Seismic stability analysis of quay walls: Effect of vertical motion

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ABSTRACT

Repeated observations from recent earthquakes show that the vertical ground acceleration can be amplified significantly and even become greater than its horizontal counterpart in certain situations, raising great concern over the potential effect of vertical acceleration on engineering structures. This paper addresses this issue for quay walls using the pseudostatic approach. The earth pressure and the resistance of quay walls to sliding and overturning are investigated for various combinations of horizontal and vertical seismic loading. The results show that while the effect of vertical acceleration is insignificant on the active earth pressure on the quay wall, it should not be overlooked in the stability analysis of the wall.

1 INTRODUCTION

Seismic design and analysis of earth structures (e.g. embankments, retaining walls, and slopes) has tended to focus on the effect of horizontal ground motion and simply disregard the vertical motion. This practice has come from the consideration that engineering structures have adequate resistance to dynamic forces induced by the vertical ground motion, which is generally smaller in magnitude and richer in high frequencies than its horizontal counterpart. If the effect of vertical motion is explicitly included in earthquake-resistant design, it is typically assumed that the ratio of vertical to horizontal (V/H) response spectra will not exceed two-thirds over the range of periods of interest (UBC, 1997); in the pseudo-static analyses, the peak vertical acceleration is usually assumed to be a half or two-thirds of the peak horizontal acceleration (Day, 2002).

In several recent earthquakes, large vertical accelerations have repeatedly been recorded, indicating that the rule-of-thumb ratio between peak vertical and horizontal ground acceleration may not be a good descriptor. For example, the peak vertical acceleration at the surface of a reclaimed site during the 1995 Kobe earthquake was found to be *twice* as high as the peak horizontal acceleration (Yang & Sato, 2000). It has been shown that ground motion amplification in vertical direction can significantly be affected by groundwater conditions (Yang & Sato, 2001; Yang, 2006). These observations suggest that various possible combinations of the groundwater and ground motion conditions need to be examined to find out a particularly severe state of hazard for earth structures. This study is aimed to explore the possible effect of vertical acceleration with regard to the seismic stability of quay walls, by taking into account a wide range of magnitudes of the vertical and horizontal accelerations. Effort is made to show how significant the effect could be on the factor of safety against sliding and overturning.

2 METHOD OF ANALYSIS

The pseudostatic approach is widely used in seismic design of earth structures. In this approach, the effects of earthquake are represented by pseudostatic forces, F_h and F_v, in the following form:

$$F_h = \frac{a_h W}{g} = k_h W \qquad F_v = \frac{a_v W}{g} = k_v W \tag{1}$$

where k_h and k_v are known as horizontal and vertical pseudostatic seismic coefficients, and W is the weight of sliding wedge or sliding wall. The vertical and horizontal inertial forces can act upward or downward and toward or away from the retaining wall during earthquakes. In this study the seismic coefficients are assumed positive when they point upward and away from the wall.

The earth pressure on a retaining wall due to dry backfill is usually estimated using the Mononobe-Okabe equation (e.g. Day, 2002), which was derived by modifying Coulomb's classical earth pressure theory to account for inertial forces. For a vertical wall retaining a horizontal backfill (Figure 1), the total active earth thrust P_{ae} is given by:

$$P_{ae} = \frac{1}{2}\gamma_d H^2 (1 - k_v) K_{ae} \tag{2}$$

where

$$K_{ae} = \frac{\cos^2(\phi - \psi)}{\cos\psi \cos(\delta_{wall} + \psi)\left[1 + \sqrt{\dfrac{\sin(\delta_{wall} + \phi)\sin(\phi - \psi)}{\cos(\delta_{wall} + \psi)}}\right]^2} \tag{3}$$

γ_d and ϕ are the unit weight and internal friction angle of the dry backfill, δ_{wall} is the angle of friction between the backfill and the wall, and ψ is defined as $\psi = \tan^{-1}[k_h/(1-k_v)]$. The exact point of application of the total earth pressure depends on the movement of the wall and is difficult to determine. Practically, it can be evaluated by combining the static and dynamic earth pressure components (Seed & Whitman, 1970).

When Mononobe-Okabe method is applied to submerged backfill soil as in the case of quay walls shown in Figure 1, two modifications are required. The vertical inertial force $(1-k_v)\gamma_d$ is replaced by $(1-k_v)\gamma_{sub}$, where γ_{sub} is the submerged unit weight of soil. The angle of seismic coefficient ψ should be replaced by ψ', the angle of seismic coefficient for submerged conditions. Note that ψ' depends on soil properties such as void ratio and permeability. For highly permeable backfill soil (gravelly and coarse sandy soil), pore water can move freely in the voids, and the horizontal inertial force is proportional to the dry unit weight γ_d of the soil. Therefore, the angle of seismic coefficient is given by

$$\tan\psi' = \frac{\gamma_d}{\gamma_{sub}} \frac{k_h}{1-k_v} = \frac{G_s}{G_s - 1}\tan\psi \tag{4}$$

where G_s is the specific gravity of soil particles. When using the above equation, both static and dynamic water pressures in the backfill should be considered (the excess pore water pressure is however beyond the scope of the present study). The approximate solution for dynamic water pressure of free stand water along vertical wall caused by a horizontal earthquake motion (Westergaard, 1933) is used here:

$$P_{wd} = \frac{7}{12} k_h \gamma_w H_w^2 \tag{5}$$

where γ_w is the unit weight of water and H_w is the depth of water. The forces acting on the quay wall are shown in Figure 1.

