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Numerical Study on the Cavity-Induced Piping Failure of Embankment

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Abstract**—**Cavities are frequently found beneath conduits on pile foundations in old embankments. Cavity reduces seepage length significantly and consequently causes piping failure of embankments. Case studies of embankment failures indicate that the relative settlement between ground and pile supported-concrete conduit was the main reason of the cavity. In this paper, an attempt to simulate the cavity-induced piping failure mechanism was made using finite element numerical method. Piping potential is examined by carrying out parametric study for influencing factors such as cavity length, water level, and flow conditions. The concentration of hydraulic gradient adjacent to cavity was found. It is found that the hydraulic gradient close to the cavity exceeds considerably the critical hydraulic gradient causing piping. Piping failure potential due to the existence of cavity is evaluated and contour map for the potential risk of an embankment for piping failure is proposed.

Keywords**—**Cavity, Embankment, Hydraulic gradient, Piping.

I. Introduction

RECENTLY, natural disasters frequently occur around the world due to climate change. It causes flooding of rivers, collapse of embankments, and loss of roads. During flood season, drainage pumps operate to exclude storm water to rivers. In this case, cavity can be formed beneath conduit by the vibration from pump stations. Formation of cavity can cause a significant effect on the stability of embankment by shortening the length of seepage from riverside to inland [1]. Reduction of seepage length causes increase of hydraulic gradient, which increases the potential of piping and eventually causes embankment failure even at the lower water level than the design flood water level. In this study, influence of cavity on the embankment failure is investigated through numerical analysis.

II. Cavity-Induced Piping Mechanism

Piping is a phenomenon which is caused by the loss of ground by scouring of soil particles. Precipitation incurs the difference of water level between riverside and inland. Seepage from riverside to inland is formed, and leakage around the toe of embankment occurs. When the seepage force exceeds the effective stress of the ground, then, the boiling of particles is started and scouring accompanying the piping channel is followed [2].

Piping can be found both in the embankment and beneath the foundation. There are several sources of piping failure in the embankment. Lack of cross section, omissions of filter layer, defects of compaction, permeable layer under the structure and flow layer from poor contact between ground and structure can be factors to generate piping [3].

Fig. 1 Example of embankment failure by piping

When pump station is in operation to exclude storm water into the river, vibration can cause considerable dynamic effects on conduits and embankment body. The vibration can induce separation between conduit and foundation ground. The gap develops cavity beneath the conduit. Fig. 1 shows an example of failure beneath conduit triggered by piping through the cavity. Insufficient contact at ground-structure interface became a main flow route and eventually caused the failure. In this situation, the cavity shortened seepage length, thus critical hydraulic gradient was exceeded and failure was occurred.

III. Modeling Considerations

A. Introduction

Numerical model including cavity is considered. Two types of flow conditions were considered; steady state and transient. In case of steady state flow, the constant hydraulic boundary condition is applied. Meanwhile, in case of transient flow, the time varying hydraulic boundary condition is described. It is assumed that the width of conduit is sufficiently wide, and 2-dimensional model is used.

B. Modeling of Inflow

The seepage occurs through the void due to the difference of water head. The void is an important factor that determines permeability of ground. The continuity equation of flow, including transient conditions, in 2-dimensional model can be expressed as (1):

$$k_x \frac{\partial^2 h}{\partial x^2} + k_z \frac{\partial^2 h}{\partial z^2} = \frac{\partial \varepsilon_v}{\partial t} \quad (1)$$

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Considering isotropic permeability conditions,

$$\frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_z}{\partial z^2} = \frac{\partial \varepsilon_v}{\partial t} \tag{2}$$

where, k is coefficient of permeability, h is difference of water head, v is flow velocity and t is time

For unsaturated soils, ε_v is defined as nonlinear function of permeability and pressure head. Fredlund & Xing model is used in this study [4].

