

**California Department of Transportation
Division of Engineering Services
Materials Engineering and Testing Services
Corrosion Branch**

CORROSION GUIDELINES

Version 3.2

MAY 2021



NOTICE

The contents of this document reflect the views of Materials Engineering and Testing Services which is responsible for the facts and the accuracy of the guidelines presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. **These guidelines do not constitute a standard, specification, or regulation.**

Neither the State of California nor the United States Government endorses products or manufacturers. Trade or manufacturers' names appear herein only because they are considered essential to the object of this document.

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1. INTRODUCTION

These guidelines outline the corrosion evaluation and recommendation aspects of site investigations for California Department of Transportation (Department) structural projects. The guidelines list the requirements for field investigations related to corrosion, including requirements for sampling of soil and water, required corrosion testing, reporting of results, requests for assistance, and corrosion mitigation measures (design alternatives).

This document is intended for use by Department staff and consultants, working on the Department's projects, performing field investigations related to corrosion, and/or providing design recommendations that include corrosion mitigation measures. This document supersedes the following report: ***Corrosion Guidelines Version 3.0 March 2018***. Additional Department guidelines such as the ***Standard Specifications, Bridge Memo-To-Designers*** and others can be found in the References section of this report.



2. THE DEPARTMENT'S FUNCTIONAL GROUPS ASSISTING WITH CORROSION INVESTIGATIONS

This section outlines the roles and responsibilities of Department staff performing corrosion assessments of project sites. The District Materials Branches are responsible for preparing a Materials Report (MR) for all projects that involve pavement structural section recommendations or pavement studies, culverts or other drainage features, corrosion studies, materials, or disposal sites. This policy is defined in Chapter 604.1 of the *Highway Design Manual (HDM)* (see References). The District Materials Branches collect soil and water samples for corrosion testing. They perform minimum resistivity and pH testing. Samples meeting the requirements of Section 6.1 of these guidelines are sent to the Materials Engineering and Testing Services (METS), Corrosion Branch for chloride and sulfate testing. Documentation of the corrosion investigation, sampling, corrosion testing, done by the districts are the responsibility of the District Materials Branch. Recommendations for culverts, drainage structures and other structures are the responsibility of the Corrosion Branch.

Geotechnical Services (GS) is responsible for preparing reports for Structure Design to support design of structure foundations, special design retaining walls and buildings. GS also prepares reports for the District Project Engineer to support design of highways, standard plan structures, earthwork and related items not designed by Structure Design. Geotechnical investigations are required for projects involving cut slopes, embankments, earthwork, landslide remediation, retaining walls, sound walls, sign structures, buildings, pump stations, groundwater studies, erosion control features, sub-excavation, and any other studies involving engineering geology. As part of the geotechnical investigation, GS is responsible for conducting a corrosion investigation of the structure site. The corrosion investigation should include sampling of soil and water for corrosion testing, summarizing corrosion test data, and a discussion of the corrosivity of the project site.

Generally, corrosion mitigation measures for structures are selected by Division of Engineering Services (DES) design staff, using appropriate measures listed in Department guidelines. Additional assistance regarding selecting appropriate corrosion mitigation measures should be obtained from the Corrosion Branch. Geotechnical Services staff does not routinely provide corrosion mitigation measures in their reports. However, the Corrosion Branch is responsible when returning testing results to notify the Geotechnical Engineer of any special mitigation measures that may be required. The Geotechnical Report should provide a note in those cases for the Design Engineer to contact the Corrosion Branch.



3. REQUIREMENTS FOR CONSULTANTS PROVIDING CORROSION ASSESSMENTS OF DEPARTMENT PROJECTS

This section outlines the roles and responsibilities of consultants providing corrosion investigation services and corrosion mitigation recommendations for Department projects. In addition, this section can be used by Department staff providing consultant oversight of corrosion investigation services and mitigation recommendations prepared by consultants.

The flowchart at the end of this section outlines the roles and responsibilities of the various Department functional groups assisting consultants performing corrosion investigations and lists the responsibilities of the consultant.

Foundation investigations are required for all structures (including bridges, tunnels, retaining walls, MSE walls, sound walls, ground anchor walls, sign structures, maintenance stations, pumping plants/stations, toll plazas, culverts, etc.). All foundation investigations require a corrosion investigation and evaluation. Preliminary and final Foundation Reports prepared by consultants should include all available corrosion data for the site and a brief discussion of the data. If corrosion data is not available or is insufficient to provide conclusive information regarding the corrosivity of the site, then additional corrosion sampling and testing is required per Department guidelines during the field investigation phases. If corrosion data can still not be obtained, then the site should be assumed to be corrosive and corrosion mitigation required. In such cases it is recommended that the Corrosion Branch be consulted.

Consultants should follow the recommendations for preparing reports as discussed in the following documents (see References): *Caltrans Geotechnical Manual, Guidelines for Preparing Geotechnical Design Reports Version 1.3* (December 2006) and the *Foundation Reports for Bridges* document (dated March 2018).

Consultants under contract to provide design related recommendations should include corrosion recommendations consistent with Department guidelines. Corrosion design recommendations should be based on the worst case test results from the site in accordance with Department guidelines. Sufficient information regarding the number and location of soil borings, sampling, and testing should be included to allow a thorough review of any corrosion recommendations by Department staff.

Corrosion testing of soil (both surface and subsurface soil samples) and water samples shall be performed in accordance with the applicable *California Test (CT)* (see References). If procedures and equipment other than those specified in the applicable *CT* are used, those variations must be approved, documented, and presented with the corrosion test results. References to the test methods used for corrosion testing must be included on each page that presents the corrosion test results and analysis. Some variations (like a one-point resistivity test instead of a minimum resistivity test) will not be allowed. If in doubt about whether alternative test methods are acceptable or not, contact the Corrosion Branch of METS before starting any testing.



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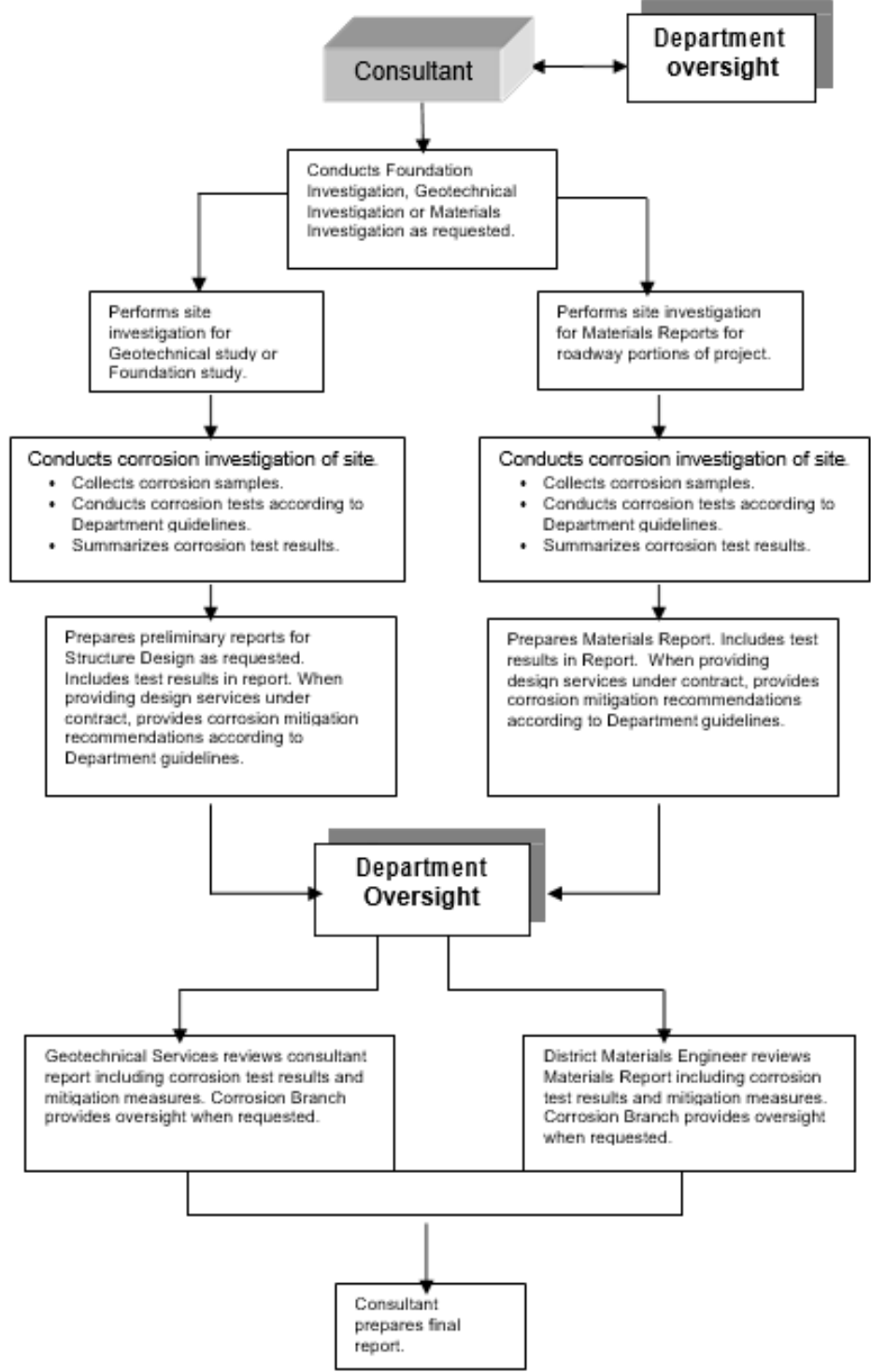
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Minimum resistivity and pH tests are outlined in *CT 643* (see References). Test procedures for determining water-soluble sulfate and chloride contents are outlined in *CT 417* and *CT 422* (see References). Consultants should follow the guidelines presented in this document for performing corrosion assessments of project sites when performing work for the Department.

