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Simulation of Drainage through a Leachate Collection Pipe of a Municipal Solid Waste Landfill in Japan

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Abstract: The landfill construction has caused many negative impacts on the surrounding environment, particularly groundwater problems. Evaluation of the function of the collecting 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 collecting pipe buried for leachate drainage. This paper paid attention to examine the validation of the assignment of the collecting pipe boundary by applying the results of the 2D vertical groundwater flow model ($2D_v$) to the $2D_h$. As such an example, the landfill in Japan was selected as the case study. The $2D_v$ of a cross section simulated the rise of groundwater table above the collecting pipe and calculated its drainage rate. The relationship between groundwater table above the pipe and drainage rate was obtained. The $2D_h$ was coupled with the recharge model to solve the partial differential equation of groundwater flow. Finite difference method and iterative successive over relaxation were applied to the models. The drainage volume of leachate collection was summed up in the whole landfill site and compared with the annual 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: *collecting pipe, landfill,* $2D_h$, $2D_v$

1. INTRODUCTION

During the past several decades, computer simulation models for analyzing flow of 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 (Reilly, 2000).

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 (Szilagyi et al., 2007). Among of them, only a few can simulate groundwater flow in unconfined aquifer with complex boundary conditions like seepage face and even fewer can also consider sloping or irregular boundaries that are quite common at most hydrogeological interface. Particularly the application of collecting pipe system and sheet walls is very rare at the landfill sites.

Besides, many researchers have examined the groundwater quality on the landfill sites such as Papadopoulou et al. (2007). Through the authors' knowledge, rare of the variably saturated models have been applied 2D numerical simulations of groundwater behavior in the unconfined aquifer in response to collecting pipe system in the landfill sites.

2. SITE DESCRIPTION

Figure 1 shows A. landfill which is located in B. City, Japan. This landfill was inaugurated in 1970s. 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 such as domestic garbage, swept refuse from streets. The domain boundaries have been almost assigned as the impermeable boundary conditions. Inside the domain area, there are three waste 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 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. The authors attempted to simulate the effect of the collecting pipe system in the landfill site.

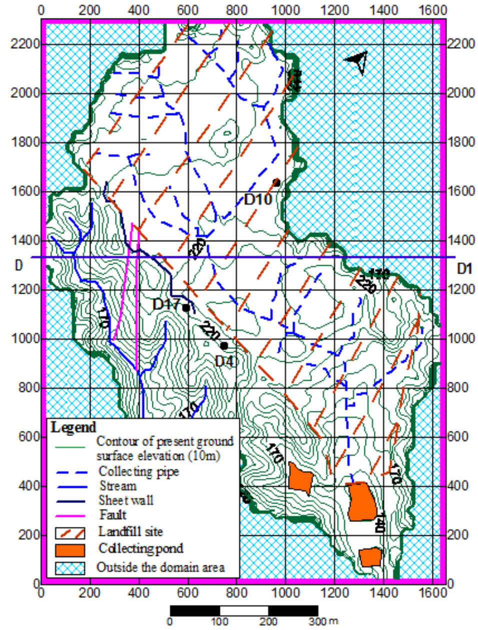

Figure 1. Study location

Figure 2 illustrates its geological conditions and the collecting pipe location. The length of the cross-section is 1221m. The highest elevation is 242m. EFGH and ABCD will be used to explain in the section 4.2. The present paper focuses on the groundwater flow surrounding of the collecting pipe in the 2Dv. The collecting pipe was constructed inside the waste material to collect the leachate. The diameter of the collecting pipe is 1m. The pressure head of the collecting pipe was assigned equal to atmospheric pressure (Bear and Verruijt, 1997). Most of these layers were formed by mudstone. The sandstone layer is considered as

