

# APPLICATION OF OPTIMIZATION THEORY TO WASTE STABILIZATION CONTROL IN COMMUNITY AND CONTROLLABLE CLOSED SYSTEM DISPOSAL FACILITIES

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**SUMMARY:** Recent studies on the waste stabilization in a landfill site have revealed the effectiveness of a washout gradually, which removes some kind of chemicals from waste. However, there is no concrete method for evaluating quantitatively the effectiveness of a washout. This study applies an optimal control theory and tried to evaluate a stabilization phenomenon of waste quantitatively. In the evaluation, the TOC concentrations in the leachate were calculated using a washout model in the process of the waste (bottom ash) stabilization a closed system disposal facility. Particularly, the effects of three operating variables in the watering for the washout, 1) intensity, 2) period, and 3) interval of watering, on the TOC concentration profiles were evaluated quantitatively. For the optimization of the sprinkling operation, a total cost in a leachate treatment until the TOC concentration reaches the acceptable level was used as an evaluation function. The optimization theory proposed in this study is a promising design method of watering and leachate treatment facilities for waste stabilization.

## 1. INTRODUCTION

Construction of landfills has recently become very difficult in Japan because of the opposition from residents who feel uneasy about environmental pollution caused by the disposal of solid waste. In response to this difficulty, a new type of landfill, called a “Closed System Disposal Facility” (CSDF), has been studied and put into practice in Japan. Because the CSDF can control emissions to the surrounding environment and the quality of landfilled waste, the CSDF is acceptable to neighboring residents. In this study, “waste stabilization control” is discussed since it is the most important function of the CSDF. Particularly, we investigated ideas and factors relating to waste stabilization and proposed an analytical method to promote waste stabilization.

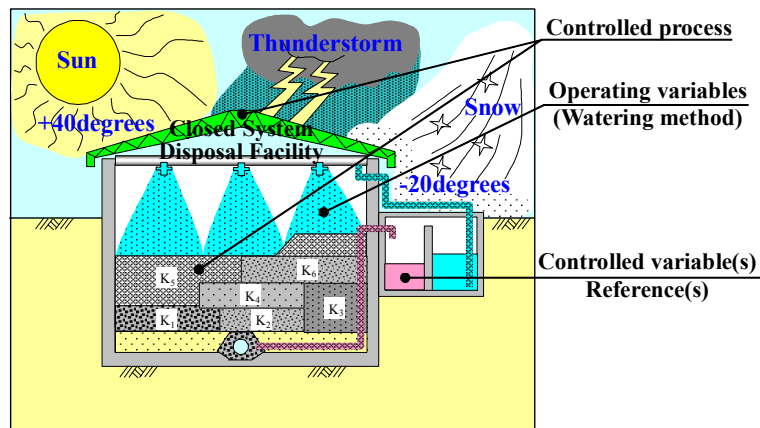


Figure 1. Global image of the control method

The phrase “waste stabilization” has various meanings. Generally, waste stabilization is a process in which organic matter in solid waste is degraded to carbon dioxide and water or where hazardous compounds are degraded or immobilized. However, while one may say that the stabilized state is a state where all pollutants in landfilled waste are completely degraded or immobilized, it is actually impossible to meet this requirement. In other words, there is a gap between actual and ideal situations in waste stabilization. This study discusses waste stabilization from a realistic viewpoint. We regard “waste stabilization” as the status where all the requirements in the “abolishment standard”, which is stipulated by the Japanese government, are fulfilled. For example, if the quality of leachate meets an effluent standard or a local standard, the operation of a leachate treatment facility can be stopped. In this study, an analytical method to promote waste stabilization was proposed to meet the abolishment standard, especially the standard for quality of leachate. The focus is placed on the stabilization of bottom ash disposed in the CSDF, and proposes the watering over the waste layer as the method to promote waste stabilization.

## 2. CONCEPTUAL CONFIGURATION

In order to control waste stabilization, it is necessary to determine a control system. A schematic representation of the control system in the case of a closed system disposal facility is shown in Figure 1.

It was assumed that landfilled waste is separated from external environmental factors such as sun, thunderstorms and snow. In addition, the permeability of the waste layer is given. A controlled variable is the concentration of TOC in the leachate. Operating variables are the methods of water application, such as a frequency, intensity and period of sprinkling.

