出國報告（出國類別：研究）

高速公路橋梁等關鍵基礎設施因應極端氣候之設計、施工以及維護管養作為

服務機關：交通部高速公路局第一新建工程分局
姓名職稱：李忠彥　正工程司兼第四工務所主任
派赴國家/地區：美國/洛杉磯、沙加緬度
出國期間：**112** 年 **5** 月 **1** 日至 **112** 年 **7** 月 **29** 日
報告日期：**112** 年 **10** 月 **2** 日

摘要

近年來，因溫室效應、氣候變遷造成的極端氣候現象益趨頻繁，在全世界造成各種嚴重的災害，危及人民生命及財產安全。我國高速公路串聯全台灣，為重要公路運輸系統及經濟和生活的大動脈，身為高速公路管理機關，面對日益嚴重的極端氣候，本局如何確保公路橋梁等關鍵基礎設施之安全性及應採取何種防護作為便顯得十分重要。

台灣高速公路系統之設計及施工等相關制度及規範大部分係參考美國，故期望藉由前往美國加州運輸署，研習該署因應極端氣候可能造成災害所採取之相關管理制度及精進作為，期能幫助提昇國內高速公路於全生命週期各階段之工程技術，達到交通關鍵基礎設施防護成效。

目錄

本文

壹、前言

一、背景與目的

近百年來，工業社會快速發展，經濟起飛，人類生活水準大幅提高，享受進步帶來的繁榮、便利與富足。但是工業發展之下，溫室氣體大量排放導致全球暖化，隨之而來的氣候變遷造成的極端氣候日益明顯，影響範圍、強度及次數急速增加，對全世界造成衝擊並帶來災難。

我國的高速公路作為貫通台灣南北的主要通衢大道，是台灣經濟大動脈，同時在發生災害時作為主要緊急搶救災的通聯道路，重要性不言而喻。加上台灣為多山的地理環境、河流長度短且坡度大，雨量又豐沛，受氣候變遷的影響更為明顯，故極端氣候對高速公路設施造成的衝擊為亟需重視的課題。

極端氣候造成降雨增加等因素可能對高速公路結構和安全產生潛在風險，考量美國在公路建設領域屬先進國家，我國公路設計與施工規範等亦多為參考美國制度，而本局與加州運輸署（Caltrans）有簽訂合作協議，故規劃至加州運輸署進行研究觀摩，以及經驗交流與學習，期能吸取新知，回饋應用於我國高速公路關鍵基礎設施的全生命週期各個階段，提升高速公路面對極端氣候的適應能力，有效達成關鍵基礎設施的防護成效。

二、計畫與準備

本計畫研究人員（以下簡稱：筆者）於 111 年 9 月 5 日獲機關通知，蒙局長垂青指派筆者提案代表本局參加交通部「選送人員赴國外專題研究實施計畫」遴選後，即著手相關準備工作。因被要求於 111 年 9 月 12 日前將專題研究計畫報局，在短時間內實不易找尋赴國外研究之機關(構)或大學，考量本局與美國加州運輸署(以下簡稱 : Caltrans)有簽訂合作協議，故經筆者洽詢該機構與本局合作業務聯繫窗口趙青先生

並取得初步同意後，擇定前往該機構進行研習。復參考本局與 Caltrans 簽訂之合作協議書中載明之合作範圍包含橋梁耐震、氣候變遷議題、橋梁檢測及維護技術等議題，選擇近年來十分熱門的氣候變遷議題，研提氣候變遷造成之極端氣候對高速公路設施之影響及因應作為作為研習主題，以期歸國後貢獻所學，提升交通關鍵基礎設施防護成效。

筆者於 111 年 11 月 1 日至交通部參加遴選面試，於 111 年 11 月 11 日接獲交通部評選正取之通知。筆者立即與 Caltrans 趙先生連繫，請其協助規劃並安排本次研習相關行程。因筆者曾於 107 年前往 Caltrans 考察該機構橋梁檢測維護技術，已與趙先生結識，故趙先生對於筆者本次研習予以大力支持並慷慨提供協助，敲定各項事宜。在此謹對趙青先生致上萬分謝意，本局長官的推薦及同事的協助，併此致謝。

筆者於 112 年 1 月 5 日將執行計畫人員基本資料表、語文能力證明文件、研究計畫執行書及經費概算表報局轉交通部審核，交通部於 112 年 3 月 30 日函文核定專題研究計畫執行書並同意撥付經費，筆者順利於 112 年 5 月 1 日赴美國加州進行為期 3 個月的研習。

在 112 年 5 月 1 日起至 7 月 29 日止之研習期間，筆者分別前往 Caltrans 位於洛杉磯及沙加緬度辦公室，行程概述如下：

（一）112 年 5 月 1 日至 6 月 29 日：Caltrans 洛杉磯辦公室

1. 主題研究
2. 拜訪 Caltrans 人員 (Structure Investigations、Structure Construction、Geotechnical Design)
3. 工程現地參訪

（二）112 年 6 月 30 日至 7 月 29 日：Caltrans 沙加緬度辦公室

1. 主題研究
2. 拜訪 Caltrans 人員(Fracture Critical Structure Investigations、Geotechnical Design、Hydraulic Design)

3. 工程現地參訪

在美研習期間，Caltrans 趙青先生以及許多位熱心協助筆者的人員提供筆者最大的幫忙，讓筆者順利完成本次研習，在此一併致謝。

三、研究預期效益

借鏡加州於重要公路橋梁因應極端氣候可能造成的災害所採取之精進作為，期能提昇國內高速公路工程技術，達到交通關鍵基礎設施防護成效。

貳、研究面向與內涵

一、Caltrans 組織概況

美國加州幅員廣闊，面積高達 423,970 平方公里，為台灣的 11.7 倍，Caltrans 負責加州高速公路系統（State Highway System, 以下簡稱 SHS）的公路設計、施工監督、營運以及維護，業務量十分繁鉅。Caltrans 總部（Headquarter）位於沙加緬度，設有規劃（Planning&Modal Program）、計畫執行（Project Delivery）、維護營運（Maintenance&Operation）、資訊科技（Information Technolony）、行政管理（Administration）、財務（Finance）、公共事務（Public Affair）、法務（Legislative Affair）等 11 個部門，另設立 12 個分區（District）辦公室負責執行營運養護業務，類似本局的養護工程分局，其組織圖詳圖 1。

