Geotechnical Earthquake Engineering

by

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Lecture – 37
Module – 9

Seismic Analysis and Design of Various Geotechnical Structures
Seismic Design of Retaining Wall
Model proposed by Nimbalkar and Choudhury (2008) for Seismic Design of Retaining Wall considering wall-soil inertia

Active earth pressure condition

Proposed Design Factors for Retaining Wall

by Nimbalkar and Choudhury (2008)

Soil thrust factor, $F_T = \frac{K_{ae}}{K_a}$

Wall inertia factor, $F_I = \frac{C_{IE}(t)}{C_{Ia}}$

where, $C_{IE}(t) = \frac{\cos \delta - \sin \delta \tan \phi_p}{\tan \phi_b} + \frac{Q_{hw}(t) + Q_{vw}(t) \tan \phi_p}{P_{ae}(t) \tan \phi_b}$

$C_{Ia} = \frac{\cos \delta - \sin \delta \tan \phi_b}{\tan \phi_b}$

Combined dynamic factor, $F_w = F_T F_I = \frac{W_w(t)}{W_w}$

D. Choudhury, IITB
Typical Variation of Soil thrust factor $F_T$, Wall inertia factor $F_I$ and Combined dynamic factor $F_W$

$k_v = 0.5k_h$, $\phi = 30^0$, $\delta = 15^0$, $H/TV_s = 0.3$, $H/TV_p = 0.16$, $H/TV_{sw} = 0.012$, $H/TV_{pw} = 0.0077$

Factors $F_W, F_I, F_T$
<table>
<thead>
<tr>
<th>k_h</th>
<th>k_v</th>
<th>Present study</th>
<th>Richards and Elms (1979)</th>
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<td></td>
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<td>F_I</td>
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<td>0.00</td>
<td>3.500</td>
<td>1.909</td>
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</table>
Model proposed by Nimbalkar and Choudhury (2007) for Seismic Design of Retaining Wall considering wall-soil inertia

Proposed Design Factors for Retaining Wall

by Nimbalkar and Choudhury (2007)

\[ F_T = \frac{K_{ae,pe}}{K_{a,p}} \]

\[ F_I = \frac{C_{IE}(t)}{C_{la,lp}} \]

\[ C_{la,lp} = \pm \frac{\cos \delta - \sin \delta \tan \phi_b}{\tan \phi_b} \]

\[ F_w = F_T F_I = \frac{W_w(t)}{W_w} \]
Variation of soil passive resistance factor $F_T$, wall inertia factor $F_I$ and combined dynamic factor $F_W$.

$k_v = 0.5k_h$, $\phi = 30^0$, $\delta = 15^0$, $H/TV_s = 0.3$, $H/TV_p = 0.16$

$H/TV_{sw} = 0.012$, $H/TV_{pw} = 0.0086$

Nimbalkar and Choudhury (2007)
Pseudo-dynamic Method in Displacement –based analysis

- Choudhury and Nimbalkar (2007) proposed pseudo-dynamic method to compute the seismic rotational displacements of retaining wall for passive earth pressure condition. (Soil Dynamics and Earthquake Engg., 2007)

Pseudo-dynamic forces acting on soil–wall system for rotational stability

Variation of rotational displacement (θ) with \( k_h \)

Provisions in Design Codes

- **Indian Design Code**
  - IS 1893 - Part 5 (1984), provides information regarding earthquake resistant design for retaining wall for active and passive case. Use of M-O method.
  - Point of application at mid-height for dynamic component.
  - Pseudo-static is used, which excludes the deformation criteria.

