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Response of Piered Retaining Walls to Lateral Soil Movement Based on Numerical Modeling

Siamak Pahlevanzadeh

Griffith School of Engineering, Griffith University, Gold Coast Campus, QLD 4222, Australia

ABSTRACT: The response of individual retaining walls employed as a preferred slope stabilization technique, to lateral loading has been widely explored in the literature. The present study focuses on the response of piered retaining walls, i.e. retaining walls supported by a pile foundation system, to lateral soil movement. Numerical analysis results by MATLAB have revealed wall-soil-pile interaction mechanism with different effective height of wall, spacing, diameter and number of piles, using different soil properties, which quantifies the behavior of piered retaining walls owing to lateral soil movement. Based on a numerical configuration sensitivity study, the relationship between lateral loading and pile/wall deflection, shear and bending moment under different influencing parameters has been established. Optimum effective parameters are accordingly defined and relevant guidance on choosing appropriate piling configuration is provided, which can be of practical use in engineering design.

Keywords: Piered Retaining Wall, Lateral Soil Movement, Numerical Modeling

1. INTRODUCTION

The problem associated with lateral earth pressure and retaining wall stability is one of the most common in the civil engineering field and a segment of soil mechanics that has been receiving widespread attention from engineers for a long time.

The typical structures whose primary or secondary purpose is to resist earth pressures may include various types of retaining walls, sheet piling, braced sheeting of pits and trenches, bulkheads or abutments, and basement or pit walls. These may be self-supporting (e.g., gravity or cantilever concrete walls) or they may be laterally supported by means of bracing or anchored ties. The lateral earth pressure depends on several factors [1]:

- The physical properties of the soil
- The time-dependent nature of soil strength
- The interaction between soil and retaining structure at the interface
- The general characteristics of the deformation in the soil-structure composite
- The imposed loading (e.g., height of backfill, surcharge loads).

Due to virtually no analytical, theoretical or field testing data on piered retaining walls, this review will focus on the literature on wall-soil interaction and the behavior of piles subjected to a lateral loading. Although the integrated structure will behave differently, numerical modeling can still be employed on the basis of how each section would behave in a traditional situation, i.e. the retaining wall behaves as a piling cap with an additional moment force due to earth pressure.

Although much research has been performed and appreciable advancement made during the past two centuries regarding the distribution of earth pressures and on the analysis of a wide range of earth-retaining structures, some of the theories formulated by Coulomb (1776), Rankine (1857) and Mononobe-Okabe (1929) still remain as the fundamental approaches to the analysis of most earth-supporting structures, particularly for sandy soils. Furthermore, although some research data and experience indicate that assumptions related to pressure distributions on retaining walls, or on the failure surface of the backfills, are not quite those depicted by these early investigators, substantial evidence exists that the analysis and design efforts based on their theories give acceptable results for most cases of cohesion-less backfills. The results are significantly less dependable for the more cohesive soils.

Recent analyses have tended to concentrate on numerical methods, in particular, the three-dimensional finite element methods. The importance of incorporating interface elements to simulate possible slippage and separation between the wall and soil, and capturing the soil nonlinearity using advanced constitutive models, has been widely recognized.

Advanced numerical analysis may be appropriate and necessary for detailed design; generally, the wall-soil interaction may be addressed with numerical simulations based on either the finite-element method (FEM), or the finite-difference method (FDM).

Goh (1993) performed finite element analyses to investigate the effects of subsoil stiffness, wall stiffness, and wall roughness on the lateral earth pressure for concrete cantilever retaining walls, and proposed a modified earth pressure distribution.

In spite of recent published methods, the tendency today in

practice is to use the values given by Caquot and Kerisel (1948) [2] and Kerisel and Absi (1990) [3].
Benmebarek et al. (2007) [4] concerned with the numerical evaluation of passive earth pressure coefficients for a rigid rough vertical retaining wall with horizontal ground surface and limited breadth subjected to translation. They conducted a numerical study of 3D passive earth pressures induced by the translation of a rigid rough retaining wall for associative soils. Using the explicit finite difference code $FLAC^{3D}$, the increase of the passive earth pressures due to the decrease of the wall breadth was investigated. FLAC uses an explicit finite difference program to study numerically the mechanical behavior of a continuous 3D medium as it reaches equilibrium or steady plastic flow. The explicit Lagrangian calculation scheme and the mixed-discretization zoning technique as presented by Cundall (1987) [5], is used in FLAC to ensure that plastic failure and flow are modeled accurately.
Numerical methods including both finite element and finite difference methods have been widely employed to study the wall-soil interaction under active and passive lateral loading due to soil movements. These methods mainly satisfy the compatible relationship between the lateral pressure and the movement. However, relatively little effort is made to assess the response of the piered retaining walls under the action of the lateral soil movements.

