**Geotechnical Seismic Design of Earth Retaining Systems**

This module presents the Caltrans practice for the geotechnical seismic design and analyses of ordinary ERS built within the State Right Way and provides guidance on how to determine the horizontal seismic acceleration coefficient ($k_h$) for seismic analysis and design. The geotechnical seismic analyses of ERS include brief discussions on seismic bearing capacity, geotechnical seismic capacity of piles, seismic global stability, simplified seismic permanent displacement, liquefaction potential, lateral spreading and surface fault rupture.

Project-specific seismic analysis including numerical analysis should be performed for the following ERS:

- Failure of the ERS would cause a substantial economic impact
- The ERS is designated by the sponsoring district or local agency as critical, in consultation with Caltrans Division of Engineering Services
- ERS site has geotechnical complexities such as excessive amount of soft clay, surface rupture, liquefaction, lateral spreading, and other geotechnical instabilities
- ERS is a tunnel portal wall

**Design Manuals and Guidelines**

For seismic design of ERS, use this module, and the following design manuals and policy:

- *2017 (8th Edition) AASHTO LRFD Bridge Design Specifications* and *2019 California Amendments*
- ERS related Geotechnical Modules in the Geotechnical Manual

For design cases that are not covered in the above documents, refer to other FHWA reference manuals including FHWA (2005) and NCHRP Report 611 (Anderson et al., 2008).

**Geotechnical Services’ Responsibilities for Seismic Design of ERS**

For seismic design of ERS, Geotechnical Services’ responsibilities are:

- Provide the design horizontal acceleration coefficient ($k_h$). When applicable, assist the structure designers in estimating a horizontal yield acceleration coefficient ($k_y$) for sliding ERS. The $k_y$ is the horizontal seismic acceleration
coefficient that causes imminent sliding or global slope failure (a factor of safety of 1.0) of the ERS

- Provide the engineering properties of soil, such as unit weight, cohesion, friction angle and seismic active earth pressure coefficient ($k_{ae}$) when the Mononobe-Okabe method (M-O) is applicable
- Provide the magnitude and distribution of seismic lateral earth pressure for complex wall geometries to the structure designer where the M-O is not applicable or when requested by structure designers
- Check liquefaction, liquefaction induced settlement, and lateral spreading when applicable
- Perform seismic global stability analysis
- Analyze the seismic bearing capacity for ERS supported on shallow foundations
- Analyze the geotechnical seismic capacity of piles and provide design pile tip elevations for ERS supported on deep foundations

**Classifications of ERS for Geotechnical Seismic Design**

The seismic design of ERS is based on performance during and after the design seismic event.

For the seismic design, an ERS is classified as either sliding ERS or non-sliding ERS. The ERS that will slide along the base during the design seismic event are sliding ERS and include conventional gravity or semi-gravity walls on spread footings. Under current design method and practice per AASHTO 11.10.7, soil nail walls and MSE walls can be included in the sliding ERS category. The external stability calculation of these ERS are based on a composite mass consisting of reinforcements, reinforced soils, and the facing elements. For the sliding ERS, simplified methods presented in AASHTO A11.5 can be used to calculate seismic displacement analysis. When deformation and/or rotation are of concern for project-specific sliding ERS, numerical analysis should be considered.

Non-sliding ERS are retaining walls that move during the design seismic event due to the deformation and/or rotation of walls (other than sliding at the base). For the calculation of the seismic movement/deformation of ERS, numerical analyses may be needed and include beam-column analysis using p-y modeling and numerical deformation analysis (refer to AASHTO 11.8.6.2 and AASHTO 11.9.6). The simplified methods based on Newmark sliding analysis are not applicable because they cannot account for the deformation and/or rotation of ERS.
Determining Horizontal Seismic Acceleration Coefficients and Seismic Displacement

The displacement of an ERS will reduce the dynamic forces and soil pressure on the ERS during a seismic event. The more an ERS moves, the less seismic lateral earth pressures on the ERS.