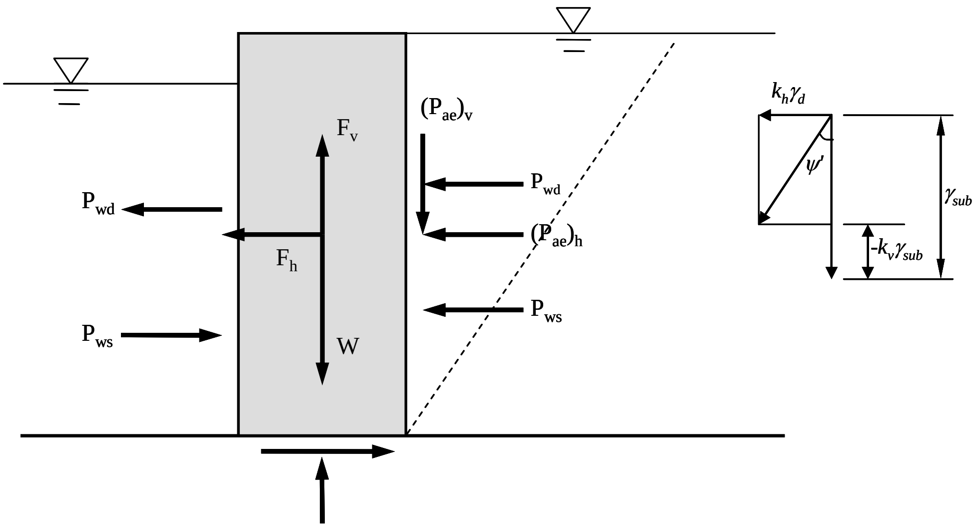


Figure 1: Quay wall model

3 RESULTS OF ANALYSIS

An illustrative example of caisson type quay walls for analysis is shown in Figure 2. The properties of the backfill soil and the dimensions of the concrete caisson are given in the figure. The angle of friction between the wall and the backfill is assumed to be 17.5°, and the angle of friction at the base of the wall is assumed to be 35°. The value of k_v / k_h is varied from (-1.5) to 1.5 to examine the influence of vertical acceleration. The results for the total active earth pressure are shown in Figure 3. The calculated values of the factor of safety against sliding and against overturning are shown in Figure 4 for various combinations of vertical and horizontal accelerations.

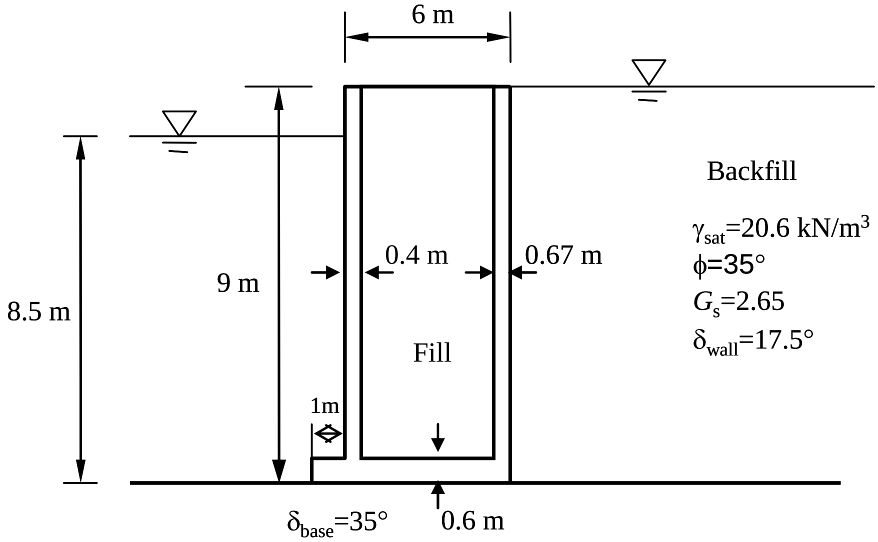


Figure 2: Illustrative example (not to scale)

