Geotechnical Seismic Design of Earth Retaining Systems

This module presents Caltrans practice for the geotechnical seismic design and analyses of ordinary earth retaining systems (ERS) and provides guidance on how to determine the horizontal seismic acceleration coefficient (k_h) for seismic analysis and design. This module includes 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 if:

- 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
- The ERS site has geotechnical complexities such as excessive amount of soft clay, surface fault rupture, liquefaction, lateral spreading, and/or other geotechnical instabilities
- The 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*
- *2020 Structure Technical Policy 11.29,* Seismic Design Criteria for Earth Retaining Systems

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 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 calculations of these ERS are based on a composite mass consisting of reinforcements, reinforced soils, and the facing elements. For sliding ERS, use the simplified methods presented in AASHTO A11.5 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 sliding ERS, the seismic fuse is either k_{y_global}, (a horizontal seismic acceleration coefficient causing sliding of potential global slope failure mass), or $k_{y\_sliding}$ (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.

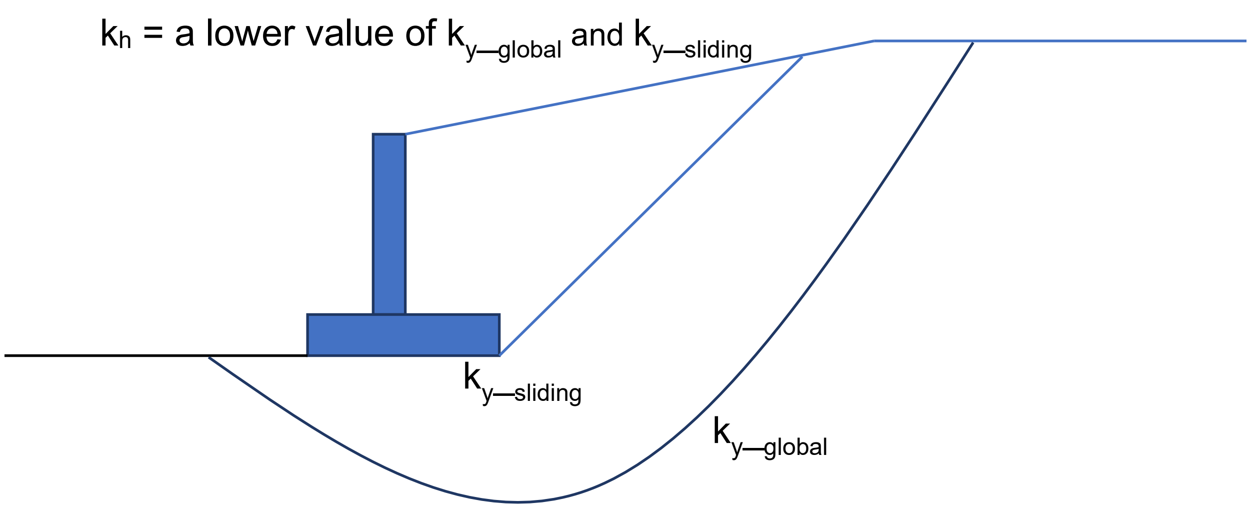

Figure 1. Seismic fuses (k_y) for a semi-gravity ERS on spread footing

Benchmark k_h Values for Seismic Design of ERS

According to AASHTO 11.6.5 the horizonal seismic acceleration coefficient, k_h is 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 for a zero period (T=0.0 sec.).

Another benchmark value that can be used for sliding ERS is k_h equal to 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 ($k_{y\_sliding}$) 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:

<u>Sliding ERS</u>

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_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 1/3 HPGA and k_{y_global}; when k_h is controlled by k_{y_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 $k_{y\_sliding}$ 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 ky_sliding from the structure engineer and determine the controlling value of kh for the design as the lower value of ky_sliding and ky_global.

<u>Non-sliding ERS</u>

For the seismic design and analysis, recommend k_h = 1/2 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 horizonal 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 Plan Retaining Walls

Standard Plan Retaining Walls (semi-gravity cantilever retaining walls) are designed based on a horizontal seismic acceleration coefficient, k_h of 0.2, which corresponds to a HPGA of 0.6 g in Caltrans seismic design practice. Therefore, Standard Plan Retaining Walls historically have only been used in areas with HPGA of 0.6g or less.

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

For the Standard Plan Retaining Walls (Case 2) where there is no concrete barrier on the top, proceed with the following steps before opting for special design if the design requirements of a Standard Plan Retaining Walls have been satisfied except for the seismic design requirement.

1. Use 0.2 as the yield horizontal coefficient, ky, for Standard Plan Retaining Walls (Case 2).
2. Calculate permanent seismic displacement using the yield horizontal seismic coefficient, ky
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 Retaining Wall

For the Standard Plan Retaining Walls (case 1 or case 3) where a yield horizontal seismic coefficient varies and can be more than 0.2, proceed with a special design retaining wall procedure if the seismic design requirement is not met. Due to varying yield horizontal seismic coefficient that can be greater than 0.2, either a special design or calculation of a yield horizontal seismic coefficient of the walls needs to be performed by the SD.

If sufficient subsurface data is available, perform this evaluation in project planning (0) 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 retaining wall 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 horizonal 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 As.

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 Ts < 0.05 second – treat the potential sliding mass as a block and use Ts = 0:

$$d\ (cm) = exp\big(-0.22 - 2.83\ln(k_y) - 0.33(\ln(k_y))^2 + 0.566\ln(k_y)\ln(HPGA) + 3.04\ln(HPGA) - 0.244(\ln(HPGA))^2 + 0.278(M-7)\big)$$

For Ts ≥ 0.05 second:

$$d\ (cm) = exp\big(-1.10 - 2.83\ln(k_y) - 0.33(\ln(k_y))^2 + 0.566\ln(k_y)\ln(S_a) + 3.04\ln(S_a) - 0.244(\ln(S_a))^2 + 1.5T_s + 0.278(M-7)\big)$$

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 Sa, use ARS Online. To calculate Ts, use the following equation:

$T_s = 4H'/V_s$

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 of ERS and find the horizontal yield acceleration coefficient (k_{y_global}) that results in a FOS of 1.0 for global seismic stability analysis. Compare the calculated k_{y_global} with the two benchmark values, ½ HPGA and 1/3 HPGA to verify the following requirements:

- k_{y_global} equal to or greater than ½ HPGA
- k_{y_global} between ½ HPGA and 1/3 HPGA and permanent seismic displacement of up to 5 inches is acceptable.

- k_{y_global} less than 1/3 HPGA but calculated permanent seismic displacement is acceptable by the design team.

Reporting for Seismic Global Stability

Include the following in the *Recommendations* section of the Preliminary Geotechnical Design Report, Geotechnical Design Report, Preliminary Foundation Report, and Foundation Report.

Design of ERS and seismic global stability:

- Design horizontal acceleration coefficient (k_h) for ERS.
- Horizontal yield acceleration coefficient (k_{y_global}), and seismic factor of safety and resistance factor of 1.0 for global slope stability of ERS.
- Permanent seismic displacement (if calculated)

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 the *Liquefaction Evaluation* module.

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 the *Liquefaction-Induced Lateral Spreading* module.

Fault Rupture

Refer to the *Fault Rupture* module.

References

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6. Kavazanjian, E., N. Matasovic, T. Hadj-Hamou, and P. J. Sabatini. 1997. "*Design Guidance: Geotechnical Earthquake Engineering for Highways*," Geotechnical Engineering Circular No. 3, Vol 1-Design Principles, FHWA-SA-97-076. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.