## 3. CONCEPT OF WASTE STABILIZATION

### 3.1 The concept of stabilized condition

In general, landfilled waste contains some pollutants that have a harmful influence on human health or the environment. “Ultimate stabilization” in landfilled waste means the condition in which the pollutants in waste are completely kept within the landfill site or where the waste no longer contains pollutants. In addition, many kinds of phenomenon (e.g., physicochemical and

biological phenomena) occur in landfilled waste until the landfilled waste is stabilized. To change landfilled waste into the ultimate stabilized condition is too expensive. This study did not deal with the ultimate stabilization of waste but a degree of waste stabilization based on Japanese law regarding termination of operation and maintenance of landfilled sites.

### **3.2 Standard for termination of operation and maintenance of landfill sites in Japan**

The standard that defines the quality of leachate for termination of operation and maintenance of controlled landfill sites in Japan is “the quality of the leachate collected into the leachate collection pipe must meet the effluent standards for two years; (a) all compounds in effluent standard every six months; and (b) BOD (60 mg/L), and COD (90 mg/L) and SS (60 mg/L) every three months”.

With regard to aspects other than leachate, there are standards that specify the temperature, gas emission rates and settling of the waste layers.

## **4. FACTORS INFLUENCING ON PHYSICAL PROPERTIES OF LANDFILLED WASTE**

### **4.1 Factors influencing on physical properties of landfilled waste**

In order to study changes in physical properties of landfilled waste in the CSDF, factors that might influence on the properties of landfilled waste were investigated. In addition, the main factors related to CSDFs were identified.

#### *4.1.1 Factors that influence the quality of waste*

These factors are (a) an intermediate treatment, such as incineration, before landfilling, (b) the compaction of the landfilled waste, and (c) the daily cover soil.

#### *4.1.2 Factors within the CSDF*

The factors that influence waste inside a CSDF are (a) the ventilation method used in the CSDF, (b) the roof structure, which may have an effect on temperature in CSDF, and (c) the supply of air and water to the waste layer.

#### *4.1.3 Operational factors within the CSDF*

These include, with regards to watering, (a) the amount of water used, (b) watering schedules, such as the period and frequency of watering, (c) the quality of the water, such as pH and concentration of salts, and (d) the temperature of the water.

### **4.2 Main operation factors for promoting waste stabilization**

In this study, we tried to develop a score table to extract the more important factors from all possible factors that have effects on waste stabilization. We constructed the table by having 10 people carry out a paired-comparison of all factors and counting the level of correlation, from 0 to 2, of the answers. For example, the amount of water supplied and the amount of pollutants (inorganic substances) washed out by watering are strongly correlated, so the answer is 2. On the other hand, the structure of the roof of a CSDF and the amount of pollutants (inorganic substances) washed out by watering are not correlated, so the answer is 0. It is noted that the landfilled waste is assumed to be bottom ash.

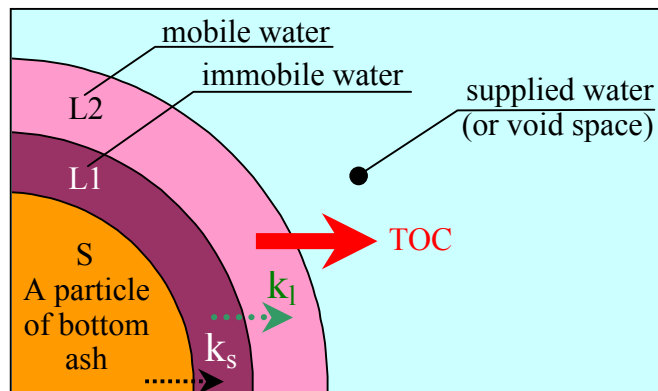


Figure 2. Idea of washout model

The following information was extracted from the table.

- The more important operational factors were amount of supplied water, watering schedule (period of watering, intensity of watering, and frequency of watering), quality of supplied water, air supply method, and whether there had been any pretreatment before landfilling.
- The more important causal factors, which are related to changes caused by operational factors in the characteristics of landfilled waste, were moisture content and water-holding capacity of the landfilled waste.
- The more important phenomena occurring in waste layers were biological or chemical degradation, quality of leachate (COD, BOD, TOC, etc.), and generation of heat and gas.

