Non-Gravity Cantilever Earth Retaining Systems (ERS)

Non-gravity cantilever ERS have vertical structural elements embedded below design grade to establish the necessary lateral resistance through passive earth pressure to counteract the lateral earth pressures. The vertical structural elements can be either discrete piles such as soldier piles, or continuous piles such as sheet piles, tangent piles, and secant piles (Figure 1 and Figure 2). The piles can be installed by driving, vibrating, or drilling. Steel soldier piles and sheet piles are the most commonly used non-gravity cantilever ERS in Caltrans projects. Tangent and secant piles (Cast-In-Drilled Hole piles) are also used in Caltrans projects related to embankment slope or landslide mitigation, and seawalls.

Advantages of non-gravity cantilever ERS include:

- Less right of way needed than competing systems, such as soil nails
- Less disruptive to traffic than ERS using bottom-up construction methods
- Less environmental impact than ERS using bottom-up wall methods
- Relatively fast construction
- Good performance under seismic loading

Some advantages such as “less disruptive” and “relatively fast construction” may not be applicable to tangent and secant pile walls, depending on drilled-hole size and subsurface conditions.

Non-gravity cantilever ERS are not feasible when there are:

- Stringent requirements that limit the wall movement during construction (e.g., the proposed wall is adjacent to or below a critical structure, such as a bridge abutment)
- Design wall heights greater than 15 feet (for such cases, non-gravity cantilever ERS are not a cost-effective option, requiring larger piles or smaller pile spacing)

Favorable subsurface conditions for non-gravity cantilever ERS are:

- Excavated face can stand unsupported and stable until the lagging is placed for soldier pile walls
- Drilled-holes can remain open and stable without casing until the piles are installed and the concrete is placed
- Granular soils, stiff clays, and weathered bedrock with favorable bedding planes

Unfavorable subsurface conditions for non-gravity cantilever ERS include:

- Soft highly plastic clay, organic soil, collapsible soil, expansive soil, cobbles and boulders, weathered rock with unfavorable bedding planes, strong rock
- Groundwater table is above design grade for soldier pile walls

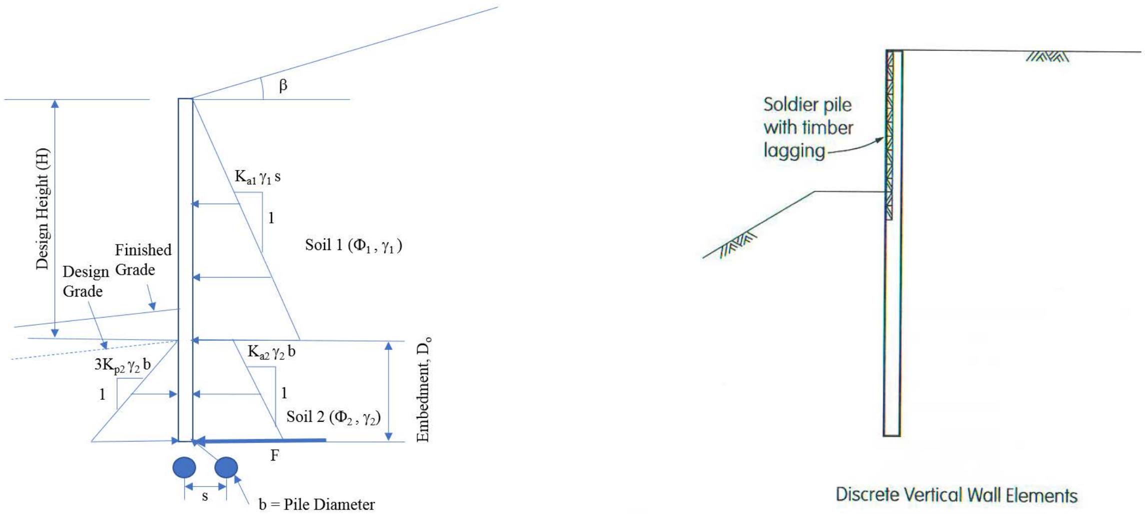

Figure 1: Typical Non-Gravity Cantilever ERS with Discrete Vertical Wall Elements Embedded in Granular Soils (Modified after AASHTO LRFD BDS, 2012 and Caltrans BDS, 2004)

