Conference Paper, Published Version

Lee, Jin-Hyung; Won, Jin-Oh; Jeong, Sangseom; Chung, Moonkyung; Kwak, Kiseok

Analysis Of Piled Bridge Pier Considering Hydraulic Pressure And Scour Depth

ANALYSIS OF PILED BRIDGE PIER CONSIDERING HYDRAULIC PRESSURE AND SCOUR DEPTH*

JIN-HYUNG LEE, JIN-OH WON, SANGSEOM JEONG

Dept. of Civil Engineering, Yonsei University, 134 Shinchon-dong, Seodaemun-gu Seoul, 120-749, Korea

MOONKYUNG CHUNG, KISEOK KWAK

Geotechnical Engineering Research Dept., KICT, 2311, Daehwa-dong, Ilsan-gu Koyang, Kyonggi-do, 411-410, Korea

In this study, 3-dimensional FEM analysis is performed to investigate the stability of a piled bridge pier foundation with the hydraulic pressure and scouring depth which rapidly increase in flood by integrating a upper structure(pier) and lower foundation(pile cap and piles). This model is able to show efficiently the complicated pile-cap-pier interaction of a real bridge foundation. To examine the influence of hydraulic pressure and scouring depth to the stability of the entire piled bridge pier foundation, the bridge foundation analysis is performed using this analysis method with the computed hydraulic pressure and scouring depth. Based on this, it is shown that it is desirable to evaluate the structural safety and serviceability in bridge system based on pile-cap-pier interaction by considering hydraulic factors and scour depth against flood.

1 Introduction

External factors causing damage to bridges have been occurred by sudden flood flows. The hydraulic pressures acting on piers and a local scour around the bridge foundations can affect the hazardous effects on structural safety and serviceability. Excessive horizontal displacement of an upper portion of pier resulting from scouring and hydraulic pressure may lead to structural damage. The pier and the foundations of the bridges are not independent structures to behavior separately each other, so that, it is need to the unified analysis method taking into account the pile-cap-pier interaction.

In this study, a piled pier subjected to hydraulic pressures and scour depth on the flood was investigated through the simplified three-dimensional finite element analysis technique. In the finite element analysis, a pile cap is modeled with four-node flat shell element, and piers and piles are modeled using three-dimensional beam elements and beam-column elements respectively, and the complex phenomenon of the pile-soil interaction is modeled by soil springs (p-y, t-z and q-z curves). A computationally efficient algorithm to analyze the behavior of a whole bridge foundation is proposed.

Through the numerical case studies, this method is appropriate for investigating the effect of hydraulic pressures and scour depth on a piled pier foundation. And the effect of a hydraulic pressure and scour depth in serviceability of piled pier foundation was examined.

* This work is supported by Korea Institute of Construction Technology.

2 Method of analysis

2.1. *Structural system of pile bridge pier*

If the scour depth affects below the pile cap, pile foundations are not failed at once but has some hazardous effects. For example, excessive horizontal displacement of a pile cap and bridge pier resulting from riverbed scouring and hydraulic pressure may lead to structural damage (Fig. 1). So, it is a three-dimensional piled bridge pier analysis method that is recommended to think over the effect of scour depth and hydraulic pressure between a pile cap and pier.

In this study, a proposed analysis method uses finite element technique. The major structural components of the system are the pile, pile cap, pier columns (Fig. 2). The piles are modeled using beam-column elements and the pier is modeled using three dimensional beam elements. The pile cap is modeled using three dimensional 4 node flat shell elements (Ibrahimbegovic, 1990).