## 5. THE WASHOUT MODEL AND PATTERN

### 5.1 Outline of the washout model

When applying an optimal control theory, it is important to model a controlled process for efficient evaluation. In this study, the washout model proposed by Ishii et al. (2003) has been adopted as a numerical model simulating elution of TOC from bottom ash.

The washout model proposed by Ishii et al. (2003) is based on the concept of a two-phase model, where one of the phases is a mobile water phase, which flows in void space. Another phase is an immobile water phase, which does not move and covers the particles of bottom ash. Ishii et al. (2003) extended this two-phase model to three-phase model by incorporating mass transfer from a solid phase to the immobile water phase, including diffusion within the particle.

A schematic representation of the washout model is shown in Figure 2. The equations constituting the model are shown below. This model simulates vertical water flow (unsaturated water flow) in the unsaturated waste layer and the consequent change of TOC concentration in the leachate.

### 5.2 Equations constituting the washout model

#### 5.2.1 Water balance

One-dimensional unsaturated water movement in a bottom ash layer is represented, by Klute's equation, as follows:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q}{\partial z} \quad (1)$$

$$q = -D(\theta) \frac{\partial \theta}{\partial z} + k(\theta) = -k(\theta) \frac{\partial h}{\partial \theta} \frac{\partial \theta}{\partial z} + k(\theta) \quad (2)$$

where  $\theta$  is the volumetric water content [-],  $q$  is the Darcy velocity [L/T],  $k$  is an unsaturated permeability for the water [L/T],  $D$  is a capillary diffusivity [L<sup>2</sup>/T],  $h$  is the matrix potential [L], and  $t$  is time [T].

### 5.2.2 Mass balance of TOC constituents in the mobile water phase (L2)

The mass balance of TOC constituents in the L2 phase is represented by advection-dispersion and mass transfer between the L2 and L1 phases.

$$\theta_{L2} \frac{\partial C_{L2}}{\partial t} = -q \frac{\partial C_{L2}}{\partial z} + \frac{\partial}{\partial z} (D_z \frac{\partial C_{L2}}{\partial z}) - k_l \theta_{L1} (C_{L2} - C_{L1}) \quad (3)$$

$$D_z = -D^0 \frac{\theta_{L2}}{\xi} + M^0 \frac{q}{\theta_{L2}} \quad (4)$$

where  $C_{L1}$  is the concentration in the L1 phase [M/L<sup>3</sup>],  $C_{L2}$  is the concentration in the L2 phase [M/L<sup>3</sup>],  $D_z$  is a dispersion coefficient [L<sup>2</sup>/T],  $k_l$  is defined as a washout coefficient between the L2 and L1 phases [1/T],  $D^0$  is an effective molecular diffusion coefficient [L<sup>2</sup>/T],  $\xi$  is a tortuosity factor [-], and  $M^0$  is the dispersivity [L].

### 5.2.3 Mass balance of TOC constituents in the immobile water phase (L1)

Mass transfers between the S and L1 phase, and the L1 and L2 phases, are represented, respectively, as follows.

$$\frac{\partial C_{L1}}{\partial t} = -k_l (C_{L2} - C_{L1}) - k_s (C_{L1} - 10^{-3} f C_s) \quad (5)$$

where  $k_s$  represents a diffusion coefficient from the S to L1 phases [1/T],  $C_s$  is the concentration in the S phase [M/L<sup>3</sup>], and  $f$  [M/L<sup>3</sup>] is defined as a conversion factor from TOC concentration in the S phase to that in the L1 phases. In other words, the factor  $f$  is an inverse number of a product of a thickness of the water film [L] and a specific surface area [L<sup>2</sup>/M] defined as a contact area between the S and L1 phases.

The mass transfer induced by diffusion in the L1 phase is neglected, because the difference in TOC concentration is expected to be small.

### 5.2.4 Mass balance of TOC constituents in the solid phases (S)

In the S phase, the mass transfer between the S and L1 phases is represented as follows.

$$\frac{\partial C_s}{\partial t} = -k_s (C_s - \frac{10^3}{f} C_{L1}) \quad (6)$$

## 5.3 Washout pattern

It was confirmed in the column experiment, which Ishii et al. (2003) conducted, that the elution behavior of TOC was significantly influenced by the watering method to a bottom ash. From

those experimental results, an intensity (I [mm/h]), a period (P [h]) and an interval (F [1/day]) are considered to be dominant factors in the watering method. Therefore, in this study, the watering method was optimized by changing these three parameters (I, P, F).