2. NUMERICAL MODELING

2.1 Method

The numerical model was created by combining two methods (Fig. 1) using C^{++} script in Matlab:

- Finite Difference Method, FDM, (Matlock and Reese, 1960) [6] revised by Guo (2003) [7],
- Finite Element Method, FEM, reviewed and verified by Chen (1998) [8] as the method of superposition, namely flag pole analysis

Basic mechanics of materials formulae is used to determine elastic deflection in the retaining wall, boundary conditions to have a statically determinant cantilever wall which can be used to determine the degree of deflection the wall itself undergoes.

Numerical modeling using Matlab is designed to calculate deflection when subject to a variety of parameters, maximum shear in each pile correlating to the applied load and bending moment at different depths, to find where the maximum moment occurs. Numerical modeling is also designed to highlight the impact of input parameters on the performance of a piered retaining wall to facilitate the development of design guidelines.

By implementing the popular p-y method, Rankine's Coulomb's and Mononobe-Okabe's general formulas for a case of static equilibrium using Matlab, results can be obtained to verify the accuracy of existing methods applied to an unfamiliar situation. This method can only be reliable for a pile group with S/D of 6 or greater where S, is the spacing between piles and D, is the diameter of each pile.

2.2 Analysis

The numerical model uses the FDM to determine the maximum bending moment and the angle of rotation in the piles, and the FEM analysis to determine pile deflection. Mechanics of materials formulae is also used to determine elastic deflection in the retaining wall. The method of critical pile depth was utilized to establish pile flexibility and boundary conditions required for a statically determinant cantilever wall to be used to determine the deflection of the wall.
The type of piered retaining wall modeled, can be either a cantilever or gravity wall retaining wall interface, with one or two rows of piles beneath it. Finite element analysis is used to determine this behaviour. The retaining wall's deflection is determined with an extension of the P-y method using the general limit static equilibrium case. The force profile and behaviour of piles are modelled with p-y curves to determine the elastic-plastic sliding depth and bending moment for a non-linear loading distribution profile.
The model is developed for a piered retaining wall subjected to active earth pressure, which behaves as a pile with fixed head. Piles are subject to passive earth pressure loading case, where soil movement occurs exclusively at and above the bottom of the retaining wall. The Matlab script is split up into three parts, input parameters, deflection calculation and pile analysis. It basically calculates the percentage of the loading transferred from the wall to the piles due to the lateral soil movement and then quantifies the behavior of piles due to the load transferred.

2.3 Model Modifications

A variety of modifications have been made to the numerical model to account for the wall – pile interaction. It was found that the numerical model best suited for a piered retaining wall which is developed for substantially long piles. In order to counteract this problem, modifications were made by imposing a relationship between the critical pile depth and the total pile length, such that the deflection was not underestimated.
Basically if a pile decreases in length the deflection will decrease, past a certain point namely critical pile depth and if a pile decreases in length below the critical pile depth, deflection will increase. After satisfactory equations were derived and verified, numerical results have been produced. Comparisons and conclusions have been obtained to deduce the suitability and feasibility of implementing piered retaining walls. The purpose of these comparisons is to determine the sensitivity of the numerical model to the influencing parameters which establishes the performance of the piered retaining wall.

