Module – 9

Seismic Analysis and Design of Various Geotechnical Structures
Seismic Design of Retaining Wall
Earth Pressures on Retaining Walls

Earth pressures-

- at rest earth pressure
- active earth pressure
- passive earth pressure

Earth pressure conditions
Failure of Retaining Walls

- Retaining walls may **fail** during an **earthquake**, if they are **not** designed to resist **additional** destabilizing earthquake forces.

Failure of gravity retaining wall

(Source: http://www.geofffox.com)  (Source: http://www.parmeeleegeology.com/)
Seismic analysis/design of retaining walls mainly consists of

- Determining magnitude of additional destabilizing forces that act during an earthquake
- Determining seismic active and passive earth pressures due to all destabilizing forces (static + seismic)
- Design section based on above parameters using
  1. Force based approach
  2. Displacement based approach – for performance based design
Pseudo-static Method

- Theoretical background of seismic coefficient lies in the application of D’Alembert’s principle of mechanics.

Example of elementary seismic slope stability analysis (Towahata, 2008)

D’Alembert’s principle of mechanics

Towhata, I., (2008), Geotechnical Earthquake Engineering, Springer, Tokyo, Japan.
Conventional Seismic Design of Retaining Walls

Pseudo-Static Approach Proposed by Mononobe-Okabe (1929)

Questions:
- Value of $k_h$ and $k_v$ to be used for design?
- Soil amplification?
- Variation of seismic acceleration with depth and time?
- Effect of dynamic soil properties? etc.
Available Literature

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…………..
Pseudo-static Method

- **Richards and Elms (1979)** proposed a method for seismic design of gravity retaining walls which is based on permanent wall displacements. *(Displacement based approach)*

Displacement should be calculated by following formula, and should be checked against allowable displacement.

\[
    d_{pem} = 0.087 \frac{v_{\text{max}}^2 a_{\text{max}}^3}{a_\text{y}^4}
\]

where, \(v_{\text{max}}\) is the peak ground velocity, \(a_{\text{max}}\) is the peak ground acceleration, and \(a_\text{y}\) is the yield acceleration for the wall-backfill system.

Pseudo-static Method


- The application of this case is for anchor uplift capacity.

- Design charts are given for calculation of various parameters like $k_{pyd}$, which can be used to compute seismic passive resistance, which is given by,

$$P_{pd} = \left( 2cH K_{pcd} + qH K_{pqd} + \frac{1}{2} \gamma H^2 K_{pyd} \right) \frac{1}{\cos \delta}$$

where $P_{pd}$ is seismic passive resistance, $K_{pyd}$, $K_{pqd}$, and $K_{pcd}$ are the seismic passive earth pressure coefficients.

Pseudo-static Method

- **Choudhury et al. (2004)** presented a comprehensive review for different methods to calculate seismic earth pressures and their point of applications. *(Current Science, 2004)*

Expression for the point of application of seismic passive resistance by,

\[
h_d = H - \frac{2\pi^2 H^2 \cos \omega \zeta + 2\pi \lambda H \sin \omega \zeta - \lambda^2 (\cos \omega \zeta - \cos \omega t)}{2\pi \lambda H \cos \omega \zeta + \pi \lambda (\sin \omega \zeta - \sin \omega t)}
\]

\[
\lambda = \frac{2\pi V_s}{\omega} \quad \text{and} \quad \zeta = \frac{2\pi V_p}{\omega}
\]

\(\omega\) excitation frequency, \(V_s\) and \(V_p\) are shear and primary wave velocities respectively, \(H\) is height of retaining wall.

Pseudo-static Method

- Subba Rao and Choudhury (2005) gave design charts for seismic passive earth resistance coefficients by using a composite failure surface for positive wall friction angle. *(Jl. of Geotechnical and Geoenvironmental Engg., ASCE, 2005)*

- Design charts were proposed for the direct computation of seismic passive earth resistance coefficients for various input parameters.

- The application of this case is for bearing capacity of foundations.
Pseudo-static Method

- Shukla et al. (2009) have described the derivation of an analytical expression for the total active force on the retaining wall for $c$-$\phi$ soil backfill considering both the horizontal and vertical seismic coefficients.

