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SEEPAGE ANALYSIS OF TWO CASE HISTORIES OF PIPING INDUCED BY EXCAVATIONS IN COHESIONLESS SOILS

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ABSTRACT: *Stability against piping for excavations in cohessionless soils is usually predicted using Terzaghi and Peck's method. This paper uses VGFlow, a two- and three-dimensional finite element software for analysis of water flow through soils to predict the water pressure around excavations, and then uses the calculated water pressure to evaluate the safety factor against piping. Two case histories of piping were analyzed. The three-dimensional shape of excavations made the water pressure higher than that of Terzaghi and Peck's method. Consequently, the excavations in cohessionless soils should be on the dangerous side if the three-dimensional effect was not considered in design.*

KEYWORDS**:** *Piping; excavations; seepage analysis; cohessionless soils; finite element method.*

1. INTRODUCTION

Boiling is a common failure mode of retained excavations in cohessionless soils, and it occurs if the water pressure is sufficient to produce critical velocities. The safety factor against piping is usually predicted using the method of Terzaghi and Peck [1]. The method considers that hydraulic head linearly reduces on the two sides of the wall below the excavation base because the gravel rests on a bed of uniform sand of which the level is the same as that of excavation base. Symons [2] proposed an equation to calculate the water pressure at the wall tip based on the assumption that the hydraulic head linearly reduces with distance around the wall from the water table position on the active side to the level of the excavation base on the passive side. These two methods do not consider the influence of the excavation shape on the water pressure. NAVFAC DM-7 [3] considers the influence of the excavation width on the safety factor against piping, and supplies charts for determining whether piping may occur. Totally, the three methods are developed for two-dimensional (2D) situations. The three-dimensional (3D) effect of water flow around excavations increases the water pressure to make piping occur easily. Thus the water pressure of 3D analysis of water flow around excavations should be used to predict piping in design if the excavation length is not large enough to consider the excavation as a 2D case. Some case histories have indicated that piping occurred though it was considered to be safe based on the three above-mentioned methods for 2D situations.

This paper uses VGFlow, a 2D and 3D finite element (FE) software for analysis of water flow through soils to calculate the water pressure around excavations, and then uses the calculated water pressure to evaluate the safety factor against piping. Here, the safety factor was defined as the ratio of the effective soil weight to the uplift load of the water pressure; this definition was identical to that in Terzaghi and Peck's method. Two case histories were analyzed using the 2D and 3D FE software for analysis of water flow through soils. The 3D effect made the water pressure higher than that in Terzaghi and Peck's method; this is just the reason why piping takes place in the excavations that were considered to be safe based on Terzaghi and Peck's method.

2. CASE Histories

2.1. Case One

This case was reported in a Special Issue, Nikkei Construction [4]. As shown in Figure 1, the excavation is 21.2m long, 11.9m wide, and 16.3m deep. The original groundwater level is 4.8m below the ground surface. The ground mainly consists of sand layer and sandy gravel layer, but the details are not reported in the Special Issue [4]. Sheet-piles are used as the retained wall, and inserted 9.2m below the excavation base. The length of sheet-piles is determined by the safety factor against piping, which is about 1.58 by Terzaghi and Peck's method. When the excavation is near the expected depth of 16.3m, boiling occurred. To stop boiling, the contractor had to use deep wells to draw down the groundwater level behind the sheet-piles.

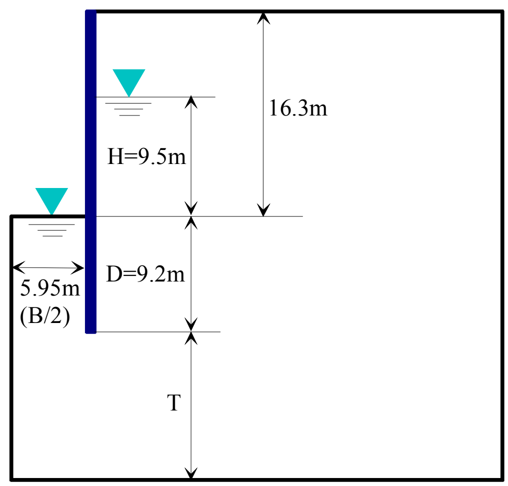

Figure 1. Schematic geometry of case one (Length of excavation=21.2m)

