On the Failure of Retaining Walls under Seismic Loading

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1. Introduction

The classical theory of plasticity, represented by Kötter's equation, has been established for static problems. Although this theory can be easily extended for dynamic plasticity problems by introducing accelerations as inertia forces, up to now no researcher has done this because of the difficulty in determining the acceleration distribution within the body when the failure occurs. The objective of this research is to develop Generalized Limit Equilibrium Method (GLEM) with the introduction of continuity condition of acceleration to investigate the following cases of potential failures of retaining structures: active failure, foundation-like failure, and slope-like failure, under a seismic loading, where the GLEM is one of the limit equilibrium methods proposed by Enoki at al.[1].

2. Continuity Condition of Acceleration (CCA)

When the relative sliding between the plastic bodies occurs, the relative acceleration vector is considered to be parallel with the apparent slip plane as shown in Fig. 1. Thus, the continuity condition of acceleration is derived as the expression in Fig. 1, in which ν is the dilatancy angle. In this paper, ν=0 is assumed, then vector $\Delta\alpha$ is parallel with the actual slip plane.

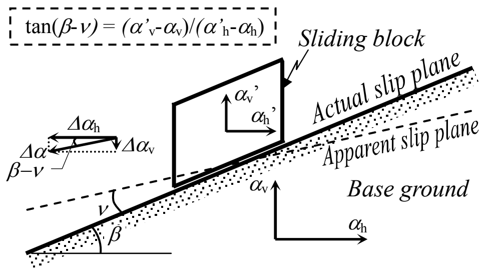

Fig. 1. Continuity condition of acceleration.

3. Formulation of Dynamic GLEM

Fig. 2, 3 and 4 show the computing models of a retaining wall subjected to seismic loadings corresponding to three cases of failures: active failure (a), failure of retaining wall as a foundation problem (b), and failure of the wall as a slope problem (c). In mode (a), the wall is considered to move outwards relative to sub-base, and causes the active earth pressure. In mode (b), the base supporting the wall is failed and both wall and sub-base slide outwards. In mode (c), both the sub-base and backfill are failed and the system slides outwards. The failed soil mass is considered as a rigid-plastic block system. Either triangular or quadrangular blocks can be used.

Before the sliding occurs, the acceleration of every soil block is the same as the acceleration of the sub-base. The equilibrium equations of every block, the failure conditions on the inter-block planes and bottom planes are used to obtain the force field.

When the sliding occurs, the accelerations of blocks are different from each other and from the sub-base. The equilibrium equations of every block, the failure conditions, and continuity conditions of acceleration on both inter-block planes and bottom planes are used. The number of unknowns and the number of equations are shown in Table 1. The sliding acceleration of the wall is minimized to obtain the geometry of the sliding surface. The classical Newton method is used herein to optimize the function value.

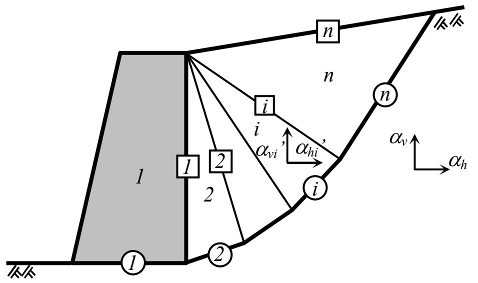

Fig. 2. Active failure (a)

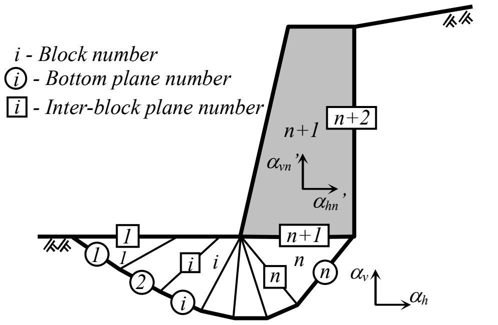

Fig. 3. Foundation-like failure (b)

4. Numerical Examples

A strip retaining wall with a mass of 25t, a height of 5m, and a width of 3m is considered. The frictional angle of back surface of the wall is 11°. The backfill and soil base have the parameters as ϕ=32°, c=0.11tf/m^2, γ=1.6tf/m^3. A sinusoidal wave is used as the input acceleration, which has the frequency of 2Hz, the amplitude of horizontal component is 6m/s^2, the vertical component equals zero. For the simplicity, the dilatancy angle is considered to be zero, and the surface of the backfill is horizontal. Four cases of analysis were carried out: case a1 - active failure mode was taken with the frictional angle of the bottom plane of the wall, δ, is 17°; case a2 - active failure mode was taken with the frictional angle of the bottom plane of the wall is 32°; case b - foundation-like failure mode was taken; and case c

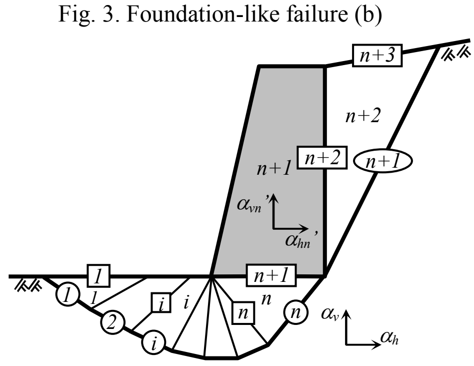

Fig. 4. Slope-like failure (c)

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- slope-like failure mode was taken.

