Estimation of Seismic Earth Pressures Against Rigid Retaining Structures with Rotation Mode

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Abstract: The evaluation of seismic earth pressures is of vital importance for the earthquake resistant design of various retaining walls and infrastructures. It is one of the key research subjects in soil mechanics and geotechnical engineering. In engineering practices, the magnitude and distribution of seismic earth pressures are greatly affected by the mode and amount of wall displacement. However, classic Mononobe-Okabe solution can only compute the seismic earth pressures at the limit state and doesn't consider the effect of the mode and amount of wall movement on the seismic earth pressure. In this paper, the formation mechanism of earth pressures against rigid retaining wall with RTT and RBT mode is revealed based on the previous studies and a new method is proposed to calculate the seismic earth pressures in such conditions. Corresponding formula are derived and computer code is written to calculate the seismic earth pressure distribution based on the proposed methodology. Variation of seismic earth pressure coefficient for the rigid retaining wall with RTT and RBT mode is calculated and discussed. In addition, the effectiveness of the method is confirmed by the experimental results.

Keywords: Seismic earth pressures, rotation mode, wall displacement, formation mechanism, calculation method.

1. INTRODUCTION

Earth retaining structures such as retaining walls, sheet pile bulkheads, cofferdams, bridge abutments and basement walls are widely used in civil engineering. Estimation of seismic earth pressures is very important for the earthquake resistant design of such retaining structures. Pseudo-static analysis based on the Mononobe-Okabe solution is most widely used in engineering practices for earthquake resistant design due to its advantage of simplicity. However, it can only compute the seismic earth pressures at the limit state and doesn't consider the effect of the mode and magnitude of wall movement on the seismic earth pressures. While earth pressures may fall anywhere between the active and passive state and are closely related to the wall displacement mode especially for seismic conditions. Model test results of Terzaghi (1934), Matsuo *et al.* (1941, 1960&1978), Ishii *et al.* (1960), Ichihara *et al.* (1973), Fang *et al*. (1986&1994) and Ishibashi *et al.* (1987) all indicate that the magnitude and distribution of earth pressure against retaining walls are closely related to the mode and amount of wall displacement [1-9]. In engineering practices, the movement mode of rotation about a point above the top of the wall (RTT) takes place in some retaining structures such as bridge abutments. While for some retaining structures whose bottoms are restrained such as the cantilever retaining wall, the movement mode of rotation about a point under the bottom of the wall (RBT) will take place. The backfill at different depth along the wall is under different lateral strain constraint and cannot reach the limit state at the same time for the retaining structures with RTT and RBT mode. Methods to evaluate earth pressures against rigid retaining structures under RB and RT mode have been proposed by some researchers such as Dubrova (1963), Chang (1997) and Gong *et al.* (2005&2006) [10-13]. However, the relation between the mobilized frictional angle and the wall displacement proposed by them is empirical. And test results indicate that a unique relation does not exist between the earth pressure coefficient and the wall displacement [14]. Zhang *et al.* (1998) conducted strain path tests controlled under different strain increment ratios and established the relation between the mobilized frictional angle and the strain increment ratio based on the analysis of the test results. On this basis they developed a new theory for determining the lateral earth pressure under any lateral deformation between active and passive states. By employing the concept "intermediate soil wedge" which depends on mobilized frictional resistance, Zhang *et al.* (1998) extended Mononobe-Okabe method to new earth pressure formulas for determining the dynamic earth pressure under any lateral deformation [14, 15]. The method has undoubted theoretical basis and clear physical concepts and is easy for application because of its simplicity. However, the characteristic of nonlinear distribution of seismic earth pressure against retaining structures with RTT mode is not fully considered. Besides, the formulas for the earth pressure distribution under rotation mode are complicated and not convenient for use.

