*The 2016 World Congress on*
***Advances in Civil, Environmental, and Materials Research (ACEM16)***
*Jeju Island, Korea, August 28-September 1, 2016*

# Effective stress analysis of levee with cavity under dynamic loading

Ho-Jong Kim[1], Yeong-Bin Kwon [2], No-Hyeon Park[3] and *Jong-Ho Shin[4]

[1), 2), 3), 4)] *Dept. of Civil Engineering, Konkuk University, Seoul 05029, Korea*
[4)] *jhshin@konkuk.ac.kr*

## ABSTRACT

A levee adjacent to a pumping station experiences pump vibration frequently during a rainy season. In the present study, the stability of the levee under dynamic loadings is investigated using a numerical modeling method. A centrifuge model test was considered as a numerical model. A particular levee which includes a cavity beneath its drainage structure is considered. The effect of dynamic loads was examined for various cavity lengths. The results show that the pump vibrations have increased pore water pressure in the levee, and accordingly, reduced effective stress. This behavior conclusively lowered the stability of the levee.

## 1. INTRODUCTION

Important issues that have been conventionally addressed in river levee studies include slope stability, piping stability, and seismic stability. Recently, levees aged 30 years or more have been collapsed along with abnormal climates and the causes are generally reported as piping (Fig. 1).

In general, during floods, drainage pump stations are operated for inner water drainage and the possibility for the vibrations of the pump stations to overlap with the flood stage during the operation to threaten the stability of levees has been raised as a problem. In particular, since existing levee piping evaluation methods do not consider such dynamic effects, the effects of pump vibrations on levees should be investigated and countermeasures should be prepared.

In previous studies related to river levee stability, dynamic effects were mainly examined in relation to earthquakes (Parish et al. 2009; Elia et al. 2011). Since the effect of earthquakes appears as the inertial force proportional to the levee body, it is expected to be different from the effect of vibrations that is delivered through certain mediators such as pump loads.

---

[1] Graduate Student
[2] Graduate Student
[3] Graduate Student
[4] Professor

Fig. 1 Cavity development and embankment collapse (Kim 2014)

In the present study, changes in the pore water pressure of a levee due to the pump vibrations generated by a pump station adjacent to levee were examined by investigating the behavior characteristics of the levee including a cavity due to pump vibrations using dynamic numerical analyses of effective stress.

## 2. Theoretical Background

### *2.1 Fluid-Mechanical-Dynamic Interaction*

The present study was intended to figure out the effects of cavities in river levees through hydraulic-dynamic linkage analyses. Therefore, the temporal changes in the behavior of displacement-water pressure combined conditions should be examined (Shin 2015). In this case, the governing equation becomes the time function of the soil medium and hydraulic behaviors. The behavior variables to determine the dynamic behavior of the effective stress of the soil are displacement: $u^T = [u_x, u_y, u_z]$, relative displacement of pore water in relation to soil particles: $w^T = [w_x, w_y, w_z]$, pore water pressure: $u_w$.

The pure pore water displacement considering the ratio of fluids in the medium can be indicated as $w/n$ when $n$ is porosity. The density of particles and the density of water are indicated by $\rho$, $\rho_f$ respectively.

First, to examine quasi-static flows through the porous medium, in this case, the resistance of fluids due to fluid viscosity is proportional to the flow velocity(Stoke's law), and the flow velocity is proportional to the hydraulic gradient(Darcy's law). Therefore, the following is established for the $x$-direction(compression positive).

$$\frac{du_w}{dx} = k_x^{-1} \left\{ \frac{dw}{dt} \right\} \tag{1}$$

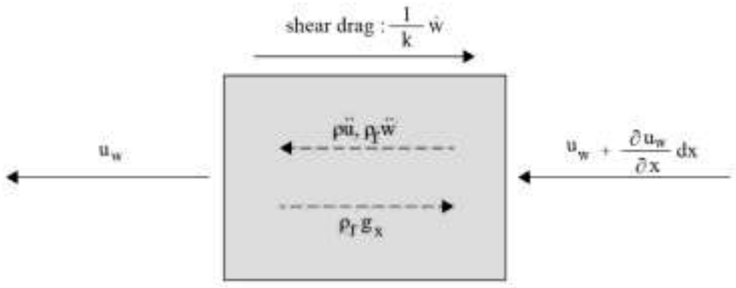



Fig. 2 Dynamic equilibrium of an element in soil mass

When $k_x = k$ is taken assuming isotropic permeability and the flows are in dynamic states as shown in Fig. 2, the equilibrium condition for the $x$-direction is expressed as follows considering the inertial force.

