Ground Anchor Earth Retaining Systems (ERS)

This module presents Caltrans practice for geotechnical investigation, design, and reporting of ground anchor ERS. A brief discussion of the design policy and procedures on Deadman ERS is also included at the end of the design section. In this module, ground anchors are referred to as sub-horizontal ground anchors.

A ground anchor ERS is constructed by installing rows of ground anchors to resist lateral loads acting on the wall. Soldier pile ground anchor walls are most commonly used in Caltrans; concrete diaphragm ground anchor walls are commonly used for Caltrans roadway widening projects under the bridge abutments (see Memo to Designers 5-12, “Earth Retaining Systems Using Ground Anchors”). A ground anchor system consists of three components: anchorage (anchor head assembly), free stressing tendon (unbonded length), and anchor (bonded length) (Figure 1). Ground anchors provide lateral resistance by pre-stressing the tendon from the anchor to the anchorage at the wall facing. The ground anchor tendon can be either steel bars or steel strands; steel strands are more commonly used as they can provide higher tensile resistance and be easily handled during installation.

Design and performance advantages of ground anchor ERS include:

- Cost effective compared with most other ERS using top-down construction methods
- Less disruptive to traffic than ERS using bottom-up construction methods
- Less environmental impact than ERS using bottom-up construction method
- Quality assurance through performance or proof tests on each anchor
- ‘Active’ system to minimize lateral movement during excavation by pre-stressing of each anchor

Ground anchor ERS are unfavorable when there are:

- Permanent easement requirements
- Underground utilities or structures within the anchor zone

Favorable subsurface conditions for ground anchor ERS are:

- Excavated face can stand unsupported and stable until the facing is structurally complete
- Drilled-holes can remain open and stable without casing until the anchor is placed and grouted.

Unfavorable subsurface conditions for ground anchor ERS include:

- Soft, highly plastic clay, organic soil, collapsible soil, expansive soil, cobbles and boulders, weathered rock with unfavorable bedding planes
- Groundwater table is above design grade for soldier pile ground anchor walls
- Very weak soils behind the wall facing
DESIGN MANUALS AND GUIDELINES FOR DESIGN AND REPORT

For ground anchor ERS design, use this module, and the following design manuals and guidelines:

- Memo to Designers 5-12, “Earth Retaining Systems Using Ground Anchors”
- Memo to Designers 5-19, “Earth Retaining Systems Communication”
- Geotechnical Manual, “Foundation Reports for 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” and FHWA Geotechnical Engineer Circular No. 4, “Ground Anchors and Anchored Systems”.

GEOTECHNICAL SERVICES’ RESPONSIBILITIES FOR DESIGN

Geotechnical Services’ responsibilities in the design of ground anchor ERS are:
• Develop interpreted subsurface cross sections; for a long wall, several subsurface cross sections along the alignment may be needed
• Determine engineering properties of subsurface materials such as unit weight, cohesion, friction angle, and associated lateral earth pressure coefficients
• Analyze lateral earth pressure and its distribution for complex wall geometries when conventional earth pressure theories are not applicable or when requested by the structure designer
• Analyze minimum pile embedment depth based on global stability requirement and required axial capacity, if pile elements are used.
• Analyze anchor unbonded zone length based on conventional earth pressure theory if applicable, or slope stability analysis
• Assist the structure designer or the district project engineer in determining necessary permanent easements

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

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

For the design of ground anchor ERS, the geoprofessional should assist the structure designer in providing all applicable lateral pressures against the wall including static and seismic earth pressure, lateral pressures induced by surcharge load, and hydrostatic pressure.

GEOTECHNICAL INVESTIGATION

Perform a geotechnical investigation to determine subsurface conditions that may affect the selection, design, and construction of the ground anchor ERS, including:

- Strength and deformation characteristics of foundation soils and rocks
- Strength and weight of soils and rocks to be retained
- Corrosion potential of soils in contact with the retaining wall
- Groundwater location
- Quantity of groundwater seepage

To plan for and carry out a geotechnical investigation, including laboratory testing, refer to the following documents:

- Geotechnical Manual, “Borehole Location”
- Geotechnical Manual, “Geotechnical Investigation”
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. Perform at least one horizontal boring, if feasible, into the slope that is to be excavated and drilled for ground anchor wall construction to obtain soil and rock specimens and evaluate the caving potential of drilled holes during construction. The number of boreholes may 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 greater.