Indian Design Code

As per IS 1893 - Part 5 (1984), active earth pressure exerted against wall can be,

\[ P_a = \left( \frac{1}{2} \right) W \cdot H^2 C_a \]

where \( C_a \) is given by,

\[
C_a = \frac{(1 \pm \alpha_v) \cos^2 (\phi - \lambda - \alpha)}{\cos \lambda \cos^2 \alpha \cos (\delta + \lambda + \alpha)} \times \left[ \frac{1}{1 + \left\{ \frac{\sin(\phi + \delta) \sin(\phi - i - \delta)}{\cos(\alpha - i) \cos(\delta + \alpha + \lambda)} \right\}^{1/2}} \right]^2
\]

where, \( \alpha_v \) vertical seismic coefficient - its direction being taken consistently throughout the stability analysis of wall and equal to \( (1/2) \alpha_h \), where \( \alpha_h \) horizontal seismic coefficient.
Codal Provisions

- Indian Design Code
- IS 1893 - Part 5 (1984), **passive earth pressure** exerted against wall can be,

\[ P_p = \frac{1}{2} W \cdot H^2 C_p \]

- where \( C_p \) is given by,

\[
C_p = \frac{(1 + \alpha_v) \cos^2(\delta + \alpha - \lambda)}{\cos \lambda \cos^2 \alpha \cos(\delta - \alpha + \lambda)} \times \left[ \frac{1}{1 + \left\{ \frac{\sin(\phi + \delta) \sin(\phi + i - \delta)}{\cos(\alpha - i) \cos(\delta - \alpha + \lambda)} \right\}^{\frac{1}{2}}} \right]^2
\]

where \( \phi \) is soil friction angle, \( \delta \) friction angle for soil and wall

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European Design Code

- **Eurocode 8 (2003)** explains the design of structures for earthquake resistance, wherein **part 5** explains the procedure for foundations, retaining structures and geotechnical aspects.

- It is based on *pseudo-static* method and follows *displacement* (for translation and rocking mode) based approach given by **Richards and Elms (1979)**.

- **Eurocode 8 (2003)** highlights guidelines to take into account values of $k_h$ and $k_v$ in absence of any study.

Codal Provisions

- **Eurocode 8 (2003)**
  - It mentions that, in the absence of specific studies, the horizontal \( k_h \) and vertical \( k_v \) seismic coefficients affecting all the masses shall be taken as-

\[
\begin{align*}
  k_h &= \alpha \frac{S}{r}, \\
  k_v &= \pm 0.5 k_h, \text{ if } \frac{a_{vg}}{a_g} \text{ is larger than } 0.6 \\
  k_v &= \pm 0.33 k_h, \text{ otherwise}
\end{align*}
\]

where, \( k_h \) and \( k_v \) are seismic horizontal and vertical coefficients, \( \alpha \) ratio of the design ground acceleration on type A ground, \( a_g \), to the acceleration of gravity \( g \), \( a_{vg} \) is design ground acceleration in the vertical direction, \( a_g \) is design ground acceleration on type A ground.
Provisions in Design Codes

• International Building Code
  – IBC (2006) categorizes sites into categories namely A, B, C, D, E, F based on soil profile, shear wave velocity, SPT values and undrained shear strength values.
  – Based on that, the design seismic category should be selected.
  – It mentions that retaining walls shall be designed to ensure stability against overturning, sliding, excessive foundation pressure and water uplift.

International Building Code (2006),
INTERNATIONAL CODE COUNCIL, INC.
Seismic Design of Waterfront Retaining Wall
Applications on Waterfront Retaining Wall / Seawall

-A soil retaining armoring structure, generally massive
- To defend a shoreline against wave attack
- Designed primarily to resist wave action along high value coastal property

(source: www.mojosballs.com/main.htm)

D. Choudhury, IIT Bombay, India
Available Literature

**On Earthquake**

Mononobe-Okabe (1926, 1929)
Madhav and Kameswara Rao (1969)
Richards and Elms (1979)
Saran and Prakash (1979)
Prakash (1981)
Nadim and Whitman (1983)
Steedman and Zeng (1990)
Ebeling and Morrison (1992)
Das (1993)
Kramer (1996)
Kumar (2002)
Choudhury and Subba Rao (2005)
Choudhury and Nimbalkar (2006)
And many others…………..