In the seismic design of ERS, there is the concept of the “seismic fuse” also known as horizontal yield seismic coefficient. This caps the dynamic force experienced by the ERS at the level that causes the controlling mode of failure to occur. The ERS experience the controlling mode of failure when the seismic fuse of an ERS is triggered before dynamic force is high enough to cause any other response. The horizontal seismic forces experienced by the ERS will not be greater than the horizontal seismic force that caused controlling mode of failure.

For the ERS classified as sliding ERS, the seismic fuse is either \( k_{y_{\text{global}}} \), (a horizontal seismic acceleration coefficient causing sliding of potential global slope failure mass), or \( k_{y_{\text{sliding}}} \) (a horizontal seismic acceleration coefficient causing sliding along the base of ERS), whichever is lower (see Figure 1). The seismic displacement occurs either via sliding along the base of ERS or sliding of global slope failure mass.

\[ k_h = \text{a lower value of } k_{y_{\text{global}}} \text{ and } k_{y_{\text{sliding}}} \]

Figure 1. Seismic fuses \((k_y)\) for a semi-gravity ERS on spread footing
Benchmark $k_h$ Values for Seismic Design of ERS

According to AASHTO 11.6.5 the horizontal seismic acceleration coefficient, $k_h$ is $\frac{1}{2}$ horizontal peak ground acceleration (HPGA) for an expected displacement of 1.0 to 2.0 inches. The HPGA is calculated using ARS Online (v3.0) for a zero period (T=0.0 sec.).

Another benchmark value that can be used for sliding ERS is $k_h$ equal to $\frac{1}{3}$ HPGA for more seismic displacement than 2 inches. The sliding ERS designed for this $k_h$ are expected to produce a permanent expected mean displacement of about 5 inches in the design seismic event.

When benchmark $k_h$ value are used for the design of sliding ERS, seismic displacement analysis is not required. However, when a calculated sliding FOS is greater than 1.1, the ERS may not experience the magnitude of displacement associated with benchmark horizontal acceleration coefficient. In such cases, horizontal yield acceleration coefficient ($k_{y,\text{sliding}}$) can be greater than the benchmark values and the increase in horizontal acceleration coefficient may need to be considered in the design.

Steps to Determine Horizontal Seismic Acceleration Coefficient, $k_h$

To determine a horizontal acceleration coefficient for the seismic design of ERS, first define a retaining wall as either sliding ERS or non-sliding ERS, then follow the steps listed below:

**Sliding ERS**

Ordinary ERS classified as sliding ERS can move and/or tolerate a mean seismic displacement greater than about 5 inches in the design seismic event. For the seismic design of these ERS, use the following steps:

1. Calculate $k_{y,\text{global}}$ of the ERS to determine whether seismic global stability controls $k_h$
2. Determine the controlling value of $k_h$ as the lower value of $\frac{1}{3}$ HPGA and $k_{y,\text{global}}$; when $k_h$ is controlled by $k_{y,\text{global}}$, calculate the seismic displacement using simplified methods presented in AASHTO A11
3. Verify with the structure engineer that the ERS analyzed using the controlling $k_h$ have the seismic sliding FOS between 1.0 and 1.1

When sliding FOS is less than 1.0, obtain $k_{y,\text{sliding}}$ from the structure engineer and perform seismic displacement analysis using simplified method to verify that the ERS can tolerate calculated seismic displacement.
When sliding FOS is greater than 1.1, obtain $k_{y\text{sliding}}$ from the structure engineer and determine the controlling value of $k_h$ for the design as the lower value of $k_{y\text{sliding}}$ and $k_{y\text{global}}$.

**Non-sliding ERS**

For the seismic design and analysis, recommend $k_h = 1/2 \text{ HPGA}$ and verify with the structure engineers that the ERS tolerates the seismic movement of 2 inches. When the ERS can tolerate seismic movement greater than 2 inches, greater reduction in the horizontal acceleration coefficient than 50% may be used in the design.

