Displacement – Based Seismic Active Earth Pressure on Rigid Retaining Walls

Deepankar Choudhury
Assistant Professor, Department of Civil Engineering, Indian Institute of Technology Bombay, Powai, Mumbai – 400 076, India
dc@civil.iitb.ac.in

and

Santiram Chatterjee
Post Graduate Student, Department of Civil Engineering, Indian Institute of Technology Bombay, Powai, Mumbai – 400 076, India
santiram@iitb.ac.in

ABSTRACT

For designing retaining walls in earthquake prone region, knowledge of seismic active earth pressure is very important. Similar to the static case, during seismic condition also, the mobilization of seismic active earth pressure depends on the amount and mode of wall movement. Very few researchers have done studies on model retaining walls to estimate the mobilized seismic active earth pressure depending on the mode and amount of wall movement. Based on the available experimental data of earlier researchers, in this paper, a semi-empirical method is proposed that can easily be used in practice to compute the seismic active earth pressure for various magnitudes of wall movements for the walls rotating about the top and bottom. The practical use of the proposed equations is shown through a worked-out example and is compared with the conventional Mononobe-Okabe method.

KEYWORDS: seismic active earth pressure, mobilization, mode of wall movement, semi-empirical method.

INTRODUCTION

For the safe design of retaining walls in the earthquake-prone zone, correct estimation of seismic active earth pressure and its distribution along the depth of the wall is very important. Several researchers have developed several methods to determine the seismic active earth pressure on a rigid retaining wall due to earthquake loading. Works done by Okabe (1926), Mononobe and Matsuo (1929), Sherif et al. (1982), Richards et al. (1999), Saran and Gupta (2003), Choudhury and Singh (2006) and many others had given
some solutions for estimating seismic active earth pressure on rigid retaining wall. Most of the available analytical solutions are based on forced-based analysis, which assumes full mobilization of seismic active earth pressure. But the mobilization of active earth pressure depends very much on mode and amount of wall movement both under static and seismic conditions. Though for active case very small movement is required for full mobilization, for some cases even this small amount of movement does not occur. In those cases, the actual value of seismic active earth pressure is in between fully mobilized active pressure and earth pressure at rest. Choudhury and Subba Rao (2002) had proposed a semi-empirical method to estimate displacement-based active earth pressure for various modes of wall movements under static condition. But such a simplified method for seismic condition is still scarce.

In this paper, a semi-empirical method for correct estimation of displacement-based seismic active earth pressure is proposed. Experimental results obtained by Sherif and Fang (1984a, b) and Ishibashi and Fang (1987) are used in the present study. These experimental results are available for a number of tests on model retaining walls, retaining different types of sand with varying values of horizontal seismic accelerations (khg). The reported values of the seismic active earth pressure distribution varying with depth and level of displacement for rotation about top and bottom modes of wall movements, have been used in the present analysis.

**PROPOSED METHOD**

Figure 1a shows a typical rigid retaining wall rotating about top. Let, $\Delta$ be the amount of wall displacement at any depth $z$ and $\Delta_a$ is the amount of displacement, which is required for full mobilization of seismic active earth pressure. $D$ is the total height of the retaining wall. The displacement at the base of the wall is denoted by $\Delta_b$ for rotation about the top (RT) mode. Similarly in Figure 1b, a typical rigid retaining wall rotating about the bottom is shown. Here, $\Delta_t$ is the displacement of the wall at top for rotation about the bottom (RB) mode of wall movement. The assumption for RT mode is that the wall displacement, $\Delta$ is a linear function of depth $z$. At the bottom when $\Delta_b = \Delta_a$, the mobilized soil friction angle $\phi_m$ will be zero at the top and full value of soil friction angle, $\phi$ at the bottom. For $\Delta_b < \Delta_a$, $\phi_m < \phi$ at the bottom and $\phi_m = 0$ at the top. For RB mode also, $\Delta$ is assumed to be linear function of depth $z$. At the top when $\Delta_t = \Delta_a$, the mobilized friction angle $\phi_m$ will be zero at the bottom and full value of $\phi$ at the top. For $\Delta_t < \Delta_a$, $\phi_m < \phi$ at the top and $\phi_m = 0$ at the bottom.