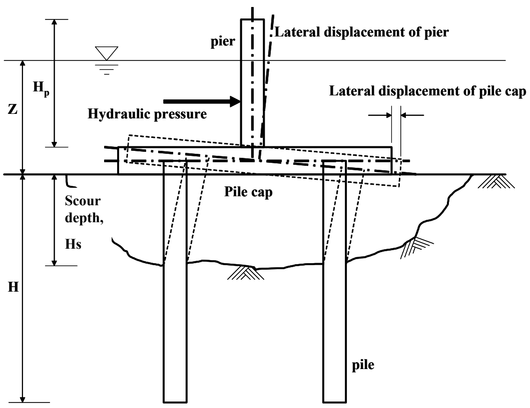

Fig. 1 - Piled bridge pier considering hydraulic force and riverbed scouring

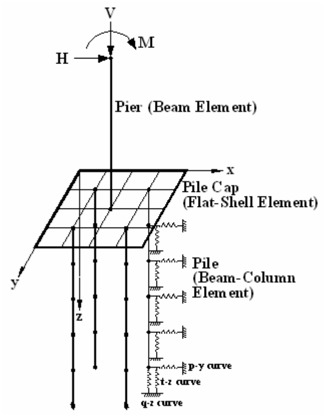

Fig. 2 - piled bridge pier 3-D FE model

2.2. *Pile cap modeling*

A Pile cap has been modeled by plate element (Clancy and Randolph 1993: Zhang and Samll 2000; Matsmoto 2002, 2003), but in this case it has a limit that can not consider horizontal degrees of freedom. But when a flat shell element, a simple one of shell elements, which the stiffness matrices of a plate bending element and membrane element consist separately like Eq. (1) are used, horizontal degrees of freedom can be considered. Additionally, a membrane element with drilling degree of freedom used, a flat shell element comes to have 6 degrees of freedom per node so that torsion behavior of individual pile can be considered and an easy connection to other beam or folded elements can be permitted. So in this study a pile cap is modeled using 4-node flat shell element developed by combining a Mindlin plate bending elements and a membrane element with a drilling degree of freedom as shown in Fig. 3.

$$K_{shell} = \begin{bmatrix} K_{plate} & 0 \\ 0 & K_{membrane} \end{bmatrix} \tag{1}$$

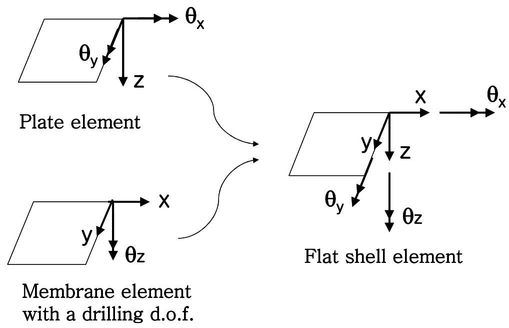

Fig. 3 - Flat shell element with a drilling degree of freedom

2.3. *Extension a pile head stiffness matrix to a beam stiffness matrix*

Fig. 4 shows the general structure coordinate system (X, Y, Z) and the pile coordinate system (u, v, w). And Eq. (2) and Eq. (3) represented an equilibrium equation at individual pile heads as a matrix form, suggested by Reese et al. (1970).

$$\begin{bmatrix} c_5 & 0 & 0 & 0 & 0 & 0 \\ 0 & c_1 & 0 & 0 & 0 & c_2 \\ 0 & 0 & c_1 & 0 & -c_2 & 0 \\ 0 & 0 & 0 & c_6 & 0 & 0 \\ 0 & 0 & -c_3 & 0 & c_4 & 0 \\ 0 & c_3 & 0 & 0 & 0 & c_4 \end{bmatrix}_i \begin{Bmatrix} \delta_u \\ \delta_v \\ \delta_w \\ \alpha_u \\ \alpha_v \\ \alpha_w \end{Bmatrix}_i = \begin{Bmatrix} F_u \\ F_v \\ F_w \\ M_u \\ M_v \\ M_w \end{Bmatrix}_i \tag{2}$$

$$\mathbf{S_i \delta_i = F_i} \tag{3}$$

where, S_i is a individual pile head stiffness matrix, δ_i is a displacement or rotation, and F_i is force or mement at the i^{th} pile head . Each component (c_1~c_6) of a pile head stiffness matrix can be estimated by single pile analysis subjected to axial and lateral forces and moments with typical boundary conditions (Reese et al. 1970).

