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Evaluating the Different Types of Analytical Methods of Piling Retaining Walls

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ABSTRACT: Piling retaining walls as soil holder elements have a wide range of applications including slope stabilization of roads, protection of coastlines against erosion, controlling lateral extension in areas prone to liquefaction, stabilization of vertical trenches and protection against excavations. These types of retaining structures have load-deformation behavior of their own as flexible elements and they practically have extreme lateral deformation under the effect of lateral soil pressure because of their small thickness; the amount of their lateral deformation is a function of clamped length and also the characteristics of the soil behind. The stability analytical methods of geotechnical structures are generally divided into three categories including closed solution method, simple methods and numerical methods. In this article, after reviewing theories of soils dynamic lateral pressure, the performance of several methods including limit equilibrium method in the analysis of retaining walls are evaluated and then they are compared with the finite element method which is one of the conventional and known numerical methods.
Keywords: Retaining walls, dynamic analysis, Mononobe - Okabe, seismic behavior, finite element

I. INTRODUCTION

Piling retaining walls are relatively thin walls made of reinforced concrete or wood which are kept together by tiebacks, clamps or resisting soil pressure. Bending capacity of such walls plays a key role in maintaining materials as a guardian structure while the role of weight of the wall is unimportant. Examples of this type of wall are: Metal piling walls, tieback or slingback piling retaining concrete walls and diaphragm walls.

Seismic behavior of piling retaining walls depends on the total pressure (including static weight pressure before the earthquake and dynamic pressure caused by the earthquake). Dynamic pressures on the flexible walls are usually estimated by quasi-static or dynamic processes.

The piling retaining walls are used in seismic active areas. Earthquakes can lead to permanent deformations of retaining structures. In some cases, these deformations are extremely large and cause significant damage. In most cases, retaining structures are fragmented during earthquakes which aresometimes with disastrous economic and physical consequences[1][2][3][4]

II. LATERAL EARTH PRESSURE

A corresponding analytical solution of the dynamic pile response is derived and subsequently verified through the comparisons against the 1D wave theory and the Finite Difference Method. The proposed model exhibits the transverse wave interferences and finds: (1) The transverse wave interference that occurred during the TLSITs can be seen gradually alleviated from the pile center to the pile edge. (2) The larger the pile dimensions are, the greater the transverse wave interference would be[5].

Seismic behavior of retaining walls dependents on lateral earth pressure. The total pressure exerted on the wall includes static pressure (caused by active and passive Lateral soil pressure) and dynamic pressure. The response of a wall is the resultant effect of these two factors. Theories of static and dynamic lateral soil pressure have been stated by individuals such as Coulomb (1776), Rankine (1857), Mononobe - Okabe (1926 and 1929) Kakooti and Krisel (1948), Sokolovskiy (1965), Chen and Liu (1990) and Lansoluta (2002).[6][7][8][9][10][11][12][13]

The retaining walls in coral sand sites are inevitably threatened by earthquakes. A series of shaking table tests were carried out to study the seismic stability of gravity retaining walls with coral sand backfill. Parallel tests with quartz sand were performed to compare and discuss the special dynamic properties of coral sand sites. The results show that the acceleration difference between the retaining wall and the coral sand backfill is 76%–92% that of the quartz sand, which corresponds to the larger liquefaction resistance of coral

sand compared with the quartz sand. However, the horizontal displacement of the retaining walls with coral sand backfill reaches 79% of its own width under 0.4g vibration intensity. The risk of instability and damage of the retaining walls with coral sand backfill under strong earthquakes needs attention[14].
Most of the methods in this regard are based on the use of simple analysis techniques such as limit equilibrium, limit analysis, stress field and etc. in this regard; the share limit equilibrium method is more than the rest. Limit equilibrium is based on assumption of a simple and tangible failure mechanism. In this method, it is supposed that all points along a hypothetical failure surface are in complete failure conditions and then overall and block balance are evaluated for the obtained wedge failure.

Detailed vertical analysis of finite difference and finite element are based on meeting the following four requirements: 1.restoring the Balance 2.compatibility with deformations 2.behavioral rule 4.boundary conditions. Simple analysis methods usually ignore one or more of the four above requirements.Thus, different methods ranging from simple and detailed analysis are not expected to provide the same answers.
Analysis methods are divided into two static and dynamic general categories in terms of the type of load.This article will review and assess the different methods of dynamic analysis of piling retaining walls.For this purpose, Mononobe Okabe method as a method based on limit equilibrium, Chen method as amethod based on limit analysis and finite element analysis asone of the methods of numerical analysis are compared and evaluated with each other in quasi-static loading conditions.
In the following, in addition to the introduction of each of these methods,assumptions used in these methods will be describedand the results of quasi-static analysis of piling retaining walls will be provided using mentioned methods and the parametric study.