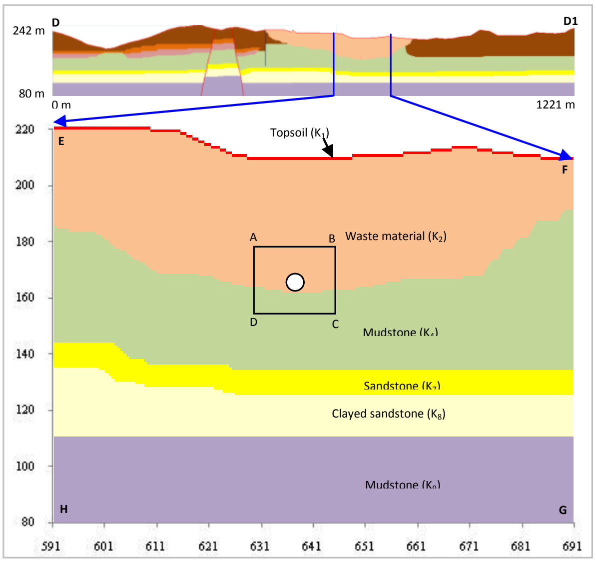

Figure 2. Geological conditions at cross section D-D1

an aquifer. The waste material was assumed to have high permeability.

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

3. DEVELOPMENT OF THEORY

The collecting pipe can be simulated by the 3D groundwater flow model to evaluate its function at the landfill sites. Due to the large calculations the 3D groundwater flow simulation requires severely the capacity of computer and time consumption but not any personal computer can be used. Therefore, the 2D groundwater flow simulation is applicable to evaluate the effects of the landfill site and reduces the requirement of the time consumption and the computer capacity. However, in the $2D_h$, simulation of the collecting pipe system at the landfill site challenges the researchers. Moreover, the groundwater table above the collecting pipe is not measured. Therefore, it is very difficult to assign the collecting pipe boundary. In order to overcome this difficulty, the authors attempted to simulate groundwater table and drainage rate of the collecting 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.

3.1. 2D vertical groundwater flow equation

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

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

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

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

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

Table 1 Van Genuchten's coefficients

Van Genuchten'coefficients	
θ_r	0.108
θ_s	0.485
n	2.0
m	0.5
α	0.000491m^{-1}

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. S_0[L^{-1}] is specific storage coefficient. β is switch number given by 0 or 1. Table 1 shows the van Genuchten's coefficients. These parameters were applied to the $2D_v$.

3.2. 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):

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

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 (Tsutsumi et al., 2004). 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.

3.3. Model process

The groundwater flow simulation was conducted for the unconfined aquifer. It should be emphasized that a sufficient understanding of natural groundwater flow without disturbances by human activities is indispensable in order to represent the essential changes and the management of the landfill. In the present paper, the mathematical model was employed to make a quantitative analysis.

Figure 3 shows the flow chart of the numerical simulation. The most important component is simultaneous numerical integration or conventional assignment of groundwater table above the pipe. Besides, the modeling of sheet walls constructed to inhibit the groundwater flow toward the outside of the landfill area was crucial. The impermeability of faults has not analyzed yet. Therefore it was assumed equal to the permeability of the aquifer. The comparison of observed and calculated values is necessary to make the model more precise.

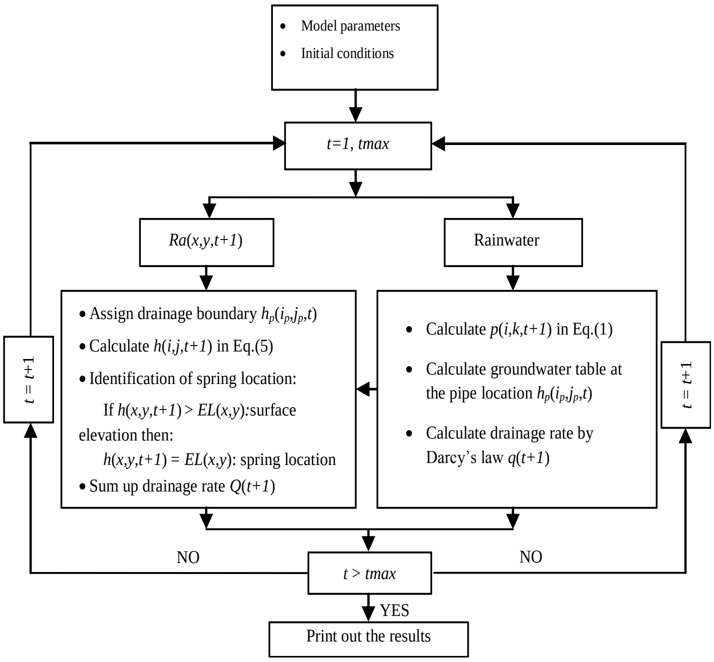

Figure 3. Simulation flow chart

Simulation of the $2D_v$ is aimed in order to obtain the groundwater table above the pipe ($h_p(i_p,j_p,t)$) and the drainage rate. $h_p(i_p,j_p,t)$ 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 collecting pipe boundary in the $2D_h$ of the landfill site. The rainfall was applied to the $2D_v$ which assigned at surface boundary.