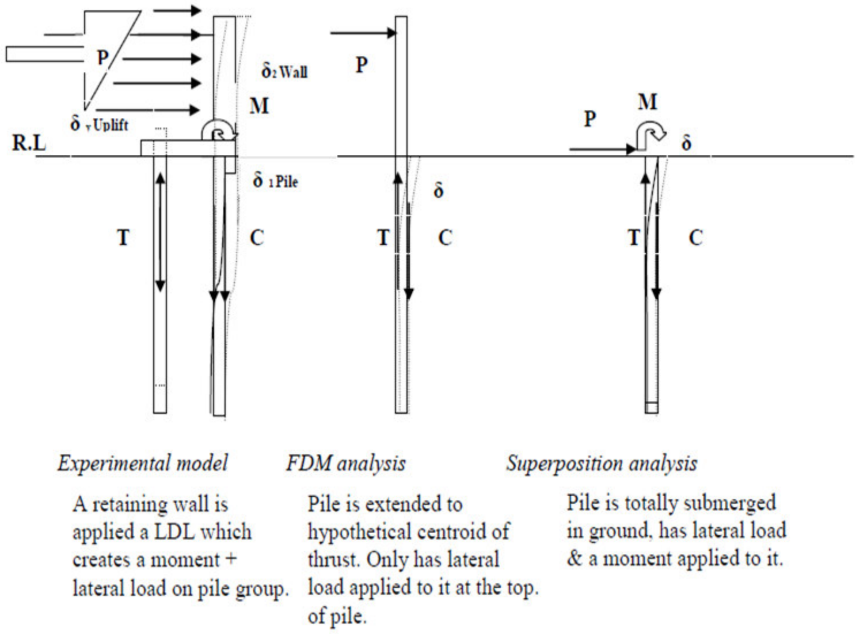

Fig. 1 - The numerical model created by combining two methods, FDM and FEM

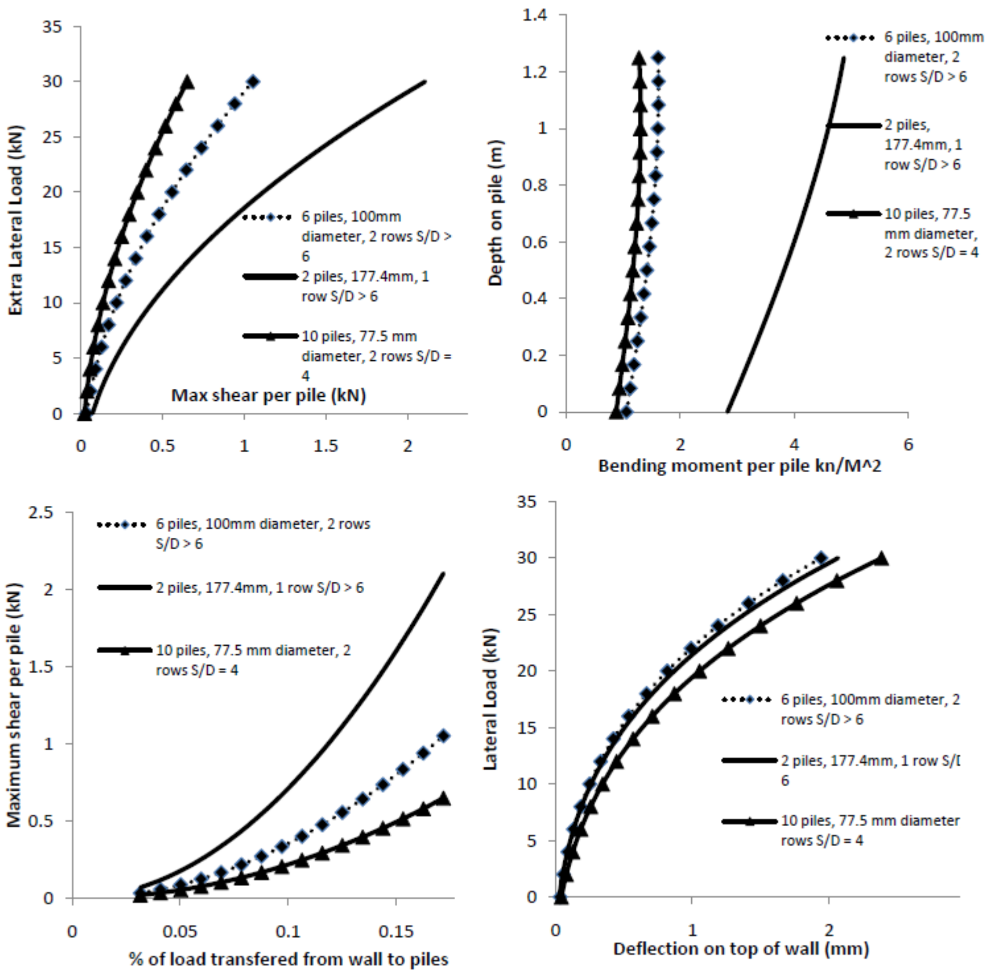

Fig. 2 - Numerical comparison between three different piling configurations for a concrete retaining wall

2.4 Results and Discussion

Fig. 2 shows the comparison between three different piling configurations for a concrete retaining wall. It includes:

- two piles, diameter of each pile 177mm, S/D>6
- Six piles, diameter of each pile 100mm, S/D>6
- Ten piles, diameter of each pile 78mm, S/D<6

The maximum shear force per pile due to a certain lateral load decreases considerably by increasing the number of piles from 2 to 6; however increasing the number of piles from 6 to 10 slightly decreases the maximum shear force per pile. The bending moment per pile at a certain depth also decreases considerably by increasing the number of piles from 2 to 6; however increasing the number of piles from 6 to 10 slightly decreases the bending moment force per pile.

