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A Feasibility Study for the Development of a Vertical Shaft Construction Technique using Ring Cutting

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ABSTRACT

Supply facilities have to be buried due to urban development from rapid population growth and a lack of land; therefore, vertical shaft construction has increased for utility tunnels. Because utility tunnels are installed in urban areas, there can be critical problems from faulty construction. Conventional construction methods used in most vertical shafts cause a decrease in the groundwater level which is one reason for ground settlement. Therefore, construction methods have been researched that take into consideration the ground settlement of vertical shafts, and the ring cut method was developed. This method first penetrates an outer section of the shaft to prevent soil inflow and extends the seepage line. Using this method, ground settlement caused by construction is expected to decrease. This study performed 2-dimensional stress-seepage coupled numerical feasibility tests to analyze the effective penetration depth of the ring cut method. Settlement and seepage were measured to evaluate its performance. The obtained data will be used to optimize the newly developed method.

1. INTRODUCTION

Due to rapid population growth and a scarcity of space, supply facilities are buried in many developed cities using utility tunnels. When constructing utility tunnels with a tunnel boring machine (TBM), constructing a vertical shaft is essential. However, most vertical shafts are made with costly conventional construction methods, and these methods could cause water table lowering, and this decrease in the water table could lead to ground settlement (Aksoy, 2008). In the past, the groundwater level was forcibly lowered to less than or equal to the level of the tunnel for safety reasons during construction. However, a design and construction that prevent lowering the

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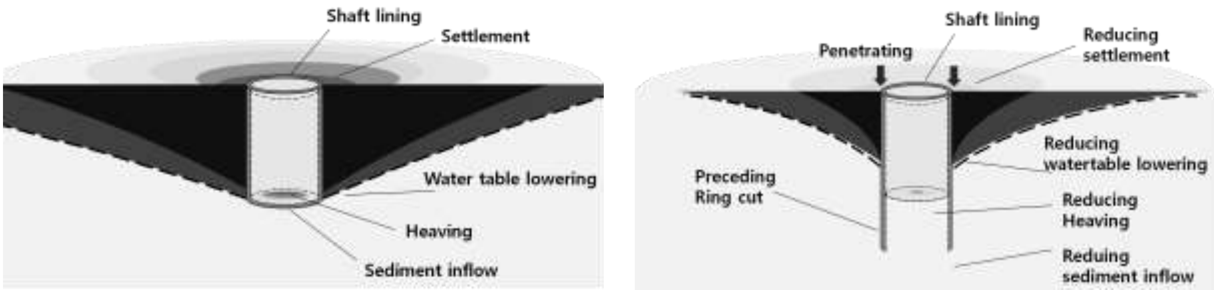
groundwater level as much as possible is necessary nowadays considering environmental factors and ground settlement due to groundwater. (Yoo, 2003). In order to construct reliable and economical vertical shafts for small diameter TBMs, a construction system simultaneously excavating the shaft face and installing the lining is necessary for stable and economical construction. Indeed, major industrialized countries have already developed vertical shaft excavation methods; for example, Herrenknecht developed the VSM8000 which has been used on a commercial scale. However, the VSM8000 is very expensive needing a wide construction site and construction waste disposal. Therefore, a rapid construction system to excavate a vertical shaft for utility tunnels has been proposed (Hong, 2016). The proposed system is the noise and vibration controllable. This system mainly consists of a vertical shaft ring-cut excavator, and of the rock excavator. This low noise and low vibration based technique takes into consideration ground settlement. This system penetrates an outer section of the shaft first to extend the seepage line and then excavates the face afterwards. This method prevents soil inflow as well as water table lowering and consequently ground surface settlement.

In this study, the performance of the proposed system was evaluated with numerical analysis. Seepage-stress coupled analysis was modelled to measure hydraulic characteristics including the flow rate and flow velocity. With this model, the performance of the system was verified.

2. VERTICAL SHAFT AND GEOTECHNICAL PROBLEMS

This research is vital for the economic advancement of underground urban infrastructures. To achieve these goals, the main technologies selected were rapid construction, noise and vibration controllable excavation and isolation construction technology systems for vertical utility tunnel shafts. A conceptual image of the proposed vertical shaft systems is drawn in Fig. 1. During conventional vertical shaft construction for a tunnel, groundwater flows into the shaft excavation face and is pumped out to keep the construction site dry. However, groundwater pumping causes water table lowering around a construction site. Drainage from pores causes pore-size decreases and settlements. The proposed vertical shaft construction system Ring cut is an improved method that reduces groundwater lowering. The developed system penetrates an outer section of the shaft before excavating the shaft face (Fig. 1, b). That process extends the seepage lines heading for the excavation side and prevents the inflow of sediment. This paper evaluated the performance of the flow rate reduction by measuring the hydraulic characteristics including the flow rate and flow velocity changes.