In the present paper, the rainwater recharge model (Tsutsumi et al., 2004) was coupled with the 2Dh. Recharge rate was calculated from rainfall, potential evapotranspiration, rainwater interception, and coefficients of surface runoff.

Table 2 Model parameters

Model parameter	Value (unit)	Note
K_1	10^{-3} cm/s	Topsoil
K_2	$5x10^{-3}$ cm/s	Waste
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
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
n_e	0.25	
S_0	$2.5x10^{-3}$/cm	
Surface	$-k(p)\left(\frac{\partial p}{\partial z}+1\right)=-rainwater$	

4. NUMERICAL MODEL

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

In the $2D_h$, the maximum of length and width of the selected area is 2,305m and 1,650m, respectively. The model domain is divided into irregular discretized grid system for x and y directions. The grid size gradually changes from 2m to 10m (Dang et al, 2009). 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 (Tsutsumi et al., 2004).

However, in this paper, the authors pay attention to demonstrate the accuracy of the collecting pipe simulation. The $2D_v$ simulated for the cross section D-D1 in figure 1. The grid sizes 1m x 1m for both directions. There are 9 simulated layers. Table 2 shows the model parameters. The table also shows the other model parameters. The data was adopted from by measured data at the study site.

5. MODEL RESULTS AND DISCUSSION

5.1. 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 (Tsutsumi et al., 2004). 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. In the study area, there are two types of landuse such as forest and landfill site where runoff coefficients (rf) are 0.3 and 0.7, respectively. The effect of rainwater interception was also considered by Tsutsumi (2004). The hourly rainfall from 2003 to 2007 was available. The rainwater recharge model was applied with hourly time series. Figure 4 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.

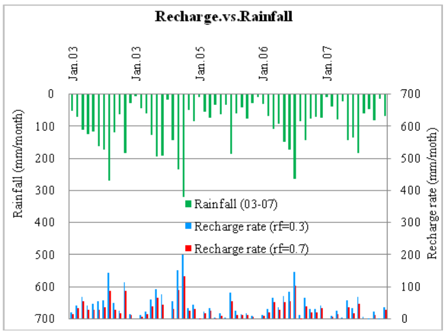

Figure 4. Rainfall and recharge

5.2. Potential distribution

Initial potential distribution is displayed in figure 5. The initial head has achieved before the landfill site was constructed (Dang et al, 2009). Figure 6 shows the potential distribution closed to collecting pipe 5 years, respectively. These figures are focusing on the pipe location at the small part ABCD which is showed in figure 2. From the calculated pressure head, the potential distribution was obtained by adding the elevation of each grid point. At collecting pipe, pressure head was always set equal to 0.0 meter. Therefore, the figures show the smallest potential at the pipe location. It means that the groundwater is drained through the collecting pipe hence drawdown of groundwater table occurs. Figure 6 shows that after 7 months, the potential distribution at the collecting pipe is less than that of the vicinity. Therefore the groundwater flows into the collecting pipe from the surrounding.