The Corrosion Branch of METS is available to review all corrosion investigations conducted by consultants, should additional assistance be needed. Upon request from the functional groups performing oversight, the Corrosion Branch will comment on the corrosion aspects of Materials Reports, Geotechnical Design Reports, Foundation Reports, and Preliminary Reports prepared by consultants.



Department/Consultants Interaction Flowchart





4. CORROSION BASICS

Corrosion is the deterioration of a metal through a reaction with its environment. Typically, corrosion involves contact of the metal with moisture and air (oxygen). The deterioration that takes place during the corrosion process is the basic tendency of the metal to revert to its natural state prior to it being developed from its primary ore material. The most common example of corrosion is the rusting of steel into iron oxide, its primary ore as found in the earth.

The corrosion process of metals is an electrochemical process involving a transfer of electrons from the metal's surface to ions in the environment (the electrolyte).

Corrosion is often described in electrical terms as an electrical circuit consisting of four key components. These include an anode (where corrosion or chemical oxidation reactions are taking place), a cathode (where chemical reduction reactions are taking place), an electrolyte (solutions or conductive media providing the supply of chemicals needed to sustain the cathodic reactions at or near the metal surface), and a metallic path.

4.1 Corrosion Terms

The anode is where corrosion or chemical oxidation reactions are taking place. These are the locations on the metal surface where electrical current is being passed by chemical means from the metals surface to ions, elements, or compounds in the electrolyte. The metal is losing electrons and combining with other elements in the environments by means of an oxidation reaction.

The cathode is where chemical reduction reactions are taking place. These are the locations on the metal surface where electrical current is being passed by chemical means from ions, elements, or compounds in the electrolyte to the surface of the metal. This chemical reaction is a reduction reaction.

ANODE

An electrode where oxidation reactions (corrosion) occur.

CATHODE

An electrode where reduction occurs.

The anode and cathode in a corrosion process may be on two different metals connected together forming a bimetallic couple, or as they may be on the same piece of metal. An area on a metal surface (or with two dissimilar metals, each respective metal) either becomes an anode or a cathode depending on the electrical potential of one area relative to the other. The electrical potential difference is the electromotive force of the cell and is the voltage difference between the anode and cathode of the cell. In any electrochemical cell, the area that is more negative in potential will undergo corrosion if coupled to the more positive area. The corrosion process is initiated by differences in the natural potential between the two dissimilar metals (bimetallic couple); metallurgical variations in the state



at different points on the surface a single metal; or localized variations in the environment such as variations in moisture content or oxygen concentration.

The electrolyte is the material in contact with both the anode and the cathode that allows ions to migrate between the two electrodes. This allows ionic current flow to occur between the anode and the cathode. The electrolyte includes the source of atoms, elements, or compounds required for ionic current flow to and from the metal electrodes. The electrolyte is the environment that the metal is in contact with including whatever salts and liquids are present (e.g., soil for a buried metal or concrete for reinforcing steel).

The metallic path completes the electrical circuit and allows electrons to flow from the anode to the cathode in the electrochemical cell.

ELECTROLYTE

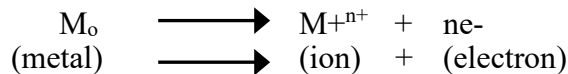
Soil and/or liquid or other conductive media adjacent to and in contact with the anode and the cathode that allows ions to migrate.

METALLIC PATH

Any conductor that allows electrons to flow.

4.2 Electrochemical Equations

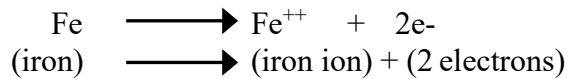
The corrosion process can be described through a series of anodic and cathodic reaction equations (electrochemical equations) depending on the metal and ionic species involved.



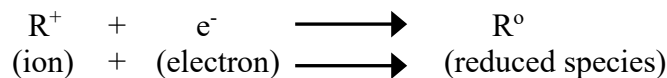
Where M_o represents a metal atom such as iron in a metallic structure; the arrow indicates the direction that reaction is occurring; the symbol M^+ represents a metal ion; and n^+ along with ne^- indicates the number of electrons involved in the chemical reaction.

A common example is that of iron corrosion:

At the anode, iron is oxidized to the ferrous state, releasing electrons.

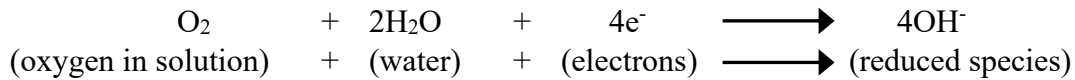
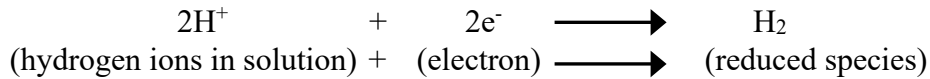


Iron gives up two electrons, which pass through the metal from an anodic site to a cathodic site where they are consumed in a cathodic (reduction) reaction. The cathodic reaction is in the form:



Where R^+ represents a positive ion in solution, e^- indicates the number of electrons gained, the arrow indicates the direction that reaction is occurring; and R^0 is the reduced atom produced as a result of the chemical reaction.

Two common examples of cathodic reactions are the reduction of hydrogen and oxygen:



4.3 Electromotive Force Series and Galvanic Series

From the previous discussion, there is a transfer of electrons that occurs during the corrosion process. The example shown was that of steel in the presence of hydrogen and oxygen (both present as dissolved species in water). Similar electrochemical reactions can occur regardless of the conductive contact medium (soil, water, concrete, etc.). The standard that has been established to provide a reference scale of electrical potential values for metals and non-metals is known as the electromotive force (EMF) series or REDOX potential series.

Another useful series is the galvanic series. The galvanic series is the electrical potential of a metal or alloy in a particular electrolytic solution (usually seawater). It is useful in determining how two or more metals will behave if electrically connected in an ionically conductive environment. The electrical potential of each metal is measured as before against a standard. A reference electrode is simply an electrode (electrical conductor) that has a stable and well know electrical potential. The high stability of the electrode potential is usually reached by employing a redox system with constant (buffered or saturated) concentrations of each participant of the redox reactions.

Examples of reference electrodes are the copper/copper sulfate (Cu/CuSO₄) reference electrode, saturated calomel electrode (SCE) reference, and the silver/silver chloride (Ag/AgCl) reference electrode.

In terms of corrosion, when looking at metals in an electrical potential series such as an electrical motive force series or a galvanic series, when two metals are coupled together, the more negative metal (the anodic metal) will corrode relative to the more cathodic (noble) metal.



5. PRINCIPLES OF CATHODIC PROTECTION

Cathodic protection (CP) is an electrochemical technique used to control corrosion. CP provides a method to minimize deterioration of a metal (or structure) due to corrosion that is occurring as a result of contact with the surrounding environment (electrolyte).

Degradation is minimized by reversing the natural electrical current flow that is occurring during the corrosion process.

CP is achieved by connecting an external anode to the metal to be protected and allowing a direct current (DC) electric current to pass from that anode to the metal (the cathode) sufficient enough to keep all areas of the metal from corroding.

When electrical current can flow from the external anode in sufficient quantity to protect all areas of the metal simply by the natural difference in electrical potential between the anode and cathode, the cathodic protection system is referred to as a galvanic CP system. When an external DC power source is needed to increase the electrical current flow to the cathode to a level that sufficiently protects all areas of the metal in question, the system is called an impressed current CP system.

5.1 Galvanic CP Systems

Galvanic CP systems use reactive metals or alloys as anodes that are connected to the metal being protected. Active metals commonly used include zinc, aluminum, and magnesium alloys. Alloys may include combinations of these metals along with slight additions of minor elements to improve the alloys stability characteristics. With Galvanic CP systems, the sacrificial anode material is connected directly to the structure (metal) that requires corrosion protection. Coupling the two materials (the anode and the metal of the structure) will cause a shift in electrical potential of the structure metal since the structure metal is now the artificial “cathode” in the anode-cathode circuit and the bimetallic couple will try and reach an equilibrium potential. Contact to the reinforcement is made either by metallizing directly over the exposed reinforcement or by attaching a stud to the reinforcement when patching is needed for structural reasons. The zinc is then metallized over the exposed stud.

5.2 Impressed Current CP Systems

Impressed current CP systems typically consist of a power source to drive the protective CP current, and an anode material that is relatively inert or that has a low dissolution rate. Impressed current CP systems are installed such that that the anode does not directly contact the metal or structure being protected. The anode is connected to the positive side of the DC power supply, and the metal being protected is connected to the negative side of the power supply. The “circuit” is completed through the electrolytic path of soil or concrete that separates the anode and cathode. This resistive path is needed so that a direct

electrical short circuit does not occur between the negative and positive leads of the power supply. Figure 5.2-1 shows a schematic of an impressed current CP system for reinforced concrete. The battery symbol represents the DC power source. The positive side of the source is connected to a titanium anode mesh. The negative side of the source is connected to reinforcement in concrete. The concrete has been omitted from the view.

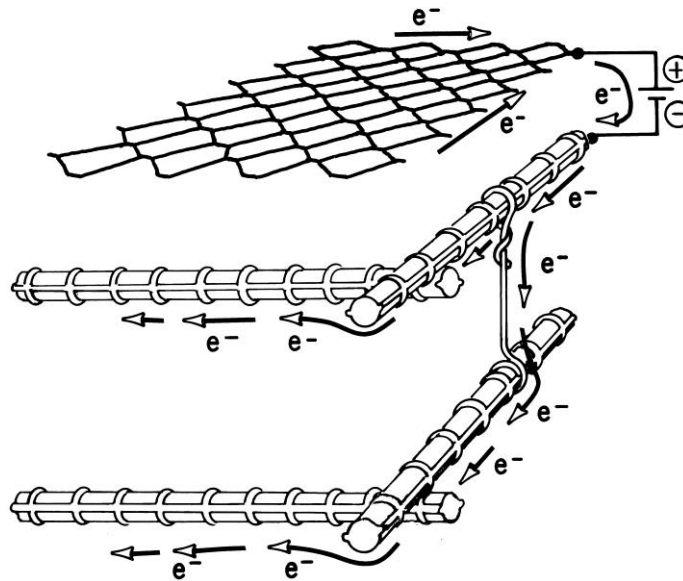


Figure 5.2-1: Schematic of an impressed current CP system for reinforced concrete. The battery symbol represents the DC power source. The positive side of the source is connected to a titanium anode mesh. The negative side of the source is connected to reinforcement in concrete. The concrete has been omitted from the view.