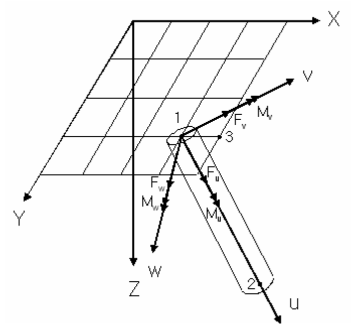

Fig. 4 - Pile coordinate systems

Generally in three dimensional finite element analyses, individual piles are modeled like beams of which toe conditions are fixed. So Eq. (2) should be extend to an equilibrium equation of a beam element that has node 1 and node 2. It can be expressed like Eq. (4), inserting a 6 by 6 pile head stiffness matrix of node 1 into a 12 by 12 beam stiffness matrix of node 1 and node 2. In the analysis, node 2 is specified by fixed condition, so only 6 by 6 pile head stiffness matrix in Eq. (2) is valid.

$$\begin{bmatrix} c_5 & 0 & 0 & 0 & 0 & 0 & EA/L & 0 & 0 & 0 & 0 & 0 \\ 0 & c_1 & 0 & 0 & 0 & c_2 & 0 & 12EI_W/L^3 & 0 & 0 & 0 & 6EI_W/L^2 \\ 0 & 0 & c_1 & 0 & -c_2 & 0 & 0 & 0 & 12EI_V/L^3 & 0 & -6EI_V/L^2 & 0 \\ 0 & 0 & 0 & c_6 & 0 & 0 & 0 & 0 & 0 & GJ/L & 0 & 0 \\ 0 & 0 & -c_3 & 0 & c_4 & 0 & 0 & 0 & -6EI_V/L^2 & 0 & 4EI_V/L & 0 \\ 0 & c_3 & 0 & 0 & 0 & c_4 & 0 & 6EI_W/L^2 & 0 & 0 & 0 & 4EI_W/L \\ EA/L & 0 & 0 & 0 & 0 & 0 & EA/L & 0 & 0 & 0 & 0 & 0 \\ 0 & 12EI_W/L^3 & 0 & 0 & 0 & 6EI_W/L^2 & 0 & 12EI_W/L^3 & 0 & 0 & 0 & 6EI_W/L^2 \\ 0 & 0 & 12EI_V/L^3 & 0 & -6EI_V/L^2 & 0 & 0 & 0 & 12EI_V/L^3 & 0 & -6EI_V/L^2 & 0 \\ 0 & 0 & 0 & GJ/L & 0 & 0 & 0 & 0 & 0 & GJ/L & 0 & 0 \\ 0 & 0 & -6EI_V/L^2 & 0 & 4EI_V/L & 0 & 0 & 0 & -6EI_V/L^2 & 0 & 4EI_V/L & 0 \\ 0 & 6EI_W/L^2 & 0 & 0 & 0 & 4EI_W/L & 0 & 6EI_W/L^2 & 0 & 0 & 0 & 4EI_W/L \end{bmatrix}_i \begin{bmatrix} \delta_{1u} \\ \delta_{1v} \\ \delta_{1w} \\ \alpha_{1u} \\ \alpha_{1v} \\ \alpha_{1w} \\ \delta_{2u} \\ \delta_{2v} \\ \delta_{2w} \\ \alpha_{2u} \\ \alpha_{2v} \\ \alpha_{2w} \end{bmatrix}_i = \begin{bmatrix} F_{1u} \\ F_{1v} \\ F_{1w} \\ M_{1u} \\ M_{1v} \\ M_{1w} \\ F_{2u} \\ F_{2v} \\ F_{2w} \\ M_{2u} \\ M_{2v} \\ M_{2w} \end{bmatrix}_i \quad (4)$$

2.4. *Nonlinear analysis technique*

Fig. 5 shows load-displacement relations of Mode I among 4 Modes about pile head movements suggested by Reese et al. (1970), specifying lateral pile head movement on unrotated pile head condition. As shown in this figure, the load-displacement curves are nonlinear characteristics and the pile head stiffness, c_1 and c_2, is decreased as the lateral movement increased. So pile head stiffness c_1~c_6 in Eq. (4) should be change at a certain displacements or rotations and an iteration techniques is necessary for this reason.