Stress-seepage coupled analysis was performed to measure the flow rate and flow velocity changes. Stress-seepage coupled analysis takes into account the changes in the pore size by drainage of groundwater. Groundwater flow through pores and the drainage of ground water cause ground deformation. By calculating the strain-stress and pore pressure with time, the inflow into the shaft face could be determined taking into consideration the changes in pore size. Partially saturated effects were considered to calculate the correct value of the saturated (0) or unsaturated state (1). With this consideration, the unit weight of the ground is calculated as a value between the saturated unit weight and unsaturated unit weight in accordance with the saturation. With this, the seepage state associated with the stress change was simulated.



(a) Conventional construction system (b) Ring cut construction system

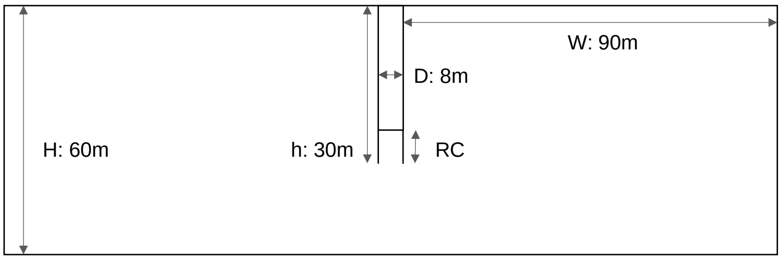
Fig. 1 Conceptual image of the vertical shaft construction system

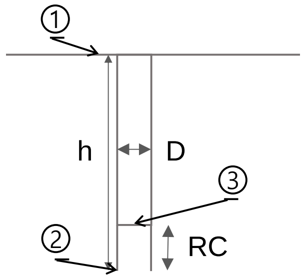
3. NUMERICAL MODELLING

In this study, 2-dimensional numerical analysis was done to evaluate the characteristics of the seepage induced by the ring cut method. Finite element based numerical analysis software Midas GTS/NX was used to evaluate the changes of the seepage flow due to the extended seepage line and pore size change. The ground and structure were modelled as an elastic solid and elastic beam, respectively. To set the structural geometries, precedent studies were researched. To evaluate land subsidence based on groundwater pumping, Shui et al. (2006), Budhu et al. (2013), Hsi (1994) and Luo et al. (2008) modeled large areas with more than a 1000 m width. However, these papers focused on settlement in a wide area. Yoo (2005) and Choi et al. (2011) did careful modeling to sufficiently avoid adverse influences.

Groundwater level was same with surface. And the vertical shaft depth was 30 m; the diameter was 8 m, and the lining thickness was 0.4 m (Fig. 2 (a)). The ground and structural properties are shown in Table 1. To assess the ground properties, the site investigation results of 6 areas where vertical shafts were constructed were averaged for a valid range. To perform a comparative analysis of the ring cut depth, 9 types of models were used. Table 2 lists the various models. A pre-outline of the shaft excavation used in the ring cutting method was unapplied in the conventional method. However, 1 to 8 m (1D) of a pre excavation outline, the ring cutting depth, of the shaft was modeled as the ring cut method.

The flow rate was measured at the shaft excavation face shown in Fig. 2 (b), ③. The flow velocity was measured on the surface near the shaft (Fig. 2 (b) ①), at the end of shaft (Fig. 2 (b) ②) and at the shaft excavation face (Fig. 2 (b) ③) to evaluate the performance of the developed system.





(a) Geometry of vertical shaft (b) Measurement position
Fig. 2 Model geometry

Table 1. Ground properties

Material	Model Type	Elastic modulus (kN/m²)	Cohesion (kN/m²)	Friction Angle (φ)	Unit Weight (kN/m³)	Hydraulic conductivity (cm/sec)	Poisson's ratio
Sandy soil	Elastic	11	5	30	18	$3.28X10^{-4}$	0.33
Weathered soil	Elastic	37	15	30	19	$2.64X10^{-3}$	0.33

Table 2. Ring cut depth for analysis

Case	Depth of outer section of ring (m)								
	0	1	2	3	4	5	6	7	8
	Conv.Method	RC 1m	RC 2m	RC 3m	RC 4m	RC 5m	RC 6m	RC 7m	RC 8m

4. ANALYSIS RESULT

4.1 flow rate

The flow rate on the shaft excavation face according to the ring cut depth was measured by FEM numerical analysis. Fig. 3 shows the flow rate on a sandy soil and weathered soil. In a sandy soil, the flow rate decreases with an increase in the ring cutting depth. In this figure, a deeper ring cut depth makes a longer seepage line and decreases the flow rate. The measured flow rate was classified as being between a negligible volume and medium volume (Woo et al. 2010). In weathered soil, similar results were obtained; however, the flow rate and change are relatively small and classified as a negligible volume (Woo et al. 2010).