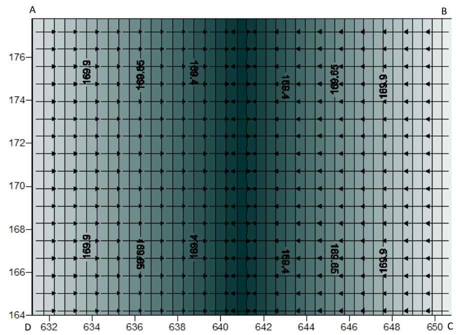

Figure 5. Initial potential distribution

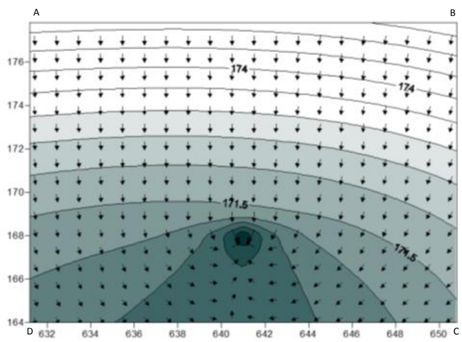

Figure 6. Potential distribution after 5 years

5.3. Groundwater table above collecting pipe

Figure 7 shows the rise of groundwater table above the collecting pipe by the application of the $2D_v$. To both directions of the collecting pipe, the groundwater table is significantly different. This happened depending on geological conditions (figure 3). At the right side of the collecting pipe, the thickness of waste material is thinner than that of left side. Below waste material, there is mudstone layer which has small permeability.

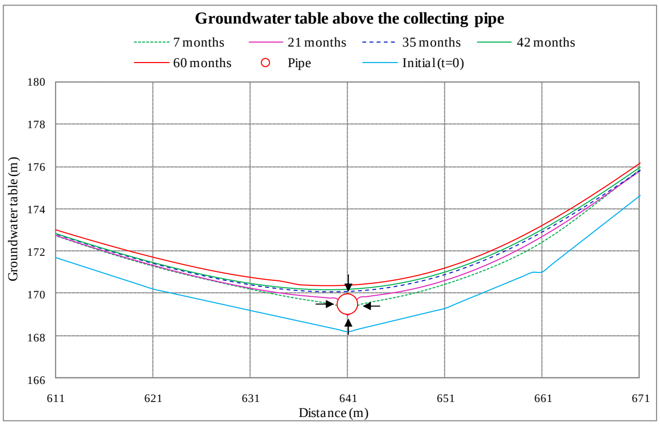

Figure 7. Groundwater table above the pipe

The significant difference of permeability induces the difference of groundwater table. The rainwater was captured and stored inside the waste material. Even though the pressure head of collecting pipe was always set equal to 0.0 meter, all of the leachate cannot be collected. Consequently, the groundwater table gradually rises up.

Moreover, the results of groundwater table above the pipe in the $2D_v$ were assigned into the $2D_h$ for each time step. The scheme of the assignment was showed in figure 3.

5.4. Relationship of groundwater table and drainage rate

Figure 8 shows the relationship between groundwater table above the collecting pipe and drainage rate. The increase 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, figure 8 shows that closes to the collecting pipe the groundwater table are seemly symmetric. Therefore, the at the same groundwater level, the drainage rate is not much difference.

Moreover, groundwater table above the pipe is seemly equal to that in both sides. In other words, to both sides 1 m, groundwater is mostly flat. The bit difference of drainage rate which is affected by groundwater table in both sides can be excluded. From this point of view, the authors applied the relationship of groundwater table above the pipe and drainage rate to the $2D_h$. When groundwater table above the pipe obtained by the $2D_h$ reached that of the $2D_v$, the drainage rate value was accounted. 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 collecting pipe system in the whole landfill site. The results will be demonstrated in the section 4.6.

5.5. Observed and calculated value in the $2D_h$

In order to verify the accuracy of the models quantitatively, the observed and calculated groundwater table were compared for the period from 2003 to 2007. Three observation wells in the study area were used to verify the accuracy of the groundwater flow model.

Figures 9 and 10 are the comparisons of measured and calculated groundwater tables of wells D4 and D10 in figure 1 for time period from October, 2005 to March, 2006. From these figures, the measured and calculated groundwater tables show a good agreement for the period. Moreover, the groundwater table fluctuations corresponded to the changes of rainfall in the study area.

