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Evaluation of Seismic Earth Pressures at the Passive Side

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ABSTRACT :

Estimation of seismic earth pressures constitutes an important subject of research in civil engineering. Previous studies showed strong dependence of earth pressure coefficient on lateral strain constraint of the backfill, i.e., the wall displacement has a significant effect on seismic earth pressures acting against retaining structures. Besides, experimental investigations and theoretical analysis indicate that when the backfill is at the passive side, the planar sliding surface assumption will overestimate earth resistance for higher wall friction angles, which will make structures such as sheet pile walls and their anchor blocks depending on earth pressures at the passive side for support underdesgned. In this paper, based on pseudo-static analysis and the concept of "intermediate soil wedge" with curved surface, a new methodology is developed to evaluate seismic earth pressures at the passive side under any boundary strain constraint for a rigid retaining structure with translational movement. It has the advantage over the Mononobe-Okabe method since it can take into account the effect of wall displacement on lateral earth pressures and the curved sliding surface is employed in the analysis. The approach can determine the seismic earth pressure coefficient of normally consolidated cohesionless soil under any lateral deformation between the isotropic compression and the passive states. Corresponding computer program is written to calculate the seismic earth pressure of a typical retaining wall system. The results are compared with those obtained based on the assumption of a planar sliding surface.

KEYWORDS: **Seismic earth pressure, intermediate soil wedge; curved sliding surface; pseudo-static analysis**

1. INTRODUCTION

Evaluation of seismic earth pressures is of practical significance for the earthquake resistant design of retaining structures such as retaining walls, sheet pile bulkheads, cofferdams, bridge abutments, and basement walls of buildings. Among the several approaches which have developed to solve the dynamic earth pressure problems (e.g., Okabe, 1924; Mononobe and Matsuo, 1929; Matsuo and Ohara, 1960; Ichihara and Matsuzawa, 1973; Wu and Finn, 1999; Richards et al., 1979&1999), the well known Mononobe-Okabe method based on pseudo-static analysis and limit equilibrium theory is still most widely used to determine the seismic earth pressure on a retaining structure due to its definite advantage of simplicity. The method is a modification of Coulomb's wedge theory by taking into account the inertia forces on a sliding soil wedge caused by earthquake accelerations. Its essential effectiveness in estimating the seismic active is confirmed by a number of experiments, field observations and predictions (Mononobe and Matsuo, 1929; Ishii et al. 1960; Ohara et al., 1970; Seed and Whitman, 1970; Sherif et al., 1982; Whitman, 1990&1991) .However, as in Coulomb' theory, the failure surface is assumed planar in the Mononobe-Okabe solution, regardless of the fact that the most critical sliding surface may be curved. Experimental investigations and theoretical analysis show that the most critical sliding surface is usually curved in the passive earth pressure case and the planar sliding surface assumption will seriously overestimate earth resistance especially for high wall friction angles. The Mononobe-Okabe method usually provides an unsafe prediction of the seismic passive resistance. Therefore, it is more suitable to employ the curved sliding surface in the analysis of earth pressure at the passive side (Terzaghi, 1943&1967; James and Bransby, 1970; Whitman and Christian, 1990). Many researchers have done a lot of experimental and theoretical researches in this field and developed some theories and methods for the determination of passive earth pressure (Chen and Liu 1990; Soubra and Kastner, 1991; Morison and Ebeling 1995; Soubra 2000; Kumar 2001; Subba Rao and Choudhury 2005). However, one of the basic requirements of all these theories and methods is that the wall should move sufficiently to create a limit-equilibrium state in the backfill, which means they are only suitable for determining the seismic earth pressure at the limit state. But this condition is not always satisfied. In many engineering practices, large deformation causing active or passive states cannot occur in the backfill behind a retaining structure so that the earth pressure may fall anywhere between active and passive pressures. Experimental evidences indicate that wall movement has significant effect on magnitude and distribution of lateral earth pressure (Terzaghi, 1934; Matsuo et al., 1978; Sherif et al., 1982&1984; Ishibashi et al., 1987; Fang et al., 1986&1994). So this important fact must be taken into consideration in seismic resistant design of retaining structures. Based on the analysis of the strain path test results, Zhang et al.（1998） established the relation between the lateral earth pressure coefficient and the strain increment ratio and developed a new theory for determining the lateral earth pressure between the active and passive states. By employing the concept "intermediate soil wedge" which depends on mobilized frictional resistance, Zhang et al. extended Mononobe-Okabe method to new earth pressure formulas for determining the dynamic lateral earth pressure under any lateral deformation. The method has undoubted theoretical basis and clear physical concepts and is easy for application because of its simplicity. However, as has been discussed previously, the intermediate soil wedge with the planar sliding surface assumption will result in higher earth resistance at the passive side and the overestimation may be very serious especially when the soil-wall interface is rough. Structures such as sheet pile walls and their anchor blocks depend on earth pressures at the passive side for support. If the supporting pressures are unconservative, the structure may be underdesigned.