5.3 Galvanic Anodes

Caltrans Construction has made use of galvanic CP anodes designed by BASF, Euclid Chemical Company, Sika Corporation and Vector Technologies for bridge expansions and repairs where new concrete is being placed in contact with older concrete. These products consist of a casing surrounding a zinc core protecting the core from damage during placement and after placement. The casing provides an environment to sustain the zinc core. It does this by modulating the pH to prevent swings that might consume the core at a greater rate. The casing also prevents any carbonation and prevents passivation of the zinc core. Passivation is a thin film of zinc oxide that forms on the zinc surface rendering it inactive. To overcome passivation, the zinc core is embedded in an active matrix (casing) which typically raises the pH to approx. 14.5 to prevent passivation.



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The anodes are tied directly to the reinforcing steel. The number of anodes are selected based on knowing the steel density ratio (surface area of steel/surface area of concrete) within the zone requiring protection, and recommended maximum spacing requirements for particular product can be attained from the manufacturer. The spacing requirements should not be exceeded. Recommended spacing requirements are based on research indicating that a current density requirement between 0.5 and 0.2 microamps per cm² of steel surface area is needed to provide some corrosion protection benefit in concrete.



6. CORROSIVE ENVIRONMENT

The Department has adopted the American Association of State Highway Transportation Officials (AASHTO) *Load and Resistance Factor Design (LRFD) Bridge Specification* requirement for a 75-year structure design life. However, culverts and drainage facilities typically require a 50-year maintenance free design life. **Table 5.10.1-1 Minimum Concrete Cover to Reinforcement (in.) for 75-year Design Life** of **Section 5.10.1** (see References) **Section 5 Concrete Structures of California Amendments (to the AASHTO LRFD Bridge Design Specifications)**) provides the four exposure conditions found in California.

- A. Non-Corrosive – soils and waters that are not corrosive to metals or concrete and do not meet the requirements in Section 6.1 below for a corrosive site.
- B. Non-Marine – Soils and waters that meet the requirements stated below in Section 6.1 for a corrosive site and not within 1000 feet of a marine surface body of water. This exposure describes the soil above and extending down to 3 feet below the current lowest ground water elevation or 3 feet below the lowest recorded/measured ground water elevation. This also applies to corrosive ground water.
- C. Marine
 - a. Atmosphere – Structural elements exposed to the atmosphere over land within 1000 ft of ocean or marine water and the atmosphere above the splash zone. Marine water, from corrosion considerations, is any body of water having a chloride content greater than or equal to 500 ppm.
 - b. Water Permanently Below MLLW Level – Structural elements permanently immersed 3 ft below the Mean Lower Low Water (MLLW) elevation.
 - c. Splash Zone – Structural elements exposed to marine water extending from 3 ft below the MLLW to 20 ft above the Mean Higher High Water (MHHW) elevation and 20 ft from the edge of water at the MHHW.
- D. Freeze/Thaw - Structural elements exposed directly to freezing/thawing cycles and or de-icing salts, snow run-off or snow blower spray.

Site specific corrosion investigations are needed to determine the corrosivity of a site and to provide appropriate corrosion mitigation measures to obtain the desired design lives. Some of the factors that contribute to corrosion include the presence of soluble salts in soil and water, pH, the presence of oxygen industrial contamination and microbial activity.

6.1 The Department's Definition of a Corrosive Environment

Corrosion of metals is an electrochemical process involving oxidation (anodic) and reduction (cathodic) reactions on metal surfaces. For metals in soil or water, corrosion other than galvanic between two metals, is typically a result of contact with soluble salts found in the soil or water or atmosphere. This process requires moisture to form solutions



of the soluble salts. Factors that influence the rate and amount of corrosion include the amount of moisture, the conductivity of the solution (soil and/or water), the hydrogen activity of the solution (pH), and the oxygen concentration (aeration). Other factors such as soil organic content, soil porosity, and texture indirectly affect corrosion of metals in soil by affecting the factors listed above.

The Department defines a corrosive area in terms of the resistivity, pH, and soluble salt content of the soil and/or water. Resistivity serves as an indicator parameter for the possible presence of soluble salts. It is **not included as a parameter** to define a corrosive area for **structures except** for MSE walls (see Section 8 of these Guidelines). In general, the higher the resistivity, the lower the rate for corrosion. A minimum resistivity value for soil and/or water less than or equal to 1500 ohm-cm indicates the presence of high quantities of soluble salts and a higher propensity for corrosion. Soil and water that have a minimum resistivity equal to or less than 1500 ohm-cm and or a pH equal to or less than 5.50 are required to be tested by a certified lab for chlorides and sulfates per CT 417 and CT 422. The Department uses the terms "corrosive" and "not corrosive" to describe the environment.

For structural elements, the Department considers a site to be corrosive if one or more of the following conditions exist for the representative soil and/or water samples taken at the site:

Chloride concentration is 500 ppm or greater, sulfate concentration is 1500 ppm or greater, or the pH is 5.50 or less.

For bridge structural elements, the term "site" above extends from Abutment 1 to Abutment X. For structural elements, appropriate corrosion mitigation measures for "corrosive" conditions are selected depending on the service environment, amount of aggressive ion salts (chloride or sulfate), pH level and the desired service life of the structure.

Chloride ions from saltwater, soil, or from de-icing salts can lead to corrosion of steel reinforcement in concrete and steel structures by breaking down the normally present protective layer of oxides (passive layer) present on the steel surface.

Like chlorides, sulfate ions may also lead to accelerated corrosion of steel reinforcement. In addition to causing metals to corrode, high amounts of sulfates are deleterious to concrete. Sulfates react with lime in the concrete to form expansive products that cause the concrete to soften and crack. Cracked concrete is more susceptible to attack by water and other aggressive ions that may accelerate the corrosion process. Sulfides in the soil can be an indicator of sulfate reducing bacteria which can lower the soil pH to more acidic levels, increasing the corrosion rates. Soils (bay muds) below a marine body of water should be tested for biological agents such as sulfate reducing bacteria so that mitigation measures can be taken.



The presence of high acidity, pH of 5.50 or less, in soil or water is also considered a corrosive condition. Soil or water with a pH of 5.50 or less can react with the lime in concrete to form soluble reaction products that can easily leach out of the concrete. The result is a more porous, weaker concrete. Acidic conditions often cause discoloration of the concrete surface. A yellowish or rust color distributed over the concrete surface should be investigated.

6.2 Survey of Site Conditions

In general, corrosion investigations, whether performed by Department staff or by consultants, should include a survey of the following site conditions:

- Extent of corrosive soils and water at the site.
- Presence of on-site fill material.
- Condition of any existing structures in the immediate vicinity that may impact the proposed structures. For example, do existing culverts show signs of corrosion or deterioration such as cracked concrete, exposed reinforcement, rust stains, failed coatings, or excessive wear due to abrasion?
- Proximity of the structure or proposed structure to salt or brackish water.
- Proximity of the structure or proposed structure to marine atmosphere.
- Presence of abrasive water or high-water flow (needed for scour consideration of structure foundations and abrasive water flows in culverts).
- Proximity to natural features such as mineral springs or local geothermal activity.
- Exposure of the structure or proposed structure to deicing salts (freeze/thaw environments, where deicing salt is applied to roadways and structures).
- Presence of existing utilities such as light rail, or cathodic protection systems on pipelines, structures and underground storage tanks which may impose stray electrical current in the soil.



7. FOUNDATIONS

Factors that contribute to corrosion include the presence of soluble salts, soil and water resistivity, soil and water pH, and the presence of oxygen. Site specific corrosion investigations are needed to perform a complete assessment of corrosivity. See Section 6.1 of these Guidelines for a definition of a corrosive environment.

Information for existing structures or facilities such as inspection records and as built plans can be found in the Bridge Inspection Records Information System (BIRIS) records maintained by Structure Maintenance & Investigations (SMI). Another source of information is the Corrosion Branch. The Corrosion Branch maintains a database of projects for which corrosion analysis has been done. This information can be useful in determining the scope of corrosion investigation required for any rehabilitation work.

For new alignments or when no maintenance records exist, a thorough review of all site investigations, sampling programs, and corrosion test results will be required to identify appropriate materials for potential corrosion mitigation.

7.1 Soil Sampling for Foundations and Geotechnical Investigations

Sampling a site for corrosion assessment requires that samples of soil and water are obtained from both surface and subsurface material to ensure representation of all soil strata at the site within the limits of the proposed construction. Sampling provides the Designer with the information required to adjust the design of the foundation to protect if necessary, against a corrosive environment. Sampling provides Construction with the necessary corrosion information to determine if mitigation by the Contractor is required after evaluating pile tests for anomalies. Representative sampling for corrosion testing should identify the **worst** case condition that exists in the materials to be encountered or used. Composite samples, those samples that combine several smaller samples to provide a single sample representing a much larger interval are discouraged.

The following designated procedures shall be used for corrosion sampling during every structure foundation investigation conducted in the field. At least one boring for corrosion purposes should be located as close as possible to each of the proposed deep foundation¹ elements for larger bridge structures. It is recommended that a minimum of one boring at each foundation element should be sufficient for bridges ; unless there is a major change in the subsurface material within the proposed substructure area. Sampling should be representative of the depth of the proposed foundation. For example, if a bore hole is drilled to a depth of 70 foot for a proposed Cast-In-Drilled-Hole (CIDH), then a single sample at a depth of 18-20 ft might not be sufficient to be considered representative for the entire borehole. The corrosion sampling guidelines listed below should be considered as the minimum requirements for representative sampling.