Here, we use 3D FE analysis of water flow through soils to clarify the reason for boiling. First, the water pressure in the ground was calculated, and then the safety factor against piping was evaluated as in Terzaghi and Peck's method. Due to the symmetry, only 1/4 of the ground under the groundwater level was analyzed. The boundary conditions are as follows: the symmetrical faces and the faces close against the sheet-piles were impervious; the outer boundaries of the analyzed zone were of known hydraulic head; the excavation base was of a such known hydraulic head that the pressure head is zero; the top surface of the mesh, located at the original water level, was also of a such known hydraulic head that the pressure head is zero as assumed in Terzaghi and Peck's method. The thickness of the soil layer under the wall T was assumed to be three times D for a soil layer of infinite depth. The distance from the center of the excavation to the outer boundaries were about 200 times the width B, or length L, respectively. The preliminary calculation has indicated that they are enough to reflect the influence range of the groundwater. The two-dimensional analysis was firstly conducted for the cross section shown in Figure 1.
Figure 2 shows the contours of pressure head for a part of the analyzed zone near the excavation of 2D FE analysis. The maximum excess water pressure U_a of 57.3kPa was at the wall tip. Even for 2D analysis, the excess water pressure U_a of FE analysis was much larger than those of Terzaghi and Peck's and Symon's methods. In Terzaghi and Peck's method, the excess water pressure $U_a = \gamma_w H/2$ at the wall tip; in Symons' method, $U_a = \gamma_w HD/(H+2D)$, where γ_w is the unit weight of water.

Thus the safety factor against piping is given by

$$F = \gamma' D / U_a \quad (1)$$

where is γ' the buoyant unit weight of soil.

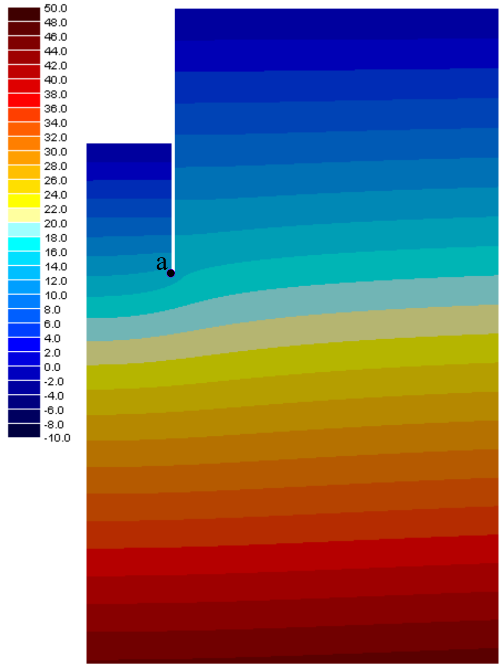

Figure 2. Contours of pressure head (unit: m) of 2D FE analysis for the cross section shown in Figure 1.

For case one, the calculated maximum excess water pressure U_a of 2D analysis by various methods and the corresponding safety factor against piping are listed in Table 1. Here, the buoyant unit weight of soil is 8.0kN/m^3 [4]. The safety factor against piping was larger than unity for any 2D methods; however, the safety factor was the smallest when it was evaluated using the maximum excess water pressure of 2D FE analysis of water flow through soils.

Table 1. Excess water pressure U_a and safety factor against piping for case one

Method	U_a (kPa)	Safety factor
Tergazhi and Peck	46.60	1.579
Symons	30.73	2.395
NAVFAC DM-7	-	1.49
FEM (two-dimensional)	57.27	1.285
FEM (three-dimensional)	76.71	0.959

The 3D FE analysis of water flow around the excavation was conducted to consider the influence of the limited length of the excavation. Figure 3 shows the contours of the pressure head of the 3D FE analysis, the contours of pressure head of the horizontal section at the level of the wall tip. The pressure head at the corner of the wall was the highest, and it was significantly larger than that at the wall tip obtained by 2D FE analysis.