In the present technical note, the previous "intermediate soil wedge" depending on mobilized frictional resistance with the planar sliding surface (Zhang et al, 1998) is modified to one with the sliding surface as a combination of a logarithmic spiral and a straight line when the wall movement renders the backfill at the passive side. On the basis a new pseudo-static methodology of analysis is developed to determine lateral earth pressures for any intermediate state form isotropic compression to passive conditions for a rigid retaining structure with translational movement. A research computer program is written to calculate the seismic earth pressure coefficient and the results are analyzed and compared with those obtained using a planar sliding surface.

2. FORMULATION OF THE METHOD

The backfill soil may extend or compress with the wall displacement, which makes the soil under different strain constraints. Roscoe (1970) emphasized the importance of strain influence on earth pressures. The model test results of James and Bransby (1970) indicated that the mobilized wall fricion angle and internal friction angle of the soil are different under different wall movements, leading to the change of earth pressures acting on retaining structures. The dependence of the coefficient of lateral earth pressure on the strain increment ratio was studied and on the basis the formation mechanism of earth pressure was discussed by Zhang et al. (1998).
Lateral strain parameter R is used to represent the lateral deformation of the soil, which is caused by the wall displacement. The relation between the soil lateral strain parameter R and the wall displacement $\triangle$ can be estimated by the formulas proposed by Zhang et al. (1998):

$$R=\begin{cases}-\left(\dfrac{|\Delta|}{\Delta_a}\right)^a & (-\Delta_a \le \Delta \le 0)\\ -1 & (\Delta < -\Delta_a)\end{cases} \tag{2.1}$$

$$R=\begin{cases}3\left(\dfrac{\Delta}{\Delta_p}\right)^p & (0 \le \Delta \le \Delta_p)\\ 3 & (\Delta > \Delta_p)\end{cases} \tag{2.2}$$

In the above equations wall displacement $\triangle$ is prescribed minus when its direction is away from the backfill while positive when its direction is toward the backfill. $\triangle_a$ and $\triangle_p$ represent wall displacements required to develop active and passive earth pressures respectively and can be estimated by the available experimental results (Terzaghi 1934, Mastuo et al. 1978; Sherif et al. 1982 & 1984, Fang et al. 1986 & 1994, Terashi et al.1991, Ishihara et al. 1995). a and p are constants changing within the ranges: $0 < a < 1$ and $0 < p < 1$ and both are recommended to take around 0.5. When the wall displacement makes the backfill soil fall between active and isotropic compression states, R changes within the range:$-1 \leqslant R \leqslant 1$. While for an intermediate stress state between isotropic compression and passive stress states, there is $1 \leqslant R \leqslant 3$.

