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Toward the conventional design of irrigation pond's dike: Formulating slope stability analysis by an infinite method

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ABSTRACT: Pond is less than 15m in height and fill dam is more than 15m in height. There are two hundred ten thousand of ponds in Japan. When we repair the pond's dike, we can't get soil materials from nearby mountains. Nobody is permitted to get from mountain's soil with license, because of environmental problems. We introduce surface watertight sheet method covered with random soil. We cover the random soil on the sheet to prevent deterioration by ultraviolet rays, also keep 80 years in durability to be equalized with previous front core type method of irrigation pond. We clarified that pond's dike should be designed by both the safety factor (F) in the covered soil as a slope sliding stability and a safety factor as a rotational slip of the whole embankment. The former is for empty conditions of construction. The latter is for saturated conditions. We clarified that the seepage line is described a parabola in the covered soil and safety factor in the covered soil is mainly controlled by PSR. We introduce Uchiharano pond by this method, one of Japanese 100 selection of national famous ponds by Ministry of Agriculture.

Keywords: irrigation pond, watertight sheet, slope stability, PSR, slope failure

1. INTRODUCTION

1.1 Judgment of repair of superannuated dike

We confirm the piping hole, crack and water erosion over 5%. We confirm the leakage is more than 1ℓ/s/100m, including dike's and foundation's leakage.

1.2 Selection of design method of superannuated dike

We show the flow chart of the pond design.

We check the transportation distance of core soil from pond to borrow-pit by track.
Borrow-pit is within 17km from site →1), 2)& 5)
Borrow-pit is more than 17km from site→4) & 5)

We check whether partial leak or whole leak from the embankment.
Whole leak from wide range →1), 2), 4) & 5)
Partial leak from short range →1), 2) & 3)

1) Front core or center core pond type
2) Homogeneous dike's pond type
3) Grouting pond type
4) Surface watertight sheet pond type
5) Combined type with front core

1.3 Japanese dike's material circumstances

Top 5 prefectures make up over 50% of the irrigation pond (210,000) in Japan. These are Hyogo, Hiroshima, Kagawa, Yamaguchi and Osaka prefecture. From environmental viewpoint, it is difficult to get enough dikes' materials from the near-by mountain area. We must investigate the dike improvement method for example 4) and 5) with low-cost and using low volume of newly materials. The drawing of a typical pond structure is shown by Figures 1-3 and Photos 1-3.

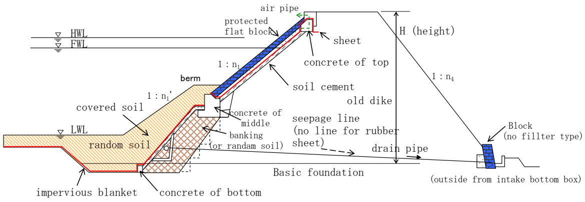

Figure 1. Outline of surface watertight sheet pond type (embedded sheet type)

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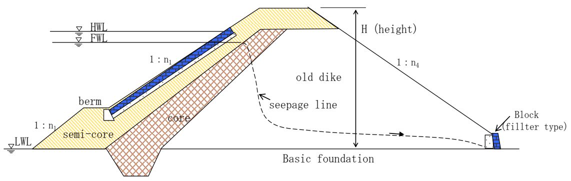

Figure 2. Outline of front core pond type

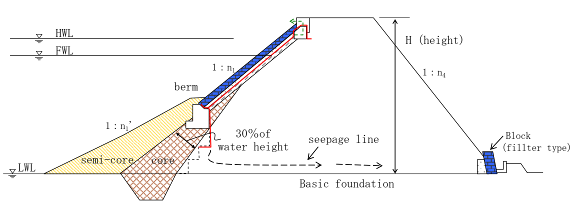

Figure 3. Outline of combined type with front core


Photo 1. Nakado shin pond
Surface watertight sheet method
(Katsuragi city homepage in Nara pref.)
[H=10.15m and L=170m]


Photo 2. Uchiharano pond
Surface watertight sheet method
(Aki city homepage in Kochi pref.)
[H=9.8m and L=340m]


Photo 3. Gongen pond
Front core type
(Sanuki city in Kagawa pref.)
[H=4.9m and L=150m]

2. SUMMARY OF THEORETICAL ANALYSIS

As for the watertight sheet design, there are two methods. The infinite method of Mukaitani and Tanaka is for a pond and Koerner & Daniel method is for a industrial waste article (Koerner, 1997).