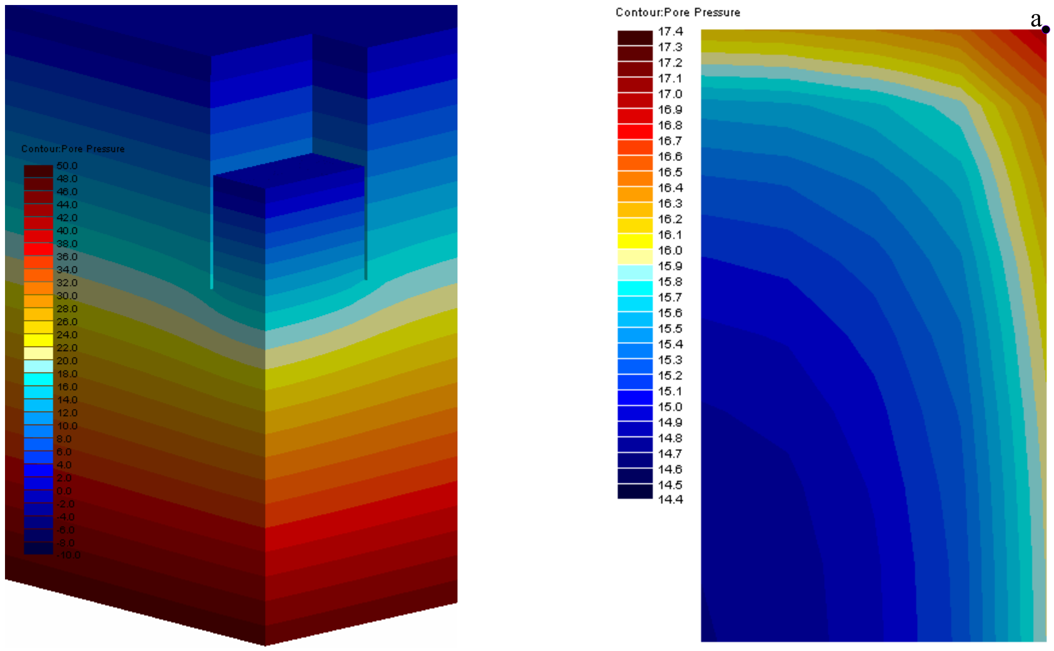

Figure 3. Contours of water pressure head (unit: m) of 3D FE analysis (left), and contours of water pressure head (unit: m) for horizontal section just below the excavation base at the level of the wall tip (right).

The calculated safety factor against piping is listed in Table 1. The safety factor is less than unity only when the water pressure is calculated using 3D FE analysis. This indicates that 3D FE analysis of water flow through soils can reproduce the boiling occurred in case one. Thus the 3D effect on the water pressure around the excavation should be considered in design. For the present computers, 3D analysis of water flow through soils does not take so long time; as an example, 3D FE mesh has 11802 nodes and 9828 eight-nodal brick elements for case one, the calculation takes about ten minutes on the personal computer with a CPU of 1.8GHz. Additionally, now some commercial softwares with strong pre- and post-processing functions are available to calculate the water pressure around the excavation.

2.2. Case Two

This case was reported by Tanaka et al. [5]. Piping occurred within a cofferdam for the construction of a bridge abutment along the left bank of the Isasa River. The excavation is 24m long, 9m wide, and the abutment is 22m long, and 4.5m wide. The cantilever sheet-piles 9.8m long are used as the earth retaining wall. The site is located on an alluvial plain, and a gravel layer is overlaid with a sandy silt layer, of which the physical properties are listed in Table 2. Figure 4 shows the details of the excavation.

Piping did not occur during excavation, but it occurred when the abutment was constructed within the cofferdam. It induced 4cm settlement of the abutment within one week because fine soil particles were being washed out. As a temporary measure, pumping water from the cofferdam had to be stopped, and the water level in the cofferdam increased to prevent a further piping. Grouting was used to improve the sandy silt layer, and to prevent piping.

Tanaka et al. [5] has studied this case using 2D FE analysis of water flow through soils. However, the size of the excavation and the abutment indicates that 3D FE analysis is necessary to consider 3D distribution of the water pressure around the excavation and the abutment. Because of the symmetry, one half of the excavation, the abutment, and the ground were analyzed, where the abutment and revetment on the excavation base was assumed impervious. The other boundary conditions were similar to those in case one.

Table 2. Physical properties of soils for case two

Parameter	Gravel	Sandy silt
Specific gravity, G_s	2.657	2.659
Uniformity coefficient, U_c	21.84	7.02
D_{50} (mm)	3.87	0.219
Permeability, k (*10^{-4}m/s)	2.82	0.463
Buoyant unit weight, γ' (kN/m^3)	11.49	9.17