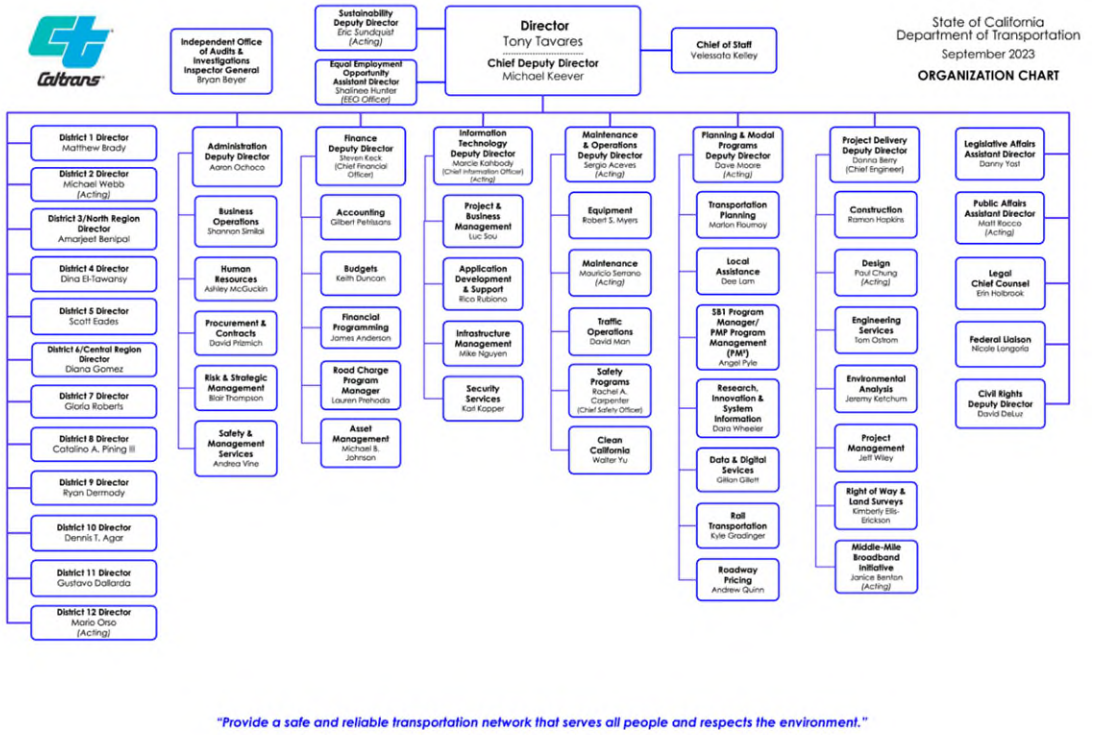


圖 1、Caltrans 組織圖

加州高速公路系統包含 3 種高速公路：州際公路（Interstate highways）、美國國道（U. S. highways）和加州公路（state highways）。Caltrans 總共管理的公路設施包含下列（管轄範圍詳圖 2）：

1.超過 50,000 車道英哩的鋪面

2.超過 35,000 英畝的植栽

3.超過 13,000 座橋

4.超過 205,000 座排水箱涵、管涵

5.超過 500 個公路附屬設施

6.超過 8 百萬平方英尺的建築物使用面積

Caltrans 目前計有員工約 21,170 人，2021 至 2022 之財政年度預算高達 173 億美金，預算除用於高速公路系統外，亦會補助加州城際軌道運輸及地方政府交通運輸相關工程。Caltrans 有充足的專業人才及機具設備，故有關高速公路設計、監造、橋樑檢測等工作均為自辦，品質可精準掌握，並有利於機關專業人才之永續培育並傳承。

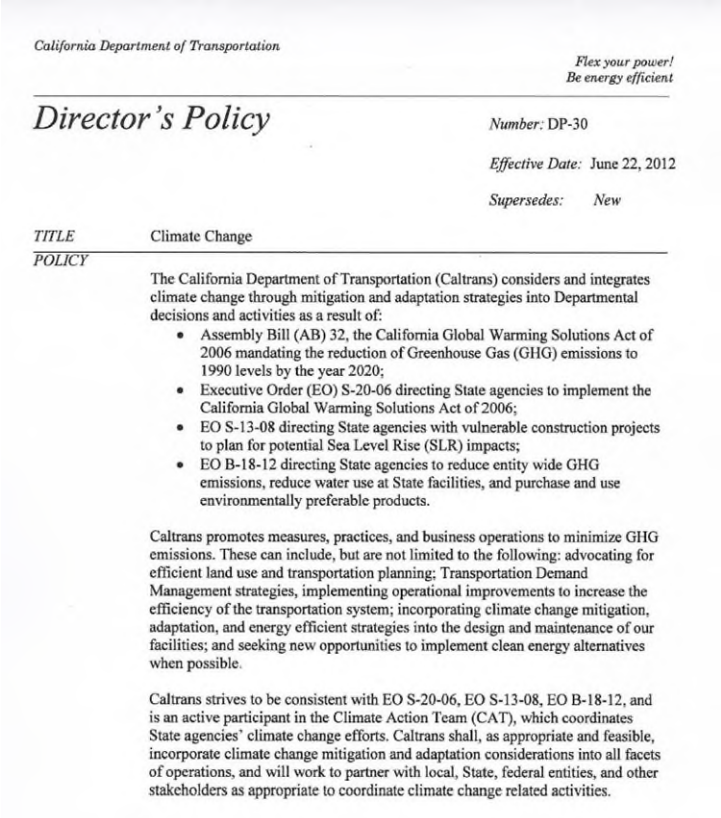
圖 2、Caltrans 管轄範圍示意圖

二、 Caltrans 因應氣候變遷的政策

Caltrans 在 2012.6.22 由機關首長發布第 30 號政策（DP-30，詳圖 3），宣示 Caltran 面對氣候變遷，將積極展開以下工作：

1. 提倡有效率的土地使用及運輸系統規劃；
2. 改善營運策略，提升運輸系統效率以降低溫室氣體排放；
3. 在公路設計及維護營運等層面納入可以減輕及適應氣候變遷造成的極端氣候的有效策略；

4. 儘可能找尋新的潔淨能源替代方案。



California Department of Transportation

Flex your power!
Be energy efficient

Director's Policy

Number: DP-30

Effective Date: June 22, 2012

Supersedes: New

TITLE Climate Change

POLICY

The California Department of Transportation (Caltrans) considers and integrates climate change through mitigation and adaptation strategies into Departmental decisions and activities as a result of:

- Assembly Bill (AB) 32, the California Global Warming Solutions Act of 2006 mandating the reduction of Greenhouse Gas (GHG) emissions to 1990 levels by the year 2020;
- Executive Order (EO) S-20-06 directing State agencies to implement the California Global Warming Solutions Act of 2006;
- EO S-13-08 directing State agencies with vulnerable construction projects to plan for potential Sea Level Rise (SLR) impacts;
- EO B-18-12 directing State agencies to reduce entity wide GHG emissions, reduce water use at State facilities, and purchase and use environmentally preferable products.