In this study, a mixed load increment and iteration method is suggested. Fig. 6 shows a calculating process of stiffness at i^{th} load increment. External forces are divided by N, and $(k_i)_j$ means the stiffness at i^{th} load increment and j^{th} iteration. In each load increment, tangential slope is adopted in j=1 and secant modulus in j>1 for the stiffness of pile head, which may be expressed as Eq. (5) and Eq. (6) respectively..

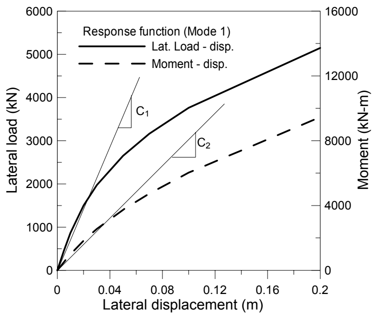

Fig. 5 - Nonlinear load-displacement relations at pile head

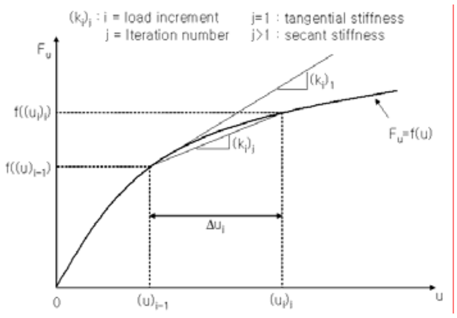

Fig. 6 - Calculating process of a stiffness

$$(k_i)_j = \left(\frac{df(u)}{du}\right)_{u=(u)_{i-1}} \quad (j=1) \tag{5}$$

$$(k_i)_j = \frac{f((u_i)_j) - f((u)_{i-1})}{(u_i)_j - (u)_{i-1}} \quad (j>1) \tag{6}$$

$$(u_i)_j = (u)_{i-1} + \Delta u_j \tag{7}$$

where, $(u)_{i-1}$ is a accumulated final displacement at previous load increment, $(u_i)_j$ is a accumulated displacement at i^{th} load increment and j^{th} iteration. At each load increment, the calculated displacement of individual pile head is Δu_j through structural analysis, and the accumulated displacement $(u_i)_j$ is estimated using Eq. (7). If the convergence criteria, $\Delta u_j - \Delta u_{j-1} < \varepsilon$ is satisfied, the accumulated final displacement, $(u)_i$ is calculated and go to next load increment. This process iterate until the load increment number reaches N. In the structure analysis, the tangential slope (df(u)/du) and load (f(u)) are estimated using cubic spline method.

2.5. *Soil modeling*

For axially loaded piles, the load-transfer curves were modeled by t-z and q-z curves. The type of t-z and q-z curves supported by the program is a linear elastic-plastic curve. In the soil, t_{max} was estimated by β method (Burland, 1973):

$$t_{max} = \beta \sigma'_z \tag{8}$$

where, β is approximately 0.3 and t_{max} is linearly increased to a critical depth (15D, D : diameter), beyond which it remains as a constant to failure.

For laterally loaded piles, the load-transfer curves were modeled by p-y curves. A hyperbolic function was used to describe the relationship of the p-y curve which has an ultimate resistance (p_u) and an initial tangent stiffness (E_s). The initial tangent stiffness used in this study was assumed to vary linearly with depth as recommended by Reese et al. (1974). Group effects are included in the analysis through p multipliers applied to the p-y curves for the individual piles. To analyze the change of group pile behavior, especially in the presence of bridge scouring, load transfer curves (p-y, t-z, and q-z curves) within the scour depth are assumed to be eliminated, beyond which they are reconstructed along the embedded pile length by reducing the ultimate resistance (p_u).

3 ANALYSIS AND RESULTS

To examine the piled bridge pier behavior with hydraulic pressure and riverbed scouring, a series of idealized cases were examined based on the major influencing parameters such as flow velocity and flow depth. Fig. 7 shows a piled bridge pier configuration to be analyzed. The material properties for piled bridge pier are shown in table 1. The cases of hydraulic force and scour depth are shown in Fig. 8. The scour depth (CSU eq.) and hydraulic pressure (AASHTO, 1998) are considered by the flow velocity and flow depth.