2.1. Mononobe Okabe method (M-O)

Okabe (1926) and Mononobe and Matsu (1929) stated the basis of Quasi-static analysis of seismic earth pressure on retaining structures. Mononobe Okabe method is the developed the theory ofColumbusstatic analysis in quasi-static conditions. In a Mononobe Okabe analysis,quasi-static acceleration is applied to activate or passivecoulombwedge and quasi-static stress of the soil is obtained from balance of forces in failure forms according to figure 1 [8, 9].Mononobe-Okabe's model is the most commonly used pseudo-static method of estimating seismic lateral earth pressures behind retaining wall worldwide. This method cannot predict the distribution of the lateral earth pressure and the overturning moment accurately [12].
The resultant forces exerted on activate wedge in a dry moat without stickiness are formed by horizontal and vertical quasi-static components which their enlargement depends on the mass of the wedge under quasi-static acceleration of $a_h = k_h g$ and $a_v = k_v g$ .The total active force exerted on the wall in a form similar to static mode is expressed as follows:

$$S_{AE} = \frac{1}{2} K_{AE} \gamma H^2 (1-k_v) \quad [1]$$

In equation 1, K_{AE} is the active dynamic pressure coefficient of soil and is calculated from the following equation[2]:

$$K_{AE} = \frac{\cos^2(\phi' - \beta - \theta)}{\cos(\theta)\cos^2(\beta)\cos(\delta + \beta + \theta)} \times \frac{1}{\left[1 + \sqrt{\frac{\sin(\delta + \phi')\sin(\phi' - \varepsilon - \theta)}{\cos(\delta + \beta + \theta)\cos(\varepsilon - \beta)}}\right]}$$

Parameters used in this equation have been shown in figure [1] and are calculated using equation (3):

$$\theta = \tan^{-1}\left[K_h \big/ (1 - K_v) \right] \quad [3]$$

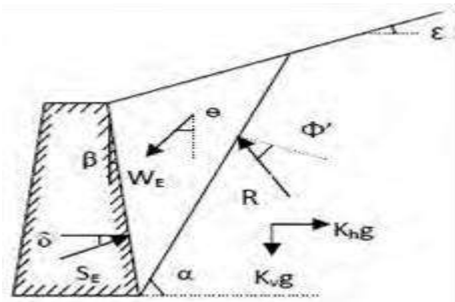

Figure 1: The symbols and units used in the M-O analysis

Based on the M-O analysis, the total active force in the distance ofH/3 is applied on the base of the wall to a height of H, while the experimental results show that the location of applied force in higher[2]. The total active force (S_{AE}) can be divided two static (S_A) and dynamic (ΔS_{AE}) sections:

$$S_{AE} = S_A + \Delta S_{AE} \quad [4]$$

Static component (S_A) is applied at the distance of H/3 from the top of the wall and dynamic component is also applied in approximate height of 6.0 H of the wall according to Sid and Whitman (1970) [15].According to this, the total active force is applied from foot of the wall at a height of h which is calculated according to equation (5) and most often occurs in the middle of the wall height.

$$h = \frac{S_A \frac{H}{3} + \Delta S_{AE}(0.6H)}{S_{AE}} \quad [6]$$

The results of M-O analysis shows that if the vertical component of earthquake acceleration (K_v) has $\frac{1}{2}$ to $\frac{1}{3}$ of horizontal component of earthquake acceleration (K_h), then it effects the calculation of total active force (SAE) less than 10%.

Total passive stress applied on retaining wall from non-adhesive levee in dry conditions is calculated from the following equation:

$$S_{PE} = \frac{1}{2} K_{PE\gamma} H^2 (1 - K_v) \quad [7]$$

In equation (6), K_{PE} is Passive dynamic pressure coefficient of soil which is calculated using equation (7)

$$K_{PE} = \frac{\cos^2(\phi' - \beta - \theta)}{\cos(\theta)\cos^2(\beta)\cos(\delta + \beta + \theta)} \times \frac{1}{\left[1 + \sqrt{\frac{\sin(\delta + \phi')\sin(\phi' + \varepsilon - \theta)}{\cos(\delta - \beta + \theta)\cos(\varepsilon - \beta)}}\right]} \quad [8]$$

Similar to the active mode, Total active force can also be divided into two static and dynamic categories.

$$S_{PE} = S_P + \Delta S_{PE} \quad [9]$$

Passive dynamic component of lateral soil pressure is applied in contrast to the static component and thus reduces the passive force [16]. M-O method has all restrictions of Coulomb method; however, because the Coulomb theory is in static conditions, analysis of M-O estimates passive soil force more than reality especially in terms of $\delta > \phi'/2$ [16]. M-O method should be used more carefully due to these reasons.