**DESIGN**

The geotechnical design of a ground anchor 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 11.9.3)
- **Strength Limit State** – stability against soil failures such as bearing failure (geotechnical axial capacity of vertical elements), anchor pullout failure, and passive failure due to insufficient vertical element embedment (AASHTO LRFD BDS Article 11.9.4)
- **Extreme Limit State** - stability against soil failures such as bearing failure (geotechnical axial capacity of vertical element), anchor pullout failure, and passive failure due to insufficient vertical element embedment, and overall/global stability (AASHTO LRFD BDS Articles 11.9.4 and 11.9.6)

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

**Calculation of Lateral Pressure**

The magnitude and distribution of lateral pressures depend upon wall type, wall movement, wall geometry/stiffness, friction at 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 for the calculation of lateral pressures.

**Static Lateral Pressure**

- Apparent Earth Pressure (AEP)
Calculation of AEP must follow AASHTO 3.11.5.7, and Caltrans MTD 5-12. The AEP was developed from top-down construction with constraining or limiting wall deformation and should be used whenever the construction method meets these conditions. The distribution of AEP should be based on construction method and sequence, stiffness of wall and anchor system, type and properties of soils, pile and anchor spacing, and expected displacement, etc.

For simple wall geometry, and subsurface profiles in which the Rankine or Coulomb active earth pressure coefficient can be used for calculation of AEP, use Equations 3.11.5.7.1-1 to 3.11.5.7.2b-2 and AASHTO Figures 3.11.5.7.1-1 and 3.11.5.7.2b-1. When calculating active earth pressure coefficient, \( k_a \), the wall interface friction angle should be equal to zero. For walls with cohesive soil conditions, both short-term condition (undrained) and long-term (drained) condition should be evaluated, and AEP should be developed for the condition, whichever results in greater lateral force.

For complex wall geometry, or subsurface profiles in which the Rankine or Coulomb earth pressure coefficient cannot be used for calculation of AEP, use Equations 5-12.1 and 5-12.2 of Caltrans MTD 5-12. Consider a total load, \( P_{total} \) as a total lateral load of AEP (\( P_{AEP} \)) in these equations. When calculating the \( P_{AEP} \) by the Limit Equilibrium (LE) analysis, use the following two methods.

Note that a multiplier of 1.33 is introduced in Method 1 to account for the effect of construction method (ground anchor installation with pre-stressing). The factor was calibrated by comparing field measured data with active earth pressure load.

Do not use the methods presented below for hard clay soils:

1. **Method 1**

   Perform LE (slope stability) analysis for stability of the retained soil mass, and find the required stabilizing (active) force, \( P_A = P_{FoS} \times 1.0 \) resulting in a factor of safety (FoS) of 1.0. The FoS of 1.0 is equivalent to the active earth pressure condition. Then multiply the \( P_A \) by 1.33 to obtain the \( P_{AEP} \) (\( P_{AEP} = 1.33 \times P_A \)). The multiplier of 1.33 was calibrated by comparing field measured data with the active earth pressure load and was also used in deriving the AASHTO Equations 3.11.5.7.1-1 to 3.11.5.7.2b-2.

\[
P_{AEP} = \frac{2K_a \gamma H^2}{3} = 1.33 \times \left( \frac{K_a \gamma H^2}{2} \right) = 1.33 \times P_A
\]

Where,

\( P_{AEP} \) = Total force based on AEP distribution (Figures 3.11.5.7.1-1 (a), and AASHTO Equations 3.11.5.7.1-1 (b).
\( P_A = \) Total force based on triangular distribution of active earth pressure.

- Method 2

Perform LE slope stability analysis and find the required stabilizing force, \( P_{FoS \_1.33} \) or \( 1.54 \), resulting in a factor of safety (FoS) of 1.33 or 1.54. The calculated stabilizing force should be considered as the \( P_{AEP} \) (\( P_{AEP} = P_{FoS \_1.33} \) or \( 1.54 \)). Do not apply the multiplier of 1.33 used in Method 1 to \( P_{AEP} \). According to AASHTO, a resistance factor of 0.75 (equivalent to FoS of 1.33) is recommended for well-defined soil parameters and a slope that is not supporting structures, while a resistance factor of 0.65 (equivalent to FoS of 1.54) is recommended for limited soil information and a slope that is supporting structures.