2.1 The infinite method of Mukaitani and Tanaka

Fundamental formula of theoretical analysis is based on the infinite slope stability.

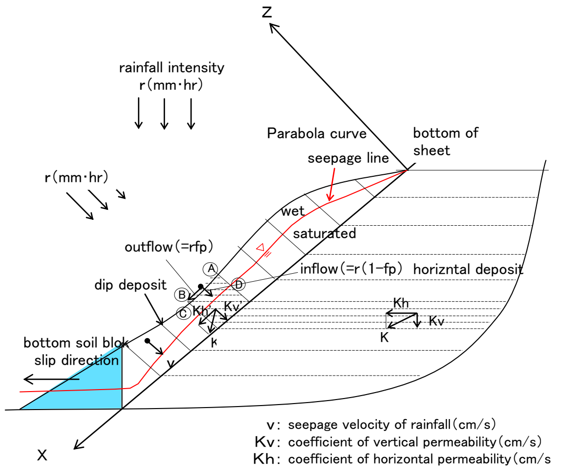

Figure 4. Schematic diagram of seepage line on the slope soil layer by rainfall

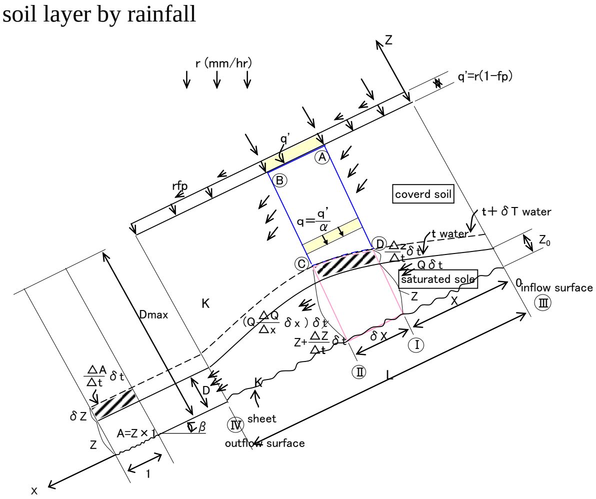

Figure 5. Seepage line analysis in pond's dike

$$\delta^2 Z / \delta X^2 = -2\cdot r\cdot(1-f_p)/(k\cdot\alpha)$$

Boundary layer conditions are as follows;

$X = 0 \rightarrow Z = Z_0$ and $X = L \rightarrow Z = D$

$$Z = \left\{ \frac{-(D^2-Z_0{}^2)}{(-L^2+2\cdot X_{max}\cdot L)} X^2 + \frac{2\cdot X_{max}(D^2-Z_0{}^2)}{(-L^2+2\cdot X_{max}\cdot L)} X + Z_0{}^2 \right\}^{0.5} \quad \cdot\cdot\ (1)$$

$$\alpha = L\cdot q'/(k\cdot \tan\beta\cdot D) \quad \cdot\cdot\ (2)$$

$$X_{max} = 0.5\{(D^2 - Z_0^2)/(D\cdot\tan\beta) + L\} \quad \cdot\cdot\ (3)$$

$$T_1 = 2e\int_0^L ZdX \ /\{(1+e)\cdot k\cdot\tan\beta\cdot D\} \quad \cdot\cdot\ (4)$$

$$PSR = \int_0^L ZdX \ /(L\cdot D_{max}) \quad \cdot\cdot\ (5)$$

where parameters in equations are as follows;

r: rainfall intensity (mm/hr)

k: coefficient of saturated permeability(cm/s)

f_p: run off percentage

$q' = r\cdot(1-f_p)$

T_1: drainage time of inflow in covered soil (s)