¹ Deep Foundations are structural assemblies that transfer load into deeper earth materials, such as piles, driven piles, drilled shafts, or micropiles as defined in *Bridge Memo to Designers 3-1* (Reference 8).



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- The frequency of sampling for corrosivity should be on par with the number of samples taken for other soil tests (such as plasticity) required for the design of deep foundations.
- Typically, 5-7 lbs. of soil material are sufficient for corrosion testing.
- Existing fill or disturbed natural soils including any cut material to be used as fill, backfill, embankment, or other purposes or any borrow (local or import) material should be evaluated for corrosion potential prior to placement. Disturbed soils are typically more corrosive than non-disturbed soils. The samples taken should be representative of the depth of the fill material or disturbed soils.
- One sample at near surface between 1 and 5 ft.
- Below the initial surface material, samples should be taken for each significant change in subsurface material or at representative intervals to the end of the borehole unless groundwater is encountered.
- One sample at the groundwater table or within 5 ft below the groundwater table (if the groundwater table is within the limits of the proposed pile foundation)
- Perched water may not be considered the same as groundwater (see Figure 7.1-1).
- Composite or bulk samples from more than one soil type or formation are not recommended. Since a single corrosive sample defines the entire borehole as corrosive, composite samples potentially dilute the corrosivity of the borehole.
- Combining samples from different boreholes will **not** be accepted for analysis.
- When borings are conducted through permanent free-standing bodies of water (marine or fresh) sampling of the underlying soils for corrosion should not be necessary.
- When sampling for proposed retaining walls with pile foundations, sampling should be representative both vertically (depth of proposed piles) and horizontally along the wall length. This is especially true close to marine environments where tidal fluctuations through the soil over time may have resulted in highly variable zones of corrosivity along the alignment of the proposed project.
- For projects with sign structures, there should be a borehole located near each sign structure with representative samples taken for corrosion analysis.

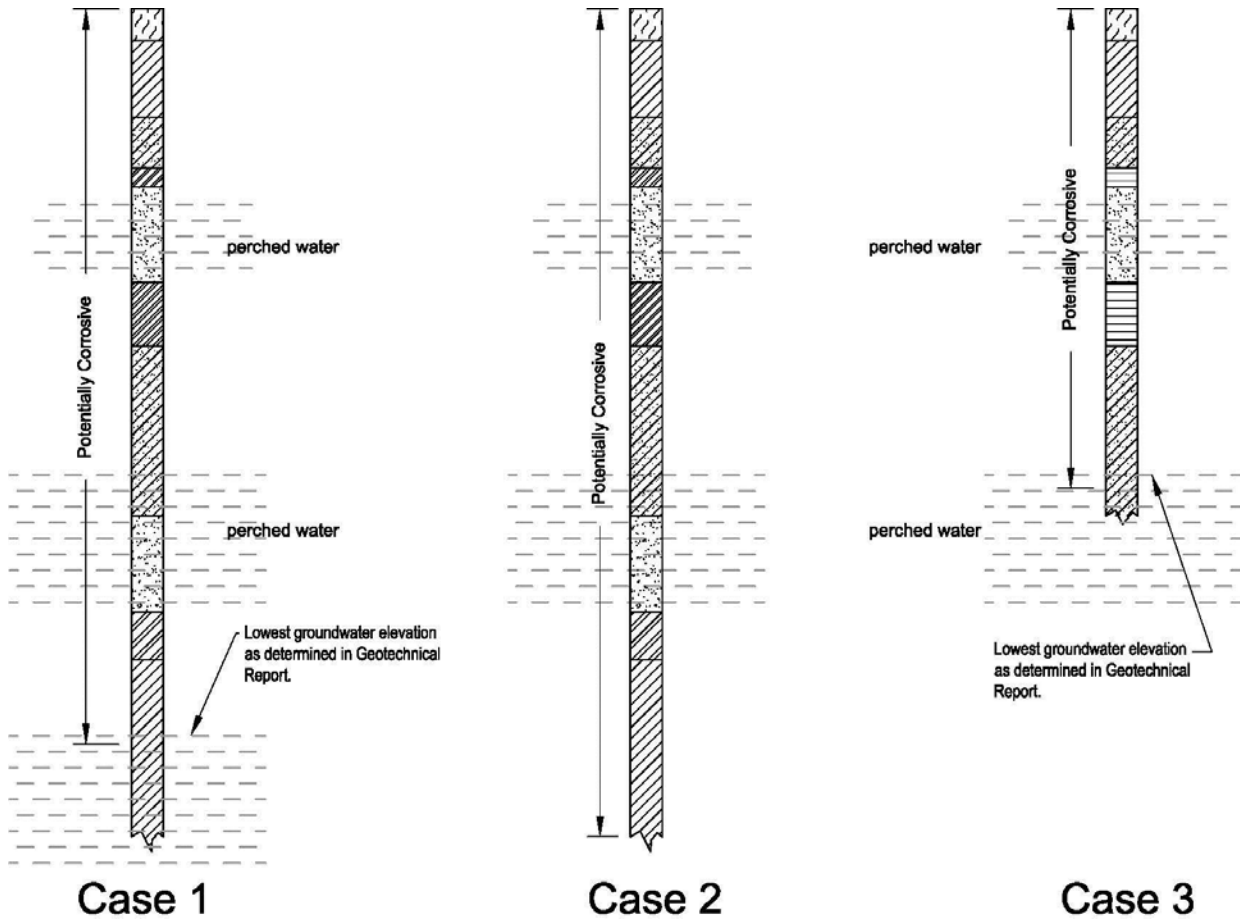


Figure 7.1-1: Cases for perched water.

- A. **Case 1.** Pile extends through 1 or more zones of perched water as identified in the Geotechnical Report, terminating below the lowest elevation for regional groundwater at the site as defined by the Geotechnical Report. For Case 1, the hole is treated as "dry" above the groundwater with corrosion potential from the surface to 3 ft below the groundwater elevation.
- B. **Case 2.** Pile extends through 1 or more zones of perched water as identified in the Geotechnical Report, terminating above the lowest elevation for regional groundwater at the site as defined by the Geotechnical Report. For Case 2, the hole is treated as "dry" with corrosion potential from the surface to the pile tip elevation.
- C. **Case 3.** Pile extends through 1 or more zones of perched water as identified in the Geotechnical Report, terminating in a perched water zone and above the lowest elevation for regional groundwater at the site as defined by the Geotechnical Report.



For Case 3, the hole is treated as "dry" with corrosion potential from the surface to three feet below the perched water elevation for the zone that the pile tip ends in.

The project Engineering Geologist or Engineer can make exceptions to the sampling guidelines. In some cases, the project geologist may feel that redundant sampling at the designed intervals is not necessary. The decision not to sample at the recommended intervals as described for each boring shall be based on valid reasons. Those reasons should be noted in writing in the field logs and in the Geotechnical Report. For example, if a soil formation is present at multiple boring locations within the same structure site, it may not be necessary to obtain samples of the same formation from all borings.

The Corrosion Branch reviews pile anomalies for Construction and Foundation Testing. As part of that review, the Corrosion Branch reviews all corrosion data related to the proposed site. This includes but is not limited to the distance from the borehole to the pile under review, number of boreholes, sampling frequency and depth in boreholes, the depth of each anomaly and the groundwater table. In some cases, the Corrosion Branch has rejected the conclusions of the Geotechnical Report that the soil is not corrosive due to insufficient representative sampling. In those cases, the Corrosion Branch recommended repair or additional testing of the soils adjacent to the pile in question. This can result in a delay of the construction work while the contractor does additional soil sampling and sends in the soils for testing. For those cases when no Geotechnical Report was prepared and anomalies occur, a claim by the Contractor may result.

7.2 Water Sampling for Foundations and Geotechnical Investigations

Water samples should be obtained from surface water bodies at or near the structure site. This includes water from nearby bodies of water even though the structure may not come into direct contact with the water. For example, *Section 5.10.1* (see References *Section 5 Concrete Structures of California Amendments (to the AASHTO LRFD Bridge Design Specifications)*), requires corrosion mitigation for reinforced concrete structures located within 1000 ft of corrosive water (i.e., surface water with more than 500 ppm chlorides). Consequently, sampling of nearby water is particularly important at coastal locations or if the water body is subject to tidal influence. Use a clean wide-mouth beaker to collect the water sample. Swirl to rinse the beaker and pour out the contents to avoid contamination from the container. Fill the rinsed wide-mouth beaker a second time and retain the sample for laboratory testing. Pour off any film that is on the surface of the sample. One liter of water is sufficient for the laboratory to conduct resistivity, pH, chloride, and sulfate testing. Transport the water sample in a sealed plastic container. The container used to transport the water should also be rinsed with the surface water to avoid contamination from the container.

If a well or piezometer is available for groundwater sampling, a narrow plastic sampling tube or bailer may be lowered into a clean, stabilized borehole. The sampler should be rinsed with the groundwater to avoid contamination from the container. After swirling and rinsing, lower the sampler a second time and retain the sample for laboratory testing. Pour off any film that is on the surface of the sample. One liter of water is sufficient for the



laboratory to conduct resistivity, pH, chloride, and sulfate testing. Transport the water sample in a sealed plastic container. The container used to transport the water should also be rinsed with groundwater to avoid contamination from the container.

7.3 Bridge Foundation Scour Assessment Related to Corrosion

Scour is a physical process that can accelerate corrosion of steel piling. If scour is anticipated, the Corrosion Branch can assist in making recommendations for steel piling provided information such as anticipated scour depth and scour frequency is available.