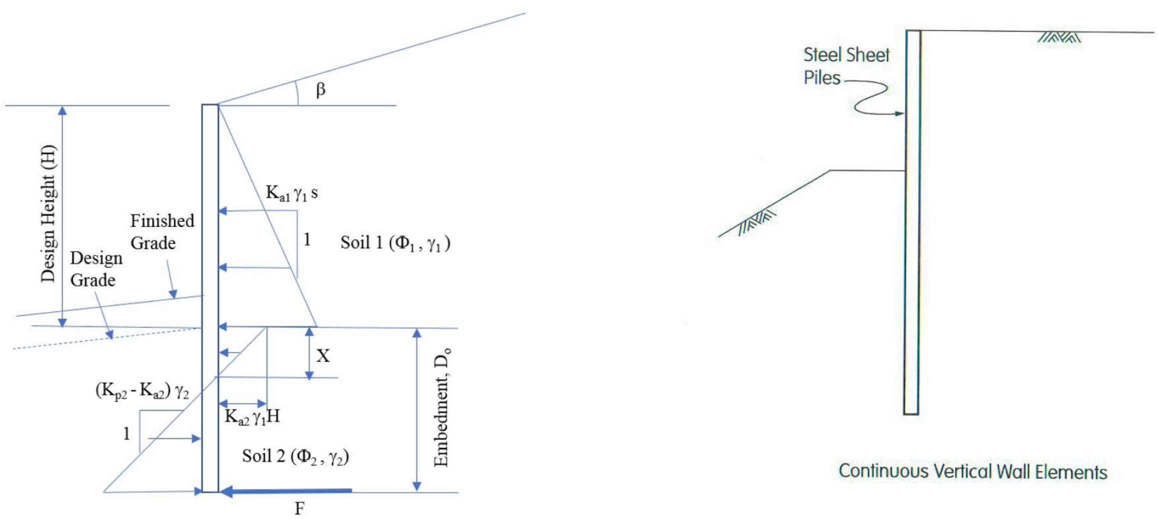

Figure 2: Typical Non-Gravity Cantilever ERS with Continuous Vertical Wall Elements Embedded in Granular Soils (Modified after AASHTO LRFD BDS, 2012 and Caltrans BDS, 2004)

Reference Manuals for Design and Communication

For non-gravity cantilever ERS design, use this module and the following design manuals and guidelines:

- AASHTO LRFD Bridge Design Specifications and California Amendments
- Memo to Designers 5-19, "Earth Retaining Systems Communication"
- Geotechnical Manual, "Foundation Reports for Earth Retaining Systems"
- Geotechnical Manual, "Seismic Design of Earth Retaining Systems"

For design cases where guidance provided in the above documents is not applicable, refer to other FHWA reference manuals including *FHWA NHI-05-094*, "LRFD for Highway Substructures and Earth Retaining Structure."

Responsibilities for Design

Geotechnical Services' responsibilities in the design of non-gravity cantilever ERS are:

- Develop interpreted subsurface cross sections. For a long wall, several subsurface cross sections along the alignment may be needed
- Estimate engineering properties such as unit weight, cohesion, friction angle, and associated lateral earth pressure coefficients
- Analyze the magnitude and distribution of lateral earth pressure for complex walls where conventional earth pressure theory does not apply, or when requested by the structure designer
- Determine the minimum pile embedment depth based on global stability requirements and required axial capacity, when pile elements are used

Information that should be provided by the structure designer for the geotechnical analysis and design are:

- Plans showing the location of the wall (beginning, end, length, and alignment)
- Elevation view of the wall (maximum and minimum design heights)
- Cross sections of the wall (for example, every 10 to 50 feet)

For the design of non-gravity cantilever ERS, the Geoprofessional (GP) should assist the structure designer in estimating all applicable lateral pressures against the wall including static and seismic earth pressures, lateral pressures induced by surcharge load, and hydrostatic pressure.

Investigations

Perform a geotechnical investigation to determine subsurface conditions that may affect the selection, design, and construction of the non-gravity cantilever ERS, including:

- Strength and deformation characteristics of foundation soil and rock
- Strength and weight of soil and rock to be retained

- Corrosion potential of soil in contact with the retaining wall
- Groundwater location
- Quantity of groundwater seepage

To plan for and carry out a geotechnical investigation refer to:

- Geotechnical Manual, “Geotechnical Investigations”
- Geotechnical Manual, “Soil and Rock Logging, Classification and Presentation Manual”
- Geotechnical Manual, “Borehole Location”
- FHWA NHI-01-031 Subsurface Investigations “Geotechnical Site Characterization”

Typical borehole spacing is about every 100 to 200 feet along the proposed wall alignment, with boreholes strategically positioned in front, behind, and directly on the retaining wall layout line. The number of boreholes should be reduced or increased based on the quality of existing data, uniformity of site geology, and the quality of site-specific geologic mapping. The depth of investigation should be more than two times the design height of the ERS or 20 feet below the ERS design grade, whichever is the greatest.