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due to stress-dilatancy vary at different depths along the wall and adjust with the lateral strain constraint of the backfill. The internal friction angle and wall friction angle are partly mobilized. When $\triangle_z \leq -\triangle_a$, R_ε=-1. At this time the soil is at the shear failure state and its shear resistance is fully mobilized. It is assumed that the soil internal friction angle and wall friction angle are both fully mobilized simultaneously. Therefore, when R_ε= -1, $\varphi'_{mob}=\varphi'$ and $\delta_{mob}=\delta$. It can be also seen from Fig. (**2b**) that for the RBT mode, the amount of wall displacement at the top of the wall is larger than that at the bottom of the wall. Therefore, the lateral deformation of the backfill near the top of the wall is also larger than that at the lower part of the backfill. With the increase of the depth of the backfill, the proportion of compression deformation in the total deformation gradually increases and that of shear deformation gradually decreases, meaning that compression effect increases and stress-dilatancy effect decreases. The mobilized frictional resistance gradually decreases with the backfill depth and the one at the lower part of the backfill is smaller than that of the upper part of the backfill. The mobilized friction angle at different depth can be determined by Eq. (2).

As is shown in Fig. (**2a**), for the RTT mode, if the top of the wall is selected as the coordinate origin $O(0,0)$, the wall displacement at a certain depth is given by the following equation:

$$\Delta_z = (nH + z)\tan\theta \tag{3}$$

in which n is the parameter indicating the location of the center of the wall rotation.

In the same way, it can be seen from Fig. (**2b**) that for the RBT mode, the wall displacement at a certain depth is given by the following equation:

$$\Delta_z = [(n+1)H - z]\tan\theta \tag{4}$$

The relation between the strain increment ratio R_ε and the wall displacement $\triangle_z$ at the active side can be estimated by the formulas proposed by Zhang *et al.* (1998) [14]:

$$R_\varepsilon = \begin{cases} -\left(\dfrac{|\Delta_z|}{\Delta_a}\right)^a & (-\Delta_a \leq \Delta_z \leq 0) \\ -1 & (\Delta_z < -\Delta_a) \end{cases} \tag{5}$$

in which a is a constant changing within the ranges: $0 < a < 1$ and is recommended to take around 0.5.

The mobilized wall friction angle δ_{mob} changes with the lateral strain parameter R and can be estimated by the following equations suggested by Zhang (1998) [14]:

$$\delta_{mob} = \left(\frac{1 - R_\varepsilon}{2}\right)^{k_1} \cdot \delta \tag{6}$$

in which k_1 is the exponent determined by tests and they can be assigned a value of unity, i.e., k_1=1, if the change in δ_{mob} with R is assumed linear.

Based on the analysis of the test results of Matsuo *et al.* (1941, 1960&1978) Ishii *et al.* (1960), Ichihara *et al.* (1973), Fang *et al.* (1986), Ishibashi *et al.* (1987), and Sherif *et al.* (1982&1984), it can be found that seismic earth pressures against rigid retaining structures under RTT mode consist of five components: (1) earth pressure induced by the soil weight, (2) earth pressure induced by the surcharge on the surface of the backfill, (3) residual earth pressure induced by the compaction of the backfill, (4) earth pressure induced by the inertial forces, (5) earth pressure induced by the soil arching effect. While that under RBT mode mainly consist of the former four.

The test results of Sherif *et al.* (1982&1984) indicate that compaction will lead to the increase of the earth pressure [16, 17]. This increment of earth pressure is called residual earth pressure. Sherif *et al.* (1984) suggested that, the residual earth pressure coefficient caused by compaction at K_0 state, denoted by $K_{rh0,}$ can be estimated by the following equation [17]:

$$K_{rh.0} = 5.5(\gamma_{actual} / \gamma_{initial} - 1) \tag{7}$$

in which γ_{actual} is the actual unit weight of soil after compaction and $\gamma_{initial}$ is the unit weight due to dead weight of the backfill. In addition, their experimental results indicate that this part of earth pressure distributes linearly along the wall.