Caltrans promotes measures, practices, and business operations to minimize GHG emissions. These can include, but are not limited to the following: advocating for efficient land use and transportation planning; Transportation Demand Management strategies, implementing operational improvements to increase the efficiency of the transportation system; incorporating climate change mitigation, adaptation, and energy efficient strategies into the design and maintenance of our facilities; and seeking new opportunities to implement clean energy alternatives when possible.

Caltrans strives to be consistent with EO S-20-06, EO S-13-08, EO B-18-12, and is an active participant in the Climate Action Team (CAT), which coordinates State agencies' climate change efforts. Caltrans shall, as appropriate and feasible, incorporate climate change mitigation and adaptation considerations into all facets of operations, and will work to partner with local, State, federal entities, and other stakeholders as appropriate to coordinate climate change related activities.

圖 3、第 30 號政策

與工程有關的政策為第 3 點。在本文件中，Caltrans 載明各階層主管、各部門要負責執行的事務，並且應用於參與高速公路系統規劃設計、施工、維護及營運等全生命週期各階段的每一位 Caltrans 員工，以期建立確保各部門能通力合作、致力於將極端氣候影響納入決策及行動方案的政策方針。

三、 因應極端氣候之策略作為

上述機關政策頒布後，Caltrans 展開因應氣候變遷導致極端氣候的各項作為。在 2020 年 5 月出版「因應氣候變遷策略報告」（詳圖 4），詳細闡述 Caltrans 面對氣候變遷造成的各種衝擊及因應策略。

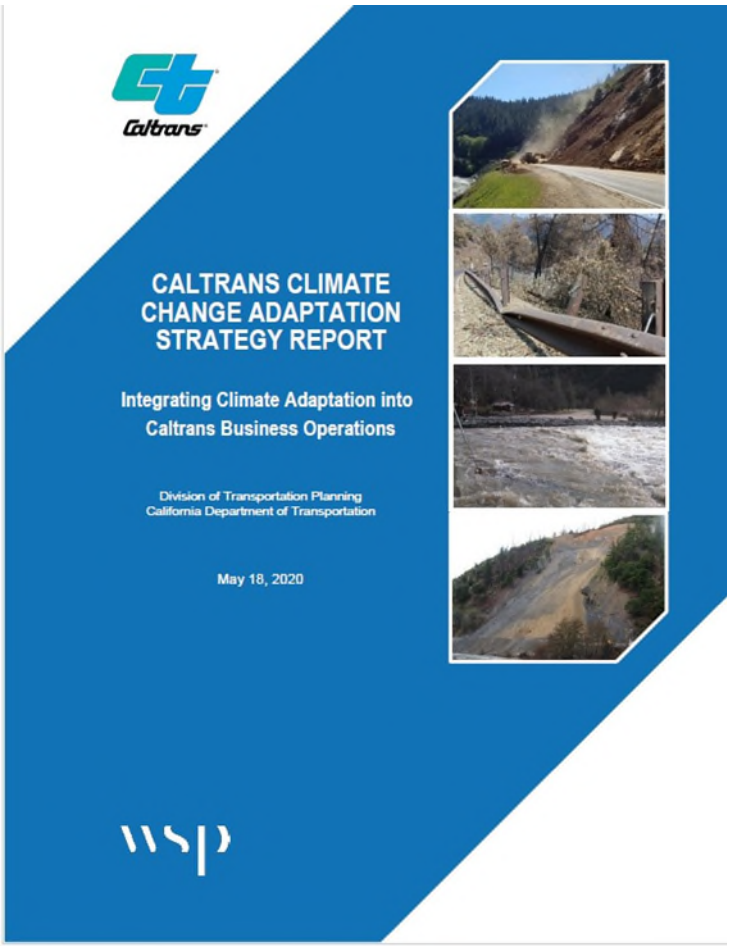


圖 4、Caltrans 因應極端氣候之策略報告

在本報告中，依據 Caltrans 先前已建立起的評估因應作為之步驟架構（詳圖 5），逐步執行各階段工作。

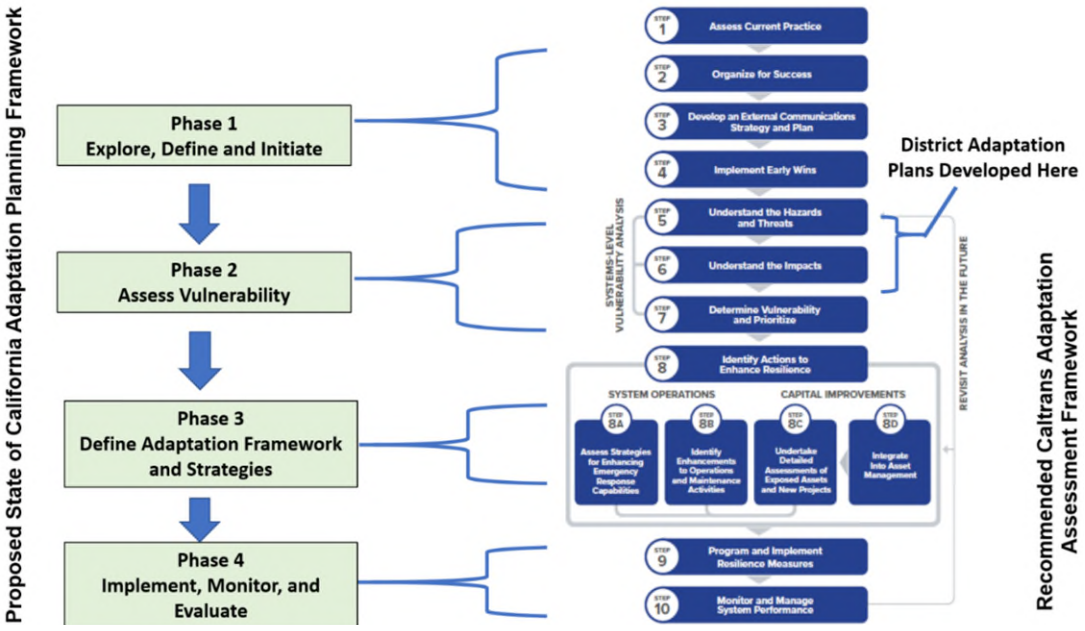


圖 5、Caltrans 評估因應作為之步驟架構

(一) 第 1 階段：探索、定義及起始

本階段為前置工作，係為找出氣候變遷因應策略打下良好基礎，包含以下工作：

1. 檢視目前已存在或建立的相關法令、政策及執行計畫等與氣候變遷及極端氣候之關聯性，
2. 明確定義組織各部門的負責事項，以利政策推動
3. 建立有效且系統性的外部溝通策略，將氣候變遷與極端氣候議題充分讓社會大眾及利害關係人知悉，以利意見整合及計畫執行
4. 執行早贏（Early Wins）方案，也就是短程方案。