$$\frac{du_w}{dx} - \rho_f g_x = k^{-1}\left\{\frac{dw}{dt}\right\} - \rho\left\{\frac{d^2u}{dt^2}\right\} - \rho_f\left\{\frac{d^2w}{dt^w}\right\} \tag{2}$$

If equations are formulated for the $y$ and $z$ directions in the same method as used for Eq. (2) and the equations are generalized using vector notations to include all directions, the following can be derived.

$$\nabla u_w - \rho_f g_x = k^{-1}\dot{w} - \rho\ddot{u} - \rho_f\ddot{w} \tag{3}$$

where, $\nabla = \left\{\frac{\partial}{\partial_x}, \frac{\partial}{\partial_y}, \frac{\partial}{\partial_z}\right\}$. Eq. (3) can be organized for $\dot{w}$ as follows.

$$\dot{w} = -\nabla u_w + \rho_f g - \rho\ddot{u} - \rho_f\ddot{w} \tag{4}$$

Considering the equilibrium condition of pore water, Eq. (4) can be expressed as follows.

$$\nabla u_w - \rho_f g = k^{-1}\dot{w} - \rho_f\ddot{u} - \rho_f\ddot{w} \tag{5}$$

Equation (5) is a governing equation that defines the dynamic behavior of soil and underground water.

## 3. Numerical analysis modeling

### *3.1 Dynamic centrifugal model tests of levees*

Park (2015) investigated the behavior of an aged levee with a freeboard of 2m and a levee crest of 6m that had a history of piping failure using centrifugal model tests. After making a model at a scale of 1/50 using a mixed soil consisting of silt 90% and kaolinite 10% as shown in Fig. 3, 50g centrifugal acceleration was applied to the model.

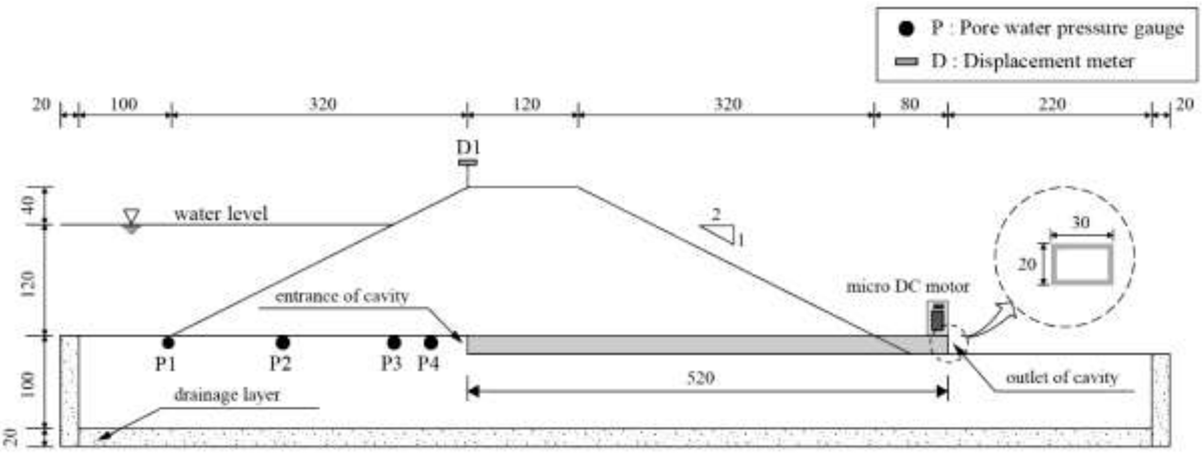



Fig. 3 Centrifugal model (Park 2015)