7.4 Reporting Corrosion Test Results for Foundations

For every soil and or water sample submitted to the Corrosion Branch, a Corrosion Test Summary Report is prepared and sent to the Engineer or contact submitting the sample for testing. These reports list the results of the corrosion tests conducted on the soil and/or water samples representative of each proposed structure site. This report also designates whether the site is corrosive or not corrosive based on the criteria established by these guidelines, and specifies the controlling (“worst case”) corrosion parameter test results that are used by the specification writers/designers to provide corrosion mitigation measures for each proposed structure. Geotechnical Services will generally summarize the corrosion test results for site samples in the Foundation Report or Geotechnical Design Report.

7.5 Steel Piles

The corrosion rate of steel piles in soil is influenced by a number of corrosion related parameters. These include soil minimum resistivity, pH, chloride content, sulfate content, sulfide ion content, soil moisture, and oxygen content within the soil. Measurement of these parameters can give an indication of the corrosivity of a soil. Unfortunately, because of the number of factors involved and the complex nature of their interaction, actual corrosion rates of driven steel piles cannot be determined by measuring these parameters. Instead, an estimate of the potential for corrosion can be made by comparing site conditions and soil corrosion parameters at a proposed site with historical information at similar sites.

As stated in the bullet under Section 7.1, existing fill or disturbed soils are typically more corrosive than non-disturbed soils due to the increased amount of oxygen available in a disturbed soil to drive the corrosion process. A disturbed soil is a soil in which digging, backfilling, or other soil upheaval has taken place. Driven steel piles generally have the majority of their length in undisturbed soil. However, excavation and backfilling for footings and pile caps creates a region of disturbed soil near the top of the piles, increasing the availability of oxygen and the probability of corrosion.

A major contributor to increased corrosion rates of driven steel piles in soil is the availability of oxygen. In general, oxygen content is greater near the upper portion of the pile, greater in disturbed soils, and greater in soil near a ground water surface. Soil disturbance in the upper region of the pile may create areas of differential aeration within and just below the disturbed soil zone. This may lead to increased pitting corrosion of the steel piles within or near the disturbed zone.



For steel piling driven into soils (whether disturbed or undisturbed), the region of greatest concern for corrosion is the portion of the pile from the bottom of the pile cap or footing down to 3 feet below the lowest recorded/measured ground water elevation.

Local corrosion cells may exist in some miscellaneous fills that can lead to increased corrosion rates of driven steel piles. These miscellaneous fills include combinations of natural soils (clays and sands), construction debris, ash and cinder material, as well as waste inorganic materials. Increased corrosion rates have been documented in these fills where soil pH was low, 5.50 or less, and soil minimum resistivity was below 1,100 ohm-cm. For these reasons, it is always recommended to test any fill material for corrosivity as specified in Section 7.1.

When steel piles are used in corrosive soil or corrosive water, special corrosion protection considerations for the steel may be needed. The extent of corrosion protection for steel piles will depend on the subsurface geology, the location of the groundwater table, and the depth to which the soil has been disturbed. Corrosion protection mitigation may include the need for sacrificial metal (corrosion allowance) or the use of protective coatings and/or cathodic protection.

Steel piling may be used in corrosive soil and water environments provided that adequate corrosion mitigation measures are specified. The Department typically includes a corrosion allowance (sacrificial metal loss) for steel pile foundations. Sacrificial metal or corrosion allowance is the thickness of metal (above what is structurally required for the pile) needed to compensate for the loss of metal that will occur as the pile corrodes. This extra metal thickness is added to all surfaces of the pile exposed to the corrosive soil or water.

The Department currently uses the following corrosion rates for steel piling exposed to corrosive soil and/or water or marine exposures (see Section 6 of these Guidelines) as specified in *Section 10.7.5 of Section 10: Foundations of California Amendments (to the AASHTO LRFD Bridge Design Specifications)* (see References).

Soil Embedded Zone	0.001 in (0.025 mm) per year
Fill or Disturbed Natural Soils	0.0015 in (0.0381mm) per year
Atmospheric Zone (marine)	0.002 in (0.051 mm) per year
Immersed Zone (marine)	0.004 in (0.102 mm) per year
Splash Zone (marine)	0.006 in (0.152 mm) per year

The corrosion rates apply only if the soil and/or water are corrosive. The Soil Embedded Zone does not apply to bed material below marine bodies of water. For a driven pile into the material below the marine water, either the Immersed Zone or the Splash Zone would dictate the steel pile sacrificial thickness. As previously mentioned, the soil below a marine body of water should be analyzed for biological agents such as sulphate reducing bacteria which can greatly accelerate the corrosion rates. The atmospheric zone is defined



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as a distance of 1000 feet measured from the surface or edge of water at the Mean Higher High Water (MHHW) elevation. If a site is characterized as not corrosive, then no corrosion allowance (sacrificial metal loss) is necessary. This information is also included in Bridge Memo to Designers (see References) Section 10-5 Protection of Reinforcement Against Corrosion Due to Chlorides, Acids and Sulfates.

The corrosion rates listed above should be doubled for steel H-piling since there are two surfaces on either side of the web and flanges that are exposed to the corrosive soil and/or water. For example, the length of a steel H-pile that is immersed in corrosive water and has a 75-year design life should have a corrosion allowance of 0.6 in (15 mm), calculated using 0.004 in/yr. (0.102 mm/yr.) x 75 years x 2 exposure faces.

Steel sheet piles should be treated similar to steel H-piling for determining the amount of sacrificial steel required since there are two surfaces potentially exposed to corrosive elements. Unlike H-piles, the two surfaces of the sheet pile may experience differential corrosion rates dependent on the corrosivity of the elements on either side of the sheet pile. An example would be a steel sheet pile holding back corrosive soils that is exposed to a combination of marine atmosphere and splash zone. Sacrificial steel would have to be added to the surface for the splash zone and conservatively, some sacrificial steel should be considered for the corrosive soil exposure. It is recommended that the Corrosion Branch be contacted to discuss mitigation measures when determining the thickness of sacrificial steel for steel sheet piles.

For driven open ended steel pipe piling with embedment into footing at cutoff line or a cast-in-steel-shell pile (CISS) used in corrosive soil and/or water, the corrosion allowance is only needed for the exterior surface of the pile. The driven open ended pile is considered to have a soil plug which prevents the interior wall from being exposed to sufficient oxygen to support significant corrosion. The CISS pile is backfilled with concrete so no sacrificial steel is required on the inside.

The above corrosion rates and allowances for steel pipe piles are also applicable to permanent steel casings and micropiles used at corrosive sites that are intended to carry axial or lateral structural load. When a permanent steel shell as mentioned above is placed in an oversized drilled hole which will be grouted (between the shell and undisturbed ground), the Corrosion Branch should be contacted to discuss corrosion mitigation options. In such situations, it's possible that coatings or corrosion resistant grout could be considered as alternatives to sacrificial steel.

Steel casings do not need a corrosion allowance when they are used only for constructability and are not intended to carry axial or lateral structural load.

The use of coatings on driven steel piles may be considered as an alternative corrosion protection strategy. Before this alternative is selected, however, the need to protect the coating from damage during the driving operation, coating repair strategies, and the method



of field coating pile splice sections should be considered. Contact the Corrosion Branch for assistance with selecting coating alternatives.

When coatings are proposed to mitigate corrosion of steel piles, the effect of the coating on the skin friction capacity of the pile should also be considered. Contact the DES Geotechnical Services for assistance with concerns related to reduced skin friction capacities of piles.

7.6 Cast-In-Drilled-Hole (CIDH) Pile Anomalies

CIDH piles with anomalies may need to be repaired, supplemented, or replaced depending on the extent of anomalies within the CIDH pile. *Bridge Memo to Designers* (see References) *Section 3-7 Design Data Documentation and Evaluation of Anomalous Concrete Shafts* provides information regarding the acceptance, rejection, and mitigation requirements for CIDH piles. The Corrosion Branch reviews anomalies indicated on the Pile Design Data Forms (distributed by the Foundation Testing Branch) for corrosion potential.

Consideration of corrosion potential is only needed for anomalies that are between the top of the pile down to 3 feet below the lowest recorded/measured ground water elevation (see Section 7.1 for perched water considerations). For anomalies outside these limits, and where no stray current source is identified, no consideration of corrosion potential is required. The rationale for this requirement (excluding the issue of possible corrosion from outside electrical sources) is that sufficient oxygen is not available below the ground water surface to promote significant corrosion of nearly exposed or exposed steel (such as reinforcement at or near a pile anomaly).

7.7 Structural Backfill

All structural backfill must be tested per Section 6.1 of these Corrosion Guidelines to determine if it is corrosive or not. There are two options for structural backfill:

1. Clean structural backfill must be tested prior to placement and meet the requirements of Section 6.1 for a not corrosive environment or site.
2. Sites identified as corrosive can waive the clean structural backfill providing the native tested corrosive material is used. Imported structural backfill material must be tested prior to placement and cannot exceed the existing corrosivity of the native material.

For the first option above, the structural backfill must be clean so as to not introduce corrosive elements resulting in deleterious effects on the proposed structure.

The second option above is a site identified as having one or more corrosive elements in the Foundation Report or is a site subject to a corrosive environment such as marine, or freeze/thaw and deicing salts. Structures built in a corrosive environment require corrosion mitigation to achieve a 75-year design life. The following bullets expand on



Option 2.

- a. Placement of clean structural backfill provides initial mitigation until the corrosive elements in the native soils migrate through the clean structural backfill coming in contact with the structure.
- b. Placement of native corrosive soils as structural backfill is not a concern as the structure has been designed to mitigate for those corrosive elements per the Foundation Report.
- c. Imported structural backfill is allowable providing the imported structural backfill is tested prior to placement to ensure that it does not exceed the existing corrosivity of the site.

- Example:

The existing site is tested for corrosion and a single sample at Abutment 1 has a pH of 5.0. The entire site from Abutment 1 to Abutment X is considered corrosive based on the pH. Contractor imports structural backfill which when tested prior to placement has a chloride value of 675 ppm, a sulfate value of 1000 ppm and a pH of 7.6. The proposed import structural backfill material is rejected as the chloride value exceeds both clean structural backfill requirements as well as the tested native material and the structure was not designed for chloride mitigation.