(二) 第 2 階段：評估資產的脆弱性（Vulnerability）

本階段主要工作為認知極端氣候帶來的災害與威脅，了解這些威脅會對高速公路設施產生哪些衝擊，並且決定公路設施面對各種不同衝擊的脆弱性並加以排出優先順序。

Caltrans 的各分區辦公室已在 2019 年至 2020 年間完成所轄高速公路設施氣候變遷脆弱性評估報告（詳圖 6，以第 7 分區為例），報告內容如下：

1. 與聯邦及州內相關氣象及資源單位合作，收集加州各地氣候資料，藉以精確了解公路系統受極端氣候影響的潛在衝擊；
2. 進一步確認及盤點因極端氣候造成的災害如何影響各項公路設施，包含設計在內；
3. 了解各種設施受不同極端氣候影響可能造成何種損害，進而加以防範，確保設施長久安全。

經過分析，Caltrans 列出 4 項對公路設施會造成衝擊的極端氣候因子及其可能造成之災害型態：

1. 降雨型態改變：近年來加州降雨有逐年減少趨勢，但是短延時的強降雨發生頻率越來越高，造成災害包含近河岸地區淹水、河川沖刷侵蝕與流向改變、山坡因雨水沖刷造成山崩等等，以上災害發生次數逐年增加，造成工作人員緊急搶災以及道路封閉次數增加，增加社會成本；

2. 海平面上升(Sea Level Rise，以下簡稱 SLR)：根據氣候資料，1900 年至 2020 年，海平面已上升 16 至 21 公分，其中有一半的高度是發生在近 25 年。主要造成的災害包含海岸地區洪水及海岸線侵蝕、岸邊崖線後退及因風暴造成的潮湧現象加劇。

3. 氣溫上升、極端酷熱：根據加州氣候資料，從 1986 年至 2016 年的平均氣溫已經較 1901 年至 1960 年間的氣溫上升華氏 1 至 2.9 度，並且以全球氣候模式模擬預估，至本世紀末，平均最高日氣溫將會較現在上升華氏 5.6 度。主要造成的災害包含野火發生頻率大幅上升、鋪面因高溫更容易損壞、乾旱情形及範圍日趨嚴重以及高溫對工作人員健康造成影響；而以上災害發生次數逐年增加，亦造成更多維修工作、植栽面積需復舊以及道路封閉次數增加，增加社會成本。

4. 逐年增加的野火：加州相關單位評估，從 1984 年至 2015 年，因氣候變遷導致的野火燃燒面積，為沒有氣候變遷發生的 2 倍。主要發生的災害包含公路設是遭焚毀或融化、山坡植被遭焚燒導致邊坡裸露，山崩發生機率大增、對工作人員健康影響甚鉅；同時因野火焚燒植被，道路封閉及緊急搶修次數增加、植被復舊工作也大量增加。

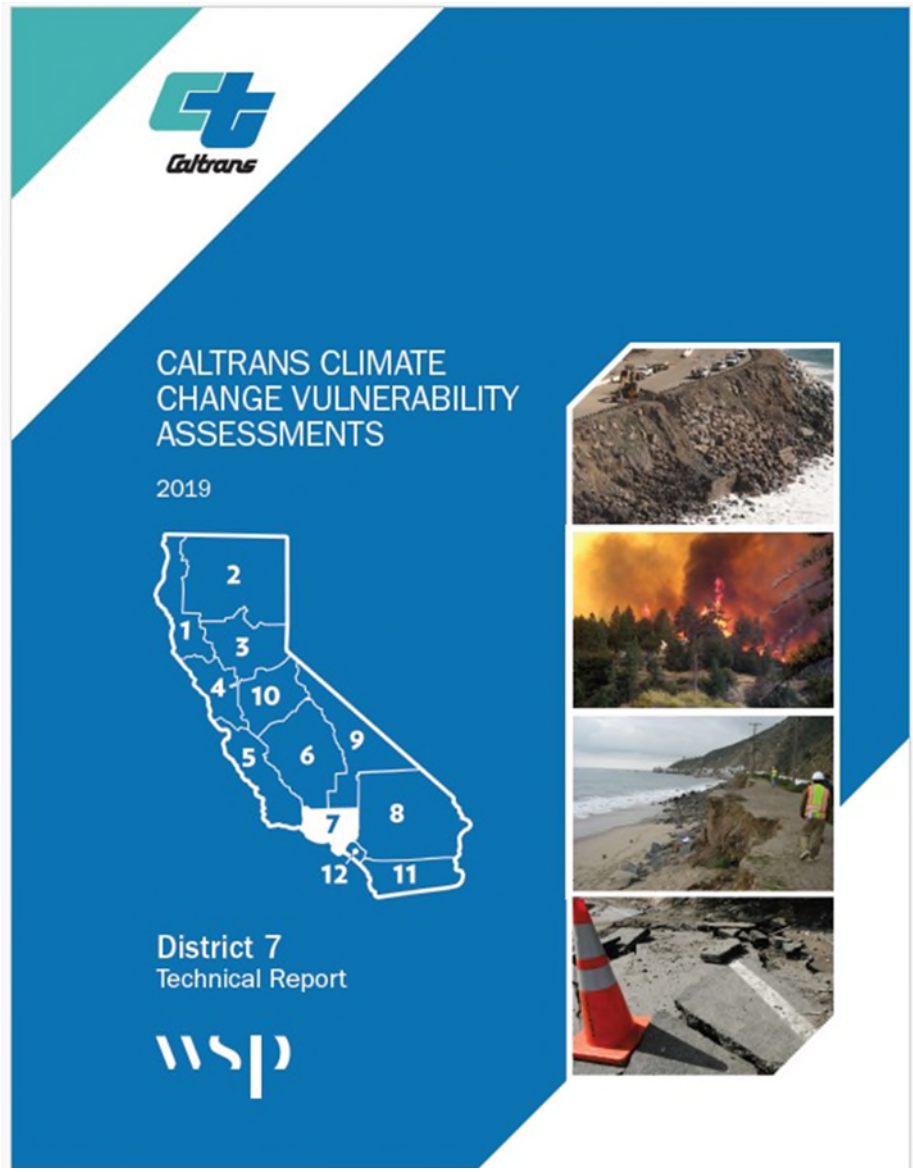


圖 6 第 7 分區公路設施脆弱性評估報告

上述報告依據所有公路設施所在的位置及當地的氣候資料，詳加評估上述災害對公路設施造成可能的衝擊及損壞，以利下一階段工作的進行。

在完成上述公路設施脆弱性評估報告之後，各分區辦公室進行下一階段的重要工作：建立優先排序準則，並將前揭報告評估可能受到極端氣候影響的各項公路設施進行優先順序，以執行後續更詳細的資產評估及執行因應作為。目前各分區辦公室均已完成優先排序報告（圖 7，以第 7 區為例）。