![Figure 1](http://www.ejge.com/2006/Ppr0660/Ppr0660.htm)
Rotation about the Top (RT)

The experimental results reported by Sherif and Fang (1984a) and Ishibashi and Fang (1987) for seismic active earth pressure distribution along the depth of the wall for RT mode with various wall movements are used in the present semi-empirical approach. The steps used in the present analysis are as follows,

(a) The mobilized seismic active earth pressure coefficient $K_{ae}$ at any depth is calculated as:

$$K_{ae} = \frac{\sigma_{ane}}{\gamma z (1 - k_v)} \quad (1)$$

where $\sigma_{ane}$ is the measured normal seismic earth pressure at any depth, $z$, $\gamma$ is the unit weight of soil, and $k_v$ is the vertical seismic coefficient.

(b) Using Mononobe-Okabe equation (see Kramer, 1996), mobilized soil friction angle, $\phi_m$ is obtained for corresponding $K_{ae}$.

(c) In the full mobilization case, at the base $\Delta_b = \Delta_a$, so $\phi_m = \phi$ at the base and at top $\phi_m = 0$. Therefore, correction factor at the base is $\phi/\phi_{cal}$ and at the top is zero. By assuming linear variation of the correction factor, the calculated values of $\phi_m$ are corrected.

(d) Finally all results are expressed in terms of two non-dimensional parameters viz.

$$x = \left(\frac{\Delta}{\Delta_a}\right) \left[15.0k_h^3 - 8.9k_h^2 + 2.1k_h + 0.7\right] \quad (2)$$

$$y = \left[\left(\phi_m / \phi\right) / \left(\Delta / \Delta_a\right)\right] \quad (3)$$

where, $k_h$ is the horizontal seismic acceleration coefficient.

(e) The values of ‘$y$’ thus obtained are plotted for different values of ‘$x$’ as shown in Figure 2 and it is found that all the points are falling within a narrow band after using iterative normalization technique and fitted with a linear curve $y = x$ with regression coefficient of 0.97.
Figure 2. Proposed semi-empirical relationship between mobilized soil friction angle, wall movement and seismic acceleration coefficient for RT mode.

Table 1. Typical calculation to obtain mobilized friction angle (RT mode)  
(Experimental data are taken from Sherif and Fang (1984b)

$\gamma = 15.97 \text{kN/m}^3$, $\phi = 39.3^\circ$, $\delta/\phi = 0.5$, $k_v = 0$, $k_h = 0.21$, $i = 0^\circ$, $\beta = 0^\circ$ and $\Delta_b/\Delta_a = 1$)  

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Seismic active earth pressure $\sigma_{ane}$ (kPa)</th>
<th>$K_{aem}$</th>
<th>Calculated $\phi_m$ (degree)</th>
<th>Correction factor</th>
<th>$\phi_{mcorr}$ (degree)</th>
<th>$\Delta/\Delta_a$ (degree)</th>
<th>x</th>
<th>$y = (\phi_m / \phi_m (\Delta/\Delta_a))$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>0.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.200</td>
<td>4.25</td>
<td>1.304</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.400</td>
<td>2.50</td>
<td>0.383</td>
<td>38.70</td>
<td>0.166</td>
<td>6.421</td>
<td>0.394</td>
<td>0.431</td>
<td>0.415</td>
</tr>
<tr>
<td>0.600</td>
<td>2.45</td>
<td>0.251</td>
<td>51.00</td>
<td>0.249</td>
<td>12.693</td>
<td>0.594</td>
<td>0.622</td>
<td>0.547</td>
</tr>
<tr>
<td>0.800</td>
<td>1.75</td>
<td>0.134</td>
<td>66.75</td>
<td>0.332</td>
<td>22.151</td>
<td>0.787</td>
<td>0.806</td>
<td>0.718</td>
</tr>
<tr>
<td>1.016</td>
<td>0.30</td>
<td>0.018</td>
<td>93.25</td>
<td>0.421</td>
<td>39.300</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
</tbody>
</table>

(f) Some experimental points very near to the ground are neglected considering some possible experimental errors due to some arching action near the ground as also mentioned by experimentalists in their works. The typical calculation to obtain the mobilized soil friction angle is shown in Table 1.

Rotation about the Bottom (RB)

Here also the experimental results reported by Sherif and Fang (1984b) for seismic active earth pressure distribution along the depth of the wall for RB mode with various wall movements are used in the present
semi-empirical approach. The steps used are as follows,

(a) The mobilized seismic active earth pressure coefficient, $K_{aem}$ at any depth is calculated using equation (1).