Based on the analysis of earth pressure model tests of Matsuo 1941, Ishii *et al.* 1960, Ichihara *et al.* 1973, Sherif *et al.* 1982&1984, Zhang *et al.* (1998) pointed out that this part of residual earth pressure varies with the lateral strain constraint of the backfill. The following equation is proposed by Zhang *et al.* (1998) to determine the relation between the residual earth pressure coefficient and the strain increment ratio [15]:

$$K_{rh} = K_{rh.o}(1 + R_\varepsilon)^{m_1} \quad (-1 \leq R_\varepsilon \leq 0) \tag{8}$$

in which m_1 is the parameter determined by experiments and can be taken as 1 approximately.

3. FORMULATION OF THE METHOD

3. 1. The Method for Rtt Mode

Earth pressure induced by the soil weight, surcharge and inertial forces can be obtained by the analysis of the force equilibrium of the "intermediate soil wedge", whose concept is proposed by Zhang *et al.* (1998) [15]. In this paper, the method of horizontal differential element is employed to calculate the earth pressure distribution because the experimental results of Fang *et al.* (1986) and Ishibashi *et al.* (1987) indicate that earth pressure distribution against retaining structures with RTT mode is significantly nonlinear [7, 9]. k_h and k_v are used to denote the horizontal and vertical earthquake coefficients respectively. In seismic conditions, in addition to static loads of the soil weight G and surcharge q_0, the soil wedge is also subject to $k_h G$, $k_v G$, $k_h q_0$ and $k_v q_0$. As is shown in Fig. (**3**), force equilibrium is made on a horizontal differential element taken from the soil wedge. The differential equation about q is established according to force and moment equilibrium conditions. The equation is solved and then the earth pressure distribution is obtained

Fig. (5). contd….

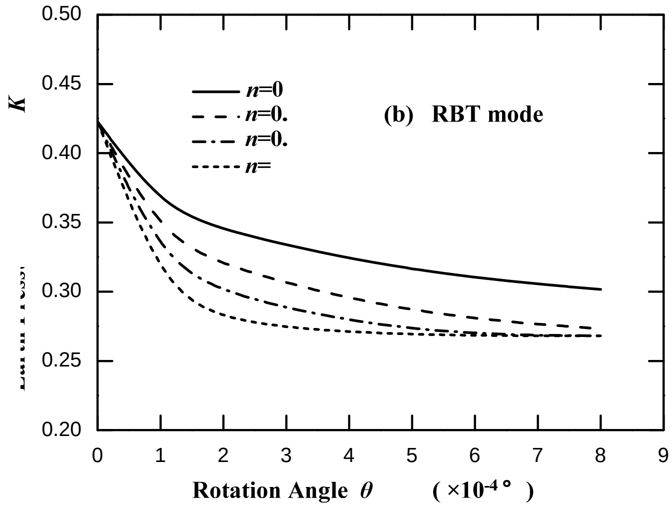

Fig. (5). A chart showing the variation of earth pressure coefficient with the parameter *n* ($k_h = 0.1$, $k_v = 0$, $\varphi' = 40^{\circ}$, $\delta = 0$)