Method 2 is commonly used for the design of slope stabilization or landslide mitigation. According to the Geotechnical Engineer Circular No. 4, “Ground Anchors and Anchored Systems”, \( P_{FoS \_1.3} \) is close to \( 1.3P_{FoS \_1.0} \) for reasonably homogeneous soils with competent soils below the bottom of excavation. For walls supporting critical structures, \( P_{FoS \_1.5} \), a higher value, may be used for \( P_{AEP} \) to reduce wall deformation and its effect on nearby structure. The \( P_{AEP} \) (\( P_{FoS \_1.33} \) or \( 1.54 \)) calculated from Method 2 should not be less than the \( P_{AEP} \) (1.33 \( P_A \)) calculated from Method 1.

When soft or very loose soils exist below the bottom of excavation, and basal stability is of concern, extend LE analysis below the design grade. However, ground anchor ERS are not suitable at sites with soft soils that extend to a significant depth below the design grade.

In addition to AEP, appropriate hydrostatic water pressure, lateral pressures induced by surcharge load, and seismic earth pressure should be included in the analysis.

- Surcharge Load

Use AASHTO 3.11.6 for the lateral pressure against the wall induced by surcharge loads.

- Hydrostatic Water Pressures

When water is present behind the wall, hydrostatic water pressure must be considered in the design in addition to other lateral earth pressures. When the hydrostatic water pressure is applied to the wall, calculate lateral earth pressure including apparent earth pressure with effective unit weight of soils. For ground anchor ERS with continuous wall facing such as sheet piles, tangent piles and secant piles, hydrostatic pressure differential 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 the 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 effects of seepage (Equations 15 to 17, and Figure 32), and 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 of no greater than 0.5\(\phi\) as per AASHTO 3.11.5.4, where \(\phi\) is friction angle of the soil.

  When AASHTO Figures 3.11.5.6-1, 2, 4 and 5 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 AASHTO C11.8.6.3.

**Seismic Lateral Earth Pressure**

For calculation of seismic lateral earth pressures, use AASHTO 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 AASHTO Figure 11.8.6.2.1. As shown on Figure 11.8.6.2.1, a seismic active earth pressure resultant, \(P_{AE}\) is considered only above the design grade, while \(P_A\) and \(P_{PE}\) are applied below the design grade. In addition, according to AASHTO 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 top of wall to a point where the critical failure line of LE analysis intersects with vertical element below design grade. For walls supporting seismic critical structure, seismic active earth pressure should be extended below the design grade to the toe of the vertical element to account for uncertainties in the seismic distribution below design grade.

- **Seismic Active Earth Pressures**

  For the calculation of seismic active earth pressures, use AASHTO 11.6.5.3. These standards present 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 for which the M-O Method is not suitable, either Trial Wedge method or LE method can be used.
Because seismic horizontal acceleration and resulting seismic earth pressure greatly depends on the magnitude of seismic displacement of a ground anchor ERS, consult the structure designer for tolerable permanent seismic displacement of a ground anchor ERS, and assist the structure designer in estimating the horizontal seismic coefficient ($k_h$). The $k_h$ associated with the tolerable permanent seismic displacement should be used for calculating seismic active earth pressures.

When wall displacement analyses using numerical methods such as finite element or finite difference methods, and the beam-column approach is to be performed by the structure engineer, soil spring parameters such as p-y curves should be provided by the geoprofessional according to AASHTO C11.8.6.4.

- **Seismic Passive Earth Pressures**

  For calculation of seismic passive earth pressures, use AASHTO 11.8.6.3 and A11.4. In these articles, the log spiral procedure 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 AASHTO 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 pressures when there are no specific guidance or research results for a seismic wall interface friction. For the wall with embedment depth less than 5 feet below finished grade, use the static method for the seismic passive pressure according to AASHTO 11.6.5.5.

**Limit State Design**

The design of ground anchor ERS must meet displacement and stability requirements for each limit state below, and appropriate scour shall be considered in each limit state if the wall is in a flood prone area. For the guidance related to scour evaluation, refer AASHTO 2.6.4.4.2 and 11.7.2.3.