Fig. 3 shows the comparison between three different cases of soil properties for a large reinforced concrete piered retaining wall. These cases are including sand with:

- φ =30 □ friction angle and 79% relative density
- φ =32.5 □ friction angle and 84% relative density
- φ =35 □ friction angle and 89% relative density

The maximum shear force per pile due to a certain lateral load increases by decreasing the friction angle and relative density of soil. The bending moment per pile at a certain depth also increases by decreasing the angle of friction and relative density of soil.

The deflection at top of wall due to a constant lateral loading increases accordingly by decreasing the angle of friction and relative density of soil.

Fig. 4 shows the comparison between three different cases of effective wall heights for a large reinforced concrete piered retaining wall. These cases are including piered retaining wall with:

- h= 150mm, 190mm submerged into the soil
- h= 200mm, 140mm submerged into the soil
- h= 250mm, 90mm submerged into the soil

Where h is the effective wall height. The maximum shear force per pile due to a certain lateral load increases by increasing the effective wall height. The bending moment per pile at a certain depth also increases by increasing the effective wall height. The deflection at top of wall due to a constant lateral loading increases accordingly by increasing the effective wall height.

3 CONCLUSION

To gain a relatively better understanding of the effect of piling beneath a simple typical retaining wall, a numerical modeling and analysis has been conducted using Matlab. The model utilizes a combination of both FDM and FEM methods in order to calculate the earth pressure on the wall due to applied lateral loading, determine the percentage of load transferred from wall to piles and quantify the pile behavior accordingly.

Discussing the improvement of the engineering behavior of a simple typical retaining wall by piling beneath the retaining wall also reveals that:

- There is optimum number of piles to use beneath any particular retaining wall, since the numerical modeling indicates that the maximum shear force per pile due to a certain lateral load and the maximum bending moment at a certain depth decrease by increasing the number of piles to a certain number and additional piling will not considerably improve the lateral capacity. This optimum number of pile can be determined running the developed numerical model in the present study.

- Decreasing the friction angle and relative density of soil, increases the maximum shear force per pile due to a certain lateral load and also the bending moment per pile at a certain depth. This conclusion illustrates the effect of soil properties on the model. The deflection at top of wall due to a constant lateral loading increases accordingly by decreasing the angle of friction and relative density of soil. The numerical model developed in the present study is able to consider different soil properties in order to produce appropriate outcome.

- There is optimum effective wall height, since increasing the effective wall height will result to increase in the maximum shear force per pile due to a certain lateral load and also the bending moment per pile at a certain depth. The deflection at top of wall due to a constant lateral loading increases accordingly by increasing the effective wall height. This shows the effect of piered retaining wall dimensions on the total improve in the lateral capacity. The optimum effective wall height can be determined using the numerical model developed in the present study.

A generalized improvement over a retaining wall can be shown by running this numerical model in Matlab. If the percentage of load transferred to piles from the wall is low, the piling impact is not substantial and using piered retaining wall is arguable, since the use of piles beneath the retaining wall will not considerably improve the total lateral capacity. As the percentage of load transfer from wall to piles increases, the impact of piles becomes more prevalent and the necessity to utilize a piered retaining wall to achieve a desired lateral capacity instead of a simple typical wall becomes more obvious.