Matrix form of governing equation for flow behavior can be written as:

$$[K]\{h\} + [M]\{h\}t = \{Q\} \tag{3}$$

where, $[K]$ is matrix of element coefficient of permeability, $[M]$ is matrix of mass, $\{Q\}$ is vector of discharge, $\{h\}$ is vector of water head and t is thickness of element.

Numerical analyses using the above equations were performed. The distribution of hydraulic gradient is arranged for the cases with and without cavity beneath the conduit.

C. Analysis Cases

Reference [5] investigated the piping potential in accordance of cavity length beneath the drainage structure based on in-door model test. The cavity generally grows to the riverside, thus, on the model, the cavity was set from toe to the front of left slope of embankment as shown in Fig. 3.

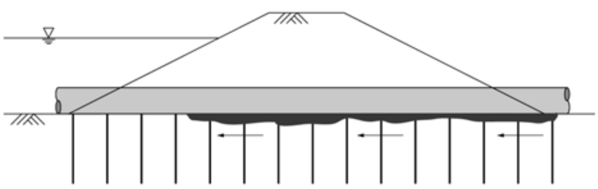


Fig. 2 Cavity formation beneath conduit

The model for the numerical analysis was from the centrifuge model test [1], [5] of which scale is 1:50. Total length of the model is 1.20m, the ground level of riverside land is 0.12m, inland is 0.10m and slope is 1:2.

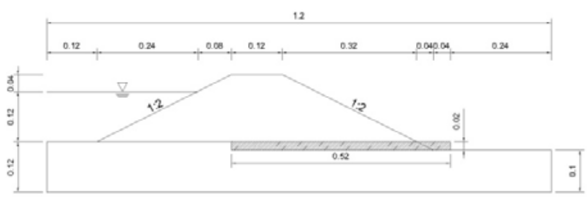


Fig. 3 Numerical value of model

Boundary conditions were set for the flood water level at left riverside slope, and potential seepage at inland side. Conditions of Q=0 were set along top and bottom of the cavity.

TABLE I
CONDITIONS OF FLOW ANALYSIS

Classification	Steady Flow Analysis	Transient Flow Analysis
Water head conditions	0.04m 0.08m 0.12m	0 - 0.12m
Formation of cavity	Without cavity With cavity	

Analysis cases are shown in Table I. In order to evaluate the effect of the water level, various water levels were considered in case of steady flow. Analyses were carried out for the case with and without cavity. Changes of water level with time for the case of transient flow are shown in Table II. And the coefficient of permeability of cavity was set 1/1000 of embankment body. Pre-parameter analysis to evaluate sensitivity of the cavity shows smooth flow when the permeability is 1000 times higher than that of the surrounding ground. Table III shows the material properties used.

TABLE II
HEAD CONDITIONS OF TRANSIENT FLOW ANALYSIS

Classification	Water Head(m)	Time(sec)
In-situ level	0	0 - 30
Level increase	0 - 0.12	30 - 45
Level maintenance	0.12	45 - 3600

