10.10 VERTICAL GROUND ANCHORS

10.10.1 GENERAL

This memo provides guidance on designing vertical ground anchors commonly used for foundations of bridges and reinforced concrete retaining walls, such as Caltrans Type 7B walls. This memo describes different failure mechanisms and controlling load cases to be considered when designing vertical ground anchors. For design requirements, refer to AASHTO-CA BDS and Structure Technical Policy 10.10 (STP 10.10).

Vertical ground anchors are downward-inclined structural systems (also known as “tie-downs”) installed in rock or soil to develop ground resistance through a tendon that resists tension. Vertical ground anchors can be used for foundation elements subject to uplift, overturning, or lateral forces. Vertical ground anchors are often used when piles or shafts are not economical or feasible due to site conditions, such as where rock exists close to the ground surface, that driven piles may not develop sufficient geotechnical tensile resistance against uplift. Vertical ground anchors are highly effective in combination with spread footings founded on rock to resist overturning or uplift as part of a seismic retrofit system. The basic structural components of vertical ground anchors include tendons and anchorage. Additional information related to vertical ground anchors is covered in Section 46 of the Standard Specifications.

10.10.2 DEFINITIONS

Grout - Portland cement grout that is injected into the anchor hole prior to or after the installation of the anchor tendon to facilitate the force transfer to the surrounding ground along the bonded length of the tendon.

Tendon – Tendons are commonly pre-stressing steel elements. Tendons can be composed of multiple wire strands or high-strength bars that transfer tensile force. The tendon has bonded and unbonded zones.

Anchorage – Anchorage is an assembly of structural elements used to transfer the load from one structural element to another, such as a bridge footing. The anchorage includes a bearing plate, a trumpet (a steel tube welded to the bearing plate), and an anchor head with wedges for strands (or a threaded nut for bars). A corrosion protection cap may be included as part of the anchorage system.

Bonded Zone - The bonded zone is where the tendon is bonded to the ground to develop resistance without moving relative to the ground.

Unbonded Zone - The unbonded zone is where the tendon is isolated from bonding with the ground and is free to move relative to the ground. This is typically protected against corrosion with a combination of grease and grout along the unbonded length.

10.10.3 NOTATION

m_p = percentage of lock-off load used in the P'_u calculation

f_{pu} = specified tensile strength of pre-stressing steel

P_u = maximum factored tensile force effect per anchor due to external loads from the strength and extreme event limit states, without the effect of lock-off load

P'_u = P_u plus the additional forces in the anchor due to the effect of P_{lock} and soil-structure interaction, ($P'_u = (m_p\, P_{lock})/100 + P_u$)

P_{lock} = lock-off load per anchor (the pre-stressing force in the tendon immediately after transferring the load from the jack to the anchor head after seating loss)

P_{TL} = test load per anchor, ($P_{TL} = P'_u / \phi$)

ϕ = anchor pullout resistance factor (AASHTO-CA BDS Table 11.5.7-1)

10.10.4 DESIGN CONSIDERATIONS

During the design of ground anchors, the Structure Designer (SD) should consult with the Geo-professional (GP). The recommended minimum unbonded length is 10 feet for bar ground anchors and 15 feet for strand ground anchors. The typical anchor bonded length ranges from 15 to 40 feet. Ground anchor bond strength highly depends on the drilling equipment, drilling practices, and grouting scheme. Therefore, final bonded lengths are determined by a specialty ground anchor contractor.

The SD should consult with the GP to determine the recommended center-to-center spacing between ground anchors. The recommended minimum center-to-center spacing between ground anchors is 5 feet. GP should consider the cone failure mode and the possibility of laminar failure mode when choosing the anchor horizontal spacing and length of the unbonded zone. For closely spaced anchors, it is often advisable to consider a staggered anchor layout where some anchors have longer unbonded zones than others.