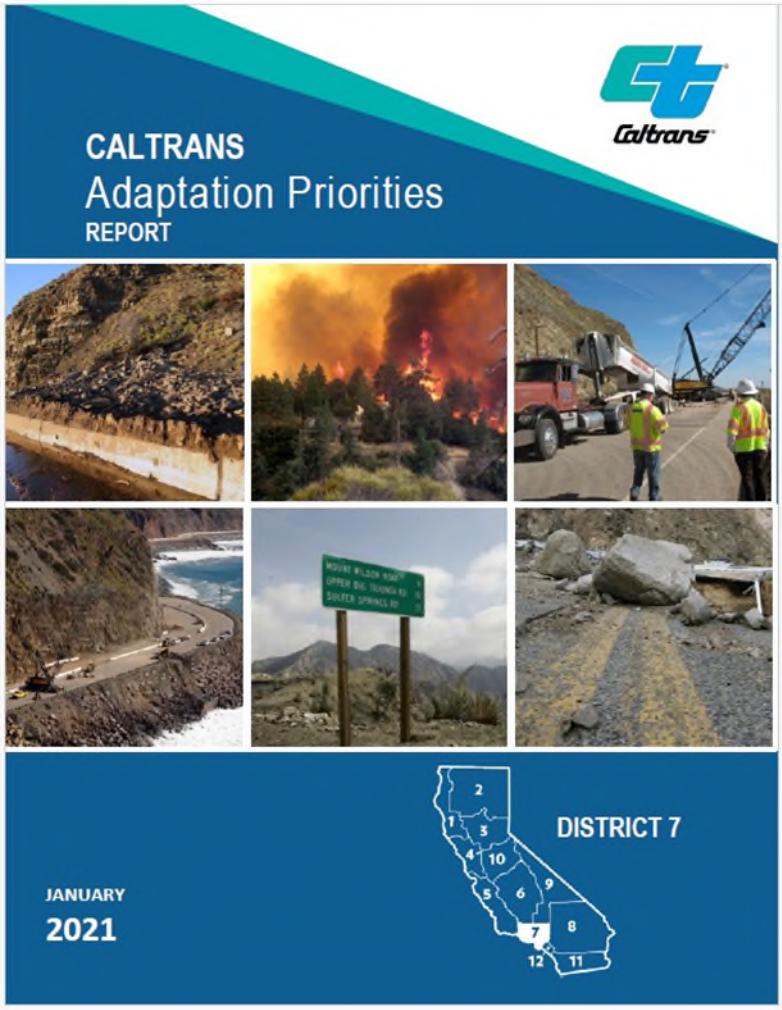


圖 7 第 7 分區公路設施脆弱性優先排序報告

優先排序考量的因子包含極端氣候衝擊發生的時間、其嚴重性與受影響範圍大小、公路設施本身的狀態、公路設施損壞而被影響到的用路人人數以及該公路設施損壞對於該地區交通路網系統的贅餘度（Redundancy）。公路設施分為橋梁、大型排水箱（管）涵、小型排水箱（管）涵、平面道路及鋪面。評估完成後，每項公路設施會得到 0~100 的分數，按分數高低分為 5 級優先排序等級。每個等級的公路設施數量儘量相同。

以橋梁為例，第 7 分區辦公室所轄共 210 座橋梁，經優先排序評估後，計有 40 座橋梁列為第 1 優先順序，必須優先處理，如圖 8 所示，紅色點位之橋梁即為第 1 優先排序者。

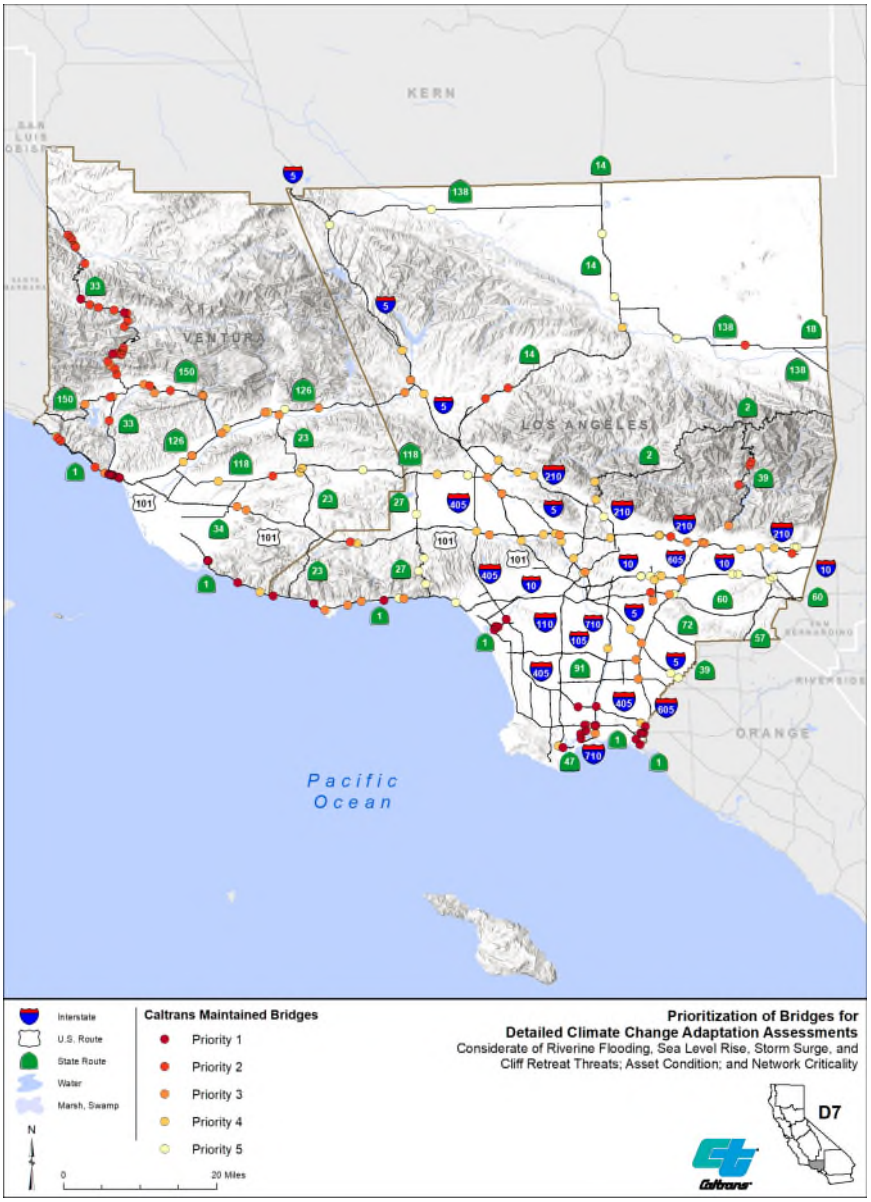


圖 8 橋梁脆弱性優先順序評估結果

(三) 第 3 階段：定義因應框架及策略

完成第 2 階段後，將就公路設施進行更詳細的資產評估以及擬定因應策略。因應框架的面向包含分為兩個平行軌道，一個著重於增強彈性並考量增強適應能力的營運措施和（步驟 8A 和 8B），另一個著重於確定可增強公路設施適應能力的基本建設或改善計畫（步驟 8C 和 8D）。這些代表了利用前階段所完成的公路設施脆弱性優先排序報告中的資訊所應採取的後續步驟。