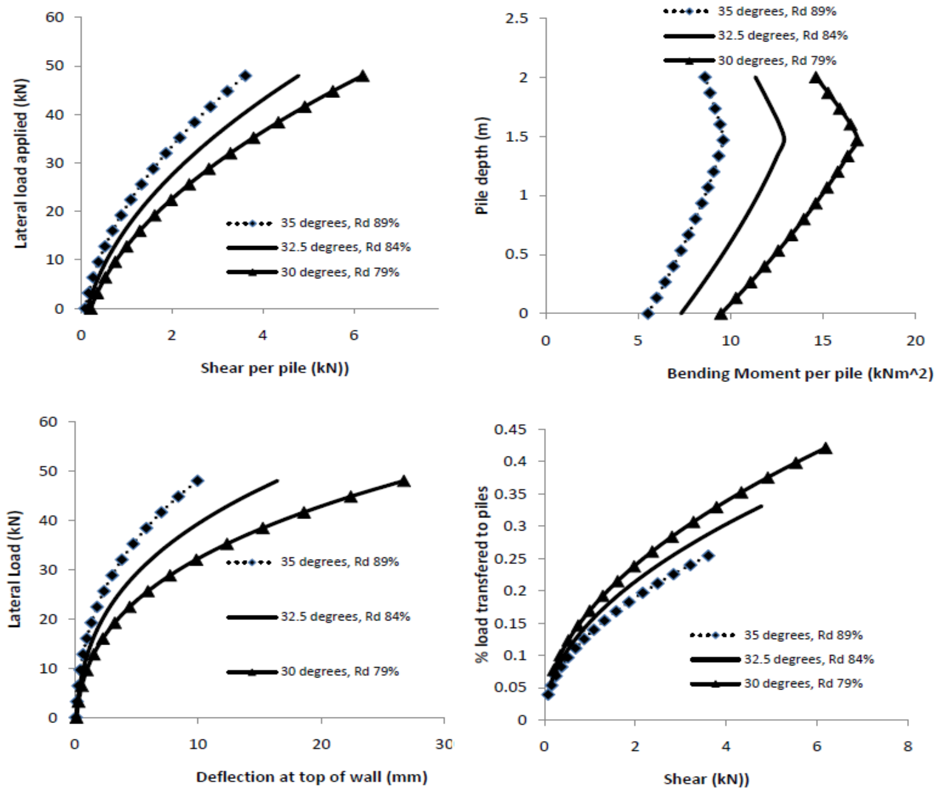

Fig. 3 - Numerical comparison for a large reinforced concrete piered retaining wall in three different sets of soil properties

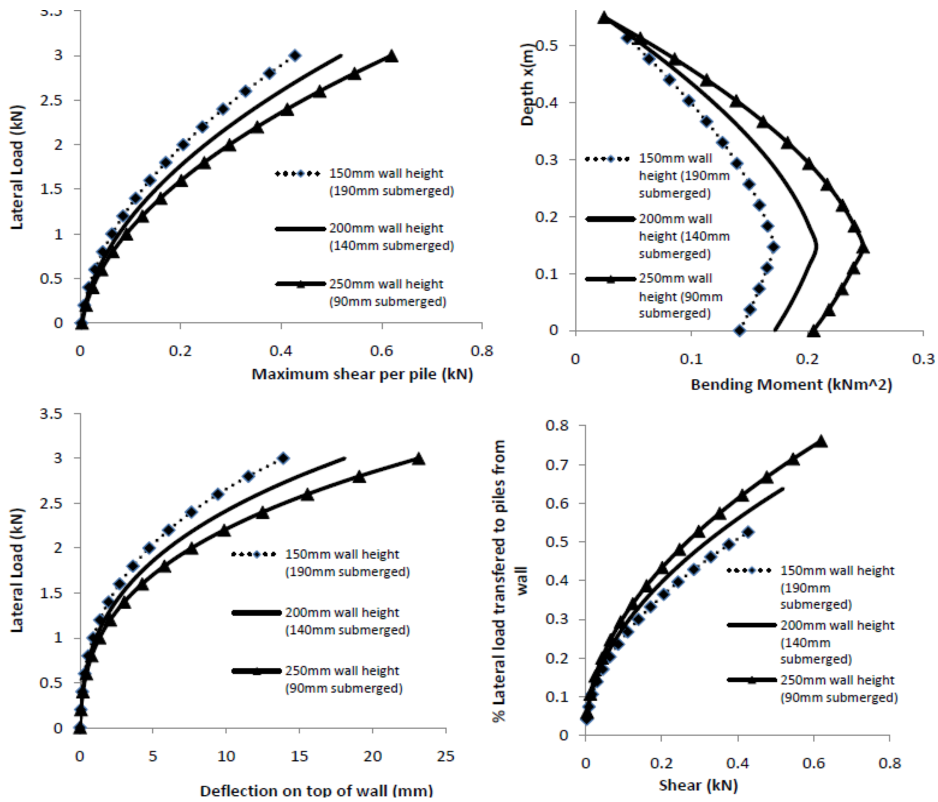

Fig. 4 - Numerical comparison between effective wall heights 150mm, 200mm, and 250mm

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Corresponding Author: Siamak Pahlevanzadeh