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):

$$\delta_{mob} = \left(\frac{1-R}{2}\right)^{k_1} \cdot \delta_a \qquad (-1 \le R \le 1) \tag{2.3}$$

$$\delta_{mob} = \left(\frac{R-1}{2}\right)^{k_2} \cdot \delta_p \qquad (1 \le R \le 3) \tag{2.4}$$

Where k_1 and k_2 are exponents determined by tests and they can be assigned a value of unity, i.e., k_1=k_2=1, if the change in δ_{mob} with R is assumed linear. In the equations δ_a and δ_p represent wall friction angles mobilized at active and passive states respectively.

Zhang et al.(1998) investigated the dependence of the lateral earth pressure coefficient on the strain increment ratio based on a series of strain path tests and established the relation between the earth pressure coefficient K and the lateral strain parameter R.

$$K = \frac{K_0}{1-(1-K_0)R} \qquad (-1 \le R \le 1) \tag{2.5}$$

$$K = 1 + \frac{K_p - 1}{2}(R-1) \qquad (1 \le R \le 3) \tag{2.6}$$

In which K_0 is the earth pressure coefficient at rest and K_p is the passive earth pressure coefficient. When R-value is –1 or 3, the backfill is at the active or passive state and the corresponding earth pressure coefficient is the active earth pressure coefficient K_a or the passive one K_p. When R value is 1, the soil is at the isotropic compression stress state and the earth pressure coefficient is 1 for isotropic soils.

Based the equation (5) and (6) Zhang et al.(1998) extended Mononobe-Okabe theory to evaluate the seismic earth pressure for retaining walls under any lateral displacement. However, as has been discussed, for the stress state of backfill soil between isotropic compression and passive states, with the increase of wall displacement and mobilized wall friction angle it is more rational to employ the intermediate sliding wedge with the curved surface for the evaluation of seismic earth pressure. Therefore, a modified method using curved sliding surfaces based on the pseudo-static concept is adopted for the computation of the seismic earth pressure coefficients at the passive side. The soil-wall and the dynamic intermediate soil wedge at the passive side for the analysis is given in Fig. 1. A dry, homogeneous, and isotropic cohesionless backfill with surcharge is assumed in the analysis. It's required to estimate the magnitude of seismic earth pressure against a rigid retaining structure of vertical height H with an inclination α to the vertical, as shown in Fig. 1, in the presence of horizontal earthquake acceleration $k_h \cdot g$ and vertical earthquake acceleration $k_v \cdot g$. The ground surface is horizontal. The mobilized wall friction angle δ_{mob} increases with the increase of wall displacement. Horizontal and vertical seismic coefficients k_h and k_v can be determined based on an equivalent seismic coefficient (Zhang et al. 1998) for considering the non-uniform seismic acceleration distribution with height of the backfill soil. Investigations show that there is a considerable reduction in the shearing resistance of the soil when the average ground acceleration exceeds a certain critical value (Okamoto, 1956; Richards, 1990). In the present analysis it is assumed that the basic soil parameters: unit weight γ and internal friction angle φ are not affected by the occurrence of an earthquake. So the seismic earth pressure coefficients presented in this technical note is only applicable for earthquake acceleration magnitude less than such critical values.

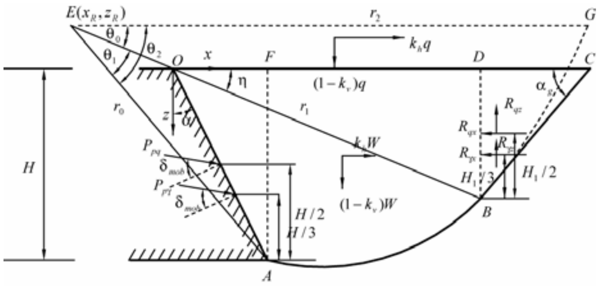
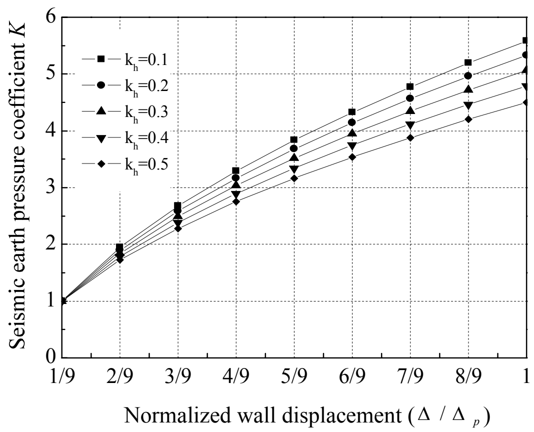