If a site is determined to be corrosive after construction has begun and no corrosion mitigation was provided to the structural elements, then structural backfill must meet the requirements for clean structural backfill per Option 1 above. Depending on the degree of corrosive elements, the Corrosion Branch should be contacted for additional protective mitigation measures such as protective wraps.



8. MSE STRUCTURES

Most Mechanically Stabilized Embankment (MSE) structures are proprietary systems that require prior design and material use approvals. The list of pre-approved alternative Earth Retaining Systems is maintained by the Department

(<https://dot.ca.gov/programs/engineering-services/authorized-materials-lists>). The DES Subdivision of Structure Policy & Innovation (SPI) approves the design. The Corrosion Branch of METS reviews the corrosion aspects of newly proposed systems.

Most MSE structures are equipped with inspection elements that are either galvanized steel rods or straps, depending on the form of soil reinforcement (rod or strap) used in the actual MSE structure construction. Inspection elements are included in the initial construction of MSE structures so that they may be retrieved at a later date and assessed for corrosion and remaining structural capacity. Since the inspection elements are placed at various locations and levels in the wall, and since they are exposed to the same conditions as the actual MSE soil reinforcement, they may be used to provide an estimate of the overall condition of the MSE structure. Inspection elements are typically scheduled for retrieval at 5, 10, 20, 30, 40, and 50-year intervals.

8.1 Corrosion Requirements for MSE Structure Backfill

The Department's *Standard Specifications Section 47-2.02C Structure Backfill* (see References), requires that the structure backfill material for an MSE structure meet the following corrosion related requirements:

1. Minimum resistivity 2000 ohm-cm, *CT 643*
2. Chloride concentration must be less than 250 ppm, *CT 422*
3. Sulfate concentration must be less than 500 ppm, *CT 417*
4. pH must be between 5.50 and 10.0, *CT 643*

MSE backfill material that meets the above criteria will be considered not corrosive to both the metallic soil reinforcement as well as the reinforced concrete retaining wall. In addition to specifying not corrosive soil, the metallic soil reinforcement must be galvanized in accordance with the Department's standard galvanizing requirements *Standard Specifications Section 47-2* (see References).

8.2 Corrosion Sampling and Testing for MSE Structures

The contractor is responsible for using non-corrosive soil and water for MSE wall construction. When a source of backfill material (borrow site) is being proposed for use in constructing an MSE structure, the entire source area should be representatively sampled and tested to establish that all the material within the area to be used for structure backfill meets the minimum requirements. This may require taking many samples to properly describe the corrosivity of the proposed backfill material. If any of the material within a proposed borrow source does not meet the minimum requirements, those areas shall be clearly defined as “off limits”.



In addition to "borrow-site" sampling performed by the contractor, the Department requires backfill sampling and testing during construction for quality assurance. ***Bridge Construction Memo 145-8.0, Mechanically Stabilized Embankment Wall Construction Checklist, June 28, 2006***, (see References), advises the Structure Representative to obtain one 60 lb. sample of backfill material for each level where inspection elements are installed. The Corrosion Laboratory only requires **10 lb.** of backfill for corrosion testing.

8.3 Reporting Corrosion Test Results for MSE Structures

Corrosion test results for backfill samples, submitted to the Corrosion and Structural Concrete Field Investigation Laboratory for testing, will be reported on a Corrosion Test Summary Report and sent to the Engineer or contact submitting the sample for testing.



9. SOIL AND ROCK ANCHOR SYSTEMS

Soil and rock anchors typically consist of steel bar-type tendons or strand-type tendons and anchor assemblies that are grouted in cored or drilled holes. Soil or rock anchors are classified as Ground Anchors, or Soil Nails. The following information is intended to give some brief background regarding these systems. Additional detailed information can be found in the Department's *Foundation Manual, Memo to Designers 5-12* and the *Caltrans Geotechnical Manual* (see References).

9.1 Sub-Horizontal and Vertical Ground Anchors

Sub-horizontal ground anchors (tieback anchors) are used in both temporary and permanent structures. These types of anchors are typically associated with retaining walls and may contain either bar-type or strand-type tendons that are grouted into drilled holes of on-site foundation materials (either soil or rock).

Vertical ground anchors (tiedown anchors) are typically foundation anchors for bridge footings that are grouted into cored, formed or drilled holes. They are used to provide additional restraint against rotation of the footings and can be installed in both soil and rock. Components of both sub-horizontal and vertical ground anchors are similar.

Corrosion mitigation measures for ground anchors are specified in the *Standard Specifications Section 46*, the recommendations of the Post-Tensioning Institute (PTI) *Specification for Unbonded Single Strand Tendons* and *Recommendation for Prestressed Rock and Soil Anchors*. They include the use of PVC, HDPE, or polypropylene sheathing, corrosion inhibiting grease and cementitious grout.

9.2 Soil Nails

Soil nailing is a technique that is used to reinforce and strengthen an existing embankment. It is an effective technique used for large excavations. The basic concept is that soil is reinforced with closely spaced, grouted soil anchors or "nails" that are inserted (drilled) into the existing foundation material. Unlike sub-horizontal and vertical ground anchors, Soil Nails are not post-tensioned. They are forced into tension as the ground deforms laterally in response to the loss of support caused by continued excavation. Corrosion mitigation measures are provided based on the corrosivity of the site, and are included in the contract special provisions and *Standard Specifications Section 46*. Depending on the site conditions, corrosion mitigation measures may include sheathing with HDPE, epoxy-coated reinforcement and cementitious grout.

9.3 Rockfall Mitigation

Rockfall protection facilities in corrosive environments should be protected against corrosion. In accordance with the plans, special provisions and type of system specified, galvanizing and epoxy coating are typical acceptable protective measures. Where wire or cable may be subjected to damage by rockfall, stainless steel should be considered. For assistance regarding the corrosion evaluation and mitigation, contact the Corrosion Branch.



9.4 Gabions

Section 72-16 Gabions of the *Standard Specifications* details the requirements for Gabions. For assistance regarding the corrosion evaluation and mitigation measures for gabions, refer to the 2001 *Gabion Mesh Corrosion* publication and the *Caltrans Geotechnical Manual* (see References).



10. CULVERTS

The District Materials Branch (or the consultant under contract) is responsible for conducting a corrosion investigation for drainage facilities. This includes culverts to be repaired or replaced in addition to proposed new sites. For a rehabilitation project, it is common practice to perform a culvert survey of existing drainage facilities to determine the need for clean-out, repair, and/or replacement.

When a culvert has failed prematurely, sampling and testing of in-situ soil and water for selection of appropriate replacement culvert materials is suggested. Representative samples of both the soil and drainage water should be collected and tested. Detailed photos of the distressed pipe can be sent to the Corrosion Branch to assist in an analysis of the causes and for recommendations on repair.

10.1 Corrosion Sampling and Testing for Culverts

Corrosion investigations for culverts should include sampling of in-situ soil within the limits of the existing or proposed culvert, sampling of water that will or does flow into the culvert, and sampling of any fill material used as backfill for the culvert. If a project will have multiple culverts, samples of soil and water should be obtained from each specific location on the project site.

Representative surface water samples taken for proposed off-site drainage should be selected from the live stream or existing standing water at the inlet end of the facility. Water samples should never be taken when the water level is elevated due to recent storm runoff or flooding. Elevated stream flows dilute chemical concentrations in the stream making the sample concentrations appear lower than usual. Corrosion testing of soil samples (both surface and subsurface soil samples) and water samples shall follow the methods outlined in the *California Tests* (see References).

When imported material is used as structure backfill for metal products such as steel pipe culverts or reinforced concrete culverts and headwalls, the imported backfill should be less corrosive than the native soil material. Consequently, the contract special provisions should specify corrosive parameters for the imported fill that are less corrosive than those of the native soil. The imported backfill should be tested in accordance with *CTs 643, 417, and 422* prior to placement. This applies to imported soil and lightweight aggregate fill.

Slag based materials high in sulfate concentrations can attack the cement mortar in reinforced concrete pipe. If slag aggregate has been or is proposed for use as culvert backfill, it must be tested to determine its suitability as structure backfill material.

Field screening tests for resistivity and pH can be used to quickly identify the most aggressive on-site soil samples for corrosion testing. This simple screening test can eliminate the need for obtaining multiple soil samples for lab tests. If suitable field-measuring equipment is not available to perform the screening tests, it is important to



obtain sufficient soil material to be representative of all material within the proposed limits of the culvert.

10.2 Culvert Material

The selection of culvert material is based on the corrosion test results from *CT 643* (both soil and water testing) and the criteria presented in Chapter 850 of the *HDM*. The software, *ALPIPE* see Reference, (*Alternative Pipe Culvert Selection (ALPIPE)*) is available for selecting culvert material based on site conditions. *ALPIPE* requires a value for chlorides and sulfates and the Corrosion Branch occasionally receives request to run the program without actual values for chlorides and sulfates for the soil. If the resistivity and pH are greater than specified in Section 6.1 of these Guidelines a placeholder of 100 ppm can be used to run the program. Whenever possible, it is recommended that water samples be collected and tested for chlorides, sulfates and other halides. The Corrosion Branch has an extensive database of soil values available for additional reference values.

Galvanized Steel Pipe

The years to first perforation and the maintenance-free service life are based solely on the minimum resistivity and pH of the soil and/or water samples as shown in Figures 855.3A (Minimum Thickness of Metal Pipe for 50 Year maintenance-Free Service Life) and 855.3B (Chart for Estimating Years to Perforation of Steel Culverts), Chapter 850 of the *HDM*. Galvanized steel pipe is not recommended where high sediment load exist as the galvanized coating can be worn away in as little as 15 years. The Corrosion Branch has investigated numerous galvanized metal culverts and it is common to see abrasion wearing down the metal ribs (along the flowline) at a faster rate than that of corrosion. The Corrosion Branch has a standard detail for paving and repairing the inverts of galvanized metal culverts that have degraded sufficiently that to reveal the bedding underneath.