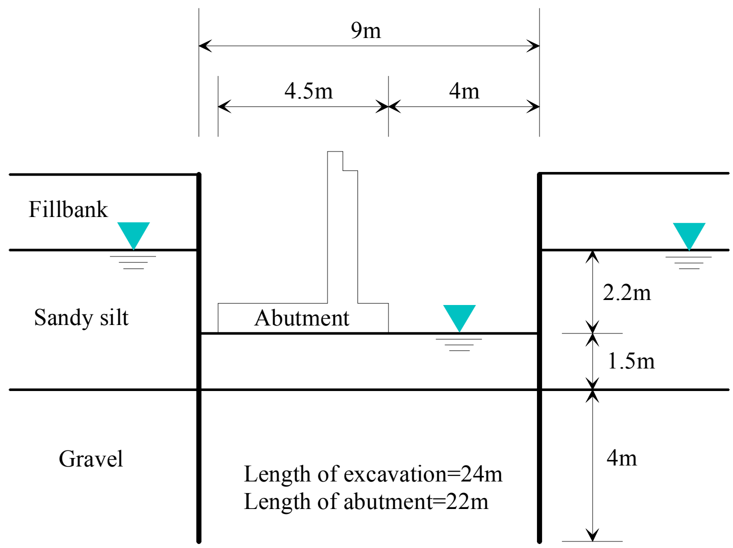

Figure 4. Schematic geometry of case two

Finite element seepage analysis was conducted to calculate the water pressure before the construction of the abutment. Because of the symmetry before the construction of the abutment, only one half of the analyzed zone was used to show the results. Figure 5 shows the contours of pressure head of 3D FE analysis, and the contours of pressure head of the horizontal section just below the excavation base at the level of the wall tip, and at the level of the boundary between the sandy silt and gravel layers. The difference of pressure head was about 0.4m on the horizontal section at the level of the wall tip; however, it was only about 0.1m on the horizontal section at the level of the boundary between the sandy silt and gravel layers.

The maximum water pressure was at the corner of the wall, as in case one. The excess water pressure at the corner of the wall at the level of the wall tip U_a and at the level of the boundary between the sandy silt and gravel layers U_b, and in turn the safety factor against piping were calculated using Equation (1). The results are listed in Table 3. The safety factor against piping F_b at the level of the boundary between the soil layers was much smaller than F_a at the level of the wall tip. This indicates that, for two-layered ground, the upper layer is much more dangerous for piping if its permeability is smaller than that of lower layer. Terzaghi and Peck's method gave a larger safety factor especially for the lower layer than 3D FE analysis because Terzaghi and Peck's method does not consider the 3D effect of the excavation shape. The safety factor against piping is only 1.186, calculated using the water pressure of 3D FE analysis. Such a low safety factor indicates that the excavation is near piping even before the construction of the abutment.

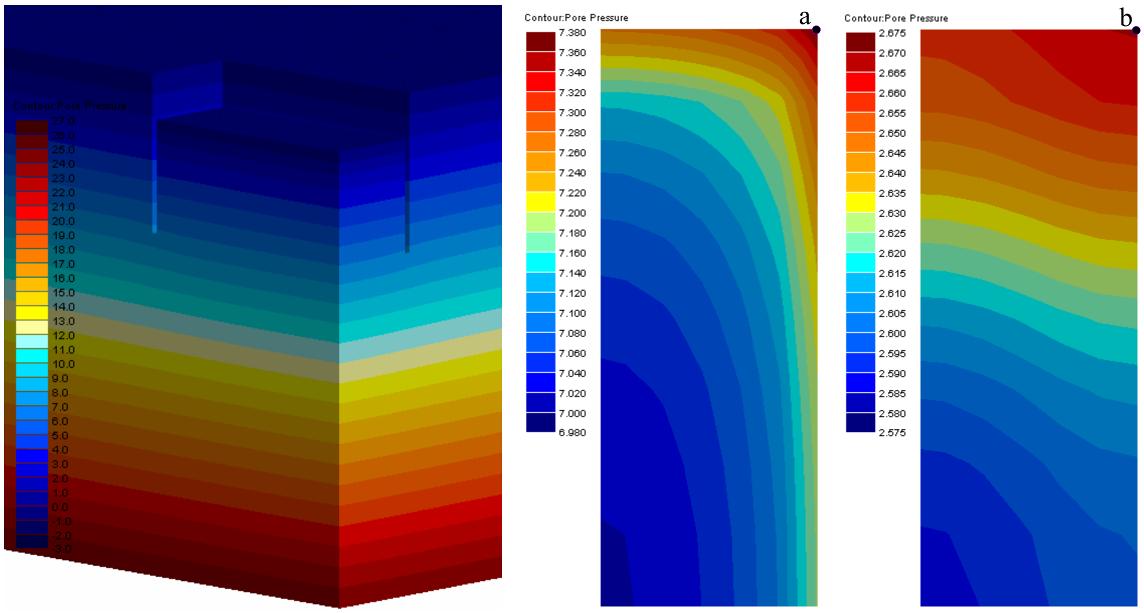

Figure 5. Contours of water pressure head (unit: m) of 3D FE analysis (left), and contours of water pressure head (unit: m) for horizontal section at the level of the wall tip (center), and at the level of the boundary between the soil layers (right) before the construction of the abutment.