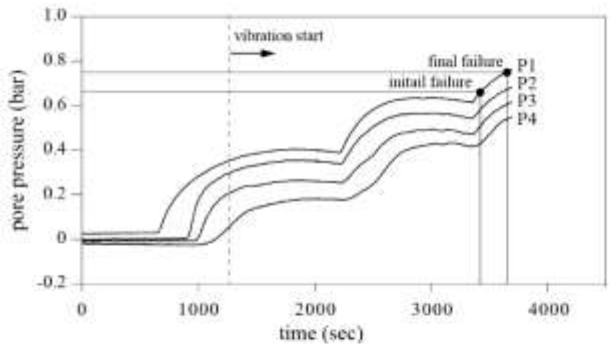



Fig. 4 Results of centrifugal model test (Park 2015)

When dynamic loads were applied, the incipient failure occurred at a water level of 0.253m with a pore water pressure of 0.665bar. The dynamic test showed gradually subsiding behavior. The failure occurred at the low water level in the dynamic test is considered attributable to the fact that the dynamic load due to pump vibrations caused increases in the pore water pressure and piping occurred due to the rise of the saturation line.

In the present study, the dynamic centrifugal model test conducted by Park (2015) was reproduced through dynamic numerical analyses of effective stress to examine the possibility of numerical analytical simulations and based on the results of the examination, cavity on levees were examined.

### *3.2 Numerical modeling of centrifugal model tests*

Fig. 5 shows the numerical analysis model for the centrifugal model of Park (2015). Since dynamic loads due to pump vibrations are simulated in the present numerical analysis were applied as dynamic boundary conditions (Itasca, 2012). Point P below the upstream region of the levee crest were set as reference points for result analysis. The physical properties of the soil material used in the analysis are shown in

Fig. 5. The cavities were simulated as a solid element with a coefficient of permeability 100 times higher than that of the soil to simulate smooth flows through the cavities.

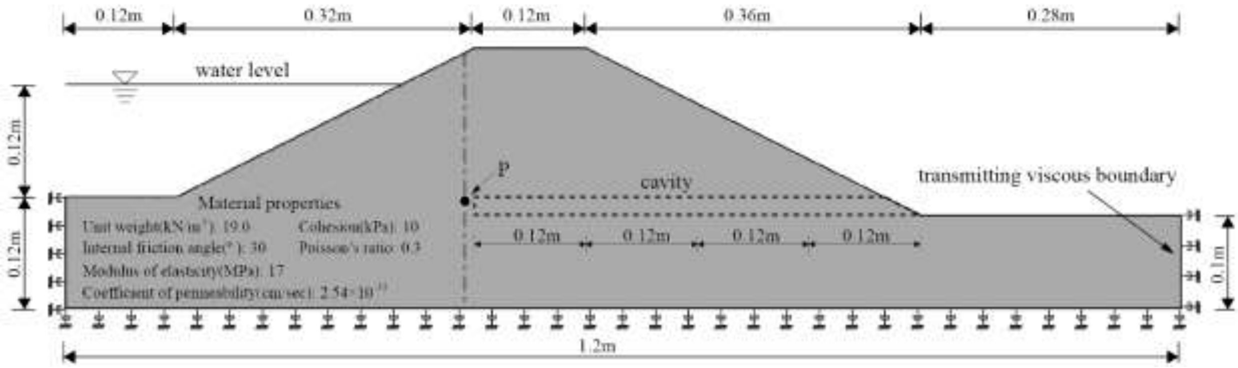
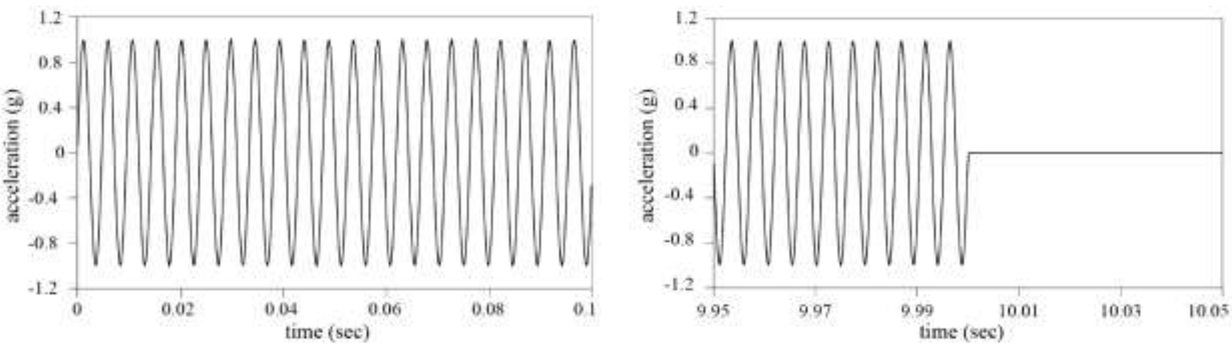


