Numerical simulation on arching effect of circular vertical shaft during excavation process

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1. INTRODUCTION

The circular shaft has been widely constructed for several purposes, ventilation system, an emergency exists, and temporary structure for tunneling construction, in accordance with the mechanical advantage of cylindrical geometry to effectively resist external pressure. Nevertheless, the design criteria for a circular vertical shaft of Japanese design code is taken from conventional retaining wall design, 2-dimensional consideration, which is providing an unreasonable design.[1)] In according to the cylindrical structure with deformation, mechanical behavior of both structure and soil are generally associated by arching effect.[2)] Therefore, the understanding of an arching effect in the surrounding soil, which could be leading to clarify earth pressure acting on a cylindrical shaft, should be firstly clarified. Hence, this 3-dimensional analysis of circular vertical shaft during the excavation process was performed for the elucidation of arching effect surrounding circular vertical shaft.

2. OUTLINE OF NUMERICAL ANALYSIS

This numerical analysis was conducted in Finite Difference Method operated by FLAC3D[3)] to simulate the large deformation. This analysis model focused on a deep circular vertical shaft based on soil mixing wall (SMW)[4)]. The general diameter and length of the shaft are 20 m and 120 m respectively: the excavation depth is from 20 m to 80 m[5)]. Therefore, this analysis model follows the real construction of a deep circular vertical shaft as shown in **Figure 1**.

The shaft itself is expressed in elastic model whose parameters are shown in **Table 1**. Mechanical behavior of soil is modeled by Modified Cam-clay model[6)]; the profiles of the soil is shown in **Table 2**.

Considering the mechanism of generating arching (ring) effect of the structure or the soil, it is important to clarify various inner displacements of the shaft induced by excavation process, which was carried out by using stress relaxation and mesh removal, respectively. Therefore, this analysis was performing three stiffnesses of the circular shaft based on the elastic model as shown in **Table 1**.

3. Results and discussion

3.1. Earth pressure coefficient

Figure 2(a) shows the earth pressure coefficient of pressure acting on a circular vertical shaft after 80 m excavation calculated as the ratio between the current earth pressure and vertical stress, σ_r/σ_v. The earth pressure coefficient is gradually decreasing until the excavation surface (80m). Moreover, the earth pressure coefficients in each case of the rigidity of shaft are providing a different tendency, the earth pressure

Table 1 Shaft parameters
Elastic model (circular shaft)

Poisson's ratio	0.33
Density [g/cm^3]	2.20
Young's modulus [*GPa*]	
Case-1	0.1
Case-2	1.0
Case-3	10.0

Table 2 Soil parameters
Modified Cam-Clay model (soil)

Maximum elastic bulk modulus K_{max} [*GPa*]	5.0
Density [g/cm^3]	1.6
Swelling index, κ	0.0045
Slope of consolidation line, λ	0.07
Poisson's ratio	0.33
M (Frictional constant)	1.36
OCR	2.0
Specific pressure at reference point, P_1 [*KPa*]	98.0
Specific volume at reference point, V_1	2.1

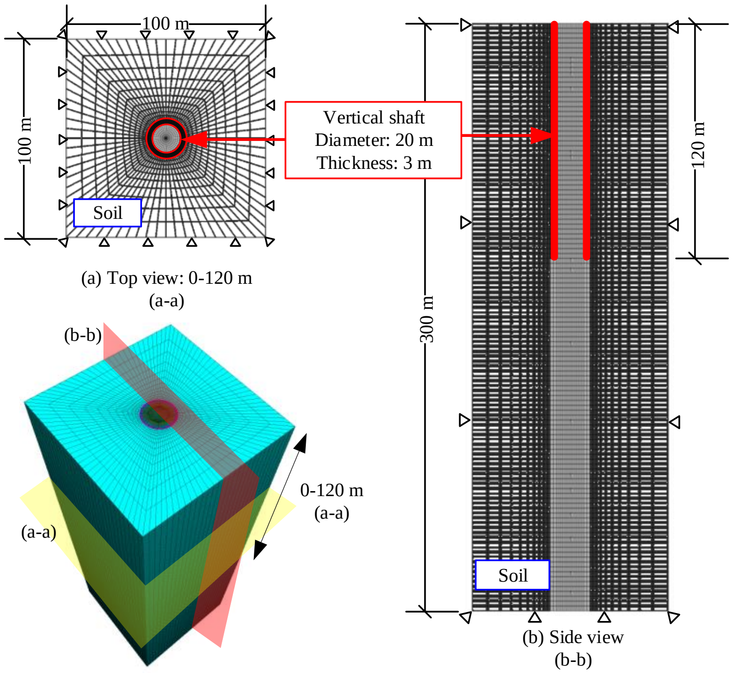

Figure 1. Schematic section of analysis model and parameters

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coefficient tend to be lower in case flexible (soft) vertical shaft in accordance with the differences of shaft inner-displacement after excavation.