2.2. Limit analysis method

This method is based on the state of mass of soil behind the wall in various behavioral modes. Behavioral modes depending on the amount of wall movement and strain levels in the soil can be Elastic, elasto-plastic and plastic. Active and passive seismic lateral pressures are limited to lower bound and upper bound depending on the mentioned behavioral modes. Lower bound is related to conditions when retaining wall is on the verge of failure by establishing a dynamic balance and yield criterion. While the upper bound occurs when the rate of work done by external forces is greater or equal to the rate of energy dissipation by internal forces and this is related to the mode when failure has definitely happened and the object has large movements. Calculation of the upper bound should take place with assumption of a geometrically acceptable speed field.

An important point in relation to the limit analysis method is that this method is the same as the limit equilibrium method and does not meet some of four general Essentials to solve the question. Specifically, the lower bound method in limit analysis ignores compatibility of deformations law and boundary conditions of displacement, while the upper bound method ignores the law of balance of the forces and boundary conditions of forces. Thus, these methods are not expected to provide similar answers and will provide different answers depending on the failure mechanism and the field of hypothetical speed.

Chen and Rouzneqrab (1973) and Chen (1981) calculated active and passive seismic pressure on retaining walls with assumption of the spiral failure mechanism with the help of upper bound in the analysis limit method and provided the following equation [10][16]

$$K_E = N_\gamma + \frac{2q}{\gamma H} N_q + \frac{2c}{\gamma H} N_c$$ [10]

In this equation, γ is soil bulk density, q is the uniform surcharge on the surface of Levee, c is soil cohesion and H is wall height. N_γ ، N_q ، N_c Coefficients have been calculated by Chen and Liu (1990) based on the most critical failure mechanism and have been provided in tables [17].

III. NUMERICAL ANALYSIS

Numerical analyses are based on meeting four theoretical considerations in solvation of a general question and there usually different numerical analyses which are: Finite Elements (FEM), Finite Differences (FDM), discrete elements (DEM), boundary elements (BEM) and other methods which are try to meet the requirements relating to compatibility balance of deformities, behavioral rules and boundary conditions of displacement and force. This study evaluates and compares the results of these analyses in comparison with simple methods including limit equilibrium and limit analysis by focusing on Finite Element Method and using PLAXIS Business Commercial software. For this purpose, the dynamic lateral pressure is evaluated using quasi-static analysis of retaining walls. In this study PLAXIS 8.2 software has been used to model a piling retaining wall. Types of plane strain analysis and drained condition have been considered. Elementation is based on 15 nodes triangular elements in this application. Elastic behavior of retaining wall has been assumed to be linear and contour elements are used for modeling of soil and structure interaction in place of contact with soil and wall. Behavioral parameters related to contour elements are calculated using the following equations based on stiffness and strength parameters of soil behind the wall:

$$\phi_i = \tan^{-1}(\tan\phi_s \times R_{int})$$ [11]

$$C_i = C_s \times R_{int}$$ [16]

$$G_i = G_s \times R_{int}^{1/2}$$ [13]

In above equations, i subscript is related to the contour and s subscript is related to the soil behind the wall. Thus, behavioral parameters between the elements can be introduced by selecting suitable value for the R_{int} interaction coefficient.

Figure 2 shows a schematic form of the geometry of the question for the studied piling retaining in this article. As it can be seen, an excavation holder piling retaining wall to a depth of 4 meters in sandy soil drainage conditions has been modeled. The required parameters for the structural analysis have been presented in Table 1.

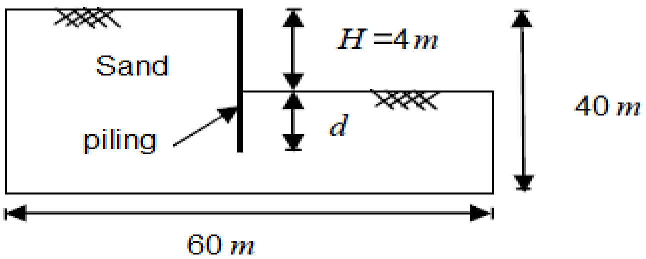

Figure 2:schematic form of the geometry of the studied question

Table 1: Behavioral parameters of materials used in numerical analysis

Studied parameters	Value
Effective internal friction angle of sand (ϕ')	30º
Modulus of Sand deformation (E)	5 MPa
Poisson's ratio (v)	0.35
especial dry density ofsand (γ_d)	17 KN/m^3
Axial stiffness of piling (EA)	3x10^6 KN/m^3
Flexural stiffness of piling (EI)	8x10^6 KN.m^2/m
The interaction coefficient (R_{in})	0.67

This study evaluates the static-like behavior of piling retaining wall the by considering different length of 3, 4 and 5 for the fixed end in Quasi-static load effect which its range is from 0.1 g to 0.5 g.