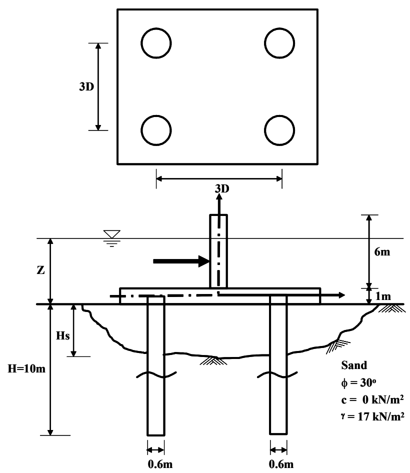

Fig. 7 - A piled bridge pier configuration with hydraulic force and scouring

Table 1. Material properties and analysis case for piled bridge pier.

Pile	Diameter	0.6 m
	Length	10 m
	Elastic modulus	2,000,000 kN/ m^2
Soil (uniform sand)	Friction angle	30 degree
	Cohesion	0 kN/m^2
	Unit weight	17.0 kN/m^3
Pier	Diameter	1.0 m
	Length	6.0 m
	Elastic modulus	3,000,000 kN/m^2
Connectivity condition	Fixed	
Loading	Hydraulic pressure	Fig. 8(a)
Scour depth	Fig. 8(b)	
Analysis case	Case 1	Hydraulic pressure
	Case 2	Hydraulic pressure and scour depth

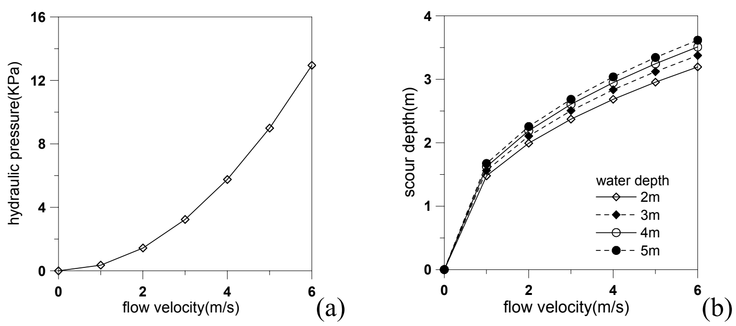

Fig. 8 - Hydraulic pressure (a) and scour depth (b) caused by flow velocity and depth

Fig. 9 and Fig. 10 show the displacement of a cap and pier top with varying hydraulic pressure and scour depth caused by varying flow velocity and flow depth (as shown in Fig. 8). As shown in these figures, the displacement of the pile cap and the pier top is increased as the flow velocity increases and the magnitude is seem to be significantly larger for the pier top displacement than pile cap.

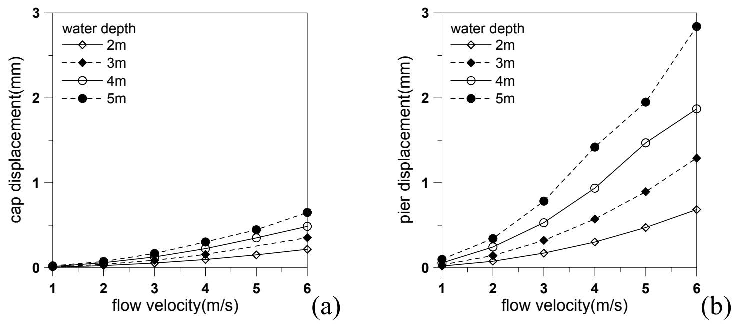

Fig. 9 - Lateral displacement caused by hydraulic pressure (case 1); (a) pile cap, (b) pier

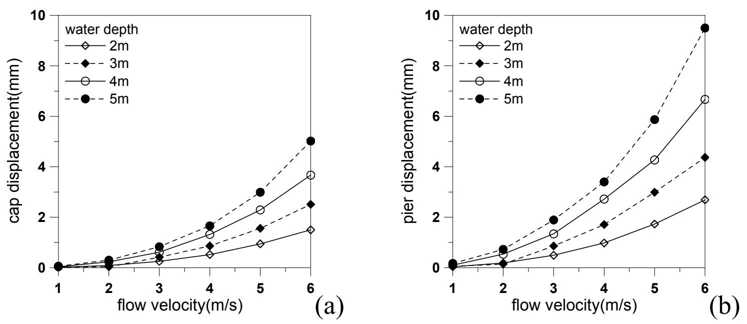

Fig. 10 - Lateral displacement caused by hydraulic pressure and scouring (case 2); (a) pile cap, (b) pier

