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Research Paper

Numerical investigation of spatial aspects of soil structure interaction for secant pile wall circular shafts

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ABSTRACT

Implementation of fast and cost-effective shoring systems has become very necessary to overcome the technical challenges such as variable soil and rock profiles, high groundwater tables and limitations imposed by the built environment. Secant pile wall shoring systems allow the construction of overlapped piles in almost all subsurface conditions. They are constructed in a circular plan layout to form a vertical shaft which provides unique advantages such as compression ring behavior. This paper presents a numerical study to investigate various aspects of the behavior of circular shafts constructed using secant pile walls. The studied aspects include the identification of earth pressure distributions exerted on circular shafts, the impact of excavation of single and multiple holes on the shaft stresses, and the stresses in the shaft in the case of sloping bedrock. A three-dimensional finite element model is developed to conduct the present analyses taking into consideration the actual behavior of soils surrounding the walls. The stress concentrations calculated for circular shafts were seen to vary from the results of the infinite plate with hole solution. The sloping bedrock was also seen to result in significant deviations from the compression ring behavior. A large increase in the maximum compressive stresses and emergence of some significant tensile stress zones were observed for bedrock inclinations larger than 20°. The results presented in this study address some practical design concerns and were considered to be of interest to those involved in design and construction of vertical shafts.

1. Introduction

Diaphragm wall shoring systems are used to facilitate deep excavations and can be formed with various layout options depending on the shape of the required excavation. These systems can be supported by various means as the excavation advances. The common construction approaches utilized for these structures include slurry walls and secant pile walls. The use of diaphragm walls in a circular layout forms vertical shafts which perform as a compression ring under lateral earth and hydrostatic pressures acting on them. Such vertical shafts are formed by installing a series of overlapping concrete piles to form a continuous, water tight wall. The secant pile walls are constructed by installation of an array of primary piles. The installation of primary piles is followed by installation of secondary piles, which are cut into the primary piles forming a continuous wall. Concrete with a slow rate of setting is typically used. Before the concrete sets, the sharp edged secondary pile cases are driven and cut into the primary ones. This procedure is repeated until the entire wall is completed. Piles can be constructed of either structural or lean concrete.

This paper focuses on evaluation of various aspects such as the realistic distribution of earth pressures and the external loads, the stress concentrations caused by excavation of holes on the walls of the circular shaft, the impact of socketing of the secant walls into the bedrock and inclination of the bedrock surface are of significant importance for a successful design and implementation of a secant pile wall circular shaft. The treatment of the earth pressures of diaphragm walls differ from that of other wall types because of the unique installation approach used in their construction. Since the diaphragm walls installed to form a circular shaft are allowed to harden before the excavation proceeds, the in-situ stresses in the ground are assumed practically to remain unchanged after the excavation (e.g. [21]). Several recent studies suggested that the earth pressures behind diaphragm walls are affected by the installation (e.g., [9,20,8,24,1,2]).

The interaction between the circular shaft and surrounding soil was also studied by many authors using reduced scale model tests. Muller-Kirchenbauer et al. [22] studied the earth pressures exerted on a circular shaft by dry sand. The results of this study indicated

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that rigid models do not allow recess and provide the ultimate pressures whereas; flexible models allowed wall deformations and exhibited larger reduction in pressures. Lade et al. [15] used centrifuge testing to study the earth pressures exerted on a vertical circular shaft in dry sand. The earth pressures were slightly exceeded at-rest values prior to the excavation of the soil inside the shaft. However, earth pressures reduced substantially with the excavation of the soil and resultant inward movement of the shaft walls. Shin and Sagong [27] performed model tests to determine the earth pressures on a circular shaft. It was shown that the earth pressures on the shaft reduce substantially if wall deformations larger that 1.5% of the shaft radius takes place. At small deformations, the earth pressures remained between at-rest and active conditions. The analytical and numerical studies have shown that the pressures acting on the exterior surfaces of a circular shaft are less than at-rest pressures assumed in plane strain conditions due to the stresses relief during the excavation if sufficient deformations occur in the wall [27]. Horizontal arching effects also influence the distribution of earth pressures on the circular exterior surface of the walls. However, due to the construction techniques employed in the construction of secant pile walls, only small deformations take place and the deviation of earth pressures from at rest conditions toward active conditions due to the wall deformations remain insignificant even at large shaft diameters. The stresses generated in the shaft walls are calculated with the assumption of compression ring behavior, which results in purely compressive stresses. However, there are practical situations that will result in deviations from these stress conditions. For example, the excavation of a hole(s) on the circular shaft and existence of sloping bedrock conditions cause the stress distributions in the shaft that will result in tensile stresses that are not observed in a pure compression ring behavior.