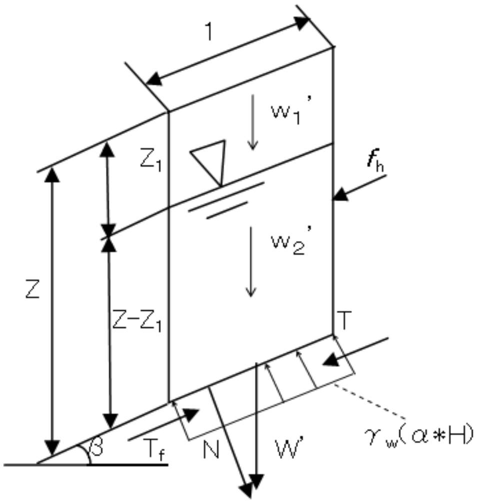

Figure 6. Outline of seepage pressure

The seepage pressure f_h and the safety factor F are defined as follows;

$$f_h = \sin\beta\cdot\gamma_w\cdot(Z-Z_1)\cdot\cos\beta \quad \cdot\cdot\ (6)$$

$$F = \frac{1}{\{PSR\cdot\gamma_{sat} + (1-PSR)\cdot\gamma_t\}\ \tan\beta}$$

$$\times[\{PSR\cdot\gamma' + (1-PSR)\cdot\gamma_t\}\ \tan\phi'$$

$$+(c' - \alpha\cdot\gamma_w\cdot H\cdot\tan\phi')/(Z\cdot\cos^2\beta)] \quad \cdot\cdot\ (7)$$

where parameters in equations are as follows;

F: safety factor by Mukaitani's method

c', ϕ': strength parameters of a covered soil

H: water hight (m)

α: the coefficient of the seepage water pressure $\leqq c'/(\gamma_w\cdot H\cdot\tan\phi')$

PSR: pararell submergence ratio

$$(Z-Z_1)/Z = PSR$$

$$Z_1/(Z-Z_1) = (1-PSR)/PSR \quad \cdot\cdot\ (8)$$

2.2 Comparison the infinite method of Mukaitani and Tanaka with Koerner and Daniel's method

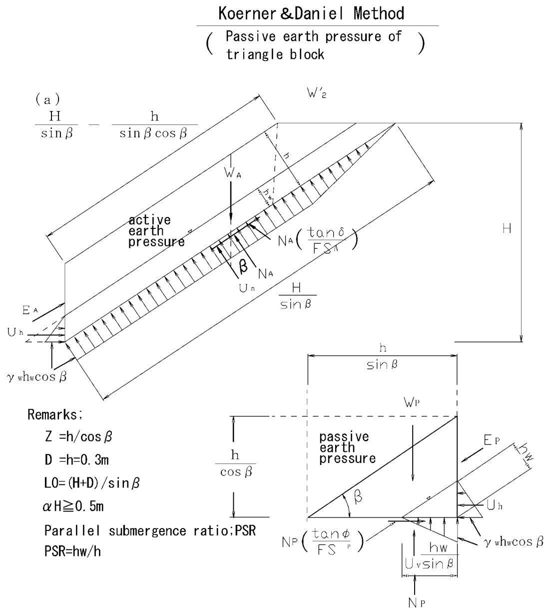

Figure 7. Summary of Koerner and Daniel's method

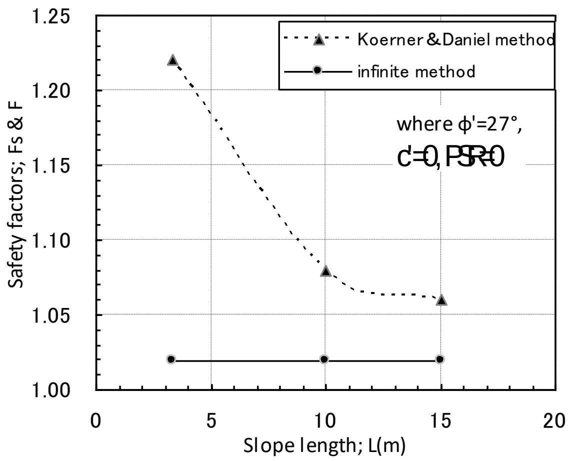

Figure 8. Safety factors by a infinite method (F) and Koerner and Daniel's method (Fs)

The safety factor by Koerner's method is Fs. The safety factor by our infinite method is the constant value of F(1.019)against the change of the slope length for safety side. The safety factor by Koerner method decreases to our value with the slope length growing. Koerner's method is 6.6% greater than our one on 10m of the slope length.

$$Fs = F\cdot(1+1/L^{1.18}) \geqq 1.5 \quad \cdot\cdot(9)$$

Effects of the coefficient of the seepage water pressure were calculated two cases as shown in Figure 9 and 10.