**On Tsunami/Hydrodynamics**

Westergaard (1933)
Fukui et al. (1962)
Ebeling and Morrison (1992)
Mizutani and Imamura (2001)
CRATER (2006)
And few others……….
Design Solutions for Waterfront Retaining Walls (Sea Walls) subjected to both Earthquake and Tsunami

(1) For Tsunami attacking the wall (passive case)
   (a) Against Sliding mode of failure
   (b) Against Overturning mode of failure

(2) For Tsunami receding away from wall (active case)
   (a) Against Sliding mode of failure
   (b) Against Overturning mode of failure
Case 1(a): Passive Case – Pseudo-static

Combined effects of tsunami and earthquake
On rigid waterfront retaining wall

Case 1(a): Passive Case – Pseudo-static (Results)

Factor of safety against sliding

Factor of safety against overturning

\[ FS_s = \mu \left[ \left( \frac{b}{H} \right) \gamma_c (1 - k_v) - K \sin \delta \right] + \frac{1}{2} \gamma_{we} \left( \frac{h_{wd}}{H} \right)^2 + K \cos \delta \]

\[ = \left( \frac{h_{wd}}{H} \right)^2 \left[ \frac{1}{2} \gamma_{we} + 4.5 \gamma_w \left( \frac{h_e}{h_{w0}} \right)^2 \right] + k_h \frac{b}{H} \gamma_c + \frac{7}{12} k_h \gamma_w \left( \frac{h_{wd}}{H} \right)^2 \]

\[ K \text{ is a constant} = 0.5 K_{pe} \bar{y} \left( 1 - k_v \right) \left( 1 - r_u \right) \]

\[ FS_o = \]

\[ = \frac{1}{2} \left( \frac{b}{H} \right)^2 \gamma_c (1 - k_v) + \frac{1}{2} \gamma_{we} \left( \frac{h_{wd}}{H} \right)^3 + K \gamma c \cos \delta \]

\[ = \left( \frac{h_{wd}}{H} \right)^3 \left[ \frac{1}{2} \gamma_{we} + 4.5 \gamma_w \left( \frac{h_e}{h_{w0}} \right)^2 \left( \frac{1}{2} \frac{h_i}{h_{w0}} + 1 \right) + \frac{1}{2} k_h \frac{b}{H} \gamma_c + \frac{2}{12} k_h \gamma_w \left( \frac{h_{wd}}{H} \right)^3 \right] \]

Design solutions proposed by Choudhury and Ahmad (2007)

Factor of Safety against Sliding Failure:

\[
FS_{\text{sliding}_r} = \frac{\frac{1}{2}\gamma_w(h/H)^2 + \mu((1 - k_v)(b/H)\gamma_c + \frac{1}{2}K_{ae}\gamma \cdot \sin \delta)}{\frac{1}{2}\gamma_{we}(h/H)^2 + \frac{7}{12}k_h\gamma_w(h/H)^2 + \frac{1}{2}K_{ae}\gamma \cdot \cos \delta + k_h(b/H)\gamma_c}
\]

\[
FS_{\text{sliding}_f} = \frac{\frac{1}{2}\gamma_w(h/H)^2 + \mu((1 - k_v)(b/H)\gamma_c + \frac{1}{2}K_{ae}\gamma \cdot \sin \delta)}{\frac{1}{2}\gamma_{we}(h/H)^2 + \frac{7}{6}k_h\gamma_w(h/H)^2 + \frac{1}{2}K_{ae}\gamma \cdot \cos \delta + k_h(b/H)\gamma_c}
\]

Factor of Safety against Overturning Failure:

\[
FS_{\text{overturning}_r} = \frac{\frac{1}{6}\gamma_w(h/H)^3 + \frac{1}{2}(b/H)^2(1 - k_v)\gamma_c + \frac{1}{2}K_{ae}\gamma(b/H) \sin \delta}{\frac{1}{6}\gamma_{we}(h/H)^3 + (2.8/12)k_h\gamma_w(h/H)^3 + \frac{1}{4}K_{ae}\gamma \cos \delta + \frac{1}{2}k_h(b/H)\gamma_c}
\]

\[
FS_{\text{overturning}_f} = \frac{\frac{1}{6}\gamma_w(h/H)^3 + \frac{1}{2}(b/H)^2(1 - k_v)\gamma_c + \frac{1}{2}K_{ae}\gamma(b/H) \sin \delta}{\frac{1}{6}\gamma_{we}(h/H)^3 + \frac{5.6}{12}k_h\gamma_w(h/H)^3 + \frac{1}{4}K_{ae}\gamma \cos \delta + \frac{1}{2}k_h(b/H)\gamma_c}
\]