![Proposed semi-empirical relationship between mobilized soil friction angle, wall movement and seismic acceleration coefficient for RB mode.](image)

(b) Using Mononobe-Okabe equation (see Kramer, 1996), mobilized soil friction angle, $\phi_m$ is obtained for corresponding $K_{aem}$.

(c) In the full mobilization case, at the base $\Delta_t = \Delta_a$, so $\phi_m = \phi$ at the top and at bottom $\phi_m = 0$. Therefore, correction factor at the top is $\phi / \phi_{cal}$ and at the bottom is zero. By assuming linear variation of the correction factor the calculated values of $\phi_m$ are corrected.

(d) Finally all results are expressed in terms of two non-dimensional parameters viz.

\[
X = \left( \frac{\Delta}{\Delta_a} \right) / \left( 1 - \Delta / \Delta_a \right) \left[ 11.5k_a^2 + 7.8k_b^2 - 1.3k_b + 1 \right] 
\]

\[
Y = \frac{\phi_m}{\phi} \left( 1 - \Delta / \Delta_a \right)
\]

(e) The values of ‘Y’ thus obtained are plotted for different values of ‘X’ as shown in Figure 3 and it is found that all the points are falling within a narrow band after using iterative normalization technique and fitted with a linear curve $Y = X$ with regression coefficient of 0.99. The typical calculation to obtain the mobilized soil friction angle is shown in Table 2.
WORKED EXAMPLE

Consider a rigid vertical retaining wall of height, D = 6m, supporting cohesionless horizontal backfill with properties $\gamma = 18 \text{ kN/m}^3$, $\phi = 40^\circ$, $\delta/\phi = 0.5$. And for this type of backfill $\Delta_a$ is assumed as 0.2% of D (see Bowles, 1996; Choudhury and Subba Rao, 2002). It is required to calculate the seismic active earth pressure distribution for $\Delta_b/\Delta_a = 1.0$ for RT mode and $\Delta/t/\Delta_a = 1.0$ for RB mode of displacement with horizontal seismic acceleration coefficient, $k_h = 0.1$. The calculations for RT mode and RB mode are shown in Table 3 and Table 4 respectively and the results are plotted in Figure 4.

### Table 2. Typical calculation to obtain mobilized friction angle (RB mode)

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Seismic active earth pressure $\sigma_{ane}$ (kPa)</th>
<th>$K_{aem}$</th>
<th>calculated $\phi_m$ (degree)</th>
<th>correction factor</th>
<th>$\phi_{mcor}$</th>
<th>$\Delta/\Delta_a$ (degree)</th>
<th>$X$</th>
<th>$Y=[(\phi_{m}\phi)/\Delta(1-\Delta/\Delta_a)]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.23</td>
<td>-</td>
<td>39.3</td>
<td>1.000</td>
<td>39.30</td>
<td>0.000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.15</td>
<td>0.90</td>
<td>0.368</td>
<td>36.5</td>
<td>0.852</td>
<td>31.11</td>
<td>0.148</td>
<td>5.425</td>
<td>5.362</td>
</tr>
<tr>
<td>0.30</td>
<td>1.20</td>
<td>0.245</td>
<td>48.0</td>
<td>0.705</td>
<td>33.83</td>
<td>0.295</td>
<td>2.314</td>
<td>2.915</td>
</tr>
<tr>
<td>0.50</td>
<td>1.70</td>
<td>0.209</td>
<td>52.3</td>
<td>0.508</td>
<td>26.56</td>
<td>0.492</td>
<td>1.031</td>
<td>1.373</td>
</tr>
<tr>
<td>0.60</td>
<td>2.10</td>
<td>0.215</td>
<td>51.6</td>
<td>0.409</td>
<td>21.13</td>
<td>0.591</td>
<td>0.702</td>
<td>0.910</td>
</tr>
<tr>
<td>0.80</td>
<td>2.90</td>
<td>0.222</td>
<td>50.6</td>
<td>0.213</td>
<td>10.76</td>
<td>0.787</td>
<td>0.283</td>
<td>0.348</td>
</tr>
<tr>
<td>0.96</td>
<td>5.40</td>
<td>0.345</td>
<td>38.3</td>
<td>0.055</td>
<td>2.11</td>
<td>0.945</td>
<td>0.065</td>
<td>0.057</td>
</tr>
<tr>
<td>1.016</td>
<td>9.10</td>
<td>0.550</td>
<td>25.0</td>
<td>0.000</td>
<td>0.000</td>
<td>1.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