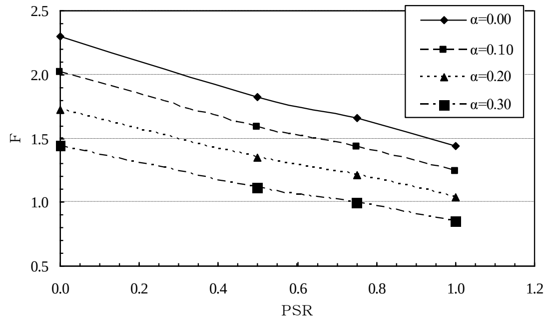

Figure 9. Relation between safety factor and PSR
[ϕ '=20°, c= 3 kN/m^2, L_0= 4.025m, 1:n=1:2]

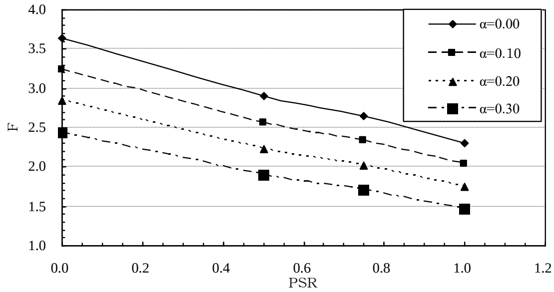

Figure 10. Relation between safety factor and PSR
[ϕ '=27°, c= 5 kN/m^2, L_0= 4.025m, 1:n=1:2]

3. A TYPICAL CASE STUDY OF FAILURE DIKE

Failure of sheet method pond is in a rainfall of 20 mm/hr at the stage of construction.

Photo 4. Failure of sheet method pond
[1:n=1:1.5, h=0.3m, H=1.5m]

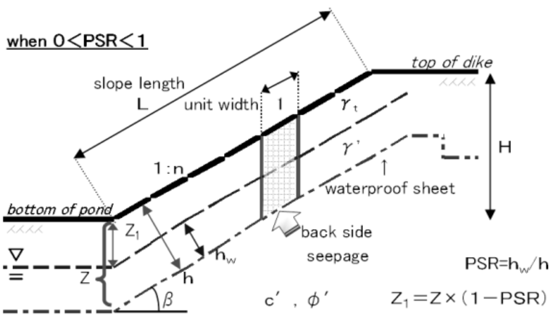

Figure 11. Schematic diagram of a typical case study

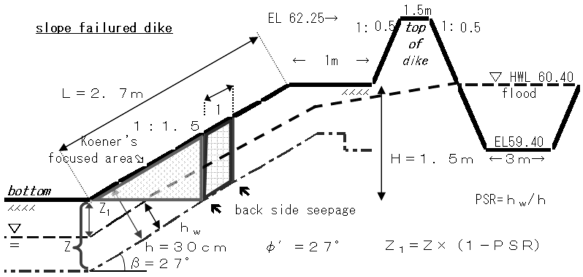

Figure 12. Uplift by seepage water pressure of a river

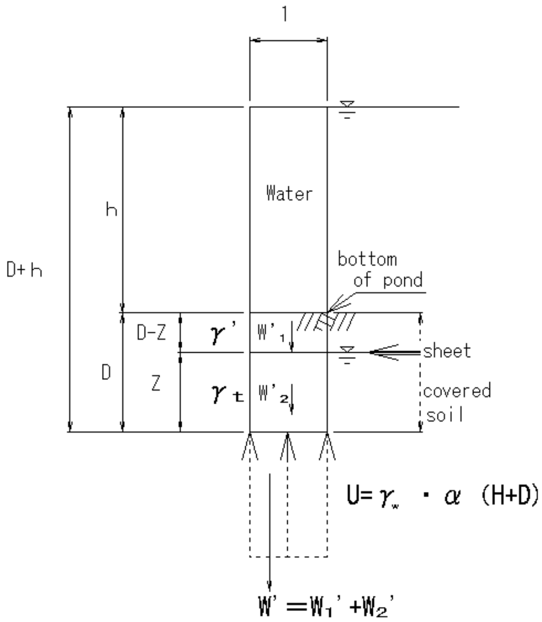

Figure 13. Water balance on a sill sheet

$$\sigma_A = \gamma_t \cdot (D - Z) + \gamma ' \cdot Z$$
$$SF_1 = [\sigma_A / U]_{Z=0}$$
$$= \gamma_t \cdot D / \{\alpha \cdot \gamma_w \cdot (H + D)\} \geqq 1.2$$
$$D \geqq 1.2 \cdot \alpha \cdot \gamma_w \cdot H / (\gamma_t - 1.2 \cdot \alpha \cdot \gamma_w)$$

where parameters in above mentioned equations are as follows;