Table 3. Excess water pressure and safety factor against piping for case two

Method	U_a or U_A (kPa)	U_b or U_B (kPa)	F_a or F_A	F_b or F_B
Before the construction of the abutment				
Terzaghi and Peck	10.79	10.79*	5.534	1.275
FEM (three-dimensional)	18.56	11.60	3.217	1.186
After the construction of the abutment				
FEM (three-dimensional)	19.23	13.31	3.105	1.033

Note: *the excess water pressure was calculated not to consider the loss of hydraulic head in the gravel layer.

The abutment and the revetment were considered as impervious boundary condition for 3D FE analysis of water flow through soils after the construction of the abutment. Figure 6 shows the contours of the pressure head for the horizontal section just below the excavation base and at the level of the wall tip and the contours of pressure head for the horizontal section just below the excavation base and at the level of the boundary between the soil layers. Because the abutment and revetment are impervious, it was considered that piping should not occur under the abutment and revetment in the left side. At the level of the wall tip, the maximum excess water pressure within the zone where the piping may take place was at point A, and U_A was 19.23kPa. Thus the safety factor against piping was 3.105. At the level of the boundary between the soil layers, the maximum excess water pressure within the zone where the piping may take place was at point B, and U_B was 13.31kPa. Thus the safety factor against piping was 1.033. It is the safety factor against piping very close to unity that explains the 4cm settlement of the abutment within one week because fine soil particles were being washed out.

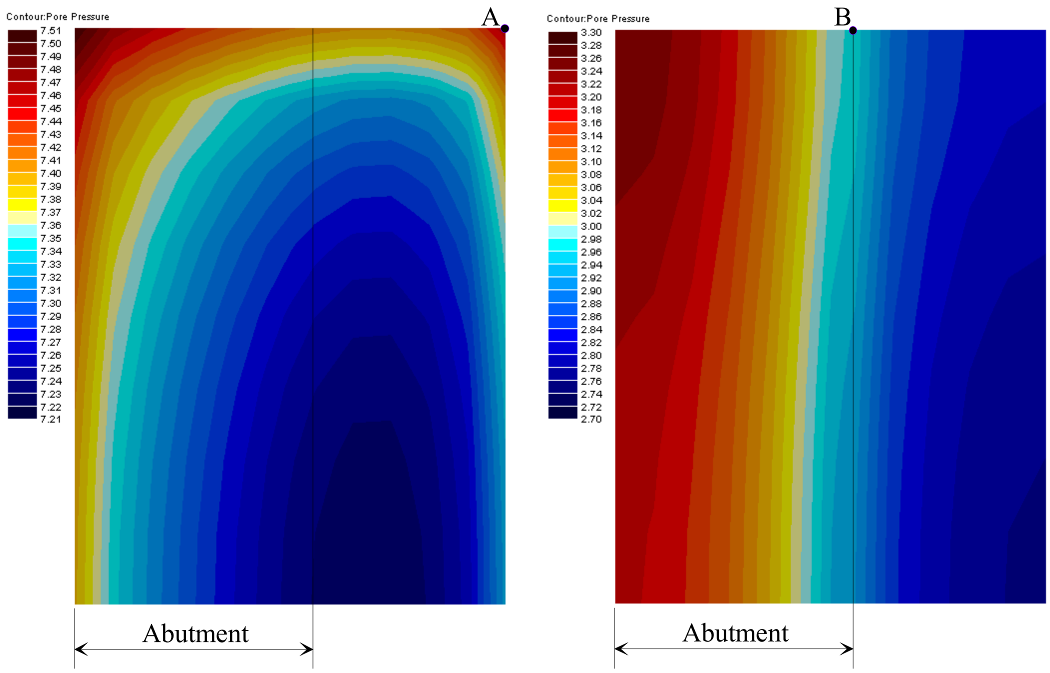

Figure 6. Contours of water pressure head (unit: m) for horizontal section at the level of the wall tip (left), and at the level of the boundary between the soil layers (right) after the construction of the abutment.

3. CONCLUSIONS

This paper analyzes two case histories of piping induced by excavations in cohessionless soils using VGFlow, a 2D and 3D FE software for analysis of water flow through soils to calculate the water pressure around the excavations. The safety factor against piping was defined as in Terzaghi and Peck's method, and was evaluated using the calculated maximum excess water pressure. The boiling or piping of the two case histories was well reproduced only when 3D FE analysis was used to calculate the water pressure around the excavations. The 3D effect on the water pressure and in turn on the safety factor against piping is significant for the two case histories where the length is about two times the width of the excavation.

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