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# Analysis of lateral earth pressure on a vertical circular shaft considering the 3D arching effect

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ABSTRACT

The lateral earth pressure on a vertical circular shaft is investigated using both experiments and numerical analyses. The study focused on quantifying the magnitude and distribution of the lateral earth pressure, which was measured by considering the three-dimensional arching effect. A framework for determining distribution of the earth pressure based on centrifuge model tests and 2D FE analysis is introduced. The FE modelling techniques and the constitutive relationships of the soil are presented in detail. Parametric analyses showed that the arching effect on the lateral earth pressure is highly dependent on the diameter and height of the shaft, the internal friction angle and the cohesion value of the soil, the end-bearing conditions and the flexural modulus of the shaft. The study found that when the arching effect is considered, the lateral earth pressure on a vertical circular shaft is approximately 80% less than that calculated using Rankine's theory. The study also found that the arching effect of the soil is more significant for flexible vertical shafts than for rigid vertical shafts embedded in weathered soil.


## 1. Introduction

Underground space and structures are under great demand. Since 1980, many large excavation projects have been undertaken in urban areas to create underground space for power stations, subways, high-speed railways, and other lifelines (Jeong and Seo, 2004). Although the shape and size of underground structures vary widely, they can generally be classified into two groups. The first group includes long or wide underground structures (horizontal tunnels), and the other includes tall vertical underground structures (vertical shafts). These structures are deeper and larger than typical existing foundations and tunnels. For this reason, a proper estimation of the earth pressures is a key factor in the design of underground structures, particularly vertical shafts.

Geotechnical engineers have traditionally estimated the earth pressure that acts on structures using either Rankine's (1857) or Coulomb's (1773) theories. Both theories assume that the distribution of lateral earth pressure that acts on a structure is triangular. However, this is different from reality and these methods do not consider the mode of structural movement. Many experimental studies have shown that the non-linearity of the earth pressure distribution is a result of arching effects (Handy, 1983), but these methods are widely used in engineering practice with no significant modifications.

Arching is the process by which stress is transferred around a region of soil, which then is subjected to lower stresses (Paik and Salgado, 2003). Many studies have investigated the lateral earth pressure that acts on rigid retaining walls by considering the arching effect. Handy (1983) analyzed soil arching behind retaining walls, and Wang and Yen (1973) performed this analysis for slopes. Nakai et al. (1997) performed a series of physical model tests under 1 g conditions and carried out numerical analyses of these tests to investigate the arching effect. They results obtained from the model tests agreed well with the results of the numerical analyses. Janssen (1895) suggested a theoretical basis for understanding arching effects in silos. Based on this theory Spangler and Handy (1984), Harrop-Williams (1989) and Wang (2000) proposed equations recently to estimate the non-linear distribution of active pressure on retaining walls. More recently, Kim et al. (2013) conducted centrifuge model tests and full-scale field tests of vertical shafts and concluded that the lateral earth pressure that acts on a circular vertical shaft is less than other types of geotechnical structures because of three dimensional arching effects (i.e., convex arching and/or inverted arching). However, no practical solutions that consider shaft displacements and movements of the surrounding soil are currently available for the determination of the lateral earth pressure.

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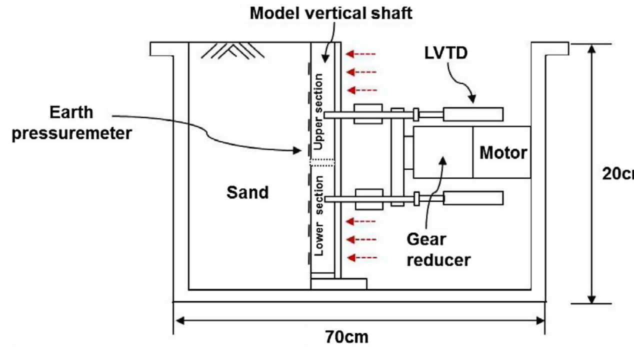
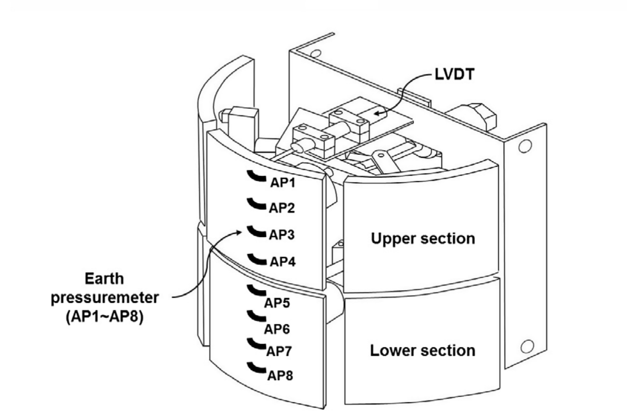
(a) Model vertical shaft

(b) Soil sample box

**Fig. 1.** Testing apparatus.




(a) Sectional view




(b) Vertical circular shaft model

**Fig. 2.** Sectional view of the soil sample box and vertical shaft model.

In engineering practice, the displacements are often controlled or limited by the choice of a suitable factor of safety, and excessive yielding is prevented by an appropriate construction sequence (Wong and Kaiser, 1988).

The performance of the active earth pressure distribution caused by the installation of a circular vertical shaft has been investigated by several researchers using experimental or numerical analyses. Walz (1973) investigated the active earth pressure on a circular vertical shaft using a model shaft equipped with a cutting edge ring. Lade et al. (1981) and Konig et al. (1991) performed physical modelling in which the excavated soil was replaced by a flexible rubber bag filled with liquid or gas. The liquid or gas pressure was reduced in stages to simulate the excavation of the shaft. Additionally, a mechanical system was used to move the vertical shaft to simulate the displacement of soil that may occur during the excavation process. Several researchers (e.g., Fujii et al., 1994; Imamura et al., 1999) have adopted simplified models to simulate the radial displacement of the lining. Herten and Pulsfort (1999) and Chun and Shin (2006) modified previous models by considering radial symmetry to model only a portion of the structure. More recently, Tobar and Meguid (2009) developed a mechanical system model both the full shaft geometry and the radial displacement of the lining. In contrast, Herten and Pulsfort (1999) conducted numerical analyses to simulate the construction of a laboratory scale shaft in granular material using the discrete element method (DEM). Tran et al. (2014) performed numerical studies to characterize large deformations and particle movements. Relatively little work has addressed the distribution of lateral earth pressure that acts on flexible and circular vertical shafts. And the effect of the staged construction of a vertical shaft on the lateral pressure along the shaft and the deformation of the shaft has not been investigated previously.

The objective of this study is to investigate the magnitude and distribution of lateral earth pressure on a vertical circular shaft according to the excavation sequence by considering the three-dimensional arching effect in weathered soil. A series of centrifuge model tests and FE analyses of a vertical shaft were performed. To obtain enough information to cover a wide spectrum of vertical shaft designs, comprehensive parametric studies were conducted by varying the combinations of several key design factors. To verify the accuracy of the numerical analyses, the results of the experimental measurements from this study are compared with those from the numerical analyses.

## 2. Centrifuge model test

### 2.1. Testing apparatus

A series of centrifuge model tests were performed to investigate the distribution of earth pressure on a vertical circular shaft in