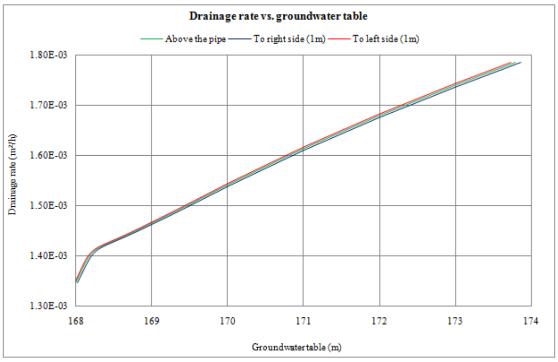

Figure 8. Groundwater table above the pipe and drainage rate

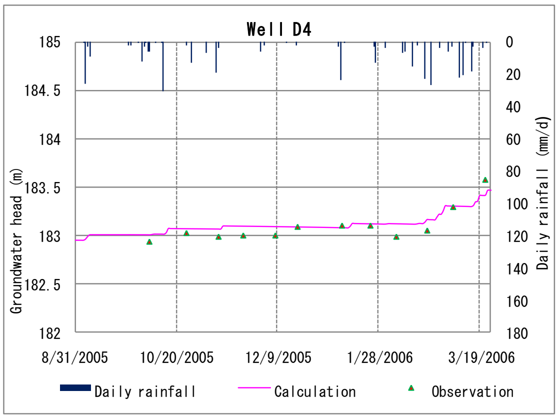

Figure 9. Observed and calculated groundwater at well D4

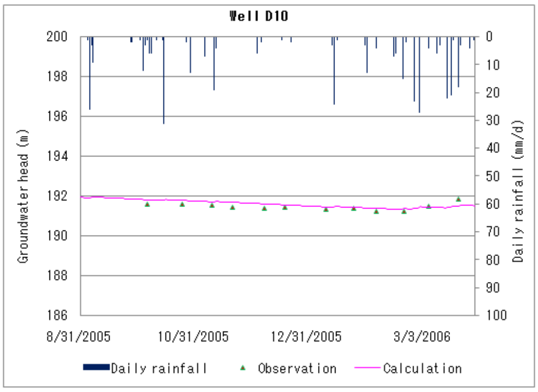

Figure 10. Observed and calculated groundwater at well D10

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

5.6. Drainage rate confirmation

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

Figure 11 shows the calculation of collected leachate volume from the collecting pipe system and daily average of treated waste water. The calculation of leachate volume shows a good correspondence with daily rainfall. The mean of calculation value shows a good agreement with the daily average volume of treated waste water from 2003 to 2007. The highest treated waste water was reported and calculated in 2004. This is due to the highest of rainwater in 2004 produced the highest leachate volume. Therefore, the $2D_v$ can be applied for future to calculate the leachate volume.

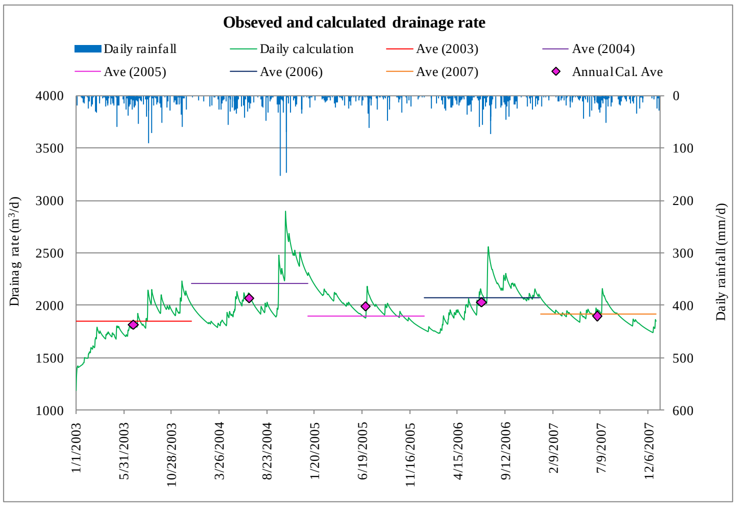

Figure 11. Observation and calculation of drainage rate

6. 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 collecting 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 collecting pipe and collected leachate volume. The authors illustrated the relationship between groundwater table above the collecting pipe and its drainage rate is very useful to evaluate the function of the collecting pipe and calculate the volume of collected leachate in whole landfill site.

Even though the collecting 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 collecting 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 collecting pipe should be carefully constructed for the new landfill sites.

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