The results of analyses are presented in Fig. 5 and 6. It can be seen from Fig. 5 that the solutions of the active failure mode are very different with the change of δ. When δ=17°, the active failure occurs earlier than foundation-like failure mode (case b) and slope-like failure (case c), and it is in opposite situation for the case δ=32°. The graph also indicates that the foundation-like failure occurs later than slope-like failure in this analysis. As stated in [2], the Fig. 6 once again shows the comparison between the proposed method and Mononobe-Okabe method (M-O) [3] for the dynamic earth pressures. It is clear to realize that, corresponding to the sliding process, the M-O method has overestimated the earth pressure.

Table 1: The number of equations and unknowns

Equations				Unknowns			
Equilibrium conditions	*(a)*	*(b)*	*(c)*	*On bottom planes*	*(a)*	*(b)*	*(c)*
In vertical direction	n	$n+1$	$n+2$	Normal forces	n	n	$n+1$
In horizontal direction	n	$n+1$	$n+2$	Shear forces	n	n	$n+1$
Failure conditions				*On inter-block planes*			
On bottom planes	n	n	$n+1$	Normal forces	$n-1$	$n+1$	$n+1$
On inter-block planes	$n-1$	$n+1$	$n+1$	Shear forces	$n-1$	$n+1$	$n+1$
CCA				*Block accelerations*			
On bottom planes	n	n	$n+1$	α_{vi}'	n	$n+1$	$n+2$
On inter-block planes	$n-1$	$n+1$	$n+1$	α_{hi}'	n	$n+1$	$n+2$
Total	$6n-2$	$6n+4$	$6n+8$		$6n-2$	$6n+4$	$6n+8$

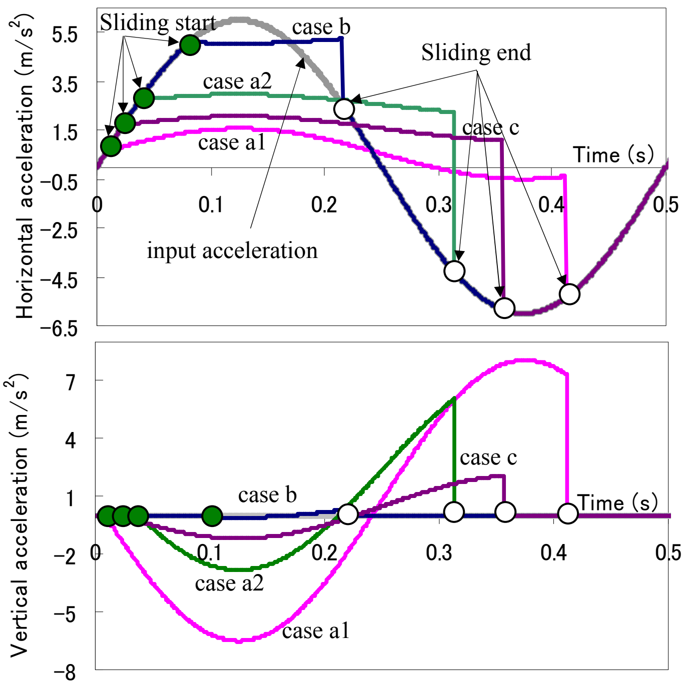

Fig. 5. Accelerations corresponding to analyzed cases

5. Effect of Roughness of Wall-bottom Surface

An investigation on the relation between the frictional angle of the wall-bottom surface and the critical acceleration, at which the sliding starts to occur, was carried out. The analysis condition is the same as the example above. The interrelation between δ and the critical accelerations corresponding to every failure mode is presented in Fig. 7. In this analysis, when δ<25.47°, the failure mode likely to happen is active failure. When δ>25.47°, the failure mode likely to happen is slope-like failure. The wall seems to be safe with foundation-like failure.

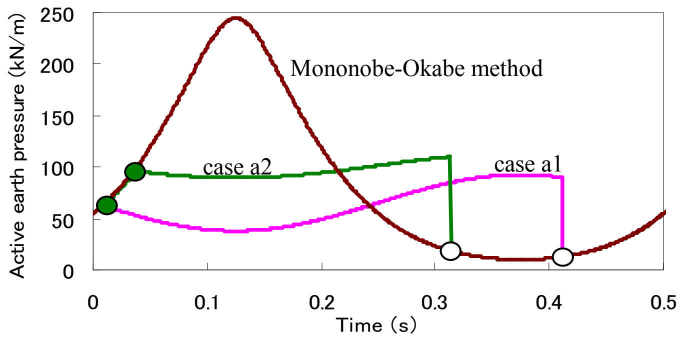

Fig. 6. Dynamic active earth pressure

6. Conclusions

The continuity condition of acceleration, which governs the distribution of acceleration within the rigid-plastic body when the failure occurs, was discovered and applied in the calculation procedure. The formulation of the GLEM for dynamic problems concerning retaining wall was established. The dynamic earth pressure as well as the motion of every part of the structure under seismic loadings was analyzed.

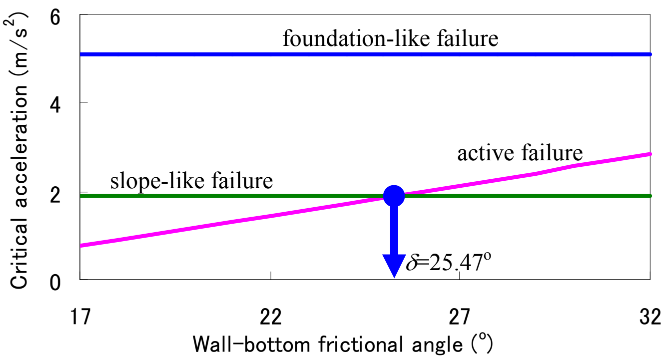

Fig. 7. Bottom surface roughness of the wall and failure modes

References

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