According to AASHTO 11.8.6.2 and AASHTO 11.9.6, numerical analyses may need to be performed for non-sliding ERS to verify acceptable wall movement. The numerical analyses include beam-column analysis using p-y modeling and numerical deformation analysis.

**Standard Plans ERS**

Standard Plan ERS (semi-gravity cantilever retaining walls) were designed based on the horizontal seismic acceleration coefficient, $k_h$ of 0.2 that is corresponding to a HPGA of 0.6 g in Caltrans seismic design practice. Therefore, Standard Plan ERS historically have only been used in areas with HPGA of 0.6g or less.

Standard Plan ERS have been commonly used to support slopes, highway embankment, and other flexible components that are not displacement-sensitive and can tolerate a lateral displacement that may be considered as excessive such as 12 inches or even greater. Case histories have proven that Caltrans Standard Plan ERS perform well without collapse during seismic events. Therefore, Standard Plan ERS may be considered in areas with a HPGA greater than 0.6 g if resulting permanent displacement are within tolerance for the project.

When the design requirements of a Standard Plan ERS have been satisfied except for the seismic design requirement, proceed with following steps before opting for Special Design ERS.

1. Use 0.2 as the yield horizontal seismic coefficient, $k_y$ for Standard Plan ERS, or obtain the $k_y$ from the ERS specialist responsible for the applicable Standard Plan ERS
2. Calculate permanent seismic displacement using the yield horizontal seismic coefficient, $k_y$
3. Provide the calculated permanent seismic displacement to the District Project Engineer to determine whether calculated permanent displacement is acceptable or not
4. If the value is not acceptable, proceed with Special Design ERS
If sufficient subsurface data is available, perform this evaluation in project planning phase and include the calculated permanent seismic displacement and recommendation in District Preliminary Geotechnical Report (DPGR) to assist District in determining whether the Special Design ERS is needed or not.

Permanent Seismic Displacement for Sliding ERS

When the calculation of permanent seismic displacements is needed, use AASHTO A11.5 which presents three different methods to estimate the seismic displacement using horizontal seismic acceleration coefficient and vice versa. Because Caltrans uses ARS Online webtool for seismic ground motions and response spectra, some parameters used in the methods presented in AASHTO A11.5 need to be modified:

A11.5.1 – Kavazanjian et al. (1997)

For Equation A11.5.1-1, use \(k_y\) for \(k_h\) and HPGA for \(A_s\).

A11.5.2 – Anderson et al. (2008)

For Equations A11.5.2-1 and A11.5.2-3, use HPGA/g for \(k_{h0}\) with a wave scattering factor (a) of 1.0. The wave scattering effect has not been used in Caltrans GS practice and may not be significant for most of Caltrans ERS. If there is a need to consider the wave scattering effect on \(k_h\), use Equation A11.5.2-2 with a site class adjustment factor \((F_v)\) of 1.0. The site class adjustment factor shall be set as 1.0 for all applicable equations as the ARS Online webtool generates an ARS curve that reflects site conditions using a time-averaged shear wave velocity for the upper 30 meters of the soil profile, \(V_{s30}\). For details on how to use the ARS Online webtool, refer to the Design Acceleration Response Spectrum Module.

A11.5.3 – Bray et al. (2010) and Bray and Travasarou (2009)

For \(T_s < 0.05\) second – treat the potential sliding mass as a block and use \(T_s = 0\):

\[
d (cm) = \exp\left(-0.22 - 2.83 \ln(k_y) - 0.33(\ln(k_y))^2 \right.
\]
\[
+ 0.566 \ln(k_y) \ln(HPGA)\]
\[
+ 3.04 \ln(HPGA) - 0.244 (\ln(HPGA))^2 + 0.278 (M - 7)\right)
\]