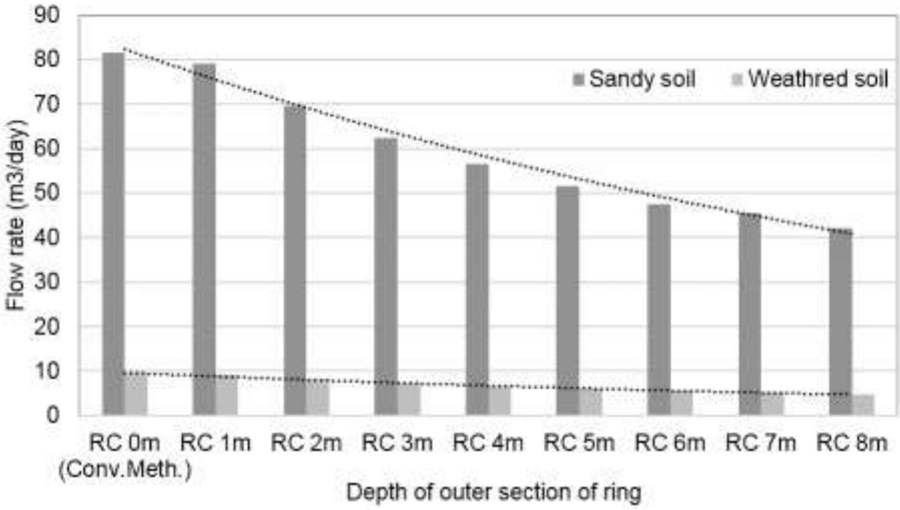


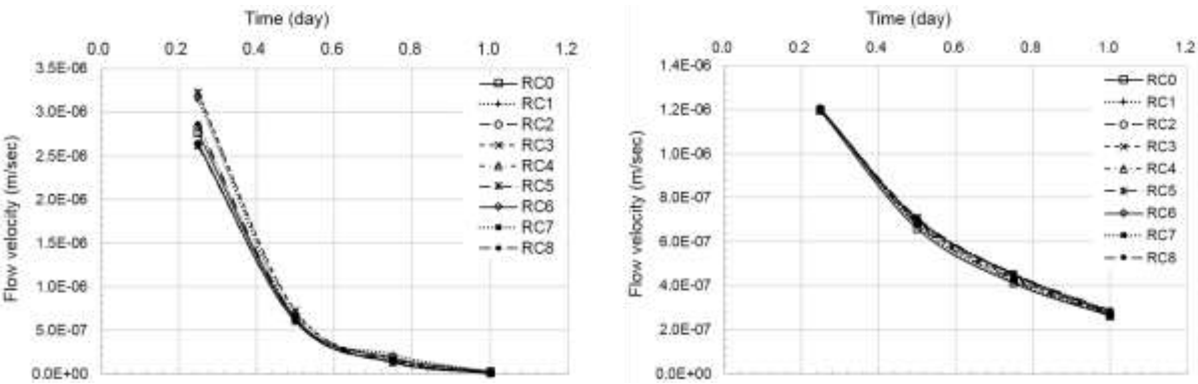
Fig. 3 Flow rate versus ring cut depth

4.2 flow velocity

Ground surface Fig. 4 shows the flow velocity on the ground surface drawn for different ring cut depths. These curves demonstrate that the pore-size on the surface near the shaft decreased during groundwater inflow into the excavation face and pumping. Flow velocity changes as the pore-size changes, and flow velocity decreases dramatically right after excavation.