TABLE III
MATERIAL PROPERTIES OF EMBANKMENT

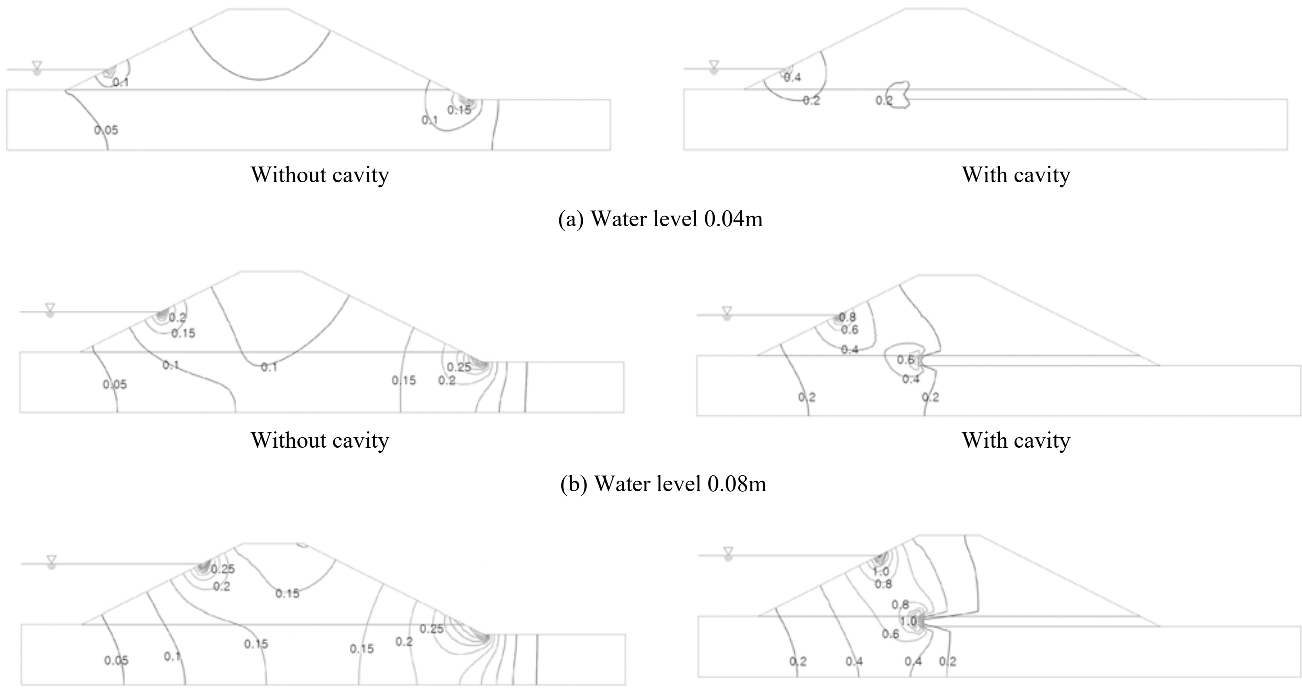
Constitution	Coefficient of permeability (m/sec)	Moisture content (%)	Void ratio	Degree of saturation (%)
Silt 90% Kaolinite 10%	2.58E-6	17	0.525	81.8

IV. RESULTS & ANALYSIS

Piping stability was evaluated based on the critical hydraulic gradient.

A. Steady State Flow

As the water level rises, the hydraulic gradient in inland slope has increased. In case with cavity, the existence of cavity increased hydraulic gradient at the beginning point of cavity. The water level reaches the critical hydraulic gradient when the water level is 0.088m. However, in case without cavity, the hydraulic gradient does not reach critical value even the water level rise to the flood water level. The existence of cavity causes shorter seepage line than normal state, and consequently increases the potential of piping failure. Analysis results for each water level and cavity conditions are shown in Fig. 4.



Without cavity With cavity

(a) Water level 0.04m

Without cavity With cavity

(b) Water level 0.08m

Without cavity With cavity

(c) Water level 0.12m

Fig. 4 Hydraulic gradient distribution of steady flow analysis

Fig. 5 shows the maximum hydraulic gradient for the water level of 0.12m. Without cavity, maximum hydraulic gradient of 0.66 was obtained at toe of embankment, meanwhile with cavity, 1.53 at the beginning point of the cavity.

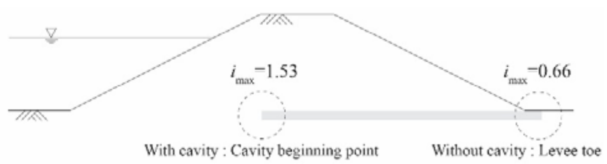
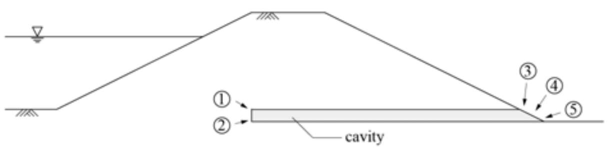
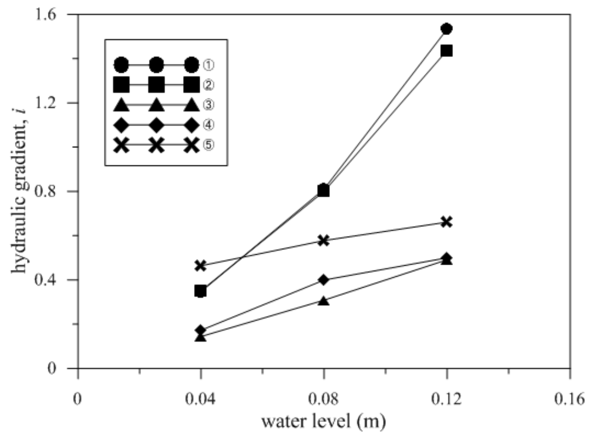