Design

The geotechnical design of a non-gravity cantilever ERS must meet displacement and stability requirements for the following limit states defined by LRFD design methodology:

- Service Limit State – movement and overall (global) stability (*AASHTO LRFD BDS* Article 11.8.3)
- Strength Limit State – overall stability - soil passive failure due to insufficient vertical element embedment (*AASHTO LRFD BDS* Article 11.8.4)
- Extreme Limit State - overall stability - soil seismic passive failure due to insufficient vertical element embedment, and overall/global stability (*AASHTO LRFD BDS* Articles 11.8.6)

For each of the limit states, the load and resistance factors should be applied in accordance with the *AASHTO LRFD BDS* Articles 3.4.1 (Table 3.4.1-1) and 11.5.6, and *California Amendments* (Table 11.5.7-1).

This module is developed for non-gravity cantilever ERS constructed by the top-down construction method.

Calculation of Lateral Pressure

The magnitude and distribution of lateral pressures depends upon the wall type, wall movement, wall geometry/stiffness, friction at the wall-soil interface, retained soil type, groundwater conditions, earth surcharge/sloping ground conditions, traffic, and construction-related live load surcharge. These factors should be considered in the calculation of the lateral pressure.

Static Lateral Pressure

- Active Earth Pressure

  Use *AASHTO LRFD BDS* Article 3.11.5 to calculate the active earth pressure coefficient and associated earth pressure. According to Article 3.11.5, the active earth pressure coefficient and associated earth pressure can be calculated using Coulomb, Rankine, or trial wedge methods. For the design of non-gravity cantilever ERS, Rankine and Coulomb methods are typically used. When these methods cannot be used due to complex geometry or multiple soil layers, the trial wedge method should be used.

  For walls with cohesive soil conditions, both the short-term condition (undrained) and long-term (drained) condition should be evaluated. In addition, the magnitude of active earth pressure should be at least 0.25 times the effective overburden pressure at any depth, or 0.035 ksf/ft of wall height, whichever is greater (*AASHTO LRFD BDS* Article 3.11.5.6).

  For the distribution of active earth pressure in different soils and rocks, refer to Figures 3.11.5.6-1 through 3.11.5.6-7 of *AASHTO LRFD BDS* 3.11.5.6.

- Surcharge Load

  Use *AASHTO LRFD BDS* Article 3.11.6 for the lateral pressure against the wall induced by surcharge loads.

- Hydrostatic Water Pressure

  When water is present behind the wall, hydrostatic water pressure must be considered in addition to other lateral earth pressures. When the hydrostatic water pressure is applied to the wall, calculate the lateral earth pressure with effective unit weight of soils. For continuous wall facing such as sheet piles, tangent piles, and secant piles, hydrostatic pressure differentials can develop between the back and front of the wall face and can cause seepage or piping (boiling) in cohesionless soils. For such cases, perform seepage analyses using a flow net or numerical analysis to ensure base stability against seepage. Section 5.2.9 of *Geotechnical Engineering Circular No. 4*, “Ground Anchors and Anchored Systems” presents procedures to calculate porewater pressure considering the effects of seepage (Equations 15 to 17, and Figure 32), and a simplified flow net for homogeneous soil (Figure 31). For non-homogeneous soil or special drainage conditions which may alter water boundary conditions, use numerical seepage analysis.

- Passive Earth Pressure

  For the calculation of passive earth pressure, use the log-spiral method with an appropriate wall interface friction angle. When the log-spiral method can’t be used due to complex geometry or multiple soil layers, use the trial wedge method with the wall interface friction angle no greater than 0.5ϕ according to *AASHTO LRFD BDS* Article 3.11.5.4, where ϕ is friction angle of the soil.

When Figures 3.11.5.6-1, 2, 4 and 5 in *AASHTO LRFD BDS* are used for calculation of passive earth pressure against embedded discrete vertical elements, use the Rankine passive earth pressure coefficient. The figures were developed based on Broms' Method (1964), in which the Rankine passive earth pressure coefficient was used to derive the effective width of 3 times the pile diameter. When different soil arching factors need to be used in the design, refer to *AAASHTO LRFD BDS* C11.8.6.3.

Seismic Lateral Pressure

For the calculation of a seismic lateral earth pressure, use *AASHTO LRFD BDS* Articles 11.6.5.2, 11.8.6 and 11.9.6. All the seismic loads for the design of non-gravity cantilever ERS are shown on Figure 11.8.6.2-1 of *AASHTO LRFD BDS*. As shown on Figure 11.8.6.2-1, the seismic active earth pressure resultant, P_{AE} is considered only above the design grade, while the P_A and P_{PE} are applied below the design grade. In addition, according to *AASHTO LRFD BDS* C11.8.6.2, for walls with continuous vertical elements, such as sheet pile walls, tangent pile walls, and secant pile walls, the P_{AE} will be distributed from the top of the wall to the point where the critical failure line of Limit Equilibrium (LE) analysis intersects with the vertical element below the design grade. For a wall supporting seismically critical structures, the seismic active earth pressure should be extended below the design grade to the toe of the vertical element to account for the uncertainties in the seismic distribution below the design grade.