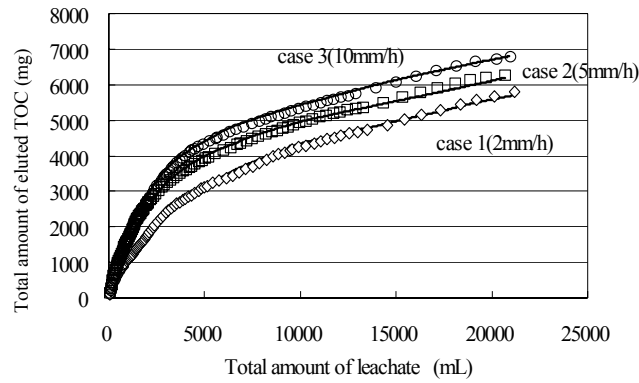


Figure 3. Influence of intensity of watering on the total amount of eluted TOC

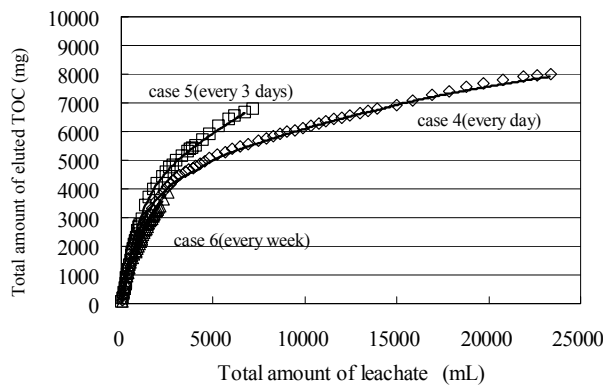


Figure 4. Influence of frequency of watering on the total amount of eluted TOC

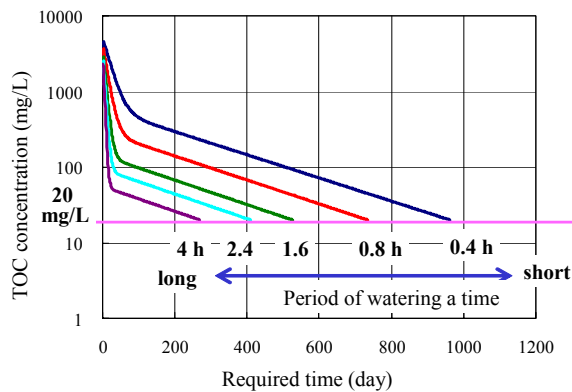


Figure 5. Influence of period of watering at a time on the required time until TOC concentration is less than 20 mg/L

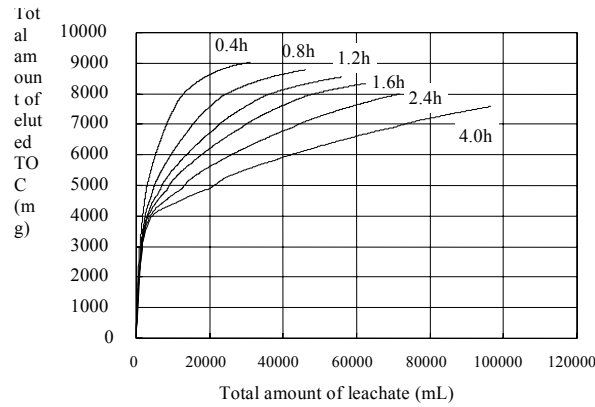


Figure 6. Influence of period of watering at a time on the total amount of eluted TOC

### 5.3.1 Intensity of watering

Figure.3 showed that higher intensity of watering washes out larger amounts of TOC from the beginning of the experiment until 5000 mL of leachate was generated. However, after this, the elution rate of TOC in each case was almost the same.

### 5.3.2 Frequency of watering

Figure. 4 shows that watering every 3 days could wash out larger amounts of TOC than watering every day and a week, which also supports the washout model. However, the total amount of eluted TOC was not large when watering every week (case 6) because such a large interval may cause changes in the characteristics of the bottom ash layer, for example, by changing the leachate flow due to precipitation of salts such as calcium.