Each of the mentioned analysis were carried out in 4 separate and consecutive steps: suppression operation in the soil was executed in the first step, excavation in two successive stages was carried out in second and third steps and ultimately Quasi-static acceleration was applied in fourth step and finite element analysis was performed.

3.1. Analysis result

Figure 3 shows the model made in PLAXIS software. Lateral boundaries is limited against horizontal movement and the lower bound limited against any movement and constant acceleration related to quasi-static conditions has been applied on the center of gravity for all triangular elements and finally, analysis of stress - strain was carried out and quasi-static lateral pressure behind the wall was calculated. The software is able to calculate the bending moment in piling according to the calculated lateral pressure.

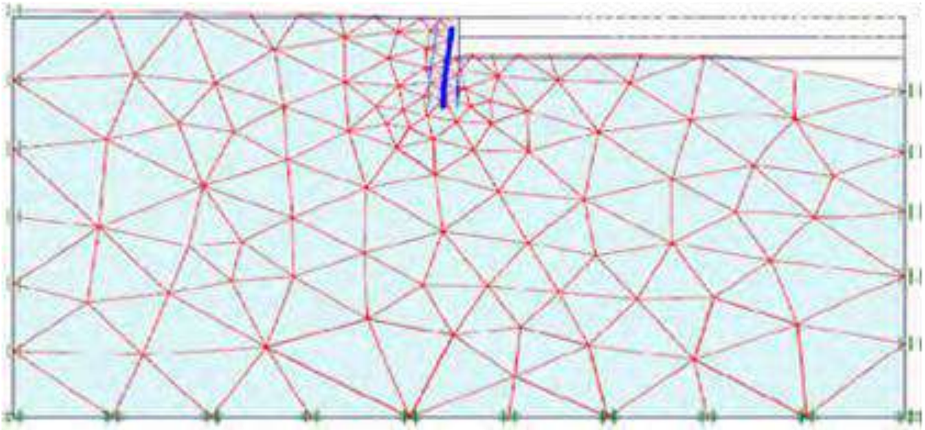

Figure 3: model made in PLAXIS software along with applied mesh

Bending moment calculated by numerical analysis has been drawn over the wall for different K_h. It can be observed that increased range of acceleration will increase the K_h of created bending moments on piling retaining wall.

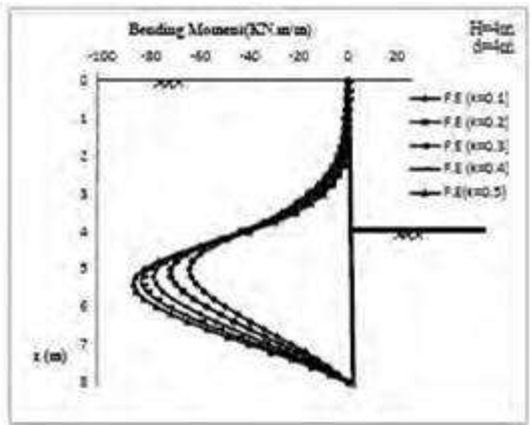

Figure 4: bending moment in the height of the wall obtained from quasi-static finite element analysis

Changes Profiles of active and passive quasi-static lateral pressure on soil of piling retaining wall have been calculated using different methods such as finite elements, Mononobe - Okabe and limit analysis and have been drawn in figure 5. The results indicate that behind the Walls (active conditions) Finite element analysis provides larger values for the lateral pressure compared to the other two methods (limit equilibrium and limit analysis). The reason for this is that, limit equilibrium and limit analysis theories assume that the height of the wall is free and ignore the fixed end of front side of the wall. Thus they are expected to provide lower values compared to the active mode. While Calculation of passive lateral pressure in front of the wall (passive conditions) regardless of soil behind the wall could provide larger answers. In other words, passive pressure and force in front of the front wall plays a resistant force role to calculate the active pressure behind the wall and ignoring it in active pressure calculation leads to a calculated value lower than the real value. On the other hand, active pressure and force behind the wall plays the role of driving force in calculation of the passive pressure in front of the wall and ignoring it in passive pressure calculation leads to a calculated value higher than the real value.