### Table 3. Calculation for worked example (RT mode)

<table>
<thead>
<tr>
<th>Depth $z$ in m</th>
<th>$z/D$</th>
<th>$x$</th>
<th>$y$</th>
<th>$\phi_m/\phi$</th>
<th>$\phi_m$</th>
<th>$K_{aem}$</th>
<th>Seismic active earth pressure $\sigma_{ane}$ (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>0.083</td>
<td>0.125</td>
<td>0.125</td>
<td>0.010</td>
<td>0.418</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1.00</td>
<td>0.167</td>
<td>0.224</td>
<td>0.224</td>
<td>0.037</td>
<td>1.491</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1.50</td>
<td>0.250</td>
<td>0.314</td>
<td>0.314</td>
<td>0.078</td>
<td>3.138</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2.00</td>
<td>0.333</td>
<td>0.399</td>
<td>0.399</td>
<td>0.133</td>
<td>5.322</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2.50</td>
<td>0.417</td>
<td>0.481</td>
<td>0.481</td>
<td>0.200</td>
<td>8.017</td>
<td>0.854</td>
<td>38.43</td>
</tr>
<tr>
<td>3.00</td>
<td>0.500</td>
<td>0.560</td>
<td>0.560</td>
<td>0.280</td>
<td>11.204</td>
<td>0.745</td>
<td>40.23</td>
</tr>
<tr>
<td>3.50</td>
<td>0.583</td>
<td>0.637</td>
<td>0.637</td>
<td>0.372</td>
<td>14.869</td>
<td>0.645</td>
<td>40.64</td>
</tr>
<tr>
<td>4.00</td>
<td>0.667</td>
<td>0.713</td>
<td>0.713</td>
<td>0.475</td>
<td>19.000</td>
<td>0.552</td>
<td>39.74</td>
</tr>
<tr>
<td>4.50</td>
<td>0.750</td>
<td>0.786</td>
<td>0.786</td>
<td>0.590</td>
<td>23.587</td>
<td>0.466</td>
<td>37.75</td>
</tr>
<tr>
<td>5.00</td>
<td>0.833</td>
<td>0.859</td>
<td>0.859</td>
<td>0.716</td>
<td>30.621</td>
<td>0.387</td>
<td>34.83</td>
</tr>
<tr>
<td>5.50</td>
<td>0.917</td>
<td>0.930</td>
<td>0.930</td>
<td>0.852</td>
<td>34.904</td>
<td>0.317</td>
<td>31.38</td>
</tr>
<tr>
<td>6.00</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>40.000</td>
<td>0.2526</td>
<td>27.28</td>
</tr>
</tbody>
</table>

### Table 4. Calculation for worked example (RB mode)
DISCUSSIONS AND COMPARISON OF RESULTS

From Figure 4, it can be seen that the seismic active earth pressure distribution for rotation about top or rotation about bottom mode of wall movement is non-linear but the conventional Mononobe-Okabe’s theory shows a linear seismic active earth pressure distribution which was shown to be incorrect by some previous researchers like Fukuoka and Imamura (1984) through the experimental observations and by Choudhury and Nimbalkar (2006) through analytical results. Also from Figure 4 it is found that the point of application of seismic active earth pressure for RT mode is above 1/3rd distance from the base of the wall and that for RB mode is below 1/3rd distance from the base of the wall. Typical comparison of proposed equations with Mononobe-Okabe method is also reported in Figure 4.

Figure 4. Comparison of proposed method with Mononobe-Okabe method for worked example.
CONCLUSIONS

Mobilization of seismic active earth pressure depends on the mode and amount of wall movement. A simple theory is proposed to compute the displacement-based seismic active earth pressure distribution. Using the proposed equations, which are based on semi-empirical approach, where for a given seismic acceleration and amount of wall movement, the mobilized soil friction angle, can be determined. From the mobilized soil friction angle, mobilized seismic active earth pressure coefficient can be calculated, which in turn gives the seismic active earth pressure distribution over the height of the wall. The worked example clearly shows the requirement and application of the proposed equations compared to the existing pseudo-static analytical methods.

REFERENCES