α : seepage water pressure ratio
$0 \leqq \alpha \leqq 1$
γ_t : wet unit weight of soil (kN/m^3)
$\gamma '$: submerged unit weight of soil (kN/m^3)
γ_{sat} : saturatded unit weight of soil (kN/m^3)
γ_w : water unit weight (≒10 kN/m^3)
H : The difference of water level of front and seepage water pressure (see Figure 7) (m)

4. Analysis of a parametric study

4.1 Soil characteristics in covered soil

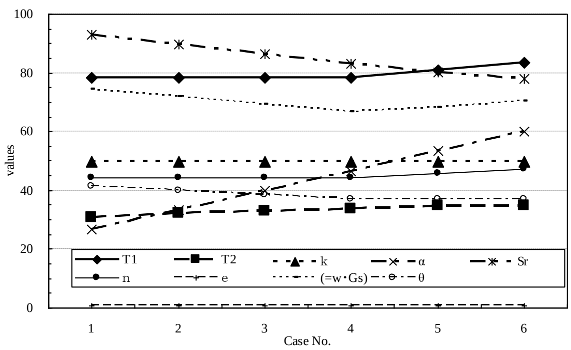

Figure 14. The partitioning of soil character

Parameters in Figure 14 and Table 1 are as follows;

$T_2 = D_{max} / v$

D_{max}: thickness of covered soil layer on the watertight sheet material

$v = i_0 \cdot k_0$

v: flow velocity (cm/s)

naked ground: 2-3 mm/hr

lawn ground : 5-6 mm/hr

plant field : 18 mm/hr

compression ground: 10-300 mm/hr

i_0: hydraulic gradient

k_0: unsaturated hydraulic conductivity (cm/s)

n: porosity(%) {= e/(1+e)×100}

e : void ratio

sand: e = 0.8-0.6

clay : e = 0.7-2.5

organic soil : e = 3.0-5.2

T_1: drainage time (s)

T_2: percolation time (s)

k: saturated hydraulic conductivity (cm/s)

S_r: degree of saturation (%)

w: water content (%)

Table 1. Typical properties for the case study

Case No.	T_1 (s)	T_2 *10 (s)	k *10^4 (cm/s)	α *10	S_r (%)	n (%)	e	$e \cdot S_r$ (=w･Gs)	k_0 *10^4 (cm/s)	PSR	r	θ 1/100*n*S_r (%)
1	78.3	30.9	50	26.7	93.0	44.4	0.80	74.4	45	0.528	20	41.3
2	78.3	32.3	50	33.3	89.8	44.4	0.80	71.9	43	0.528	25	39.9
3	78.3	33.1	50	40.0	86.6	44.4	0.80	69.3	42	0.528	30	38.4
4	78.3	33.9	50	46.7	83.2	44.4	0.80	66.6	41	0.528	35	36.9
5	80.9	34.7	50	53.3	80.3	45.9	0.85	68.3	40	0.528	40	36.9
6	83.4	34.7	50	60.0	78.0	47.4	0.90	70.2	40	0.528	45	37.0

θ : water content by volume (%)

Following comments were investigated by Figure 14 and Table 1.

a) The rainfall (=r) is in proportion to the drainage time (=T_1) .

b) The unsaturated hydraulic conductivity (=k_0) is in proportion reversely to the percolation time (=T_2) in covered soil.

c) The storage coefficient of aquifer (= α) is in proportion to the drainage time (=T_1) .

d) The percolation time (=T_2) is in proportion to the storage coefficient of aquifer (= α).

e) The percolation time (=T_2) is in proportion reversely to the parameter. (=$e \cdot S_r$) .

f) Porosity (=n) is in proportion to the parameter. (=$e \cdot S_r$) .

g) If rainfall rises, the degree of saturation (=S_r) becomes down in covered soil.

h) The coefficient of volume moisture content (θ) is in proportion reversely to the drainage time (=T_1) .

i) The degree of saturation (=S_r) becomes down, so that unsaturated hydraulic conductivity (=k_0) becomes down.

j) If void ratio (=e) becomes large, unsaturated hydraulic conductivity (=k_0) becomes large, too.