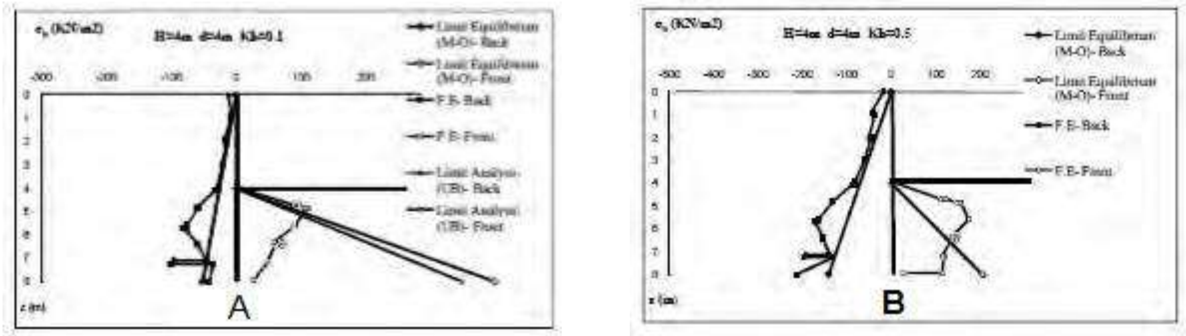

Figure 5: comparison of Quasi-static lateral and passive pressure of the soil using Finite element analysis, limit equilibrium and limit analysis methods A) K_h=0.1 and B) K_h=0.5

Thus, as seen in Figure 5 in the front of the wall which has passive conditions, Finite element analysis smaller values for passive lateral pressure compared to other two methods.

Furthermore, Results related to quasi-static calculation of active and passive force behind and in front of the piling retaining wall using changes profile of lateral earth pressure have been provided in figure 6 and confirms above items. As it can be observed Quasi-Static active force to piling is higher compared to other methods for different values of quasi-static acceleration in active conditions and vice versa, passive quasi-static force is lower in Passive conditions that in great accelerations passive force increases and the difference decreases probably due the plastic shaped area in front of the wall.

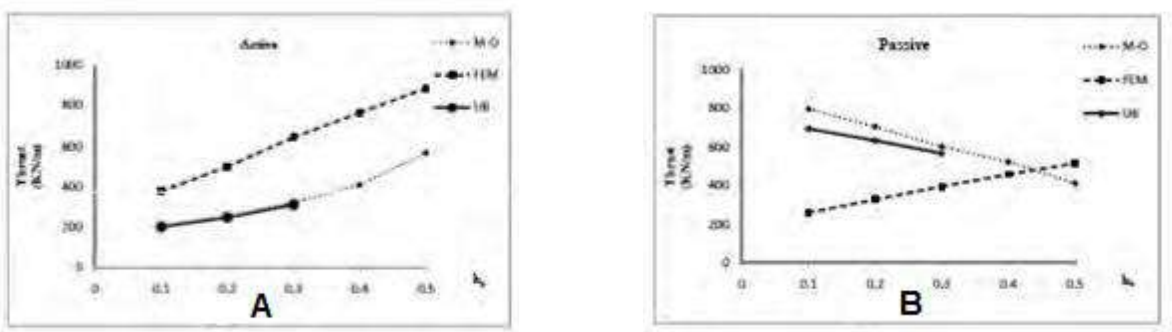

Figure 6: active and passive Quasi-static lateral force calculated using Finite element analysis, limit equilibrium and limit analysis methods A) active conditions (behind the wall) B) passive conditions (in front of the wall)

IV. CONCLUSION

Finite element analysis results compared to other simple methods such as limit equilibrium and limit analysis show that:

1. Bending moments created in the piling increases by increasing quasi-static acceleration applied to the finite element model of piling retaining wall.
2. Behind wall where active soil conditions are established, results related to the calculation of pressures and quasi-static active force obtained from limit equilibrium and limit analysis methods are lower than the results related to finite element analysis in the same loading conditions. This is due to the fact that in the development of equations related to limit equilibrium (Mononobe - Okabe method) and limit analysis (based on the assumption of failure mechanisms and the formation of a failure wedge); a part of the piling retaining wall that is clamped has been ignored. In other words, these theories have been provided for gravity retaining walls which are built almost at ground level.
3. In front of the wall where passive soil conditions are established, results related to the calculation of pressures and quasi-static passive force obtained from limit equilibrium and limit analysis methods are higher than the results related to finite element analysis in the same loading conditions. This is due to the fact that in the calculation of passive pressure of soil, active force behind the wall that acts as the driving force is ignored and therefore higher answers are calculated.

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