Per STP 10.10, vertical ground anchors shall not be locked off less than 25% of P_u. Stress limits for pre-stressing steel need to be determined at the service limit state. Lock-off load from the ground anchors increases the bearing stress demand on foundations. When evaluating the external stability, such as bearing, sliding, and eccentricity of a foundation with ground anchors, the SD needs to include the effect of external loads and lock-off load. Bearing and sliding should be checked for all stages of construction. Along with the load factors outlined in the AASHTO-CA BDS Article 3.4.1-3, a load factor $\gamma_p = 1.0$ is used for lock-off load, P_{lock}. Ground anchors with a minimum lock-off load may be considered when retrofitting an existing foundation or when a design engineer expects the underlying foundation soil to have a reduced bearing capacity. Generally, a higher lock-off load is recommended for ground anchors in bridge abutments and retaining walls located in high seismic regions to provide adequate resistance against sliding. Higher lock-off loads in ground anchors prevent the uplift of the foundation and reduce fatigue on the ground anchor system. Ground anchors with high lock-off loads on soft soil are expected to cause increased settlement/rotation and tendon relaxation, which lessens the force in the vertical anchor after the application of P_{lock}. Vertical ground anchors may be pre-stressed to a lock-off load as high as 100% of P_u plus losses due to settlement.

The SD should evaluate structure stability in consideration of the effect of foundation deformation and tendon elongation at all stages of construction due to the application of external loads on the structure. For structures with vertical ground anchors, overturning moment due to lateral earth pressure tends to increase tendon demand above the lock-off load.

An in-house Finite Element Analysis (FEA) conducted on vertical ground anchors has revealed that the application of pre-stressing lock-off load (P_{lock}) to a foundation system, considering soil-structure interaction, leads to an increase in the tendon forces. STP 10.10 indicates the anchor shall be designed for the resultant of P_u and the internal force effects of pre-stressing. The pre-stress force effect may be determined through a soil-structure interaction analysis that considers the stiffnesses of the soil, the ground anchor, and the foundation. A limited parametric study (Caltrans, 2022) using FEA was conducted on anchored bridge abutments and bridge bents. The results of the study provided an empirical value, m_p, which serves to estimate the increase in pre-stressing forces arising from P_{lock}, considering a range of subgrade stiffness levels. In the absence of FEA and code requirements, the m_p values shown in Table 10.10.4-1 may be used for vertical ground anchor systems on different subgrade stiffness.

Table 10.10.4-1 m_p - Percentage of P_{lock} for P'_u Calculation

Structure Type	m_p (percentage) for subgrade stiffness (50 ksf/ft – 500 ksf/ft)	m_p (percentage) for subgrade stiffness (501 ksf/ft -1500 ksf/ft)	m_p (percentage) for subgrade stiffness (Greater than 1500 ksf/ft)
Abutment footing or retaining wall footing	50	35	28
Bridge column footing	65	40	25

The study proved that under an ideal situation, where a ground anchor is used on an infinitely stiff subgrade, m_p would approach 0% for all structure types. The SD is encouraged to perform an analysis using the Finite Element Model (FEM) to determine P'_u for complex structures or when footing settlement cannot be satisfactorily predicted by the modulus of subgrade reaction values.

The SD and GP, as a minimum requirement, should refer to Articles 3.4, 5.8, 5.9, 5.10, 10.9, and 11.9 of the AASHTO-CA BDS and the Standard Specifications.

The SD and GP must also consider various possible failure modes during the design of vertical ground anchors. Failure modes of vertical ground anchors depend on the soil or rock type, the bonded length of the anchor, the strength of the tendons, the bond between the grout and the tendon, the magnitude of anchor loads, and the anchor layout. Tendon tension failure, grout-tendon interface failure, post-tensioned anchorage zone failure, ground-grout interface failure, and ground mass failure are some of the failure modes that should be considered in the design of vertical ground anchors.

10.10.4.1 Tendon Tensile Rupture

In a vertical ground anchor system, the tension demand in the steel tendon increases as the footing is loaded. If the applied factored tensile force is greater than the factored tensile resistance of the tendon, the tendon will break. This kind of failure is referred to as tendon tensile failure. For post-tensioned anchors, tensile failure does not typically control the design. The tendon area is designed and tested to resist P_{TL}. When calculating the minimum area of pre-stressing steel needed to resist P_{TL}, it is required to satisfy the stress limitations specified in Article 5.9.2.2 of the AASHTO-CA BDS.