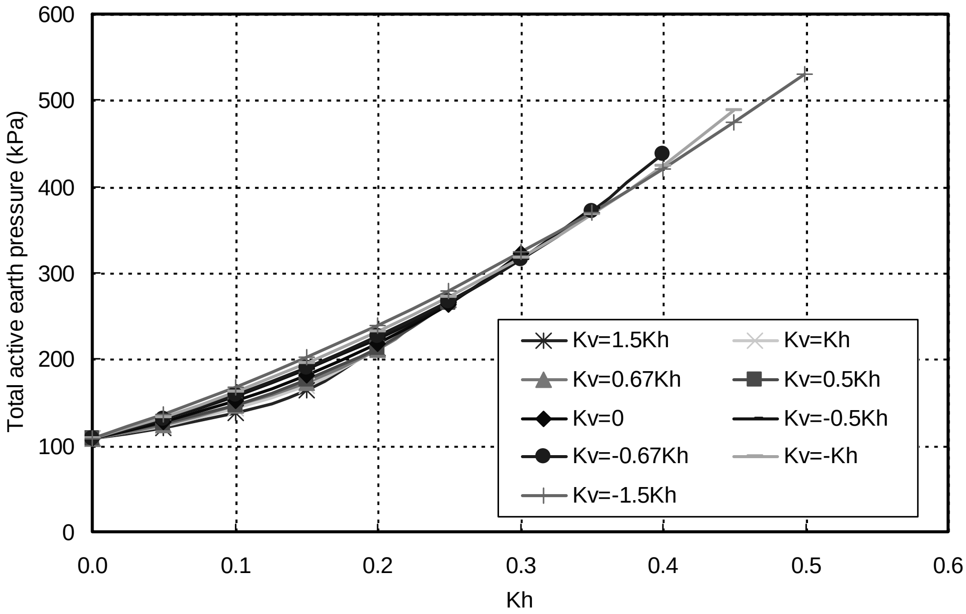
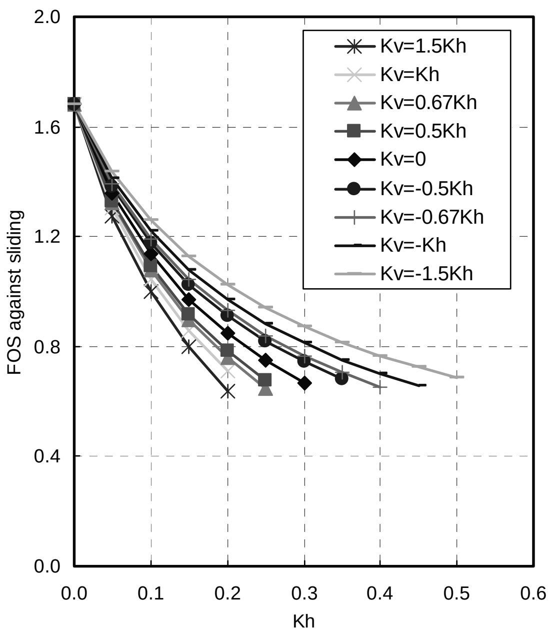
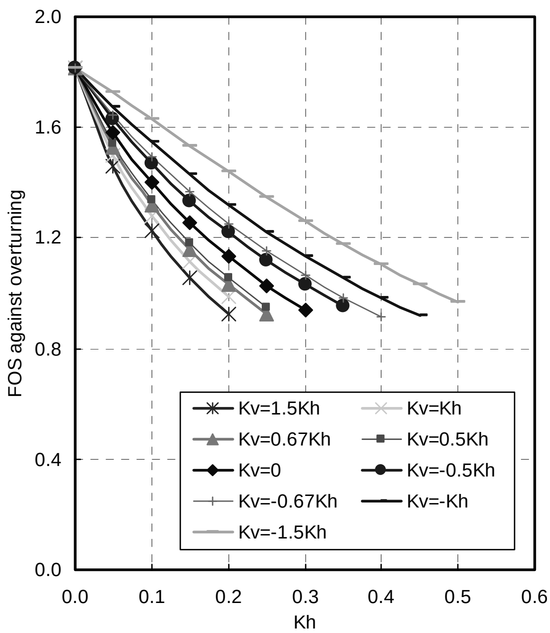


Figure 3: Effect of vertical acceleration on active earth pressure



(a)



(b)

Figure 4: Effect of vertical acceleration on factory of safety against (a) sliding and (b) overturning

The results in Figure 3 indicate that as k_v increases from -1.5k_h to 1.5k_h, the total active earth pressure decreases. This is because when k_v increases, the effect of increase in the angle of seismic coefficient is smaller than the effect of decrease of the factor (1-k_v) applied to the unit weight of soil, thus giving a lower total active earth pressure. Interestingly, when k_h becomes large (e.g. greater than 0.3), the above situation is reversed. However, the effect of k_v on the total active earth pressure is generally insignificant and may be ignored.

On the other hand, the effect of k_v is found to be significant on the factor of safety against sliding and overturning. When k_v increases, the safety factor decreases. This is because that as k_v

increases, the effect of the decrease of stabilizing frictional resistance due to the upward inertia force is larger than the effect of the decrease of destabilizing total active earth pressure. Therefore, the net effect is that the factors of safety decreases.

4 CONCLUSIONS

This paper discusses the possible effect of vertical acceleration that has been ignored in the current practice of seismic design of earth structures. Using the pseudostatic approach, an analysis has been conducted of a caisson type quay wall. The results have shown that while the effect of vertical acceleration is insignificant on the active earth pressure on the quay wall, it should not be overlooked in the stability analysis of the wall.

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