Fig. 1. Dynamic intermediate soil wedge with curved surface

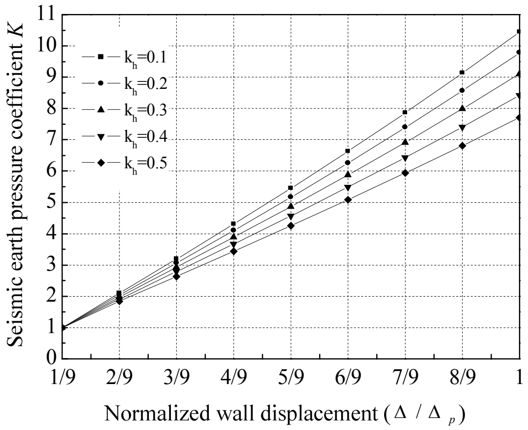
If the wall moves toward the backfill while its displacement is not large enough and does not reach $\triangle_p$, the shear strength of the backfill soil is not able to be fully mobilized, and therefore, a passive soil wedge cannot be formed behind the wall. However, in principle, a soil wedge producing the maximum lateral earth pressure against the wall exists for any given level of wall displacement. This soil wedge at the passive side is therefore called an "intermediate sliding wedge" with a curved surface, as shown in Fig. 1. The sliding surface of the intermediate soil wedge *OABCO* is assumed to be of a composite shape comprising an arc of the logarithmic spiral *AB* and a straight line *BC* near the ground. In this case, mobilized internal friction angle of soil on the composite sliding surface and wall friction angle mobilized are designated by φ_{mob} and δ_{mob}. The seismic earth pressure coefficient at the passive side can be evaluated by the equation (2.6). However, as is pointed out, the seismic passive earth pressure coefficient K_p in equation (2.6) shouldn't be determined by Mononobe-Okabe theory based on planar sliding surface assumption, but should be estimated by the methods based on curved sliding surface. The method proposed by Kumar (2000) is modified and extended to include the earth pressure produced by the following three parts: (Ⅰ) vertical inertial body force $k_v \cdot W$, where W is the weight of soil wedge *OABCO*; (Ⅱ) surcharge $q \cdot OC$; (Ⅲ) pseudo-static forces $k_h \cdot q \cdot OC$ and $k_v \cdot q \cdot OC$. The detailed derivation is not given here due to the limitation of the article length. And it should be noted that the wall friction angle δ in the method should be substituted by the mobilized wall friction angle δ_{mob} estimated by equation (2.4). The seismic passive earth coefficient K_p in equation (2.6) can be obtained by this modified method. The method developed in this article is suitable for the estimation of seismic earth pressures at the passive side acting on rigid retaining structures against isotropic normally consolidated cohesionless soil.