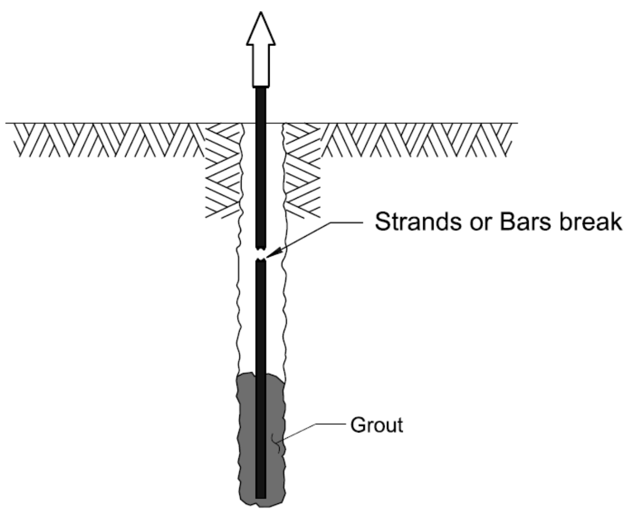


Figure 10.10.4.1-1 Tendon Tensile Rupture

10.10.4.2 Grout-Tendon Interface Failure

The shear resistance developed at the grout-tendon interface relies on adhesion, friction, and mechanical interlock between the grout and the tendon. Grout-tendon Interface failure occurs when the shear resistance along the interface of the tendon and the grout is less than the anchor tensile force. This kind of failure rarely controls the ground anchor design. Grouted-tendon bond stress depends on several factors. Normal confining pressure and stiffness, the roughness of the tendon, the grout properties, and the grout compressive strength are some of the parameters affecting the grout-tendon bond.

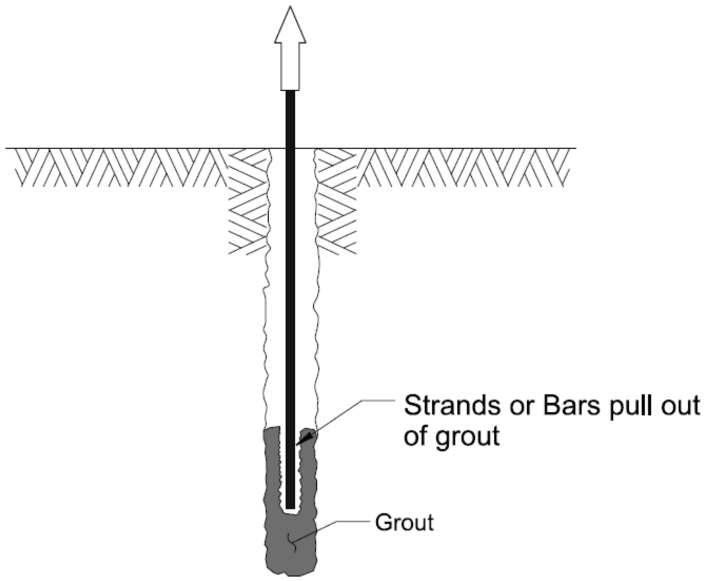


Figure 10.10.4.2-1 Grout-Tendon Interface Failure

10.10.4.3 Post-tensioned Anchorage Zone Failure

Post-tensioned anchorage zone failure pertains to a tensile failure in concrete, which occurs in the most critical portion of the ground anchor head on the concrete footing. The failure happens due to the tensile stress that develops immediately next to the anchorage plate of a ground anchor, resulting in the bursting of concrete in that region of the footing. The SD should design the anchorage zone per AASHTO-CA BDS. The design force for a ground anchor's post-tensioning anchorage zone is 1.2 times the test load (P_{TL}), as outlined in AASHTO-CA BDS Article 3.4.3.2. Furthermore, the design of the anchorage zone should incorporate relevant Articles such as 5.8.4.5, 5.9.5.6, and other pertinent portions within AASHTO-CA BDS.