This paper presents the results of parametric numerical analyses that investigate interaction between vertical circular shafts and surrounding soil with the consideration of holes on the shaft walls. The impact of the sloping bedrock conditions are also considered parametrically in order to identify the deviations from compression ring behavior. Three-dimensional nonlinear finite elements analyses were performed using the commercial finite element package, ABAQUS. Elasto-plastic soil behavior of retained soil and a non-linear soil-shaft interface was assumed in the analyses.

2. Background

2.1. Analytical evaluation of earth pressures and wall stresses

The vertical shaft behavior is significantly influenced by the gravitational forces and resultant stress state in the surrounding soil [29]. Vertical, radial and tangential stress components are usually developed around and along the shaft due to the 3D nature of the stress concentrations near a vertical circular shaft (Fig. 1a). A common shape assumption for a failure wedge is depicted in Fig. 1b, where $\beta = 45° + \theta/2$ and θ is defined in terms of the wall friction angle.

Design of circular diaphragm walls is typically performed using closed form analytical solutions assuming a uniform external pressure distribution to represent the earth pressures, hydrostatic pressures and surcharge. Kim et al. [14] provided a comprehensive summary of the earth pressure assumptions typically used in practice. In this regard, the total soil pressure (P_i) was calculated as follows:

$$P_i = K_{wa}\sigma_v \tag{1}$$

where σ_v is the effective vertical overburden pressure and K_{wa} is the coefficient of radial earth pressure which was defined in terms of the wall friction angle and other parameters (see [14] for complete mathematical derivation).

Stresses in a circular diaphragm walls can be estimated by determining the distribution of stresses in a cylinder subjected to uniform radial pressures, which change with depth, acting on the outer surface of the shaft. The theory of thick cylinders is considered if the wall radius to thickness ratio is more than 10. In this case, the meridional and hoop stresses cannot be considered uniform throughout the thickness of the wall and the radial stress cannot be considered negligible. The parametric analyses and the case studies presented in this paper comprise walls that fall under thick walled cylinder category, thus the relevant wall stresses must be determined (see Fig. 2). For a thick-walled cylinder, which is subjected to a uniform external radial pressure, q, and longitudinal pressure of zero (or externally balanced), the stresses and changes in cylinder dimensions can be expressed as:

$$\sigma_1 = 0 \tag{2}$$

$$\sigma_2 = \frac{-qa^2(b^2+r^2)}{r^2(a^2-b^2)}, \quad (\sigma_2)_{max} = \frac{-q2a^2}{(a^2-b^2)} \quad \text{at} \quad r = b \tag{3}$$

$$\sigma_3 = \frac{-qa^2(r^2-b^2)}{r^2(a^2-b^2)}, \quad (\sigma_3)_{max} = -q \quad \text{at} \quad r = a \tag{4}$$

$$\tau_{max} = \frac{(\sigma_2)_{max}}{2} = \frac{qa^2}{(a^2-b^2)}, \quad \text{at} \quad r = b \tag{5}$$

$$\Delta_a = \frac{-qa}{E}\left(\frac{a^2+b^2}{a^2-b^2} - \mu\right), \quad \Delta_b = \frac{-q}{E}\left(\frac{2a^2}{a^2-b^2}\right),$$
$$\Delta_L = \frac{-q\mu l}{E}\left(\frac{2a^2}{a^2-b^2}\right) \tag{6}$$

where σ_1, σ_2 and σ_3 are stresses in the longitudinal, circumferential and radial directions, respectively (see Fig. 2). Δa, Δb and ΔL are the changes in the dimensions of a, b and L, respectively. The major parameters to be considered for an analytical design for diaphragm wall circular shafts are the values of maximum external radial pressure q, the stresses in the wall section and the change in the radius.

2.2. Thick walled cylinders with holes

Some literature exists on the behavior of thick walled cylinders with holes. For example, Makulsawatudum et al. [18] presented elastic stress concentration factors for internally pressurized thick walled cylindrical vessels with radial, offset circular and elliptical cross holes. Laczek et al. [16] performed elasto-plastic analysis of stress–strain state in the vicinity of a hole in a thick walled cylindrical pressure vessel using the finite element method. Nihous et al. [25] studied elastic stress concentration factors for internally pressurized thick walled cylinders with oblique circular cross holes using the finite element method considering various wall cross-hole ratios. Li et al. [17] employed inelastic FE analyses to study the effect of autofrettage on the stress levels in thick walled cylinders with a radial cross-hole. Duncan et al. [5] determined the effect of a cross hole on the inelastic response by considering the shakedown and ratcheting behavior of plain thin and thick walled cylinders with a radial cross-hole, subjected to constant internal pressure and cyclic thermal loading. No literature was encountered on the stress regimes around a hole in a large diameter thick walled cylinder such as the secant pile wall circular shaft. The factors such as the external pressure distributions around a circular shaft and the location of the hole along the height of the shaft are the factors complicating the stress regime around the hole making an independent evaluation necessary.