**Service Limit State**

**Displacement**

The design of the wall must ensure that the vertical and lateral displacement does not affect the performance of the wall system. For calculation of settlement of the wall system use AASHTO Figure C11.9.3.1-1. For walls supporting low-displacement tolerance structure, numerical analysis such as finite element or finite difference methods may be required. For ground anchor 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.
Global Stability

The global stability is evaluated using acceptable methods of 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 11.6.2.3.

Strength Limit State

Axial capacity of vertical element (bearing failure)

For calculation of axial capacity of a vertical element, use AASHTO 10 and Caltrans Pile Foundations Manuals. Embedment depth of vertical elements must withstand factored axial load demands induced by the vertical component of total anchor loads, dead weight of the wall system and other external loads.

Basal Heave Stability

For walls embedded/supported on soft to medium clays, check basal heave stability to ensure adequate soil bearing capacity at the base of the excavation and no substantial increase in lateral earth pressure. The methods (Equations 34 to 37) to calculate a factor of safety against basal heave stability are presented in Section 5.8.2 “Basal Stability” of Geotechnical Engineering Circular No. 4, “Ground Anchors and Anchored Systems.” According to Section 5.8.2, significant ground movements towards the excavation will occur when the soil bearing capacity at the base of excavation is approached regardless of the strength of the supports, and it will substantially increase the load on the lowest ground anchor with decreasing FoS of basal heave stability. Geotechnical Engineering Circular No. 4 recommends the minimum FoS of 1.5 for support of the excavation. Because there is no LFRD guideline on basal heave stability, allowable stress design (ASD) with the minimum FoS of 1.5 can be used until LRFD guidelines on basal heave stability is available in AASHTO.

Anchor Pullout

Determination of anchor pullout resistance and corresponding anchor bond length are the Contractor’s responsibility.

Minimum Anchor Unbonded Length

For determination of the minimum anchor unbonded length, AASHTO 11.9.1., 11.9.4.2, C11.9.4.2, and Figure 11.9.1-1. For complex wall geometry, or subsurface profile for which Figure 11.9.1-1 cannot be used, use LE slope stability analysis for the minimum
anchor unbonded length. The minimum anchor unbonded length is the distance from wall face to the failure surface plus a minimum distance between potential failure surface and frontal anchor bond zone, 5 feet or H/5, whichever is greater. According to AASHTO Figure 11.9.1-1, H is defined as design height of vertical element above design grade.

**Extreme Limit State**

**Minimum Anchor Unbonded Length**

For determination of the minimum anchor unbonded length, use AASHTO 11.9.6. For LE slope stability analysis, use the $k_h$ associated with a tolerable seismic permanent displacement of ground anchor ERS.

**Seismic Global Stability**

For seismic global stability, use AASHTO 11.8.6.1 and 11.9.3.2. There are two threshold 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 ($T=0$) calculated from Caltrans ARS Online (v.2.3.09). Use $k_h$ of 1/3 HPGA if up to 7.0-inch seismic displacement is acceptable. Use $k_h$ of 1/2 HPGA if up to 2.0-inch seismic displacement is acceptable. If seismic global stability is not satisfied with a threshold value of 1/2 or 1/3 HPGA, use the following steps:

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

**DEADMAN**

Design guidelines for deadman anchors are not presented in AASHTO. If the deadman anchors are needed, use *Caltrans (LFD Version) Bridge Design Specifications (BDS)* Article 5.8.6.2 (2003). In *Caltrans BDS*, a deadman is termed a structural anchor. The deadman typically consists of a concrete anchor with large masses of precast or cast-in-placed concrete (*Caltrans BDS* Article 5.8.6.2.1), an anchor pile with driven or cast-in-drilled-hole (CIDH) piles (*Caltrans BDS* Article 5.8.6.2.2) and pile anchors with driven piles (*Caltrans BDS* Article 5.8.6.2.3). According to *Caltrans BDS* Article 5.8.6.2.1, the depth of the concrete anchor deadman shall be based on the active and passive earth pressures behind and in front of the deadman, and the deadman must be located far enough from the wall face to ensure the passive zone in front of the deadman does not overlap with active zone behind the wall.
For the design of the deadman, allowable stress design (ASD) may need to be used until resistance factors for the design of the deadman are calibrated and published in AASHTO. Before recommending and designing the deadman anchor, the geoprofessional must verify with the structure designer whether ASD or LRFD will be used.