10.10.4.4 Ground-Grout Interface Failure

Ground-grout interface failure is the geotechnical failure in the bonded portion of the ground anchor and the ground. This failure mechanism in vertical ground anchors is similar to a drilled shaft failure subjected to tension (uplift). Post-grouting is often used to increase the ground-grout interface resistance along the bonded length of ground anchors.

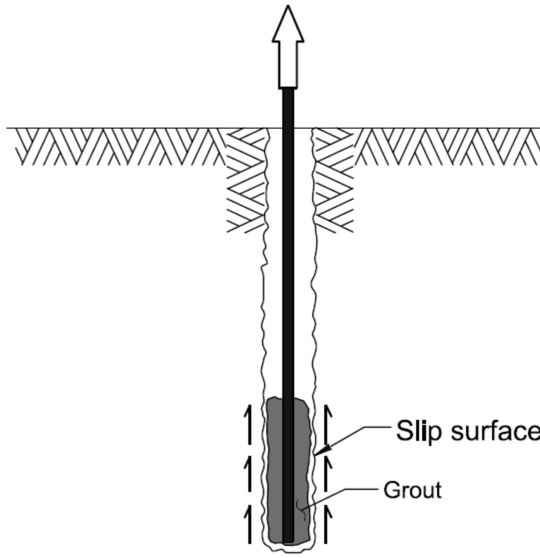
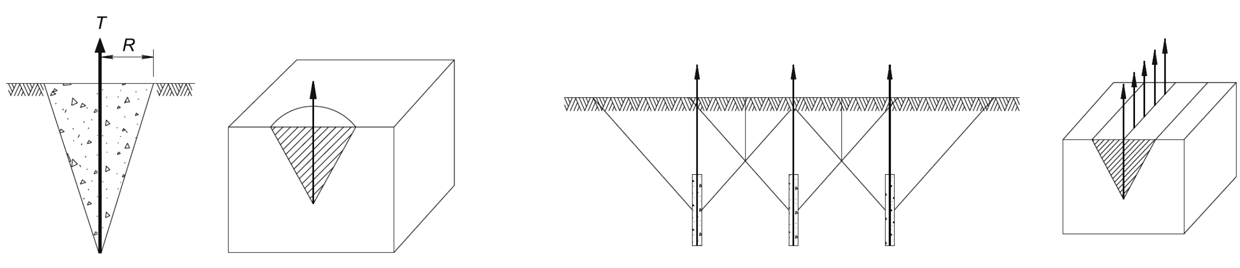


Figure 10.10.4.3-1 Ground-Grout Interface Failure

10.10.4.5 Ground Mass Failure

Ground mass failure is a geotechnical failure mode that may occur when the overlying soil/rock mass above the bonded length of the ground anchor is so shallow that shear failure occurs in the soil/rock mass, as shown in Figure 10.10.4.5-1. The shear failure in soil/rock mass propagates from the anchor bonded zone up to the ground surface with increasing diameter, forming a cone-shaped failure plane on a single anchor. The effect of a group of anchors in a single line is assumed to create a wedge-shaped failure plane. In general, this type of failure mechanism is more common in highly stressed shallow vertical anchors, where the ground anchor's unbonded length is less than fifteen feet (15 ft). Other common causes of soil shear failure are when soil is under-consolidated in situ or when soil capacity is overestimated by the contractor, the GP, or SD.