Fig. 5 Change of maximum hydraulic gradient

Fig. 6 shows the hydraulic gradient for different water level at the points where piping is potentially possible. The influence of cavity can be investigated by comparing the point ① and ⑤. At the beginning point of the cavity, the change of hydraulic gradient is very sharp. When the water level is higher than 0.12m, the hydraulic gradient exceeds critical value, thus it can be mentioned that the piping failure starts at the point.



(a) Points of piping consideration



(b) Hydraulic gradient curve

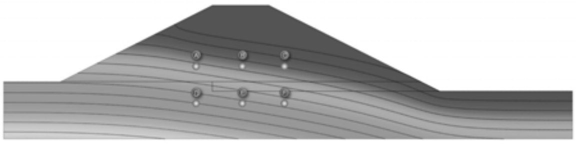
Fig. 6 Water level-hydraulic gradient curve of steady flow analysis

B. Transient Flow

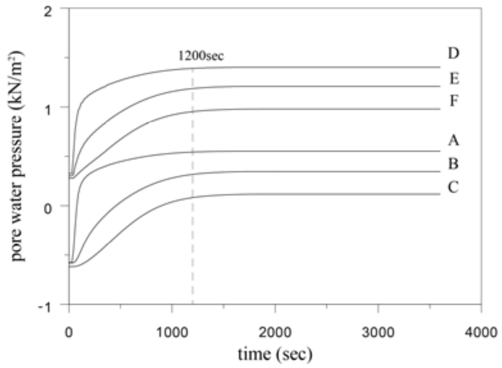
Hydraulic gradient varies with time in transient flow. Fig. 7 shows the pore pressure with time for each Case. The time required to reach steady state is different whether there is cavity or not. The time to reach hydraulic steady state was 1200sec without cavity and 600sec with cavity respectively.

Time dependence was investigated for the 6 points by carrying out analysis for the water head with water level 0.12m. This information is valuable in determining control time for the centrifuge model test.

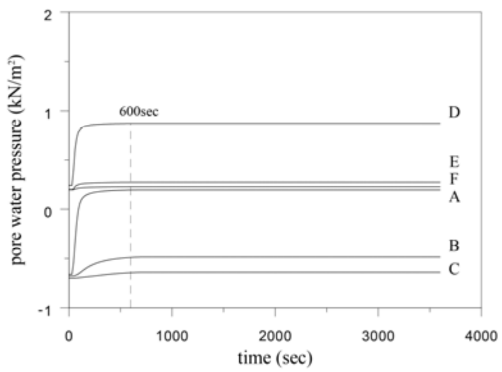
When there is cavity, the time to reach equilibrium state decreases significantly due to the reduced seepage length. Fig. 8 compares seepage lines for each case.