- The seismic active earth pressure is given by,

$$P_{ae} = \frac{1}{2} \gamma H^2 (1-k_v) K_{ae\gamma} - cHK_{aec}$$

where,

$$K_{ae\gamma} = \frac{\cos(\phi - \theta) - \frac{\sin(\phi - \theta)}{\tan \alpha_c}}{\cos \theta (\cos \phi + \tan \alpha_c \sin \phi)}$$

and

$$K_{aec} = \frac{\cos \phi (1 + \tan^2 \alpha_c)}{\tan \alpha_c (\cos \phi + \tan \alpha_c \sin \phi)}$$

$$\tan \theta = \frac{k_h}{1-k_v}$$

and $\alpha_c$ is critical failure plane angle, $\phi$ shearing resistance of soil

Pseudo-static Method

Major limitations

- Representation of the complex, transient, dynamic effects of earthquake shaking by single constant unidirectional pseudo-static acceleration is very crude.
- Relation between $K$ and the maximum ground acceleration is not clear i.e. $1.9 \, \text{g}$ acceleration does not mean $K = 1.9$

Advantages

- Simple and straight-forward
- No advanced or complicated analysis is necessary.
- It uses limit state equilibrium analysis which is routinely conducted by Geotechnical Engineers.
Development of Modern Pseudo-Dynamic Approach

Soil amplification is considered.
Frequency of earthquake excitation is considered.
Time duration of earthquake is considered.
Phase differences between different waves can be considered.
Amplitude of equivalent PGA can be considered.
Considers seismic body wave velocities traveling during earthquake.


\[ a_h(z, t) = \left\{ 1 + (H - z)(f_a - 1)/H \right\} a_h \sin \left[ \omega \{ t - (H - z)/V_s \} \right] \]
\[ a_v(z, t) = \left\{ 1 + (H - z)(f_a - 1)/H \right\} a_v \sin \left[ \omega \{ t - (H - z)/V_p \} \right] \]
\[ a_h(z, t) = a_h \sin [\omega \{ t - (H - z)/V_s \}] \quad \text{and} \quad a_v(z, t) = a_v \sin [\omega \{ t - (H - z)/V_p \}] \]

where \( \omega = \) angular frequency; \( t = \) time elapsed; \( V_s = \) shear wave velocity; \( V_p = \) primary wave velocity

\[
Q_h(t) = \frac{\int_0^H m(z)a_h(z, t)dz}{\int_0^H m(z)dz} = \frac{\lambda \gamma a_h}{4\pi^2 g \tan \alpha} \left[ 2\pi H \cos \omega \zeta + \lambda (\sin w \zeta - \sin \omega t) \right]
\]

where, \( \lambda = TV_s \) is the wavelength of the vertically propagating shear wave and \( \zeta = t - H/V_s \).

\[
Q_v(t) = \frac{\int_0^H m(z)a_v(z, t)dz}{\int_0^H m(z)dz} = \frac{\eta \gamma a_v}{4\pi^2 g \tan \alpha} \left[ 2\pi H \cos \omega \psi + \lambda (\sin \omega \psi - \sin \omega t) \right]
\]

where, \( \eta = TV_p \); is the wavelength of the vertically propagating primary wave and \( \psi = t - H/V_p \).

The total (static plus dynamic) passive resistance is given by,

\[
P_{pe} = \frac{W \sin(\alpha + \phi) - Q_h \cos(\alpha + \phi) - Q_v \sin(\alpha + \phi)}{\cos(\alpha + \delta + \phi)}
\]

The coefficient of seismic passive resistance \( (K_{pe}) \) is given by,

\[
K_{pe} = \frac{1}{\tan \alpha} \frac{\sin(\alpha + \phi)}{\cos(\delta + \phi + \alpha)} - \frac{k_h}{2\pi^2 \tan \alpha} \left( \frac{TV_s}{H} \right) \times \frac{\cos(\alpha + \phi)}{\cos(\delta + \phi + \alpha)} \times m_1 - \frac{k_v}{2\pi^2 \tan \alpha} \left( \frac{TV_p}{H} \right) \times \frac{\sin(\alpha + \phi)}{\cos(\delta + \phi + \alpha)} \times m_2
\]

where

\[
m_1 = 2\pi \cos 2\pi \left( \frac{t}{T} - \frac{H}{TV_s} \right) + \left( \frac{TV_s}{H} \right)
\]

\[
\times \left[ \sin 2\pi \left( \frac{t}{T} - \frac{H}{TV_s} \right) - \sin 2\pi \left( \frac{t}{T} \right) \right]
\]

and

\[
m_2 = 2\pi \cos 2\pi \left( \frac{t}{T} - \frac{H}{TV_p} \right) + \left( \frac{TV_p}{H} \right)
\]

\[
\times \left[ \sin 2\pi \left( \frac{t}{T} - \frac{H}{TV_p} \right) - \sin 2\pi \left( \frac{t}{T} \right) \right]
\]