Single Anchor Failure Plane Multiple Anchor Failure Plane

Figure 10.10.4.5-1 Ground Mass Failure
(Journal of Rock Mechanics and Geotechnical Engineering)
(Volume 7, Issue 1, February 2015, Pages 1-13)

10.10.5 TESTING PROCEDURES

During construction, every ground anchor of the structure is typically load-tested after installation to verify its resistance and load-deformation behavior are adequate. This load testing methodology, combined with specific acceptance criteria, is used to verify that the ground anchors can resist the design load without excessive deformations and that the assumed load transfer mechanisms have been properly developed within the bonded zone. After acceptance, the ground anchor is stressed to a specified design load and locked off. The acceptance or rejection of ground anchors is determined based on the results of the following tests:

- Performance tests: multi-cycle incremental test loading and unloading of a pre-stressed anchor, recording the movement of the tendon at each increment.
- Proof tests: Single-cycle incremental loading of a pre-stressed anchor, recording the movement of the tendon at each increment.
- Creep tests: a single load held for a specified duration and conducted as part of the performance and proof tests. The movement of the tendon is recorded over a specified duration. This test may also be required in cohesive soil with a high plastic limit or liquid limit. Extended creep tests and short-duration creep tests may be used depending on the anticipated anchor movement.

The minimum number of performance tests is determined by the GP, with the concurrence of the SD. All other anchors are proof tested. After successful testing, the anchor is stressed to a specified design load and locked off against the structure. For detailed information on testing requirements and test load, P_{TL}, refer to the Standard Specifications.

Ground anchors are designed using the controlling factored tensile force, P_u, determined by the external loads from each applicable limit state combination. The test load, P_{TL}, is determined through Equation 10.10.5-1

$$P_{TL} = ((m_p\, P_{lock})/100 + P_u)/\phi \qquad (10.10.5\text{-}1)$$

Under special situations, when vertical ground anchor systems are designed to have P_{lock} much greater than P_u, the contribution of P_u on P_{TL} becomes smaller. When P_{lock} is much greater than P_u, the design and testing of the ground anchor will depend only on P_{lock}. In this case, a minimum P_{TL} of $1.25P_{lock}$ should be considered for the designing and testing of the ground anchor.

Table 10.10.5-1 summarizes the minimum P_{lock} and P_{TL} for the bridge structures and reinforced concrete retaining walls.

Table 10.10.5-1 Test Load and Lock-Off Load

Structure Type	Minimum Lock-off Load	Test Load (See Note 1)
Bridge Foundations and Reinforced Concrete Retaining Walls	$P_{lock} = 0.25\ P_u$	Greater of, $P_{TL} = \frac{P'_u}{\phi}$ and $P_{TL} = \frac{1.25P_{lock}}{\phi}$ Where, $P'_u = (m_p\ P_{lock})/100 + P_u$

Notes:

1. The value of ϕ is determined in accordance with AASHTO-CA BDS Table 11.5.7-1. ϕ is equal to 1.0 when the proof test or performance test is conducted on all production anchors.

10.10.6 DESIGN RESPONSIBILITIES

The SD:

- Determines P_u, P'_u, P_{TL}, and P_{lock}
- Determines the minimum area of steel tendon (strand or bar) required to resist the tendon tensile failure at P_{TL}
- Reviews ground anchor shop drawings prepared by the contractor
- Designs the post-tension anchorage zone of the ground anchor

The GP:

- Provides modulus of subgrade reaction for foundation when requested by SD
- Determines the need for creep tests in addition to performance and proof tests
- Determines the minimum unbonded length
- Determines the minimum anchor spacing

The Contractor:

- Determines the type of tendon, either strand or bars, and the number of strands, or size of bar, in a given tendon to resist the tendon tensile failure at P_{TL}
- Determines the vertical ground anchor installation method
- Determines the hole diameter and anchor bonded length needed to resist both the grout-tendon interface and the ground-grout interface failure modes at P_{TL}
- Complies with the acceptance criteria, as specified in the Standard Specifications
- Prepares and submits ground anchor shop drawings for review

10.10.7 CORROSION PROTECTION

Protecting the metallic components of the tendon against the detrimental effects of corrosion is necessary to ensure adequate long-term performance of the ground anchors. Corrosion protection for ground anchor tendons, as shown in the Caltrans Bridge Standard Details xs12-030-1 and xs12-030-2 and stipulated in the Standard Specifications, includes one or more physical barrier layers that protect the tendon from corrosive environments. To protect the main sections of the tendon, the following corrosion resistant measures are employed in our standards:

1. The anchorage – an anchorage enclosure filled with grout, or concrete embedment, a trumpet, and corrosion-inhibiting compounds or grout
2. The unbonded length – corrugated sheathing and plastic tube sheathing filled with corrosion-inhibiting compounds. Also, heat shrink sleeves for any couplers that are used for pre-stressing bar tendons
3. The bonded length – corrugated sheathing and epoxy coatings for steel bars or strands. Epoxy coatings for tendons are usually not specified for reinforced concrete retaining walls unless the SD identifies a specific need based on the site conditions

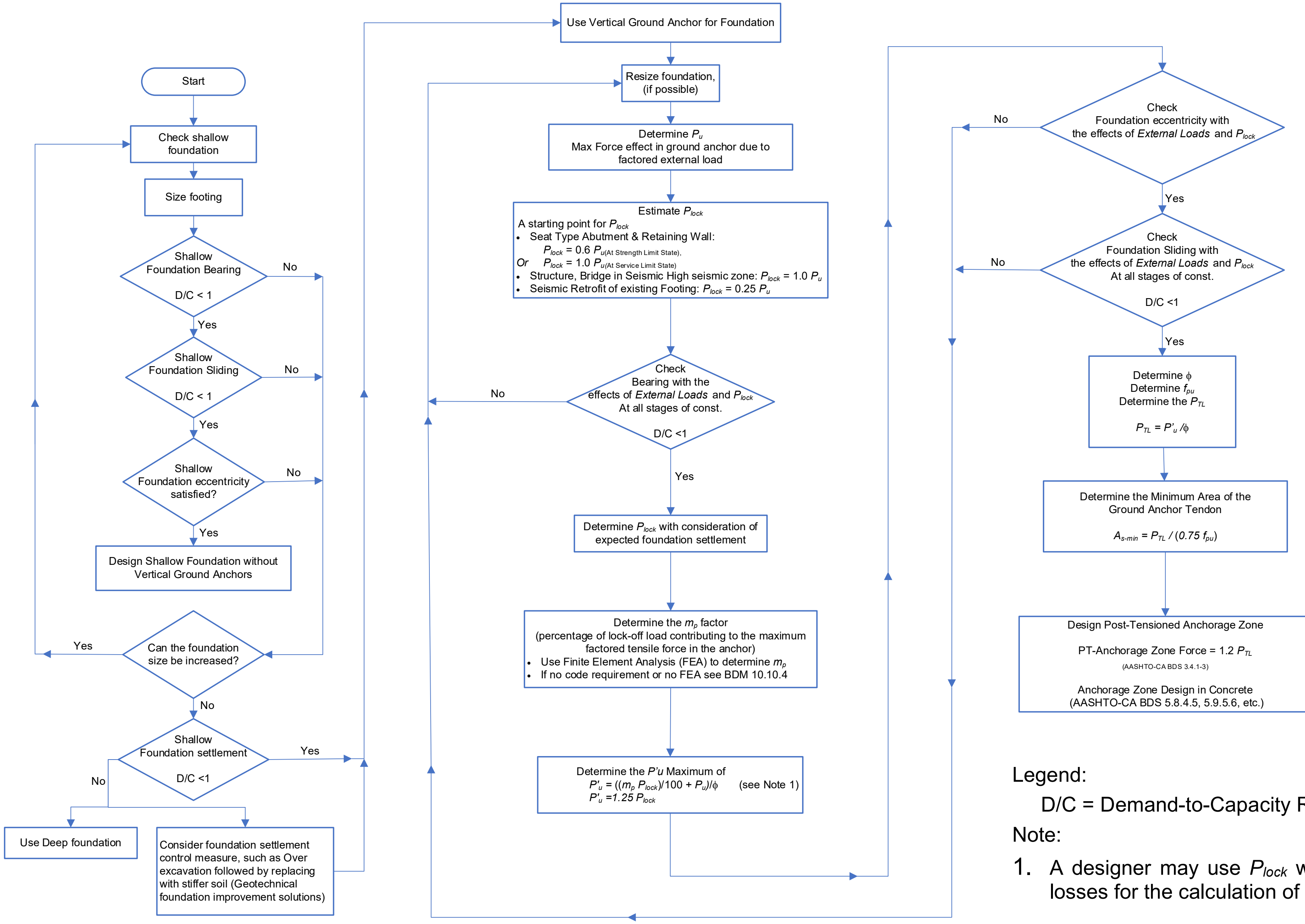
Most ground anchor failures caused by corrosion occur within 6 feet of the anchorage. The pre-stressing steel in the unbonded length is also vulnerable to corrosion. Thus, sheathing filled with corrosion-inhibiting grease is typically used. Encapsulations are used for Class I protection (PTI DC 35.1) of the tendon bonded length. Encapsulation is also shown on the Bridge Standard Details. The materials specifications and corrosion mitigation requirements are covered in the Standard Specifications Section 46.