For \(T_s \geq 0.05\) second:

\[
d (cm) = \exp\left(-1.10 - 2.83 \ln(k_y) - 0.33(\ln(k_y))^2 \right.
\]
\[
+ 0.566 \ln(k_y) \ln(S_a)\]
\[
+ 3.04 \ln(S_a) - 0.244 (\ln(S_a))^2 + 1.5T_s + 0.278 (M - 7)\right)
\]

Where:
$T_s$: Fundamental period of the wall

$M$: Moment magnitude of the design earthquake

$S_a$: Spectral acceleration (5% damping) at a degraded period of $1.5T_s$

To determine $M$ and $S_a$, use ARS Online (v3.0). To calculate $T_s$, use the following equation:

$$T_s = \frac{4H'}{V_s}$$

Where:

$H'$: 80 percent of the height of the wall measured from the bottom of the wall

$V_s$: Shear wave velocity of the soils behind the wall

Note that AASHTO Equation A11.5.3-1 is basically the same as the equation for $T_s \geq 0.05$ second above but expressed in terms of $k_y$ that is replaced by $k_h$. AASHTO Equation A11.5.3-1 is typically used to calculate a horizontal seismic acceleration coefficient given the acceptable permanent seismic displacement of the wall.

**GEOTECHNICAL SEISMIC ANALYSIS AND DESIGN**

For the seismic design of ERS and the magnitude and distribution of seismic lateral earth pressure, use the $k_h$ determined as above.

**Seismic Lateral Earth Pressure**

For the magnitude and distribution of seismic lateral earth pressure, refer to AASHTO 11.6, A11.3, and A11.4, and ERS related GS modules.

**Bearing Resistance**

For the bearing resistance of ERS, refer to AASHTO 11.5.8 and 11.6.3, and ERS related GS modules. When calculating the bearing resistance, use the effective footing width. When there is a descending slope on or near an ERS, adjust the bearing capacity equation to account for sloping ground conditions (AASHTO 10.6.3.1.2c).
Geotechnical Seismic Capacity of Piles

For the geotechnical seismic capacity of piles, refer to “Driven Pile Foundations” and “CIDH Pile Foundations” in the Geotechnical Manual.

Seismic Global Stability

Perform iterative global seismic stability analyses and find the horizontal yield acceleration coefficient \( k_{y,\text{global}} \) that results in a FOS of 1.0 for global seismic stability analysis.

For sliding ERS, seismic global stability is considered acceptable when the \( k_{y,\text{global}} \) is equal to or greater than \( 1/3 \) HPGA. When the \( k_{y,\text{global}} \) is less than \( 1/3 \) HPGA, calculate the seismic displacement of potential slope failure mass to verify that calculated displacement is acceptable.

For non-sliding ERS, calculate the seismic displacement of potential slope failure mass associated with the \( k_{y,\text{global}} \) to verify that calculated displacement is acceptable.

Liquefaction Potential

When foundation soils to support ERS are identified as liquefiable, the effects of liquefaction on ERS must be considered in design. The effects include liquefaction induced settlements, reduced bearing resistance due to reduced soil shear strength, and lateral spreading. The liquefaction potential should be evaluated during the early stages of a project, and its effects or mitigation measures should be discussed in the Type Selection Meeting.

Refer to Liquefaction Evaluation in the Geotechnical Manual.

Lateral Spreading

When foundation soils are subject to liquefaction, reduction in shear strength of liquefiable soils should be considered in seismic global stability, and the associated increase in permanent displacement should be evaluated. The effects and mitigation measures of lateral spreading should be discussed in the Type Selection Meeting.

Refer to Liquefaction-Induced Lateral Spreading in the Geotechnical Manual.
Fault Rupture

When an ERS crosses active or potentially active faults, surface fault rupture and the associated displacement hazard needs to be evaluated. The effect of surface fault rupture and mitigation measures if needed should be discussed in the Type Selection Meeting.

Refer to Fault Rupture in the Geotechnical Manual.

REFERENCES


