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Undrained limiting pressure behind soil gaps in contiguous pile walls

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ABSTRACT

Finite element limit analysis with plane strain condition is employed to determine the upper and lower bound solutions of the undrained limiting pressure behind soil gaps and the lateral force acting on a pile per unit length in a contiguous pile wall. Computed bound solutions confirm serious limitations of existing studies in predicting these two solutions. Predicted failure mechanisms and the arching effect behind soil gaps are discussed. A closed-form equation of the limiting pressure factor is proposed for a convenient and accurate prediction of the lateral force acting on a pile in contiguous pile walls in practice.

1. Introduction

In urban areas, demands on deep excavation for basements of high-rise buildings or tunnel stations have increased over the years. Steel sheet pile walls or concrete diaphragm walls are popular forms for deep excavation in soft soils. A contiguous pile wall is one option in a retaining wall system and has become commonly employed to support deep excavations (e.g. North-Lewis and Lyons [1], Moh and Chin [2], Gaba et al. [3], Ou [4], Kumar [5], Teparaksa [6], and Zhang et al. [7]). Contiguous pile walls are mostly suitable for cohesive soils where the groundwater table is below an excavation level. The wall consists of discrete column piles that are typically installed at a small gap for soft soils or greater than their diameter for stiff soils (Clayton et al. [8]). Soil gaps between adjacent piles are left and exposed during excavation. Generally, large and small diameter bored cast-in-place piles are often used to construct a contiguous pile wall for temporary or permanent structures such as deep basements, underpasses, shaft stations of tunnels, cut-and-cover tunnels, etc. Bracings of a contiguous wall are also required to ensure acceptable ground movements. The major benefits of contiguous pile walls are its cost-effectiveness since a smaller volume of concrete is used to construct unconnected piles and low-cost augers can be utilized to drill holes for these piles, thus providing another option for an economical retaining wall.

One very important factor that affects the short term performance of contiguous pile walls is a gap ratio between adjacent piles. Even though soil gaps in contiguous pile walls are freely exposed, they are stable because of a self-supporting mechanism produced by an arching effect that develops in soil gaps between two adjacent piles acting against a lateral earth pressure behind them. Predictions of the undrained limiting pressure behind soil gaps and the lateral force acting on a pile in a contiguous pile wall in relation to this factor are the most important aspects in this design problem.

Fig. 1 shows the problem definition of undrained limiting pressure behind soil gaps in contiguous pile walls in homogeneous clay. It is assumed that below a certain depth from the ground surface, soil movements take place within this cross section and thus the plane strain condition can be applied in the direction of pile depth. Thus, the studied solutions are only applicable for contiguous pile wall sections that are located at depth from the ground surface. Soil gaps with a distance, S are created from a row of equally-spaced rigid circular piles with a diameter, D. It is assumed that each column pile has a continuous bracing such that it behaves as a rigid structure whose movement is not permitted. A uniform pressure, p represents a lateral pressure behind soil gaps that causes a general failure in the soil mass. The clay has an isotropic and constant undrained shear strength, s_u, and is assumed to behave as a perfectly plastic Tresca material following an associated flow rule. The adhesion factor (α) at the soil-pile interface is considered in this study, with its definition is given below.

$$\alpha = s_{ui}/s_u \quad (1)$$

where

s_{ui} = undrained shear strength at soil-pile interface
s_u = undrained shear strength of surrounding soil

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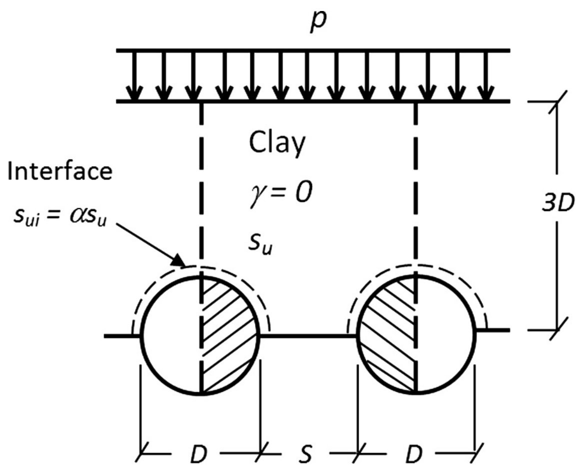

Fig. 1. Problem definition of undrained limiting pressure behind soil gaps in contiguous pile walls.