3. DISCUSSION AND COMPARISON OF RESULTS

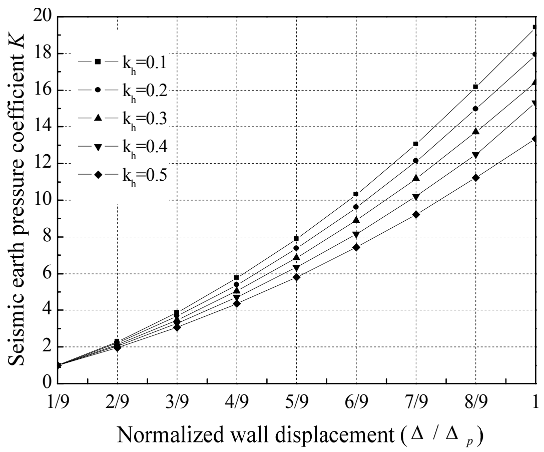
Corresponding computer code is written based on the methodology developed above. The variation of seismic earth pressure coefficient at the passive side with horizontal seismic coefficient and wall friction angle for φ=45°, k_v=0 and α=0° is presented in Fig 2.



(a) δ_p=0



(b) $\delta_p=\varphi/3$

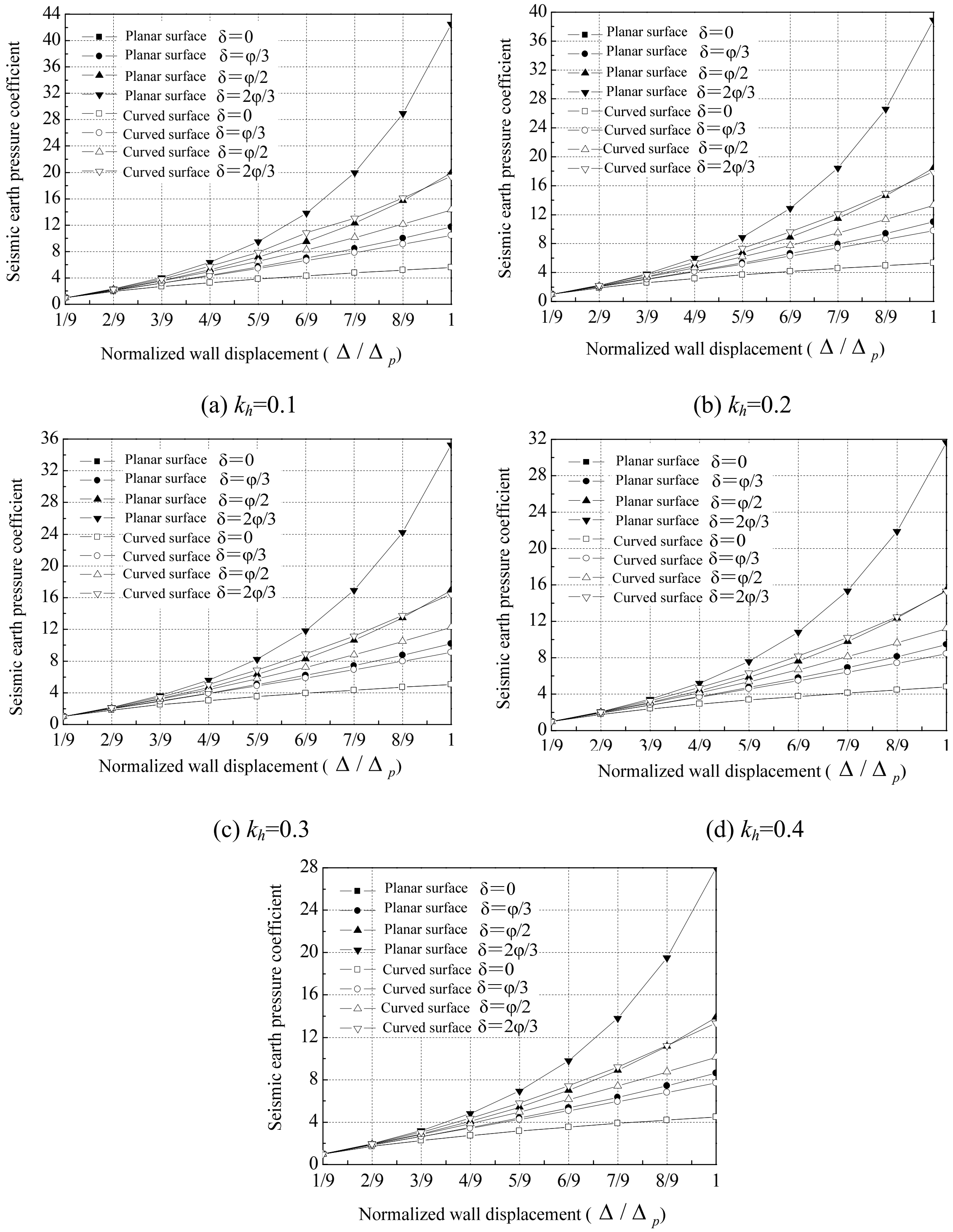


(c) $\delta_p=2\varphi/3$

Figure 2 Seismic earth pressure coefficients at the passive side

It can be seen from Fig 2 that when the wall displacement toward the backfill soil makes it fall between isotropic compression and passive states ($1\leqslant R\leqslant 3$),with the increase of wall displacement level the shear strength of soil and wall friction angle is increasingly mobilized, leading to the increase of the seismic earth pressure coefficient . When $\triangle=\triangle_p/9$, R=1, the backfill is at the isotropic compression state and the earth pressure coefficient is 1 and when $\triangle=\triangle_p$, R=3, the backfill is at the passive state and the earth pressure coefficient is the passive earth pressure coefficient based on composite sliding surface. Seismic earth pressure coefficient at the passive side decreases with increase in k_h and decrease in δ_p.

In order to study the effect of the shape of the sliding surface on the evaluation of seismic earth pressure coefficients, a comparison is made of seismic earth pressure coefficient values at the passive side obtained from present study and those based on the planar sliding surface with respect to different horizontal seismic coefficients for φ=45°, α=0° , k_v=0, which is shown in Fig. 3.



(a) k_h=0.1

(b) k_h=0.2

(c) k_h=0.3

(d) k_h=0.4

(e) k_h=0.5

Fig 3 Comparison of seismic earth pressure coefficients for φ=45°, α=0° , k_v=0