- Seismic Active Earth Pressure

  For the calculation of the seismic active earth pressure, use *AASHTO LRFD BDS* Article 11.6.5.3. The article presents three methods to calculate the seismic active earth pressure: Mononobe-Okabe (M-O) method, trial wedge method, and Limit Equilibrium (LE) method. For wall geometry or site and soil conditions where the M-O method is not suitable, either the trial wedge method or LE method can be used.

  Because horizontal acceleration and resulting seismic earth pressure greatly depends on the magnitude of seismic displacement of a non-gravity cantilever ERS, consult the structure designer for the tolerable permanent seismic displacement of a non-gravity cantilever ERS, and estimate the horizontal acceleration coefficient (k_h). The k_h associated with the tolerable permanent seismic displacement should be used for calculating seismic active earth pressures.

  When the wall displacement analyses using a numerical method such as beam-column approach is to be performed by the structure engineer, provide soil spring parameters such as p-y curves according to *AASHTO LRFD BDS* Article C11.8.6.4.

- Seismic Passive Earth Pressure

  For the calculation of the seismic passive earth pressures, use *AASHTO LRFD BDS* Articles 11.8.6.3 and A11.4. In these articles, the log spiral or the nonlinear failure surface are recommended to be used with the wall interface friction. Do not use the M-O method for estimating the seismic passive earth pressure. According to the *AASHTO LRFD BDS* Article 11.6.5.5, a wall interface friction equal to two-thirds of the soil friction angle can be used for the calculation of the seismic passive pressure when there are no specific guidance or research results for a seismic wall interface friction. For the wall with an embedment depth of less than 5 feet, use the static method for the calculation of the seismic passive pressure according to *AASHTO LRFD BDS* Article 11.6.5.5.

Limit State Design

The design of the non-gravity cantilever ERS must meet displacement and stability requirements for each limit state below, and appropriate scour shall be considered in each limit state for the walls located in flood prone areas. For the guidance related to scour evaluation, refer to the *AASHTO LRFD BDS* Article 11.7.2.3.

Service Limit State

<u>Displacement</u>

The design of the wall must ensure that the vertical and lateral displacement does not affect the performance of the wall system (*AASHTO LRFD BDS* Article 11.8.3.1). For non-gravity cantilever ERS constructed by excavating a vertical face, there is no vertical stress increase in soils, and settlement due to net vertical stress does not occur.

For a wall supporting low-displacement tolerance structures, numerical analysis such as the finite element or finite different methods may be required.

<u>Global Stability</u>

The global stability is evaluated using LE slope stability analysis such as Morgenstern-Price, Modified Bishop, Janbu, or Spencer methods. For the resistance factors used in the global stability, refer to *AASHTO LRFD BDS* Article 11.6.2.3.

Strength Limit State

<u>Soil passive failure due to insufficient vertical element embedment</u>

This analysis is the structure designer's responsibility. For soil passive failure, refer to *AASHTO LRFD BDS* Article 11.8.4.

Extreme Limit State

Seismic soil passive failure due to insufficient vertical element embedment

This analysis is the structure designer's responsibility. For seismic soil passive failure, refer to *AASHTO LRFD BDS* Article 11.8.4 and 11.8.6.

Seismic Global Stability

For the seismic global stability analysis, use *AASHTO LRFD BDS* Articles 11.8.6.1 and 11.9.3.2. There are two benchmark values for k_h, depending on tolerable seismic displacement limits, 1/2 or 1/3 horizontal peak ground acceleration (HPGA) which is the acceleration at zero period (T = 0 second) calculated from Caltrans ARS Online (v.2.3.09). Use 1/3 HPGA for the k_h if an expected mean seismic displacement of 5.0 inches is acceptable. Use 1/2 HPGA for the k_h if the 2.0-inch seismic displacement is acceptable. If the seismic global stability is not satisfied with the benchmark value of 1/2 or 1/3 HPGA, use the following steps:

1. Find the horizontal yield acceleration coefficient (k_y) using iterative LE slope stability analyses.
2. Perform seismic displacement analysis using simplified seismic displacement method according to *AASHTO LRFD BDS* Appendix A11.
3. Consult the structure designer for calculated and tolerable seismic displacement.

Reporting

Report non-gravity cantilever ERS recommendations in accordance with *Foundation Reports for Earth Retaining Systems (ERS).* Include design information, and assumptions presented in the previous sections. For geotechnical recommendations, refer to Section 3.12.2.2, *Non-Gravity Cantilever Systems*, of the *FR for ERS*.