In corrosive environments, protective coatings, linings, and pavings on the inside and/or outside of steel pipe and culverts can be used to extend the maintenance-free service life. Chapter 850 of the *HDM* and *Section 66-1.02C Protective Coatings, Linings, and Paving of the Standard Specifications* (see References) describes the various types of coatings and linings that may be selected to extend the maintenance-free service life.

Any damage to galvanizing, protective coatings, linings, and pavings that occurs during handling, installation, or construction must be rejected or repaired as specified in accordance with manufacturer's recommendations. Damage includes scratches, pinholes, cracks, or coating de-bonding.

Aluminum and Aluminized Steel (Type 2) Pipe

Aluminum culverts include corrugated aluminum pipe and pipe arches, aluminum spiral rib pipe, and structural aluminum plate pipe and arches. For a 50-year maintenance-free



service life, aluminum can only be used if the soil, backfill, and drainage water meet the following:

1. Minimum resistivity must be greater than 1500 ohm-cm, **CT 643**
2. pH must be between 5.50 and 10.0, **CT 643**

As an alternative to coating steel pipe with zinc (i.e., hot-dip galvanizing), steel pipe can be aluminized (Type 2). Aluminized steel pipe is steel pipe that is protected against corrosion by hot-dipping in an aluminum coating. For a 50-year maintenance-free service life, aluminized steel (Type 2) pipe can only be used if the soil, backfill, and drainage water meet the following:

1. Minimum resistivity must be greater than 1500 ohm-cm, **CT 643**
2. pH must be between 5.50 and 10.0, **CT 643**
3. Minimum thickness of 0.0629 in (16 gauge)

Bituminous or polymerized coatings are not recommended for corrosion protection of aluminized steel, but may be used for abrasion resistance.

Non-reinforced Concrete Pipe

The use of non-reinforced concrete pipe can be advantageous when reinforcing steel is not required to provide strength. Without reinforcing steel, the presence of chloride and stray current cannot compromise the service performance of the pipe. Acidity and sulfates in the soil and/or water, however, can affect this type of pipe by attacking the cement. For corrosive environments (see Section 6.1 of these Guidelines), **Section 90-1.02H Concrete in Corrosive Environments** of the *Standard Specifications* applies.

Reinforced Concrete Pipe, Box Culverts and Arch Culverts

Reinforced concrete pipe (RCP) is typically precast, performs well under most conditions, and is commonly selected when a corrosive environment exceeds the limits for using corrugated metal pipe. For corrosive environments (see Section 6.1 of these Guidelines), **Section 90-1.02H Concrete in Corrosive Environments** of the *Standard Specifications* applies.

Plastic Pipe

Plastic pipe is not subject to corrosion and can be a good performer in areas that are corrosive. In general, exposure to sunlight (ultraviolet rays) has an adverse effect on the service life of plastic pipes and products. For a plastic pipe, ultraviolet (UV) rays from the sun can induce degradation and ultimately cause loss of mechanical properties, which may result in premature failure of the pipe. HDPE and PVC plastic pipes approved for use by the Department have UV inhibitors added for protection against sunlight.

When plastic pipe is installed in areas that may be subject to fire, consider using concrete headwalls or metal flared end sections to reduce the potential damage to the ends of the pipe. Also, accumulated debris and trash may carry a fire into the pipe.



10.3 Cement Slurry, Controlled Low Strength Material (CLSM) or Concrete Backfill for Culverts

When placing culverts in existing roadways, it is sometimes necessary to use fast setting concrete backfill. Admixtures used to accelerate the set time of concrete must be on the *Departments Authorized Materials Lists (AML)* (see References). Placement of a cementitious backfill material does not negate the requirement to perform corrosion analysis of the native soil and water.



11. CORROSION LAB SERVICES

11.1 Testing Services

The Corrosion Branch provides various laboratory testing services for the Department's functional units. These services include corrosion testing of soil and water for minimum resistivity, pH, and water soluble sulfates and chlorides (*CTs 643, 417, and 422*, respectively); and testing of total chloride concentrations of concrete cores (*CT 404*). Other specialty tests and field investigations are performed when appropriate.

11.2 Reporting Corrosion Test Results

For soil and water samples, a Corrosion Test Summary Report (PDF format) will be emailed to the contact listed on the TL-0101. The report summarizes test results for all samples received for a particular project site, whether or not the site is corrosive, and specifies the most corrosive parameters (worst case scenario) from all samples received for the site.

For concrete samples the Corrosion Test Summary Report will summarize the testing (compressive strength or chlorides) requested by the contact. Compressive strength values are provided per ASTM C39. Chloride values are sorted by depth starting at the concrete core surface and described as shown in Table 11.1. A description of steel reinforcement condition is provided at the depth it is encountered.

Table 11.1
Soluble Chloride Concentration in Reinforced Concrete

ppm	lb/yd ³	Assumed Condition
0 to 300	0 to 1.2	Passive (not corroding)
300 to 749	1.2 to 3.0	Corrosion initiation
≥ 750	≥ 3.0	Active corrosion

Unused portions of sampled material will be kept in the Corrosion Lab for approximately 60 days after the test results are reported. After 60 days, the materials will be discarded. If needed, arrangements can be made to return the unused portions after testing. Requests to return the unused sample material should be made at the time of the requested services for corrosion testing.



12. CORROSION MITIGATION MEASURES

The following section provides some useful information regarding corrosion mitigation measures for structural elements. As previously mentioned, Department guidelines such as the *California Amendments (to the AASHTO LRFD Bridge Design Specifications - Eighth Edition)*, *Bridge Memo to Designers, Standard Specifications, Special Provisions*, and the *Highway Design Manual* have been developed to cover these topics. The purpose of the information provided in this section is to provide additional background information regarding corrosion mitigation in addition to the listed Department guidelines.

12.1 Corrosion Mitigation Measures for Reinforced Concrete

Uncontaminated, high quality concrete normally provides excellent corrosion protection for reinforcing steel. The high pH environment, greater than 12.5, of the concrete keeps the reinforcing steel in a non-active corrosion state. Intrusion of chlorides into the concrete through contact with chloride-contaminated soil, water, or marine atmosphere, however, may lead to corrosion of the embedded reinforcing steel.

Contact of the concrete with soil or water containing sulfates can, over time, cause deterioration, increased porosity, and decreased pH of the concrete. In addition to the obvious loss of integrity of the concrete, this degradation may also lead to accelerated corrosion of the reinforcing steel.

Corrosion protection of reinforced concrete is required in accordance with *Section 5 Concrete Structures of California Amendments (to the AASHTO LRFD Bridge Design Specifications)* most current edition (see References). *Table 5.10.1-1 Minimum Concrete Cover to Reinforcement (in.) for 75-year Design Life* specifies the use of increased clear concrete cover over the reinforcing steel, corrosion resistant concrete mix designs, reduced water to binder ratio as well as reinforcement coatings (*Authorized Material Lists*) and stainless steel for corrosion protection of reinforced concrete exposed to chloride environments. This document also provides mitigation measures to protect against corrosion due to acids or sulfates.

Section 90-1.02H Concrete in Corrosive Environments of the *Standard Specifications* provides specification language for corrosion resistant concrete mix designs that address corrosive conditions specified in *Section 5 Concrete Structures California Amendments* above.

Concrete mixes used by the Department to mitigate chlorides are based on the diffusion rate of chlorides using Fick's Second Law of Diffusion. Dense concrete mixes that are less permeable slow the diffusion of chlorides through concrete. Therefore, the time for chlorides in the soil or water to reach the reinforcing steel is increased. It is desirable to slow the rate of chloride diffusion in reinforced concrete because high chloride contents at the level of the reinforcing steel will cause the reinforcing steel to corrode.



The use of supplementary cementitious materials (such as fly ash, granulated blast-furnace slag (GGBS), silica fume, metakaolin, etc.), reduced water content and increased cementitious material content result in high-density, durable concrete. Additional thickness of clear cover over the reinforcing steel also increases the time it takes for chlorides to reach the level of the reinforcement. ***Bridge Memo to Designers 3-1*** and ***10-5*** (see References) provides additional guidance regarding protection against corrosion for reinforced concrete due to chlorides, sulfates, and acids.

12.2 Dampproofing and Waterproofing

When a coating is required to minimize exposure of concrete, reinforced concrete, or metal surfaces to moisture, dampproofing or waterproofing should be considered. ***Standard Specification 54 Waterproofing*** describes both methods in detail. Dampproofing and waterproofing may be considered for a concrete surface or for a column retrofit when a steel shell is used. Generally, corrosion can occur where the soil is in contact with the surface to be protected; therefore, it may only be necessary to treat those surfaces in contact with soil. Dampproofing and waterproofing may also be considered for protecting concrete surfaces exposed to highly acidic soil and/or water. These treatments may also be used as mitigation measures to protect RCP from stray current by coating the inside and outside of the pipe.

Dampproofing requires the concrete surface to be cleaned and coated with a primer, then mopped with two coats of waterproofing asphalt. Waterproofing is similar to dampproofing, but provides even more corrosion protection. In addition to cleaning and treating with a primer, two layers of saturated glass fabric membrane and three mop applications of waterproofing asphalt are required for concrete structures.

Because of air quality restrictions in some geographical regions solvent-based primer specified in ASTM D41/41M Standard Specification for Asphalt Primer Used in Roofing, Dampproofing, and Waterproofing, may not be allowed. When the ASTM D41/41M primer cannot be used, slow curing emulsion alternatives SS1h or CSS1h, specified in Section 94 of the ***Standard Specifications***, may be used (verify Volatile Organic Content (VOC) with approval of the local air quality pollution control board).