10.10.8 INFORMATION PROVIDED ON THE PLANS

The following information should be shown on the plans:

- Test load (P_{TL})
- Lock-off load (P_{lock})
- The layout of ground anchors
- Minimum unbonded length of ground anchors
- Minimum area, number, and size of the tendon (Strands or Bar)
- Minimum concrete compressive strength, at the time of post-tensioning, of the component resisting the vertical ground anchor

10.10.9 General Design Flowchart



Legend:

D/C = Demand-to-Capacity Ratio

Note:

1. A designer may use P_{lock} without losses for the calculation of P'_u

10.10.10 REFERENCES

1. AASHTO (2017). *AASHTO LRFD Bridge Design Specifications, 8th Edition,* American Association of State Highway and Transportation Officials, Washington DC.
2. Caltrans. (2024a). *Standard Specifications,* Section *46 Ground Anchors and Soil Nails,* California Department of Transportation, Sacramento, CA.
3. Caltrans. (2024b). *Structure Technical Policy 10.10 Vertical Ground Anchors,* California Department of Transportation, Sacramento, CA.
4. Caltrans. (2022). *Parametric Study on Vertical Ground Anchor,* California Department of Transportation, Sacramento, CA.
5. Caltrans. (2020). *Caltrans Geotechnical Manual, Vertical Ground Anchors,* California Department of Transportation, Sacramento, CA.
6. Caltrans. (2019a). *California Amendments to AASHTO LRFD Bridge Design* Specifications, *8th Edition*, California Department of Transportation, Sacramento, CA.
7. Caltrans. (2019b), *Foundation Reports for Earth Retaining Systems (ERS),* California Department of Transportation, Sacramento, CA.
8. Caltrans. (2015), *Foundation Manual Chapter 11 Ground Anchors & Soil Nails,* California Department of Transportation, Sacramento, CA.
9. Caltrans. (2014). *Bridge Standard Details Section 12 and Section 14,* California Department of Transportation, Sacramento, CA.
10. FHWA. (1990) *Permanent Ground Anchors,* Publication No. FHWA–DP–90–68–003*,* Federal Highway Administration, Washington, DC.
11. FHWA. *(1998). Design Manual for Permanent Ground Anchor Walls* Publication No. FHWA–RD–97–130, Federal Highway Administration, Washington, DC.
12. FHWA. (1999). *Geotechnical Engineering Circular No.4: Ground Anchors and Anchored Systems*, Publication No. FHWA-IF-99-015, Federal Highway Administration, Washington, DC.
13. FOUNDATION PUBLICATION LTD. (1977), *Rock Anchors State-of-the-art* G.S., Littlejohn and D.A. Bruce, England.
14. PTI. (2014). *Recommendations for Pre-stressed Rock and Soil Anchors,* Publication No. PTI DC 35.1-14. Post-Tensioning Institute, Farmington Hills, MI.
15. Journal of Rock Mechanics and Geotechnical Engineering (2015). *Rock engineering design of post-tensioned anchors for dams - A review,* Chinese Academy of Sciences, Milton, Queensland 4064, Australia.