(a) Points of pore water pressure measurement

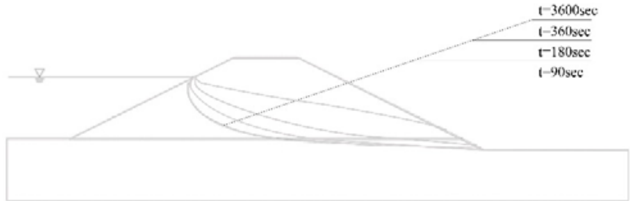


(b) Without cavity

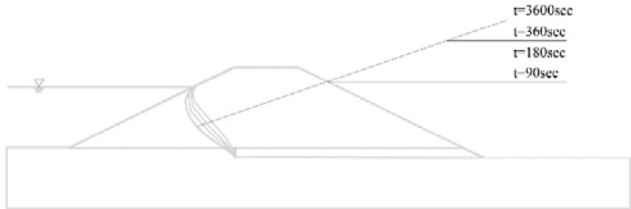


(c) With cavity

Fig. 7 Pore pressure development with time



(a) Without cavity

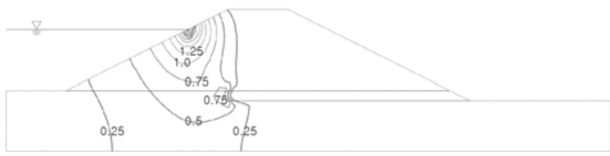


(b) With cavity

Fig. 8 Seepage line

Fig. 9 compares the concentration of hydraulic gradient for transient flow. In case where cavity is developed, concentration of hydraulic gradient occurs at the beginning point of the cavity. The concentration of hydraulic gradient is getting intensive with time. Eventually the hydraulic gradient exceeds the critical gradient, and the piping failure starts.

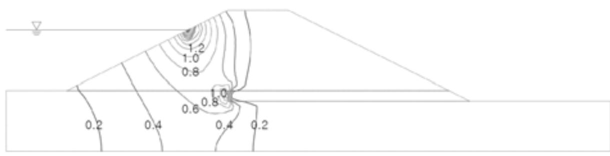
Without cavity



With cavity

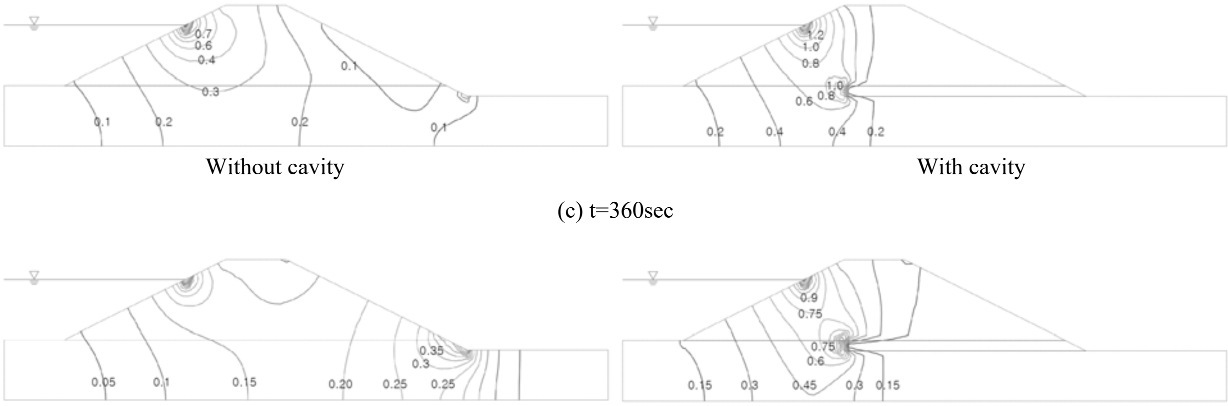
(a) t=90sec

Without cavity



With cavity

(b) t=180sec



Without cavity With cavity

(c) t=360sec

Without cavity With cavity

(d) t=3600sec

Fig. 9 Hydraulic gradient distribution of transient flow analysis

V. Conclusions

The piping development mechanism of embankment with cavity is investigated using the numerical modeling method. It is found that the effect of cavity on piping is crucial. Significant increase of hydraulic gradient was found at the beginning point of the cavity. The highest hydraulic gradient was occurred at embankment toe both for steady state and transient analysis in case without cavity, and it did not exceed the critical value. Meanwhile in case with cavity, the highest hydraulic gradient occurred at the beginning point of the cavity, and exceeds critical gradient of cavity and eventually leads to piping failure.

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