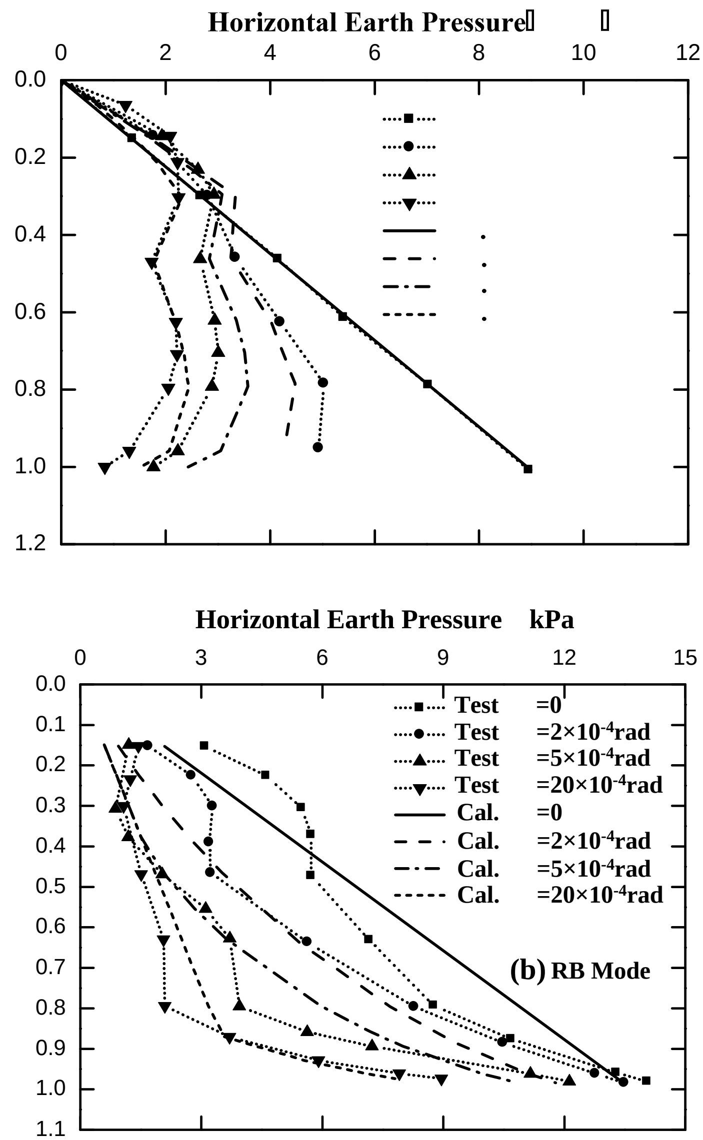

Fig. (6). Comparison of calculation results and experimental results of Fang *et al.* (1986) and Ishibashi *et al.* (1987): (a) RT mode (b) RB mode.

ranging from 1/4 to 1/3 of the wall height results in the increase of the earth pressure in this part. The earth pressure decreases in the lower part of the backfill due to the friction at the bottom of the wall. Therefore, the earth pressure distribution is the one shown in Fig. (**6a**). With the increase of the wall displacement, the soil arching effect gradually increases. The effectiveness of the method proposed for RBT method is also verified by the experimental results of Ishibashi *et al.* (1987). According to the test results, the parameters for the calculation by the RBT method are: $\gamma_{initial}$=15.21kN/m^3, γ_{actual}=16.43kN/m^3, $\triangle_a$=0.0003H, $\delta=\varphi'/2$, $\varphi'_{triaxial}$=40.1°, H=1.02m, k_h =0.215, k_v=0, n=0. It can be seen from Fig. (**6**) that the results obtained by the method proposed in the paper is basically consistent with the experimental results of Fang *et al.* (1986) and Ishibashi *et al.* (1987), showing the effectiveness of the method.

6. CONCLUSIONS

In this paper, the formation mechanism of earth pressures against rigid retaining structures under rotation mode is revealed. It is found out that under rotation mode due to the variation of lateral strain constraint along the wall, the proportion of compression to stress-dilatancy effect varies at different depths of the backfill. Therefore, the mobilized friction angle varies with different levels of compression-dilatancy coupling effect under different lateral strain constraints because of the rotation of the wall. On this basis a new method is developed for the evaluation of seismic earth pressures against rigid retaining structures with such mode and corresponding formulas are derived. Especially, for the RTT mode, the nonlinear distribution of earth pressure is considered by employing the method of horizontal differential element. Corresponding computer programs are written for the computation of seismic earth pressure distribution against rigid retaining structures with rotation mode. The method proposed in this paper has advantages over Mononobe-Okabe method because it can take into account of the effect of the amount and mode of wall movement on the earth pressure. Finally, the effectiveness of the proposed method is confirmed experimentally.

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DISCLOSURE

The major portion of this manuscript included in this article has been previously published in Advanced Materials Research (Volumes 168-170, 2011). This article is extended version/current knowledge on "Evaluation of Earth Pressures against Rigid Retaining Structures with RTT Mode" paper.

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