在營運面向上，應藉由前階段報告的結果，研究出加強緊急應變（步驟 8A）以及營運和維護（步驟 8C）的方法。 加州交通局在基本建設或改善計畫面向的下一步是對優先排序報告的公路設施進行詳細評估（步驟 8C），另將優先排序報告中的優先順序資訊也應整合到加州資產管理系統（步驟 8D）。

步驟 8C 中的詳細適應評估涉及工程的分析，以驗證公路設施暴露於相關極端氣候的危害情況。如果暴露情況得到驗證，步驟 8C 包括制定和評估適應性措施以減輕風險。將首先評估本研究中優先順序最高的資產，隨後評估優先順序較低的資產。

Caltrans 策略報告中，針對公路設施全生命週期各階段工作均提出建議做為未來的努力方向，以利將公路設施適應極端氣候的策略融入政策決定：

1. 確認組織內各部門權責；
2. 確認組織的策略願景、目標及政策指導；
3. 路廊規劃：Caltrans 已完成考量極端氣候因子的路廊規劃指引。
4. 經濟分析：建議在規劃適應策略過程中納入經濟分析以利於公路建設或改善計畫的優先排序決定。
5. 計畫起始及發展：檢視並確認將氣候變遷的適應作為考量納入 Caltrans 制定的「計畫發展程序手冊」（Project Development Procedures Manual）
6. 計畫資金來源規劃：建議為財務計畫制定氣候變遷調適資金類別，發展與資金來源規劃過程中的其他主要參與者協調達成上述目標之策略。
7. 計畫優先排序：將氣候變遷調適因子納入計畫投資決策。
8. 環境影響：研究如何在現有的作法和法規的情況下將氣候變遷適應納入環境，重點關注對社區的影響（例如洪水特徵的變化）和

對交通系統的影響（例如係統彈性）。建議制定獨立指引（或在現有技術指引中要求納入），重點在於如何將氣候變遷適應（可能與溫室氣體減排一起）納入環境分析。

9. 工程設計：

(1) 檢查既有設計手冊和指引，納入氣候變遷適應性設計概念。包含如何將風險和氣候變遷不確定性視為關鍵設計輸入，以及如何將公路設施遭受損害的潛在後果納入設計決策，需要對交通系統性能至關重要（即使短期中斷也會造成重大影響）的項目進行權衡評估。

(2) 建立修正設計指引的方法，重點在於各種氣候變遷壓力因子對各種公路設施造成的影響。目前已將路面、橋梁、涵洞、運輸管理系統 (TMS)等 4 種定義為「重點領域」，列為優先檢討修正設計指引。

(3) 檢視既有價值分析(VA)流程，納入未來公路設施因極端氣候造成災害而中斷時，對公路運輸系統和系統用路人造成的成本損失，此類成本和相關風險視為全生命週期分析的一部分。

(4) 與他州 DOT 共同研究訂定新的標準和方法，以便保持統一性，並就此辦理教育訓練將其傳授給各個部門的員工。

10. 公路設施維護：

(1) 目前 Caltrans 已在執行箱(管)涵維護計畫，優先確保高風險地區的脆弱設施維持其功能，位於關鍵設施上且容量已不足已承受流量的箱(管)涵應優先更換。

(2) 檢討現有維護做法，研究更有效、有系統地更換容易遭受火災或洪水損壞的設施。 例如，用金屬護欄取代木質護欄。應針對新的或改進的維護作法對維護人員進行培訓。

(3) 決定哪些設施可以透過新的設計選項更有效解決反覆發生損壞的問題。

(4) 透過收集有關潛在周圍環境風險（洪水水位、堤壩潰決）、過去維護問題和可能發生的後果等資訊，研判排水設施可能更換的地點。

11. 公路設施資產評估：將 SHS 面臨的風險以及存在高風險地區及設施的資訊應用於制定各地區一致的氣候變遷調適績效衡量標準、標準和因素，進而確定"需求，成為資產管理決策過程的一部分，包含制定和納入與氣候風險相關的量化生命週期風險的估計，以及考慮更廣泛的經濟和社區影響。同時應定期更新「專案風險管理手冊」，以反映透過新研究、災後報告和最新科學發現的與極端天氣和氣候變遷相關風險的最新資訊。

(四) 第 4 階段：執行、監控並評估

前 3 階段完成後，無論是營運措施還是公路建設或改善計畫，就可以依前述成果這些項目進行規劃設計並落實執行。執行後尚需對公路設持續監控，以追蹤及評估在公路設施生命週期內增強適應性。

四、加強極端氣候影響適應性之常用作法

Caltrans 在因應氣候變遷策略報告中，就各種極端氣候因子可能造成的災害整理加強或改善的作法，因應作為的主要方向為減輕（mitigation）及適應（adaptation），分如下述：

(一) 因應 SLR、潮湧及海岸侵蝕的海岸保護對策：

1. 海牆與隔板(Sea Walls and Bulkheads)：通常為大體積混凝土或工程填充結構或擋土結構，以抵抗海浪拍擊力。

圖 9 海牆

2. 護岸及邊坡侵蝕保護工(Revetments and Slope Erosion Protection)：岩質邊坡防護是應用最廣泛的方法，係放置核心岩石以提供保護的結構核心，再於其外放置大石頭、巨石或碎石作為保護層。

圖 10 護岸

3. 丁壩及碼頭(Groins and Jetties)：丁壩結構可捕獲近岸水流輸送的沙子來促進沙灘形成。透過這種堆積結構可以防止 SLR 造成的風暴潮、海灘侵蝕和懸崖退縮。

圖 11 丁壩

4. 自然海岸線(Living Shorelines / Shoreline Stabilization) 、自然防波堤及沙礁(Living Breakwaters & Reefs)：通常結合多種基於自然的策略來創建海岸線，還可以採取混合方法，在適當的情況下結合綠色和灰色基礎設施（結構、骨材和地工織物）。