Because of the assumption of plane strain condition that is applied to the direction of pile depth, a weightless soil (i.e. $\gamma = 0$) is considered in the analysis. The stability problem of the proposed study is to determine the undrained limiting pressure (p) that produces a failure in soil gaps of a contiguous pile wall and can be expressed as the dimensionless parameters as follows:

$$\frac{p}{s_u} = f\left(\frac{S}{D}, \alpha\right) \tag{2}$$

where
p/s_u = undrained limiting pressure factor behind soil gaps
S/D = ratio of soil gap

Considering a free body diagram of one pile and half of the soil gaps in each side of the pile, vertical force equilibrium can be employed to straightforwardly calculate the lateral force acting on a pile per unit length (F) from the product of the limiting pressure (p) and the corresponding width of the free body diagram, $S + D$, hence giving rise to a useful inter-relationship between F and p in terms of a dimensionless form as:

$$\frac{F}{s_u D} = \left(\frac{p}{s_u}\right)\left(\frac{S}{D} + 1\right) \tag{3}$$

where F/s_uD = lateral force factor acting on a pile per unit length in a contiguous pile wall

The arching effect in this problem may be partially similar to that in an active trapdoor problem first studied by Terzaghi [9]. Later, various studies on the stability of active trapdoor have been conducted using theoretical and numerical analyses such as the method of characteristics [10,11], upper and lower bound solution [12] finite elements analysis [13], and finite element limit analysis [11,14]. However, existing solutions for an undrained active trapdoor cannot be directly applied to the proposed study because the boundary conditions of these two problems are significantly different. There have been numerous efforts to study an arching effect in soils (e.g. [15–20]); however, there is no plasticity solution for limiting pressure behind soil gaps in contiguous pile walls. In this study, three relevant existing solutions [15,19,20] are selected for a comparison of p/s_u and F/s_uD. Ito and Matsui [15] studied the arching effect between a row of stabilizing rigid piles and employed the limit equilibrium method with a postulated failure mechanism to predict the lateral force acting on a pile per unit length for cohesive-frictional soils, as illustrated in Fig. 2. In the case of cohesive soils, their solution of F/s_uD is given as:

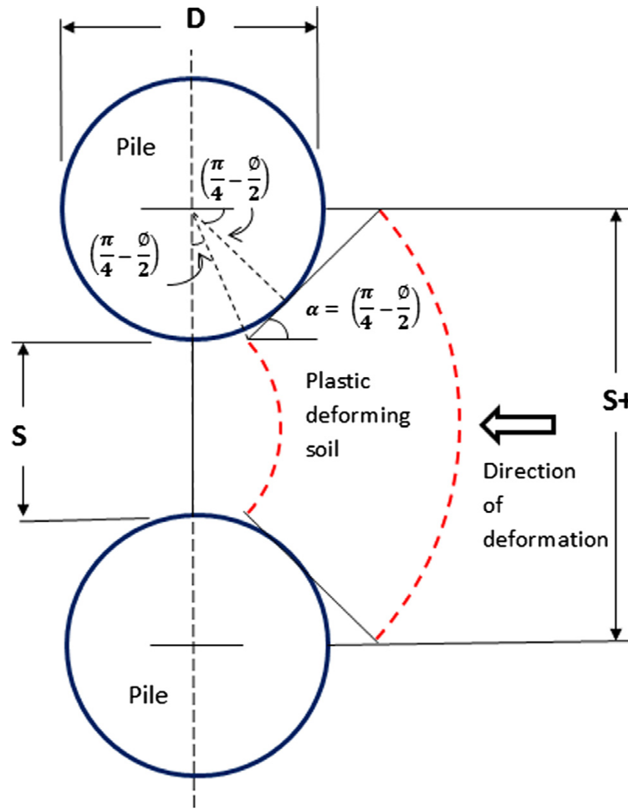

Fig. 2. Arching effect between stabilizing piles in a row and postulated failure mechanism in the limit equilibrium calculation by Ito and Matsui [15] (modified from [15]).

$$\frac{F}{s_u D} = \left(1 + \frac{S}{D}\right)\left(3\log\left(1 + \frac{D}{S}\right) + \frac{D}{S}\tan\frac{\pi}{8} - 2\right) \tag{4}$$

Later, Matsui et al. [20] employed almost the same assumptions and failure mechanism proposed by Ito and Matusi [15] and derived an expression of F/s_uD that has a slightly different mathematical form as:

$$\frac{F}{s_u D} = \left(1 + \frac{S}{D}\right)\left(3\ln\left(1 + \frac{D}{S}\right) + \frac{D}{S}\tan\frac{\pi}{8}\right) \tag{5}$$

Recently, Haema and Tanseng [19] employed physical models with high quality block clay samples to study the failure mechanism of soil gaps behind contiguous pile walls, as shown in Fig. 3. Utilizing observed failure mechanisms, Haema and Tanseng [19] derived the limit equilibrium solution of p/s_u as:

$$\frac{p}{s_u} = \frac{1}{S}\left(S + D + \frac{\alpha D \pi}{2\sqrt{2}}\right) \tag{6}$$

This paper presents new plasticity solutions of undrained limiting pressure factor (p/s_u) behind soil gaps and lateral force factor (F/s_uD) acting on a pile per unit length in a contiguous pile wall by using finite element limit analysis (FELA) software, OptumG2 [21]. Parametric studies of the soil gap ratio (S/D) and adhesion factor (α) at the soil-pile interface are performed to cover practical ranges of this problem, including S/D = 0.1–3 and $\alpha = 0$ (smooth) to 1 (rough). A closed-form approximate equation is also proposed for a convenient and accurate prediction of p/s_u and F/s_uD for a contiguous pile wall in practice.