The seismic passive earth pressure distribution is given by,

\[
P_{pe}(t) = \frac{dP_{pe}(t)}{dz} = \frac{\gamma z}{\tan \alpha} \frac{\sin(\alpha + \phi)}{\cos(\alpha + \delta + \phi)}
\]

\[
- k_h \frac{\gamma z}{\tan \alpha} \frac{\cos(\alpha + \phi)}{\cos(\alpha + \delta + \phi)} \sin \omega \left( t - \frac{z}{V_s} \right)
\]

\[
- k_v \frac{\gamma z}{\tan \alpha} \frac{\sin(\alpha + \phi)}{\cos(\alpha + \delta + \phi)} \sin \omega \left( t - \frac{z}{V_p} \right)
\]

Typical non-linear variation of seismic passive earth pressure

Choudhury and Nimbalkar (2005)

Effect of amplification factor on seismic passive earth pressure

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

\[ k_h = 0.2, \ k_v = 0.0, \ \phi = 30^0, \ \delta = 16^0 \]

Nimbalkar and Choudhury (2008)

Comparison of proposed pseudo-dynamic method with existing pseudo-static method – Passive case

\[
\frac{H}{\lambda} = 0.3, \ \frac{H}{\eta} = 0.16
\]

\[
k_h = 0.2, \ k_v = 0.5k_h, \ \phi = 30^\circ, \ \delta = \phi/2
\]

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Comparison of proposed pseudo-dynamic method with existing pseudo-static methods – Passive case

Choudhury and Nimbalkar (2005) in Geotechnique
Seismic Active Earth Pressure by Pseudo-Dynamic Approach

\[ a_h(z, t) = a_h \sin \left[ \omega \{ t - (H - z)/V_s \} \right] \quad \text{and} \quad a_v(z, t) = a_v \sin \left[ \omega \{ t - (H - z)/V_p \} \right] \]

where \( \omega = \) angular frequency; \( t = \) time elapsed; \( V_s = \) shear wave velocity; \( V_p = \) primary wave velocity.

\[ Q_h(t) = \int_0^H m(z)a_h(z, t)dz = \frac{\lambda \gamma a_h}{4\pi^2 g \tan \alpha} \left[ 2\pi H \cos \omega \zeta + \lambda (\sin \omega \zeta - \sin \omega t) \right] \]

where, \( \lambda = TV_s \) is the wavelength of the vertically propagating shear wave and \( \zeta = t - H/V_s \).

\[ Q_v(t) = \int_0^H m(z)a_v(z, t)dz = \frac{\eta \gamma a_v}{4\pi^2 g \tan \alpha} \left[ 2\pi H \cos \omega \psi + \lambda (\sin \omega \psi - \sin \omega t) \right] \]

where, \( \eta = TV_p \), is the wavelength of the vertically propagating primary wave and \( \psi = t - H/V_p \).

The total (static plus dynamic) active thrust is given by,

\[ P_{ae}(t) = \frac{W \sin(\alpha - \phi) + Q_h(t) \cos(\alpha - \phi) - Q_v(t) \sin(\alpha - \phi)}{\cos(\delta + \phi - \alpha)} \]
The seismic active earth pressure coefficient, $K_{ae}$ is defined as

$$K = \frac{1}{\tan \alpha \cos (\delta + \phi - \alpha)} \left( \frac{TV}{H} \right) \cos (\alpha - \phi) \times m + \frac{k_h}{2\pi^2 \tan \alpha} \left( \frac{TV}{H} \right) \sin (\alpha - \phi) \times m,$$

where,

$$m_1 = 2\pi \cos 2\pi \left( \frac{t - H}{T} \right) \left( \frac{TV}{H} \right) \left[ \sin 2\pi \left( \frac{t - H}{T} \right) - \sin 2\pi \left( \frac{t}{T} \right) \right]$$

$$m_2 = 2\pi \cos 2\pi \left( \frac{t - H}{T} \right) \left( \frac{TV}{H} \right) \left[ \sin 2\pi \left( \frac{t - H}{T} \right) - \sin 2\pi \left( \frac{t}{T} \right) \right]$$

The seismic active earth pressure distribution is given by,

$$P_{ae}(t) = \frac{\partial P_{ae}(t)}{\partial z} = \frac{\gamma z}{\tan \alpha \cos (\delta + \phi - \alpha)} \sin (\alpha - \phi)$$

$$+ \frac{k_h \gamma z}{\tan \alpha \cos (\delta + \phi - \alpha)} \sin \left[ w \left( t - \frac{z}{V_s} \right) \right]$$

$$+ \frac{k_v \gamma z}{\tan \alpha \cos (\delta + \phi - \alpha)} \sin \left[ w \left( t - \frac{z}{V_p} \right) \right]$$
Typical non-linear variation of seismic active earth pressure


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

Effect of soil amplification on seismic active earth pressure


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