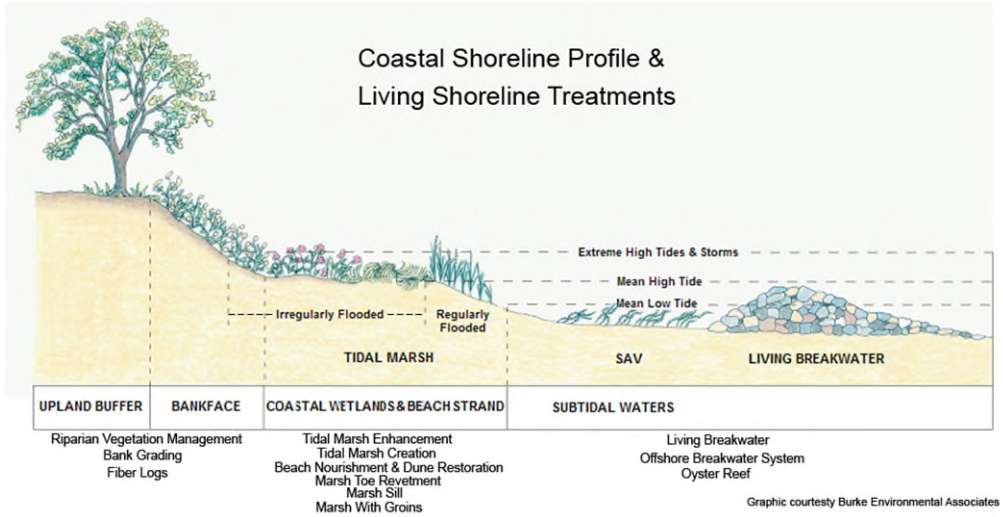


圖 12 自然海岸線

5. 屏障島(Barrier Islands)：屏障島通常是與大陸平行的長片沙地，可作為一層保護層，提供波浪衰減或消散作用，並減少大陸遭受嚴重風暴影響的程度。

圖 13 屏障島

6. 海岸森林(Maritime Forests)：海岸森林是指主要由樹木、灌木和其他植物組成的高地沿海地區，作為擋風屏障，減輕海浪沖擊海岸的力量，提供沿岸地區的過渡保護區。

圖 14 海岸森林

7. 沙灘/岩灘(Sand & Rock Beaches)：海灘可以作為沿海緩衝區，透過減緩海岸線的波浪和內陸水輸送來保護公路設施和棲息地。
8. 沙丘/海草海床 Dunes/Seagrass Beds：沙丘，特別是植被沙丘，在風暴期間透過消散波浪能量並減少沙丘後面的風暴潮洪水和鹽水入侵來提供保護。海草床的垂直結構減緩波浪的速度和高度，可充當海灘和懸崖的侵蝕緩衝區，透過減緩洋流和遠離海岸線的破碎波浪來防止侵蝕，但功效很有限。

圖 15 海草海床及沙丘

(二) 預防邊坡滑動的保護工法：

1. 加強排水系統：降雨量和強度導致邊坡不穩定和侵蝕。加強邊坡設計的主要方法是增強排水和滲透設計。運動會導致土壤不穩定。 透過工程方法或增強自然緩解來充分控制地表徑流和地下水排水。這些排水系統的長期性能取決於定期維護，以確保其按設計運作。
2. 土石流攔截柵欄：在排水道上設置土石流柵欄，以攔截土石流並阻止或減緩土石流的流動，減少破壞能力。

圖 16 土石流攔截柵欄

3. 降低驅動力/增加抵抗力：降低驅動力方面，有減少坡頂負載等方法；增加抵抗力方面，有主樁橫版條工法、土釘、岩栓、

地錨等工法。

圖 17 主樁橫板條工法搭配地錨

4. 地表下排水：可降低孔隙水壓力或地下水位，是穩定邊坡滑動的有效手段。

圖 18 地表下排水管

5. 植栽及植草：邊坡上植栽和植草，有助於固定土壤及減緩地表逕流。

圖 19 邊坡植栽及植草

6. 生物工程穩定工法 Bioengineering and Biotechnical Stabilization：有梯田、石塊以及地工織物加勁邊坡等方法。

圖 20 梯田

(三) 考量高溫因素納入鋪面設計：

極端高溫造成鋪面車轍或側邊隆起等破壞發生機率大幅提高，增加維護頻率及成本。以工程手法增加鋪面適應性的重點是透過增強結構彈性、提高路面材料和施工的耐久性和品質以減少鋪面破壞發生可能性，提高路面的適應能力。 調適措施可包括：

1. 目前 Caltrans 鋪面設計規範足以滿足目前氣候條件，但考量未來日趨嚴峻的極端氣候，必要時檢視和修改路面設計政策，以

納入未來氣候預測而非歷史氣候記錄，並提高設計彈性，將氣候不確定性納入決策中。與設計相關的具體調適措施可能包括但不限於：

(1)提高鋪面結構強度，以提高抗疲勞和車轍的能力。

(2)穩定地基，例如對地基、底基層和路基使用化學穩定、垂直排水帶和土工合成材料加固。

(3)結合縱向、邊緣和橫向排水溝、透水基底等設施，改善排水系統，防止侵蝕、滲透、滲漏造成鋪面及路基損壞。

(4)納入設計元素，例如縮短接縫間距、在接縫素混凝土路面中使用繫接路肩或加寬板、以及在連續鋼筋混凝土路面中使用更高的鋼筋，以提高整體性能。

2. 選擇更耐用的材料抵抗未來溫度和濕度趨勢帶來的衝擊：

(1)提高瀝青膠結材的高溫等級，以提高抗車轍和疲勞損傷的能力。

(2)瀝青膠結材增加使用聚合物和添加劑，提高抗車轍、濕氣損壞和氧化老化的能力。

(3)增加使用溫拌瀝青，以降低瀝青膠結材時效硬化強度。

(4)擴大使用性能改善體積設計在瀝青混合設計，以產生平衡的混合設計。

(5)擴大使用優化混凝土配合比設計，例如減少乾燥地區的乾燥收縮或提高較冷地區的凍融耐久性。

3. 提升施工工法品質來提高材料和施工品質：

(1)考慮限縮規範允許的公差以提高品質，例如增加瀝青的密度。

(2)採用施工和檢查的優化方法，例如採取更加的養護以減少早期永久撓曲和收縮的發生，監測混凝土早期老化行為，監測瀝青材料的熱均勻性，監測所有路面層的壓實度，優化黏層的應用以提高附著力等。