Fig. 5 Cross section of numerical analysis

*3.2.1 Input load*

The internal-combustion engines of the motors in the pump station were major sources of vibrations and the frequency of the vibration expressed and delivered by drainage pump stations was measured as 5.83Hz. The frequency that corresponds to the law of similarity in 50g centrifugal model tests is 290Hz. As an industrial motor with a frequency close to the foregoing frequency, a vibration motor with a frequency of 280Hz was applied. Referring to the measured values in the centrifugal model tests, the input acceleration amplitude of pump vibrations in the numerical analysis was set to 0.15g to determine the input loads during a total of 12sec as shown in Fig. 6.



(a) 0~0.1sec (b) 9.95~10.05sec

Fig. 6 Pump vibration

*3.2.2 Analysis cases*

As the first stage of the numerical analysis, centrifugal model tests were simulated and the results were compared with test results with a view to reviewing the validity of the numerical modeling. Based on the foregoing, a parameter study of the existence of cavities was conducted to examine the characteristics of the dynamic behavior of the levee. The analysis cases are shown in Table 1.

Table 1. Analysis cases

| Classification | Water level | Cavity Length |
|---|---|---|
| Case 1 | 0.24m | without cavity |
| Case 2 | 0.24m | 0.36m |

## 4. Analysis results

*4.1 Modeling of the results of centrifugal model tests*

The pore water pressure levels shown in the numerical analysis were 1,200Pa at P1 in Fig. 3, 1,064.4Pa at P2, 715Pa at P3, and 507.8Pa at P4. When converted into the pore water pressure of the original form, the pressure levels correspond to 0.6bar, 0.532bar, 0.358bar, and 0.254bar respectively. The comparison of the results of the analysis with the results of the centrifugal model test can be indicated as shown in Fig. 7 and the results were shown to agree well to each other at approximately 2,500sec when the water level was 0.24m.

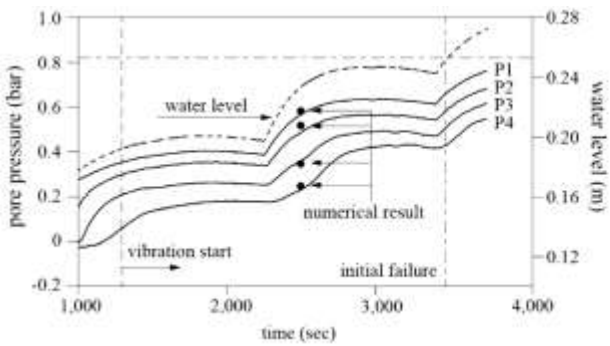
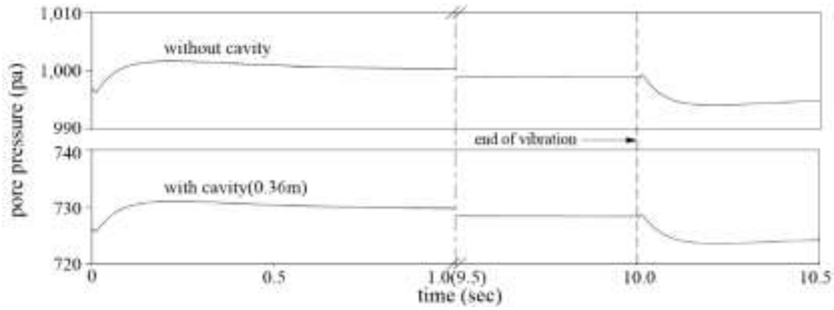