It can be seen from Fig.3 that when δ_p=0, the results obtained by both methods are identical because in this case the focus of the log spiral locates in the infinite distance from the top of the wall and the curvature of the sliding surface is very small and so the curved surface can be regarded nearly as planar. However, when δ_p is not zero, the error resulted from planar intermediate sliding wedge gradually increases when the shear strength of the soil and wall friction angle are increasingly mobilized with the increase of wall displacement. When the wall friction angle and the wall displacement are small, i.e., $\delta_p < \phi/2$ or $\triangle<4<\triangle_p/9$, the results based on planar sliding surface assumption can satisfy the precision request of the engineering. When the wall friction angle and the wall displacement are large, the backfill soil approaches the passive limit state, and it is reasonable for the engineers to divide the calculation results based on the planar sliding surface by a proper safety factor in practical design. The seismic earth pressure coefficients after reduction is similar to the ones obtained on the basis of curved or composite sliding surface.

4. CONCLUSIONS

A new methodology is developed in this technical note to evaluate the seismic earth pressure coefficients for normally consolidated cohesionless backfill under any lateral deformation between the isotropic compression and passive states. The present method has the advantage over the method proposed by Zhang et al. (1998) since it is based on the concept of "intermediate soil wedge" with curved sliding surface. Calculation results show that when the wall friction angle and wall displacement are large, the seismic earth pressure coefficients at the passive side obtained by the present method are appreciably smaller than those got based on planar surface assumption, which means that the error due to planar assumption is always on the unsafe side while the proposed method is more reasonable for this case. By the comparison with results based on sliding wedge with planar surface, it is found that when the wall friction angle and wall displacement is large, it's reasonable to divide the calculation results based on the planar sliding surface by a proper safety factor in engineering practices.

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