4.2 Safety factor (Fs) in stepping work

Safety factor of triangle block is 3.07 under stepping height (f_1=1m), where β_1=26.6° (1:2.0), β_2=33.7° (1:1.5), ϕ_1=25° , ϕ_2=27° .
Safety factor of triangle block is also 1.78 under stepping height (f_1=2m), where β_1=26.6° (1:2.0), β_2=37.6° (1:1.3), ϕ_1=25° and ϕ_2=27° .
The effects of the stepping height under the sheets and the taper of covered soil's layer on the sheet must be investigated.

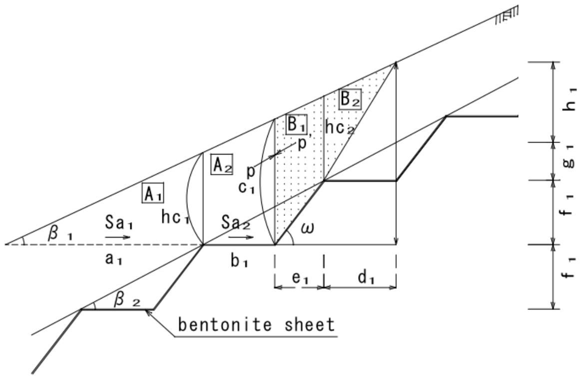

Figure 16. Analysis of efficiency of stepping

Safety factor of stepping dike from Figure 16 was formulated. This method was defined with refering by forces balance on the interaction plane between active earth pressure's block and passive one. Active earth pressure's blocks were B_1 and B_2 in Figure 16. Passive earth pressure's block were A_1 and A_2. If a stepping work is designed to repair a pond's dike, there is no appropriate method in Japan.

Parameters in Figure 16 are as follows;

$a_1 = hc_1/\tan\beta_1$ (m)

$b_1 = f_1 \cdot (1/\tan\beta_2 - 1/\tan\omega)$ (m)

$c_1 = (a_1+b_1) \cdot \tan\beta_1$ (m)

$d_1 = \{(a_1+b_1+c_1)\} \cdot \tan\beta_1 - f_1\} / (\tan\omega - \tan\beta_1)$ (m)

$e_1 = f_1/\tan\omega$ (m)

f_1: stepping height (m)

$g_1 = d_1 \cdot \tan\beta_2$ (m)

$h_1 = d_1 \cdot (\tan\omega - \tan\beta_2)$ (m)

ϕ_1: angle of shear resistance in a soil (°)

ϕ_2: angle of shear resistance between a soil and a sheet surface (°), i.e. external friction angle.

β_1: slope angle of covered soil (°)

β_2: average slope angle of stepping (°)

ω: angle of each stepping (°)

hc_1: vertical height of bottom triangle (m)

hc_2: vertical height of bottom triangle (m) $[= (a_1+b_1+c_1) \cdot \tan\beta_1 - f_1]$

p: resistance force by A_1 and A_2 blocks (kN)

p': sliding force by B_1 and B_2 blocks (kN)

$$SF = p/p' : \text{safety factor of stepping} \quad \cdot\cdot(10)$$

We shall not mention about equation (10) here for want of space. Refer to next papers based on lots of investigations ,which will be checked at in-situ data.

5. CONCLUSION

Many irrigation ponds will be repaired continuously. By lack of the core materials, we will change the previous method (front core type) in near future. At design we must check the PSR in covered soil under rainfall to the embedded surface watertight sheet method.

(1) We must be careful even if rainfall is less than 20 mm/h depending on slope conditions and rainfall time.
(2) The seepage pressure makes the slope failure which is not so filled in covered soil.
(3) The cohesion on the slope is raised using the cement mixing method. The 5 kN/m^2 of cohesion is needed by our infinite analysis against the normal slope of the pond dike.
(4) The effects of the stepping under the sheets, and the taper of covered soil's layer on the sheet must be investigated.
(5) Watertight sheet method have good points for an earthquake because filled water pressure pushes against the sliding front face of pond's dike.

We think the study which is actual model experiments against at in-situ problems and failure slope data. If this paper becomes the reference of the watertight pond's design, we are much honored.

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