Typical Results by Choudhury and Ahmad (2007)

Seismic Design of Waterfront Retaining Wall using Pseudo-Dynamic Method

Ahmad and Choudhury (2008)

\[ a_h(z, t) = \{1 + (H - z). (f_a - 1)/H\} a_h \sin \left[ \omega \{t - (H - z)/V_s\} \right] \]

\[ a_v(z, t) = \{1 + (H - z). (f_a - 1)/H\} a_v \sin \left[ \omega \{t - (H - z)/V_p\} \right] \]
Forces acting on typical seawall subjected to earthquake and tsunami (active case)

Typical Result of Factor of Safety against Sliding

Ahmad and Choudhury (2008)

Comparison of Results

Choudhury and Ahmad (2008)

Seismic Design of Reinforced Soil-Wall
Geosynthetic Reinforced Soil – Structure as Multiple Engineering Application for Earthquake Resistant Earthen Structures

D. Choudhury, IIT Bombay, India
A week after the 1995 Kobe Earthquake

24 Jan. 1995

The wall survived!

GRS RW for a rapid transit at Tanata

Ref: Tatsuoka (2010)
Typical Design of Earthquake Resistant Reinforced Soil-Wall (Internal Stability)

Typical Design of Earthquake Resistant Reinforced Soil-Wall (Internal Stability)

For $H = 5$ m, $\phi = 30^0$

Reinforcement strength and length required as per Nimbalkar et al. (2006)

Comparison of Results

Table 2. Typical comparison of present results with pseudo-static results by horizontal slice method (HSM) using method of Shahgholi et al. (2001) and results of ReSlope program by Leshchinsky (1997), Ling et al. (1997).

<table>
<thead>
<tr>
<th>$k_b$</th>
<th>$\phi = 20^\circ$</th>
<th>$\phi = 25^\circ$</th>
<th>$\phi = 30^\circ$</th>
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<tr>
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<td>ReSlope</td>
<td>HSM</td>
<td>Present study</td>
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<tr>
<td>0.0</td>
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<td>110</td>
<td>110</td>
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<tr>
<td>0.1</td>
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<tr>
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<td>187</td>
<td>187</td>
<td>196</td>
</tr>
</tbody>
</table>

Data used: $k_v = 0.0$, $H/\lambda = 0.167$, $H/\eta = 0.09$, $H = 5$ m, $\beta = 90^\circ$

Table 3. Typical comparison of present results with pseudo-static results by Ling and Leshchinsky (1998)

<table>
<thead>
<tr>
<th>$k_v$</th>
<th>Required length of geosynthetic layer, $L_e$</th>
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<tr>
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<td>Method proposed by Ling and Leshchinsky (1998)</td>
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<td>0.912</td>
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</table>

Data used: $k_b = 0.2$, $\phi = 30^\circ$, $H/\lambda = 0.167$, $H/\eta = 0.09$, $H = 5$ m, $\beta = 90^\circ$.
Typical Design of Earthquake Resistant Reinforced Soil-Wall (External Stability)

Figure 1. Two-part wedge mechanism and forces considered in direct sliding analysis under seismic conditions

Sliding stability

Choudhury et al. (2007)

Figure 2. Forces considered in overturning analysis under seismic conditions

Overturning stability

Typical Design of Earthquake Resistant Reinforced Soil-Wall (External Stability)

Length of Reinforcement for Sliding stability
Choudhury et al. (2007)

Length of Reinforcement for Overturning stability

Comparison of Results

**Table 1. Typical comparison of present results for required geosynthetic length, $L_{ds}$, with pseudo-static results by Ling and Leshchinsky (1998)**

<table>
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<tr>
<th>$k_r$</th>
<th>Required length of geosynthetic layer, $L_{ds}$</th>
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</table>

Data used: $k_h = 0.2$, $\phi = 30^\circ$, $H/\lambda = 0.167$, $H/\eta = 0.09$, $H = 5$ m, $\beta = 90^\circ$.

Choudhury et al. (2007)