### 5.3.3 Period of watering

Figure 5 shows the influence of the period of watering on the required time for the TOC concentration to reach less than 20 mg/L. A longer period of watering tends to cause the TOC concentration to reach the target value earlier. However, the total amount of eluted TOC in the case where the period of watering at a time was 4.0 h was much less than that in the case where the period of watering was 0.4h, as shown in Figure 6, because the longer period of watering generated a larger amount of leachate. This explains why the TOC concentration reached the target value earlier.

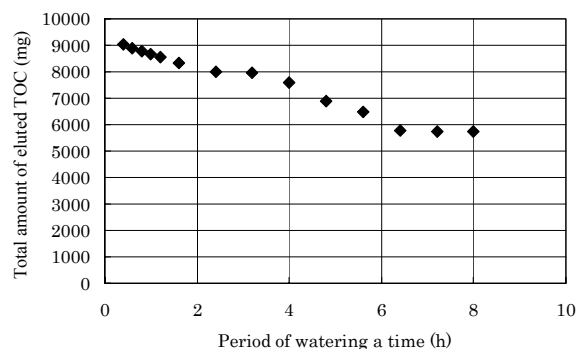


Figure 7. Relationships between Total amount of eluted TOC and period of watering

Therefore, supplying a larger amount of water at one time is not always effective for TOC elution.

Figure 7 shows the relationship between the total amounts of eluted TOC at the time when the TOC concentration meets the target value and the period of watering. The result shows that supplying water for less than 2 hours could wash out about 90% of the total amount of TOC. Watering for 0.8 h at 5 mm/h in these experiments corresponded to about 70 mL of water supplied for 3,600 g of bottom ash; the ratio of water to bottom ash was about 2% (mL water/g bottom ash). Therefore, it was found that supplying 1-5 % of water at a time to the weight of bottom ash might be an effective amount of watering. We need to conduct further studies with larger scale experiments to add to the discussion.

## 6. APPLICATION OF THE OPTIMAL CONTROL

### 6.1 Determination of operating variables

An operating variable is a variable that has an effect on an objective function. Therefore, a search is needed for a combination of operating variables so that the objective function becomes maximum or minimum. In this study, the following operating variables were set up.

The intensity of watering  $I(j)$ , the period of watering  $P(m)$ , and the frequency of watering  $F(n)$  were set as operating variables. Each operating variable is changed in the ranges of  $j = 1$  to  $J$ ,  $m = 1$  to  $M$  and  $n = 1$  to  $N$ . The effect of watering method on TOC elution in each case of combination,  $Pat(i) = \{I(j), P(m), F(n)\}$  ( $i = 1 - J * M * N$ ), is evaluated.

### 6.2 Objective function

We define the elapsed time until the TOC concentration decreases to a desired value as  $T_{end}$  [day].  $T_{end}$  is then a function of the watering method, as shown in Eq. (6). An objective function is defined as the cost of the leachate treatment facility ( $Z_{TOC}$ ), including construction and operational and maintenance costs, as shown in Eq. (7).  $Z_{TOC}$  during the period until the TOC concentration ( $C_{TOC}$  [mg/L]) is endured to meet the effluent standard is needed to be minimized. It is noted that Japan does not have an effluent standard for TOC but does for COD and BOD.  $C_{TOC}$  depends on the watering method. Therefore,  $Z_{TOC}$  is the function of the watering method and an elapsed time of watering, as shown in Eq. (7).

$$T_{end} = f(Pat) = f(I,P,F) \quad (6)$$

$$Z_{TOC}(Pat, T_{end}) = C_{ini}(Q) + C_{run}(Q, T_{end}) \quad (7)$$

where  $C_{ini}$  is the construction cost [yen], and  $C_{run}$  is the operational and maintenance cost [yen] of a leachate treatment facility. As shown in Eq. (8),  $C_{ini}$  is a function of the intensity of watering  $I$  and the period of watering,  $P$ ; as shown in Eq. (9),  $I$  and  $P$  are related to the amount of leachate to be treated  $Q$  ( $I, P$ ) [ $m^3/day$ ]. In addition,  $C_{run}$  is the function of the amount of leachate to be treated and an elapsed time of watering, as shown in Eq. (10), and is the sum of the periodical maintenance and the fixation, plus the cost adjusted to the elapsed time of watering.

$$C_{ini}(Q) = C_{ini}(I,P) \quad (8)$$

$$Q(I,k) = A * I * P / 1000 \quad (9)$$

$$C_{run}(Q, T_{end}) = C_{run0}(Q) + Fc * T_{end} \quad (10)$$

A: watering area [ $m^2$ ]



Crun0: The operating cost of the leachate treatment facility [yen]

Fc: The cost of maintenance [yen/day]

Tend: Days of maintenance [day]

### 6.3 Restriction conditions

The restriction on the period of watering at one time was considered to be the maximum amount of watering on a day.