13. STRAY CURRENT

Stray current originating from either alternating current (AC) or direct current (DC) can result in corrosion of metals. Alternating current is generally considered insignificant (more than a thousand times less) when compared to corrosion from direct current (DC). This section will only look at direct current.

Stray current (interference current) is corrosion caused by direct current from an external source that travels through paths other than the intended circuit. These currents are typically classified as static or dynamic. Static currents maintain a constant amplitude and constant path such as high voltage direct current (HVDC), ground electrodes, and cathodic protection system rectifiers. Sources for dynamic currents are direct current railways or light rail transit systems, direct current welding equipment, some signal circuits and telluric (natural sources of stray current such as disruptions in the earth's magnetic field).

For the Department, stray current corrosion is far less common compared to other sources of corrosion such as marine exposure, freeze/thaw exposure and corrosive soils. That said, stray current can result in accelerated corrosion of structural reinforcement if not addressed. Accelerated corrosion from a DC source occurs in a structure when stray current enters the reinforcing steel at one location and exits at another. The location where the current enters becomes cathodic and can experience material gain. The location where the current exits the reinforcement becomes anodic and will experience corrosion at an accelerated rate. The rate of corrosion is dependent on the frequency of exposure, and strength of the direct current. Stray currents in bridge structural elements can be caused in two ways, either through direct connection or through a soil gradient.

Direct connection involves attaching a pipeline, electric railway track, or high-voltage contact system to bridge structure elements. Installation requires an approved insulator between the pipe or rail and the bridge element, and the high-voltage contact system requires double insulation for safety. It is difficult to retrofit an existing structure to accommodate stray current. The owner of the stray current source is responsible for providing the necessary isolation details, mitigation plans and specifications for review by the Department.

Discharging current into the soil produces soil gradients. The most common source is a cathodic protection system for a pipeline, which produces a steady DC voltage in the soil near the anode(s). Pipeline cathodic protection anode bed(s) to be located near a bridge (within one bridge length) should be reviewed prior to approval. Pipelines attached to a bridge structure or located within two pipe diameters should also be reviewed. By contrast, the DC soil voltage near a traction power substation (TPSS) is zero for a totally ungrounded TPSS, pulsing for a diode-grounded TPSS, and pulsing/reversing for some heavy rail TPSS.

For new structures designed to carry rails protection against stray current comes from



proper design of the direct current source with isolation of the rails from the concrete and use of concrete with high resistivity and impermeability properties. If the reinforcement steel is passivated by the high alkalinity of the concrete, then stray current can be partially if not totally mitigated. A highly impermeable concrete made with a corrosion resistant supplementary material such as silica fume and slag are recommended for mitigation purposes. Chloride levels below that needed to initiate corrosion can still be sufficiently high to result in accelerated corrosion when stray current enters and exits the reinforcement. Reducing the permeability of the concrete and application of a deck sealer such as polyester concrete will help minimize any potential chloride intrusion.

Epoxy coated reinforcement (ECR) can be used to mitigate stray current flow as the coating electrically isolates the steel. However, damage done to the ECR during placement can lead to locations of high current densities and significant localized damage. Since the ECR is electrically isolated, there is no simple way to monitor any stray current damage.

For new bridge decks, lap weld all continuous top longitudinal rebar splices within the width of the trackway. For reinforced concrete bridge decks within the width of the trackway, provide an extra (non-structural) lap welded continuous top longitudinal #4 rebar in the deck slab at each girder and within one foot of the inside face of any future concrete barriers. Weld connect the continuous top longitudinal bars to a transverse collector #9 rebar at each bent cap, hinge diaphragm, abutment diaphragm and abutment backwall.

For pre-tensioned or post-tensioned bridges, it is vital that the tendons and anchorage assembly be electrically isolated from the rest of the bridge. Tendon ducts should be plastic and the grout should be corrosion resistant for additional protection. Where ducts are in contact with stirrups, duct protection should be provided. A system to monitor the electrically isolated strand should be installed as part of the construction.

For both existing structures and new structures, the optimum source of stray current mitigation is built into the system by the agency that owns it. It is recommended that plans submitted by outside agencies for attaching pipelines, electric rails or other sources of direct current be reviewed by the Corrosion Branch. The Corrosion Branch maintains a set of previously published bridge design railway notes and details developed by the Department regarding electrified rails on bridge structures which can be provided on request.

Measures must be taken to mitigate possible stray current problems whenever they are anticipated or suspected. The above considerations given for bridge structures also apply to long steel culverts and pipes.

13.1 Other Structures Requiring Stray Current Protection

A. Retaining Walls

Reinforced concrete walls or mechanically stabilized embankment systems (MSE) with metal elements shall be provided with stray current provisions if they are within 30 feet of light rail tracks (LRT). For other direct current sources, it is recommended that a risk assessment be conducted along with a



field survey.

B. Pumping Plants

1. Epoxy coated bar reinforcing steel shall be used throughout the entire box structure except in the dry pit shaft when the LRT travelway is 20'-0" or closer to the pumping plant endway. The epoxy coated bar reinforcement shall have all ends coated and any damaged bars shall be recoated with epoxy. When the LRT travelway is greater than 20'-0" from the pumping plant endways, reinforcement shall be as per standard plans. See Detail 13.
2. Increase bottom slab thickness by 1" to provide 3" clearance from bottom of slab to the bar reinforcing steel.
3. Permit only high density mortar blocks.



14. MISCELLANEOUS TOPICS

14.1 Dust Palliatives

At some construction sites dust palliatives may be applied for dust control. Prior to application, it must be determined whether the dust palliative will create a corrosion problem or be deleterious to concrete due to salt content in the palliative. Chlorides in the dust palliative can cause corrosion of pavement dowels, reinforced concrete, or steel structures. Also, sulfates in the dust palliative can attack Portland cement concrete pavement or concrete structures. There can be high accumulations of sulfates and chlorides, particularly if the dust palliative is applied in multiple applications. Contact the Corrosion Branch, if necessary for assistance related to the corrosion potential of dust palliative additives.

14.2 Miscellaneous Metals

Miscellaneous metal parts and components are often used in roadway facilities and transportation structures. Fasteners, concrete anchors, plates, and frames are just a few examples. Typical corrosion protection includes zinc galvanizing in accordance with the *Standard Specifications*. However, in corrosive environments such as in coastal areas, the splash zone, or underwater, improved corrosion protection may be necessary. Stainless steel is often specified instead of galvanized steel. Alternatively thermal diffusion galvanizing as specified in ASTM A1059 can be applied to small items such as pins and fasteners for corrosion protection in marine environments. For critical components in corrosive environments; stainless steel alloys (UNS designation S31603, S31653, S32304, S31803 and S32205) should be considered.

If you have questions regarding materials selection for miscellaneous metal parts and components for a particular environment, contact the Corrosion Branch for assistance.



15. REFERENCES

The following corrosion references are taken from various Department documents and are presented here for the convenience of the users of these guidelines.

1. ***Standard Specifications***
(<https://dot.ca.gov/programs/design/ccs-standard-plans-and-standard-specifications>).
2. ***Highway Design Manual, Chapter 850, Physical Standards***
(<https://www.dot.ca.gov/design/manuals/hdm.html>).
3. ***Caltrans Geotechnical Manual***
(<https://dot.ca.gov/programs/engineering-services/manuals/>).
4. ***Guidelines for Preparing Geotechnical Design Reports Version 1.3***
(<https://des.onramp.dot.ca.gov/geotechnical-manual>).
5. ***Foundation Reports for Bridges***
(<https://dot.ca.gov/programs/engineering-services/manuals/>).
6. ***Section 5: Concrete Structures of California Amendments (to the AASHTO LRFD Bridge Design Specifications -Eighth Edition)***
(<https://dot.ca.gov/programs/engineering-services/manuals/>).
7. ***Section 10: Foundations of California Amendments (to the AASHTO LRFD Bridge Design Specifications - Eighth Edition)***. (<https://dot.ca.gov/programs/engineering-services/manuals/>).
8. ***Bridge Memo-To-Designers*** (<https://dot.ca.gov/programs/engineering-services/manuals/>).
9. ***Bridge Construction Memo 145-8.0, Mechanically Stabilized Embankment Wall Construction Checklist, June 28, 20006 in the Bridge Construction Records and Procedures Manual Volume II (12/2017)***
(<https://dot.ca.gov/programs/engineering-services/manuals/>).
10. ***Foundation Manual*** (<https://dot.ca.gov/programs/engineering-services/manuals/>).
11. PTI Committee M-10, “*Specification for Unbonded Single Strand Tendons (PTI M10.2-17)*”, Post-Tensioning Institute, Farmington Hills, MI, 2017.
12. PTI Committee M-10, “*Recommendations for Prestressed Rock and Soil Anchors (PTI DC35.1-14)*”, Post-Tensioning Institute, Farmington Hills, MI, 2014.
13. Racin, James A., “*Gabion Mesh Corrosion Field Study of Test Panels and Full-Scale Facilities*”, FHWA-CA-TL-99-23, 2001.



14. **Alternative Pipe Culvert Selection (ALTPPIPE)**
(<https://dot.ca.gov/programs/design/hydraulics-stormwater/bsa-alternative-pipe-culvert-selection-altpipe>).
15. **Authorized Materials Lists (AML)**
(<https://dot.ca.gov/programs/engineering-services/authorized-materials-lists>).
16. **California Test 643, Method of Test for Laboratory Resistivity and pH for Soil and Water** (<https://dot.ca.gov/programs/engineering-services/california-test-methods>).
17. **California Test 422, Method of Testing Soils and Waters for Chloride Content**
(<https://dot.ca.gov/programs/engineering-services/california-test-methods>).
18. **California Test 417, Method of Testing Soils and Waters for Sulfate Content**
(<https://dot.ca.gov/programs/engineering-services/california-test-methods>).
19. **California Test 404, Test Method for the Chemical Analysis of Portland Cement Concrete, Fly Ash, Pozzolan, and Blended Cement**
(<https://dot.ca.gov/programs/engineering-services/california-test-methods>).