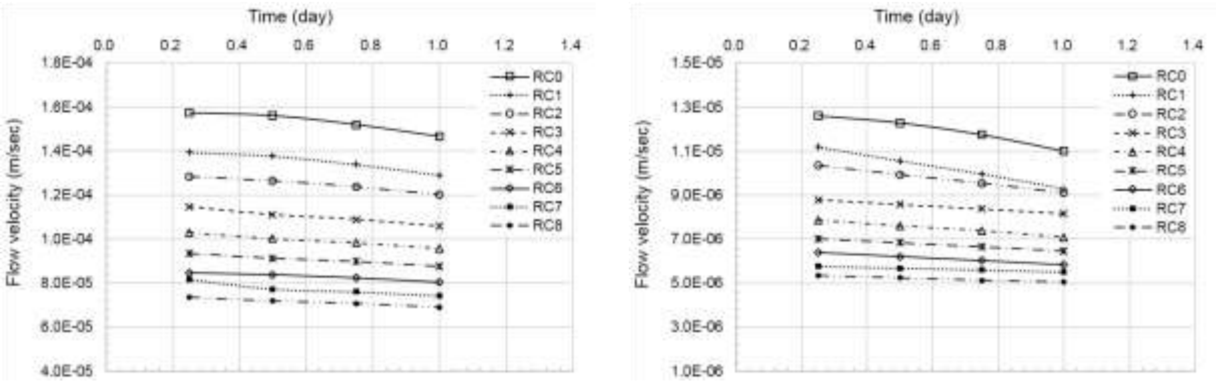
End of shaft Figure 5 shows the flow velocity at the end of shaft obtained from the FEM based numerical analysis for different ring cut depths. Near the end of shaft, the maximum flow velocities were measured and found to decrease with an increase in the ring cut depth. However, the decrements are smaller than that on the ground surface, and a small amount of changes are obtained with a deeper depth of the ring cut.

Excavation face Fig 6 shows the flow velocity on the excavation face. In this figure, the flow velocity decreases as time passes which is similar to results in a different location. These values are smaller than that of the measured ones at the end of the vertical shaft.



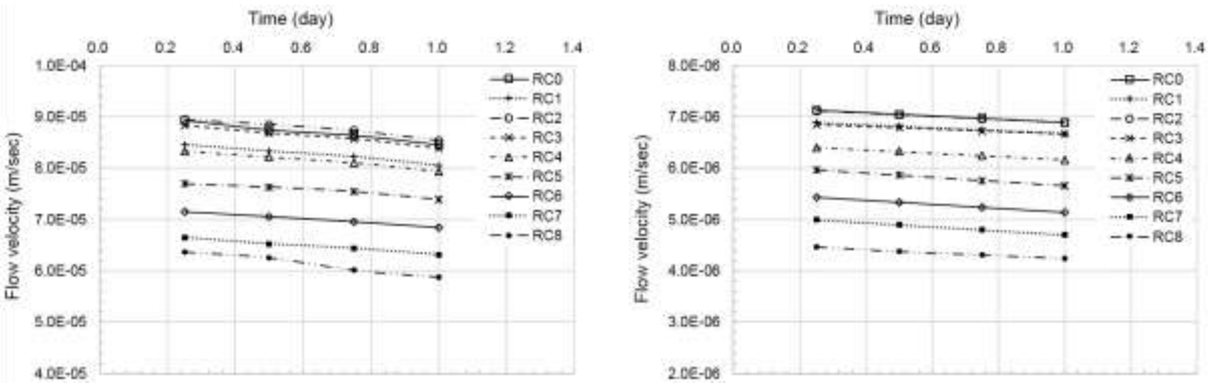
(a) Sandy soil (b) Weathered soil

Fig. 4 flow velocity changes over time on the surface



(a) Sandy soil (b) Weathered soil

Fig. 5 flow velocity changes over time at the end of shaft



(a) Sandy soil (b) Weathered soil

Fig. 6 flow velocity changes over time at the shaft excavation face

5. CONCLUSIONS

During the past few decades, vertical shafts for tunneling have been constructed by conventional methods. However, there are problems yet to be solved such as ground water lowering and settlement. Therefore, a rapid vertical shaft system for tunnels has been proposed. The developed system has low noise and vibration and takes into consideration groundwater lowering and settlement. The performance of the proposed system was numerically evaluated by measuring the flow rate and flow velocity changes. Stress-seepage coupled numerical model was done to take into account the changes in the pore size and their influence. Based on the results, the ring cut depth affects the hydraulic characteristics of this system. The effective penetration depth of the ring cutting method could be estimated with the obtained data taking into consideration constructability.

New construction technologies are applicable to transportation tunnels, mining tunnels and storage facilities. And they are expected to advance construction capabilities and the buildability of various underground structures. The results of this study are expected to contribute by reducing civil complaints, construction accidents and costs as well as improve other exceptional economic benefits.

Acknowledgement
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