.

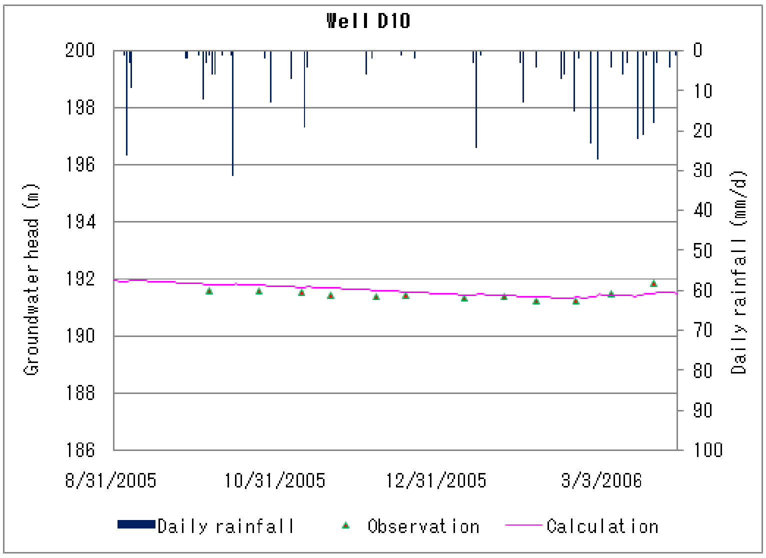

Fig.13 Observed and calculated groundwater at well D10.

Figures 12, **13** and **14** are the comparisons of measured and calculated groundwater tables of wells D4, D10 and D17 in **Fig.1** for time period from October, 2005 to March, 2006. From these figures, the measured and calculated groundwater tables show a good agreement. Moreover, the groundwater table fluctuations corresponded to the changes of rainfall in the study area.

The fluctuation is not so high because these wells are close to the landfill site where the coefficient of surface runoff is 0.7. Therefore, the rainwater infiltration is small. From these verifications, the model can be used as a proto tool to predict groundwater flow for future water management of the waste site.

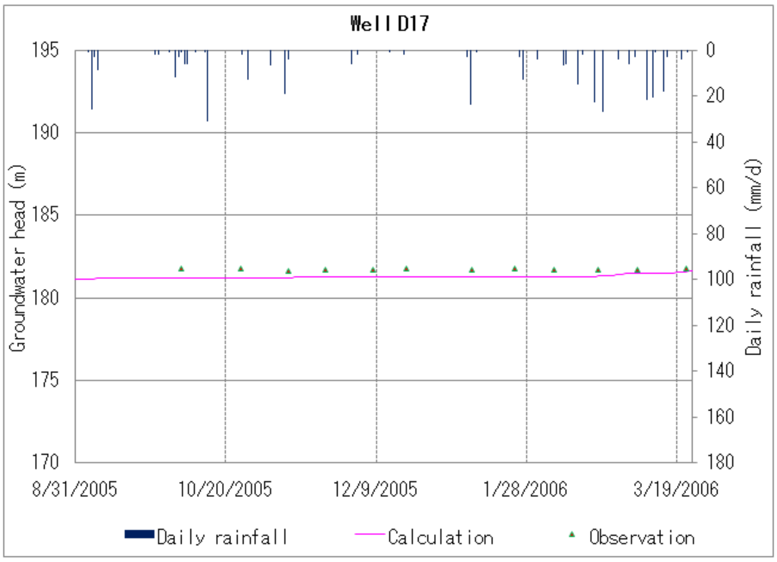

Fig.14 Observed and calculated groundwater at well D17

4.6 Drainage rate confirmation

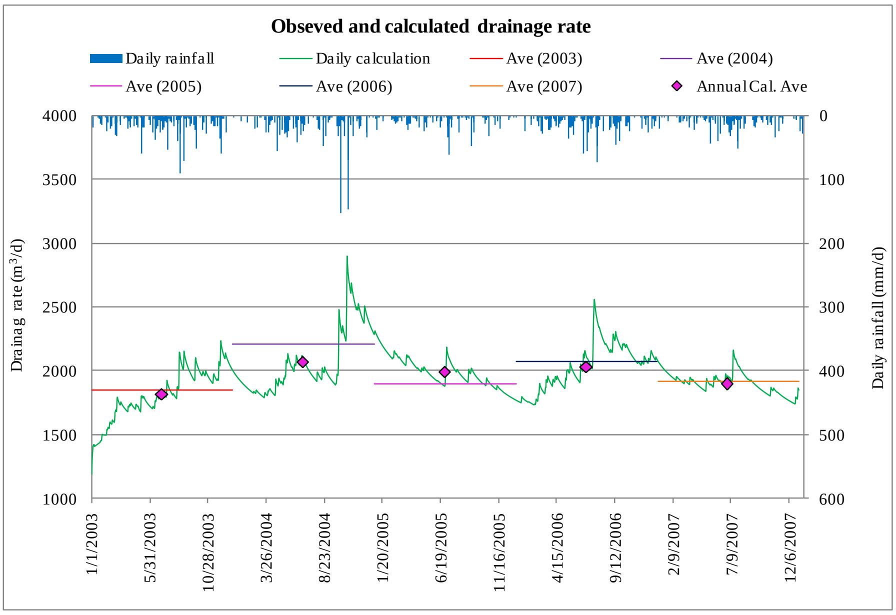

Fig.15 Observation and calculation of drainage rate

In the study site, there is no daily record of the drainage rate. However, the annual volume of treated waste water was reported from 2003 to 2007. Therefore, the daily average of annual treated waste water was applied to check the calculated drainage rate in whole region.

Figure 15 shows the calculated leachate volume from the leachate collection pipe system and daily average of treated waste water. The calculation of leachate volume shows a correlated response with daily rainfall. The mean value of numerical solution shows a good agreement with the daily average volume of treated waste water from 2003 to 2007. In 2004 both recorded volume of treated waste water and calculated volume of waste water collection indicate the maximum values. This is due to the highest of rainwater in 2004 produced the maximum leachate volume. Thus, the proposed scheme of the numerical simulation combining the $2D_v$ and $2D_h$ seems to be applicable for the estimation of the daily leachate volume that needs to be treated.

5. Conclusion

The groundwater simulation for the wide region with fine meshes by the three dimensional model faces on a hurdle of time consumption and limitation of capacity of personal computer. On the other hand, the two dimensional numerical simulation is practical for the wide groundwater analysis. However, the estimation of drainage rate and assignment of water level at the leachate collection pipe are difficult for the $2D_h$. To overcome this problem, the combination of the $2D_v$ and $2D_h$ were proposed to the real site.

A detailed comparison between the observed data and the simulation results showed that good agreement was obtained. The maximum volume of leachate collection was created due to the highest rainwater. The success of the $2D_h$ demonstrated that the $2D_v$ can be utilized to simulate groundwater table above the leachate collection pipe and collected leachate volume. The authors illustrated the relationship between groundwater table above the leachate collection pipe and its drainage rate is very useful to evaluate the function of the leachate collection pipe and calculate the volume of collected leachate in whole landfill site.

Even though the leachate collection pipe still functions to convey the leachate produced inside the landfill site but all of the leachate volume cannot be collected. Therefore, for the old landfills sites where had been constructed before the guidelines of landfill facilities was promulgated, the maintenance of the leachate collection pipe should be conducted to prevent the accumulation in the waste site and leak of the leachate to the surrounding environment. The design of the leachate collection pipe should be carefully constructed for the new landfill sites.

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