The restriction on the intensity of watering was the limitation of the maximum intensity, which corresponds to the maximum infiltration rate of the waste layer. Other restrictions were limitation of the equipment for watering, etc.

### 6.4 An analysis method by an optimization theory

#### 6.4.1 Input data for the patterns of watering

The sprinkling-water patterns used in the example of application of the proposed analysis were set as shown in Table 1. The number of watering patterns, Pat (i), becomes 343, with all the combinations of 7 different values of each operating variable.

#### 6.4.2 An example of the application of an analytical method proposed

The Q matrix in Table 2 was created from Eq. (9) supposing that the area A of the watering range is 1,000 m<sup>2</sup>.

Using this leachate throughput matrix, the sprinkling-water equipment cost for each sprinkling-water pattern was computed.

An analysis method to optimize the objective function is shown in Figure 7. As one of example of the calculation, the calculated value of the objective function using this analysis is shown in Figure 8. Figure 8 (a) indicates the relationship between the values of the objective function,  $Z_{TOC}(i)$  and  $T_{end}(i)$  in the case of watering method of Pat(i). Figure 8 (b) indicates the rearrangement of  $Z_{TOC}(i)$  in the numerical order. For example, when the optimization ranking is "Low", the value of  $Z_{TOC}$  is larger. Conversely, when the optimization ranking is "High", the value of  $Z_{TOC}$  is lower. Therefore, the optimal watering method corresponds to the rightmost point (the ranking of an objective function is the highest) in Figure 8 (b). In Figure 8 (a), when sprinkling-water pattern, "Pat", is "Pat{I, P, F} = {2, 1, 1}", " $Z_{TOC}$ " shows the minimum value.

Table 1. Table of sprinkling-water pattern (operating variable)

Operating variable	Table column index						
	1	2	3	4	5	6	7
Intensity I (n) [mm/h]	I(1) = 1	I(2) = 2	I(3) = 3	I(4) = 4	I(5) = 5	I(6) = 6	I(7) = 7
Period of watering P(m) [h/day]	P(1) = 1.0	P(2) = 1.5	P(3) = 2.0	P(4) = 2.5	P(5) = 3.0	P(6) = 3.5	P(7) = 4.0
interval F(n) [day]	F(1) = 1	F(2) = 2	F(3) = 3	F(4) = 4	F(5) = 5	F(6) = 6	F(7) = 7

Table 2. Amount of leachate for one day

Q [m <sup>3</sup> /day I		1	2	3	4	5	6	7
		I(1) = 1	I(2) = 2	I(3) = 3	I(4) = 4	I(5) = 5	I(6) = 6	I(7) = 7
1	P(1) = 1.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0
2	P(2) = 1.5	1.5	3.0	4.5	6.0	7.5	9.0	10.5
3	P(3) = 2.0	2.0	4.0	6.0	8.0	10.0	12.0	14.0
4	P(4) = 2.5	2.5	5.0	7.5	10.0	12.5	15.0	17.5
5	P(5) = 3.0	3.0	6.0	9.0	12.0	15.0	18.0	21.0

On the contrary, when "Pat" is "{7, 4, 7}", "Z<sub>TOC</sub>" shows the maximum one. Moreover, when "I" and "P" increase (the patterns where the amount of water per day increases), it turns out that "Z<sub>TOC</sub>" increases. And, when "F" changes from 1 to 7 (the patterns where period of sprinkling-water increases), it turns out that "T<sub>end</sub>" becomes larger.