Unlike ground anchor ERS, in which AEP is used in the design, Caltrans BDS Article 5.8.2 recommends active earth pressure with triangular distribution for design of the deadman anchors. The recommendation of the active earth pressure with triangular distribution may indicate that the deadman is a passive anchorage with no pre-stressing, and the anchor is activated when the retained mass is deformed.

**REPORTING**

Prepare the report following the requirements in “Foundation Reports for Earth Retaining Systems (ERS)” in the *Geotechnical Manual*. Include design information and assumptions presented in the previous sections. When construction concerns are expected, such as construction difficulties and monitoring of displacements, include them in “Construction Considerations” of the FR. The information and instructions included should be clear enough for the specification engineers to edit and compile the special provisions and non-standard special provisions.

**Design Parameters**

Provide the magnitude and distribution of lateral earth pressure along vertical wall elements or provide the engineering properties required for the calculation of lateral earth pressure. For walls with simple geometry and homogeneous soils, provide the following engineering properties for foundation soils and rocks below design grade and retained soils and rocks behind the wall:

- Moist unit weight
- Cohesion
- Friction angle
- Rock strength
- Static earth pressure coefficients
- Horizontal seismic coefficient with expected displacement
- Seismic earth pressure coefficients
- Design groundwater elevation

For walls with complex geometry, inhomogeneous soils, or cohesive soil layers, or when requested by Structure Design, provide the following information in addition to the above information:
• Static AEP diagram, or total stabilizing force (unfactored), $P_{AEP}$ for retained soils
• Static earth pressure diagram, and static earth pressure coefficient for embedded soils and rocks
• Seismic earth pressure diagram and seismic earth pressure coefficient
• Steady-state water pressure distribution
• Soil spring parameters such as p-y curves (AASHTO 11.8.6.4) if soil structure interaction analysis is performed by the structure designer

Recommendations

• Minimum pile embedment below design grade for required geotechnical axial capacity, global stability, and basal heave stability
• Length of anchor unbonded zone
• Minimum lagging or wall face embedment below finish grade for erosion, local stability and global stability
• Drainage system details and specifications, if horizontal drains are recommended to intercept the flow at a distance well behind the wall

Construction Considerations

Review the current list of Caltrans standard special provisions (SSP) and provide information that the specification engineer will need to edit the geotechnical related SSP. Ground anchor ERS related SSP are:

SSP No. 19-3.01D(2) – Soil Nail Wall and Ground Anchor Wall.
Provide wall zones for each ground anchor wall using the following table.

<table>
<thead>
<tr>
<th>Wall Zone</th>
<th>Beginning Station</th>
<th>End Station</th>
<th>Upper Elevation (feet)</th>
<th>Lower Elevation (feet)</th>
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</table>

SSP No. 46-1.01A – Ground Anchor Work Sequence
Provide instructions on specific work sequencing concerns related to ground anchor construction such as the timing of ground anchor stressing relative to the construction of other elements.
SSP No. 46-2.03A – Difficult Ground Anchor Installation

Provide locations and descriptions of difficult site conditions for ground anchor installation. The difficult site condition includes difficult drilling due to caving or hard excavation, overhead and underground utilities, constraints on installation method such as noise, and vibration, staged construction and traffic control.

SSP No. 49-4.03B – Hard Drilling for Steel Soldier Piling

If rocks or boulders are anticipated and conventional drilling equipment may not be suitable for drilling holes for the piles, provide the location and description of difficult site conditions for drilling.

When applicable, review and include SSP for Section 49-2.xxxx.– Driven Pile and 49-3.xxxx – CIDH Concrete Piling.

In addition to the above SSP, common construction concerns for pile construction associated with ground anchor ERS are:

- Corrosiveness of the project site
- Pile installation methods – list of installation methods not allowed
- Difficult pile installation – caving and difficult excavation due to cobbles, boulders, hard rocks and groundwater etc.
- Pre- and post-construction monitoring program if needed

Construction concerns when determining the size of drilled holes for soldier piles are:

- Water in the drilled hole for soldier pile foundation should be avoided when possible since gamma-gamma testing of the concrete is not possible. In cases where water cannot be avoided, the hole size must allow room for a tremie tube to be inserted next to the pile.
- Drilled hole size should be 2.5 to 3 times the size of the largest cobbles to allow for their extraction from the hole with normal drilling equipment.