3.2. Tangential stress ratio and Strain ratio of soil along vertical shaft, ($\varepsilon_{rr}/\varepsilon_{tt}$)

The tangential stress will be increasing while the radial stress is decreasing under generation of arching effect in the surrounding soil. Here, a tangential stress ratio is defined in the ratio between the tangential stress at the current step of the excavation to the initial tangential stress. Therefore, the tangential stress ratio could be showing the region of an arching area in accordance with the tangential stress ratio criteria, the tangential stress ratio is greater than 1.0 if the arching is forming. **Figure 2(b)** shows the tangential stress ratio of soil surrounding a circular vertical shaft after excavation about 80 m. The tangential stress ratio surrounding rigid shaft (Case-3) is close to 1.0. Conversely, in the surrounding soft circular shaft (Case-1), the arching zone is obviously forming above the excavation surface of 80 m. According to arching in the soil, the stress would be changing in both radial and tangential direction as well as strain generation. Hence, strain ratio of radial between tangential, ($\varepsilon_{rr}/\varepsilon_{tt}$)**,** could be used to elucidate particular characteristic of soil behavior undergoing with arching effect. Additionally, the sign convection of strain will be negative and positive for compressive strain and tensile strain, respectively. Therefore, the strain ratio of the surrounding soil, which experiencing with arching effect, would be a negative value in corresponding with opposite direction of radial strain (tensile strain) and tangential strain (compressive strain). Although, the arching is developing along surrounding excavation area, the strain ratio is not constant as shown in **Figure 2(c)**; in addition, the strain ratio above excavation surface become larger in a deeper position.

4. Conclusion

The arching effect is a major cause of soil stress generation, which is experiencing a reduction in radial stress and inclination in tangential stress, surrounding the cylindrical shaft after excavation sequence or shaft deformation.

The radial stress reduction induced by arching effect depends on several factors, such as confining stress (depth factor) even or inner-displacement. Moreover, the analysis results could show the fluctuation of earth pressure coefficient in depth direction. Additionally, the earth pressure coefficient in the case of the flexible shaft is relatively lower than the rigid case. The strain ratio result will be leading to show another aspect of the uncertainty of the earth pressure coefficient in depth direction. The strain ratio would be expressed as the effectiveness of stress generation in arching effect as well, the lower strain ratio would be giving a more reduction in radial stress. In corresponding with earth pressure coefficient, when the observation position is going deeper, the earth pressure coefficient becomes decreasing.

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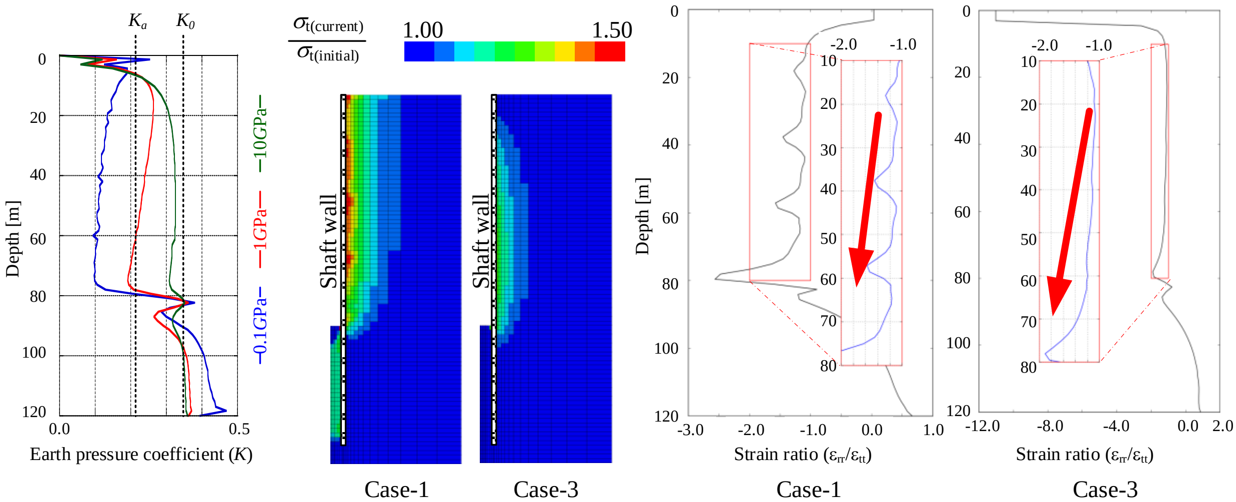

(a) Earth pressure coefficient (b) Tangential stress ratio contour (c) Strain ratio of soil along shaft wall

Figure 2. Earth pressure coefficient, tangential stress ratio contour, and strain ratio of soil along circular shaft wall