## 6.5 Future studies

In order to achieve the practical application of the optimization model proposed in the future, the following modifications, in addition to those mentioned above, should be required;

- Data collection in pilot-scale experiments
- Model development allowing the change in characteristics of structure of waste layer and the elution phenomena influenced many factors
- Risk evaluation on the objective function
- Simplification of the model to design watering equipment

## 7. CONCLUSIONS

- The numerical-analysis model can predict quantitatively the TOC concentration in the column and pilot-scale experiments.
- An intensity, a period, and interval have strong influences on the elution behavior of the bottom ash by sprinkling water.
- The optimization theory may possibly be applied to determine a watering method in the CSDF. Collection of data in pilot-scale experiments is required to achieve an increase in the precision of the model.
- In order to realize more realistic evaluation, we have to incorporate a risk evaluation into an objective function.
- In this study, only the TOC concentration is considered. However, in actual situations physical, chemical and biological phenomena are related to each other and unsteady.

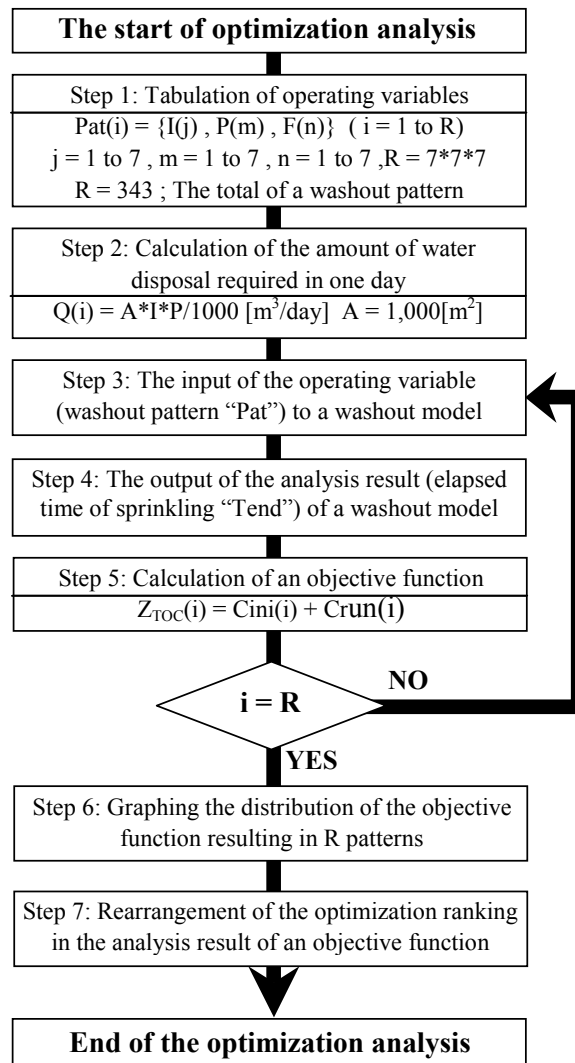


Figure 7. Flow of optimization

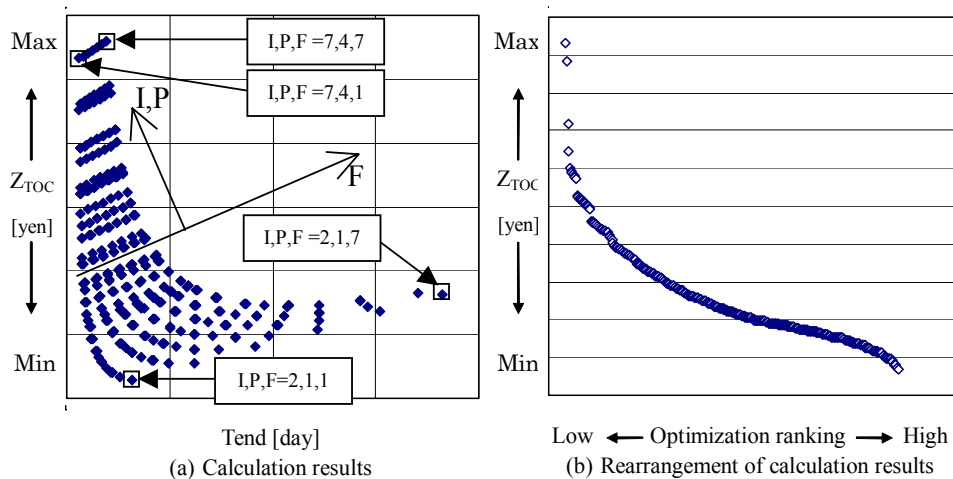


Figure 8. Distribution of objective function by sprinkling-water pattern

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