Also, it was found that the scour depths much affected on the displacement of pile cap and pier than hydraulic pressure and the displacement of pile cap and pier was increased steeply, so the maximum displacement was occurred at pile cap and pier top in case 2.

The stability of piled bridge pier is investigated by a displacement of pile cap and/or pier. In case of the flood, the stability of pier can be assessed by analyzing the range of displacement which upper structure permits, because lateral displacement is estimated as relatively large in pier compared to that in pile cap.

4 CONCLUSIONS

In this study, 3-D FE analyses are developed to investigate the stability of a bridge foundation with the hydraulic pressure and scouring depth which rapidly increase in flood by integrating a pier structure and foundation (pile cap and pile). To integrate the upper part and the lower part of piled bridge pier foundation, a pier is modeled as 3-dimensional beam elements, a pile cap as 3-dimensional flat shell elements and a pile as a beam-column element. This modeling method is able to show efficiently the complicated interaction of pile-cap-pier interactions of a real bridge foundation.

To examine the influence of hydraulic pressure and scouring depth to the stability of the entire bridge foundation, the bridge foundation analysis is performed using this analysis method with the computed hydraulic pressure and scouring depth. According to the analysis, the lateral displacements of a pile cap and a pier increase as increasing hydraulic pressure and scour depths. Especially the displacement of a pier is relatively larger than that of a pile cap and this may cause structural damage or hazardous effects on the serviceability of a bridge. Based on this, it is shown that it is desirable to evaluate the structural safety and serviceability in bridge system based on pier-cap-pile interaction by considering hydraulic factors and scour depth against flood.

Acknowledgments

This paper was supported by Bridge 200 Development of Technology for Extended Duration of Bridge Sub-structure of the KICT. Their support is gratefully acknowledged.

References

Reese, L.C., M.W. O'Neill and Smith, R.E. (1970). "Generalized analysis of pile foundations." *ASCE*, Vol. 96, No. SM1, January, pp.235-250.

O'Neill, M.W., O.I. Ghazzaly and Ha, H.B. (1977). "Analysis of three-dimensional pile groups with nonlinear soil response and pile-soil-pile interaction." *9th Annual Offshore Technology conference in Houston*, Ex. May 2-5.

Zhang, L., M.C. McVay and Lai, P. (1999). "Numerical Analysis of Laterally Loaded 3×3 to 7×3 Pile Groups in Sands." *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, Vol. 125, No. 11, November, pp.936-946.

Clancy, P. and Randolph, M.F. (1993). "An Approximate Analysis Procedure of Piled Raft Foundations." *Int. J. Numer. Anal. Meth. Geomech.*, 17:849-869.

Zhang, H.H. and Small, J.C. (2000). "Analysis of Capped Pile Groups subjected to Horizontal and Vertical Loads." *Computers and Geotechnics*, 26, pp.1-21.

Hoit, M.I., McVay, M., C. Hays and Andrade, P.W. (1996). "Nonlinear Pile Foundation Analysis using Florida-Pier." *Journal of Bridge Engineering*, Vol. 1, No. 4, November, 1996, pp.135-142.

Ibrahimbegovic, A. R.L. Taylor and Wilson, E.L. (1990). "A Robust Quadrilateral Membrane Finite Element with Drilling Degree of Freedom." *Int. J. Numer. Methods eng. Eng.*, 30, 445-457.

Richardson, E.V. and Davis, S.R. (2001). "Evaluating Scour at Bridges." FHWA NHI 01-001, HEC No. 18, U.S. Department of Transportation, Washington, D.C.

AASHTO (1998). AASHTO LRFD BRIDGE DESIGN SPECIFICATION.