Fig. 7 Numerical results and comparison with centrifuge test

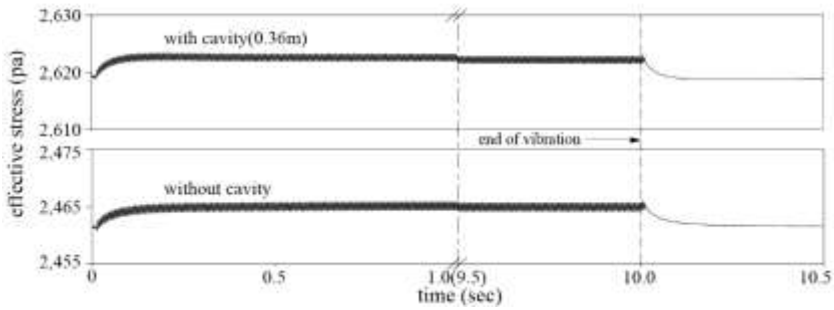
The centrifugal model test was simulated with a numerical analysis and the results showed that the results of the test relatively agreed well to the results of the analysis in the range of continuum behavior before the occurrence of failure. In the present study, the effects of diverse influence factors such as the existence of cavities on the behavior characteristics of levee bodies were examined.

*4.2 Analyses of the effects the existence of a cavity*

Differences in pore water pressure behavior according to the existence or non-existence of a cavity in the levee were analyzed by comparing the results of analyses of Case 1 with no cavity and Case 2 with a 0.36m long cavity. The levee water level was maintained identically at 0.24m. Fig. 8 shows the effects of the existence of a cavity for measuring point P.




(a) pore pressure at Point P




(b) effective stress at Point P

Fig. 8 Effect of cavity existence

As shown in Fig. 8, the pore water pressure behavior tended to be similar regardless of whether there was a cavity or not. When there was no cavity, pore water pressure at Point P increased from 996.7Pa before vibrations to 1,001.73Pa after vibrations. When the dynamic loads finished, the pore water pressure decreased to 995.6Pa so that the pore water pressure before the vibration was almost recovered. When there was a cavity, the pore water pressure increased from 726.2Pa before vibrations to 731.01Pa after vibrations and became 724.8Pa when the dynamic loads finished.

When there was a cavity, the pore water pressure were lower than when there was no cavity. This means that the existence of the cavity causes the drop of pore water pressure and shortens penetration distances to increase the risk of piping.

## 5. CONCLUSIONS

The characteristics of the dynamic behavior of a river levee in the state of flood when the levee was subject to drainage pump vibrations were examined using numerical analyses of dynamic effective stress. The validity of the numerical analysis modeling was checked by comparing the results of centrifugal model tests and the results of numerical analyses. The results indicated that the vertical displacement agreed well to the pore water pressure in the incipient failure state immediately before the occurrence of sink.

Parametric studies of the existence of a cavity were conducted to examine the stress behavior of the levee and important results are as follows.

- Immediately after vibrations, the horizontal flows of pore water were activated due to the effects of particle relocation so that pore water pressure dropped temporarily but the pore water pressure increased soon to show decreases in the effective stress.
- The existence of a cavity concentrated flows on the cavity to cause decreases in the pore water pressure leading to increases in the effective stress.

## ACKNOWLEDGEMENT

This preparation of this paper was supported by the National Research Foundation of Korea under Research Project 2015R1A2A1A05001627. The authors greatly appreciate the support provided.

## REFERENCES

Elia, G., Amorosi, A., Chan, A.H.C. and Kavvadas, M.J. (2011). “Fully coupled dynamic analysis of an earth dam”, Geotechnique, **61**(7), 549-563.

Itasca Consulting Group, Inc. (2012), “Fast Lagrangian Analysis of Continua in 3 Dimensions, User’s Manual, Example Applications, Fluid-Mechanical Interaction, Dynamic Analysis”.

Kim, K.H. (2014), “Evaluation of dynamic piping stability for embankments with flood water level”, Master Thesis, Konkuk University(in Korean).

Parish, Y., Sadek, M. and Shahrour, I. (2009), “Numerical analysis of the seismic behaviour of earth dam”, Natural Hazards and Earth System Sciences, **9**(2), 451-458.

Park, G.C. (2015), “A Study on Piping Failure of Levee Using Centrifuge Model Test”, Master Thesis, Konkuk University(in Korean).

Shin, J.H. (2015), “Geomechanics & Engineering Ⅰ”, CIR, Seoul, 427-511.