(四) 在易發生洪水區域更新排水箱(管)涵：

為增加排水能量，可採取加大斷面、改變管涵形狀（方形箱涵取代排水管）、改變材質(混凝土取代波浪鋼管)、增加管涵數量等作法。目前 Caltrans 的箱(管)涵設計準則為 100 年週期洪水下，在箱(管)涵上游端的水位不得超過管涵高度的一半，並完全跨越有效寬度，經評估應足以因應未來氣候變遷的影響，惟仍需視需要調整設計。

(五) 在洪水造成河川水位上升區域的橋梁設計：

1. 加強上構設計：增加橋梁的跨度是增加橋梁未來安全性的有效方法，然而需綜合考量施工成本增加議題。另外，大部分情形下，橋梁上構並無設計抵抗提升力。在大洪水時，橋梁上構可能會因水流而被提升。某些結構類型，例如預製梁，由於上部結構未連接到下部結構，並且大多數橋樑由座式橋台支撐，因此很容易脫離。防止上部結構抬升的一項措施是添加錨桿，在上部結構和下部結構之間提供連接。
2. 增加出水高：Caltrans 橋梁結構設計準則為 50 年週期洪水水位下保有最小出水高為 2 英尺。提高最小出水高標準，將為洪流提供更大的開口，可降低流速，降低橋梁損壞的機率。另外，可選擇設計為在沒有出水高的情形下可抵抗 100 年週期洪水水位，也可以考慮提高設計洪水頻率（例如按 200 年週期洪水水位進行設計），以提高結構抵抗日益嚴重洪災的能力。
3. 拋石護岸，墩柱混凝土包覆，基礎改採深基礎：可能發生高頻率和高水位洪水的地區，沖刷和侵蝕是主要問題。可以採取緩解侵蝕和沖刷的措施，例如拋石護岸（沿著海岸線、斜坡和橋樑基礎或橋台放置的鬆散岩石、混凝土塊或其他材料，以防止沖刷和侵蝕）或混凝土渠道襯砌，以保護橋梁基礎或橋台免受侵蝕影響。此外，應避免在易於沖刷的區域使用淺基礎，採用深基礎可有效減輕沖刷和侵蝕的影響。

圖 21 拋石護岸

4. 河道設計及監控：加寬或增加橋梁位置渠道的橫斷面，可以減慢水流速度，減少洪水水位高漲。河道堤岸植被也有助於減緩侵蝕並吸收增加的洪水。要求檢查員固定在河流或渠道底部乾涸季節評估橋樑基礎，改善沖刷的維護作業應安排在水位較低的時期，以免沖刷變得難以控制。位於洪水地區的道路，適應及緩解道路漫溢的方法包括抬高道路高程、加固道路路堤或將重新改線將道路移至洪氾區外。

(六) 內陸之易淹水區地區，考量未來洪水位上升的因應做法：

1. 洪氾區保護/保護，內陸濕地復育：河流防洪最有效、最廉價的自然基礎設施策略通常是洪氾區保護和保護。維護現有的自然洪氾區，可持續提供防洪，吸收洪水期間的溢流。 這些天然洪氾區通常是內陸濕地生態系統，例如淡水沼澤，是減少河流災害風險的有效選擇。
2. 洪水退縮距離：洪水退縮距離規定河道和公路設施之間的最小垂直或水平距離，使設施遠離可能的洪水區域。河流和設施之間的退縮區域可以成為天然的洪氾區，保護附近的基設施免受洪水侵襲。
3. 河堤植被和植草：可沿著河岸種植植物，植物的根將土壤固定在適當的位置，而植物可以捕獲沉積物，還可以減緩洪水的流速，還可收固碳、增加生物多樣性和改善美觀之效益。

4. 河道內結構：在河道內裝設巨石或淺灘等設施，以轉移水流並降低水流速度。此外，巨石和淺灘都可以改善魚類棲息地：巨石可以為魚類創建保護區，而淺灘可以增加下游的氧氣含量。
5. 河道渠道化：緩解河川洪水最佳的策略是渠道化。挖掘新河道，形成一條額外通道，增加河流的承載洪水能力並從主要水道分流。渠道化允許更多的水流過河流，而不影響河流流量。
6. 生物窪地、植物窪地和生物滯留池：生物窪地、植物窪地和生物滯留池充當雨水的吸收集水區來減輕雨水洪水的影響。 植物可減弱水流並將土壤固定在適當的位置，而可滲透的地面覆蓋物可以滲透到土壤中，並可能補給地下水位。
7. 樹木：樹木可降低雨水的影響，透過根部攔截和吸收雨水，減少水量樹根還可以固定土壤並防止侵蝕。

(七) 抵抗野火採取耐旱、耐火景觀美化與防禦空間：

1. 防禦空間：透過維持公路設施與其周圍植被之間創建的緩衝區來避免點燃野火，減緩或阻止野火的蔓延，並額外保護建築物免受輻射熱影響。
2. 防火景觀：耐火植物通常是耐旱的本地植物，使用不易點燃且汁液含量低的高水分含量植物、比其他物種不易燃的樹木以及岩石、覆蓋物、花園、石牆等來創建防火景觀。
3. 強化：使用耐餘燼和耐熱材料來防止公路設施著火和損壞。例如用金屬管涵取代塑膠管涵；用金屬取代木材標誌桿、護欄和柵欄。建築物使用不燃材料，並遵循與減輕火災風險相關的其他標準。

五、與 Caltrans 人員交流以及工程現地參訪

由於 Caltrans 目前仍維持新冠病毒防疫期間的居家上班政策，各單位人員進辦公室的時間不多，大多維持 1 週上班 1 至 2 天，故本次研習筆者與 Caltrans 人員交流的模式大多是由 Caltrans 人員帶領筆者至各工地參訪，並在參訪過程中了解目前 Caltrans 就極端氣候議題在工程實際執行面的情形。

(一) 辦公室參訪

筆者參訪 Caltrans 位於洛杉磯的結構維護與檢測部門（Structure Maintenance & Inspection，以下簡稱 SM&I）辦公室，拜訪資深設計工程師 Tony Brake，交流氣候變遷議題。Tony 表示，橋梁和道路面臨洪水及海岸侵蝕問題，最有效且根本的方式就是避開及加高，這在路廊規劃時是重要的考量因子。目前大地工程的設計準則仍依循現有相關規範，氣候變遷因子大多採安全係數酌以放大方式因應。另表示，目前 Caltrans 在減少溫室氣體的排放的作為，已將大部分公務車輛改為電動車，另外，在家辦公政策，減少同仁在上下班塞車過程中排放的廢氣，亦有所幫助。

圖 22 拜訪 Caltrans SM&I 資深工程師 Tony Brake

另筆者前往北加州時，亦前往 Caltrans 位於沙加緬度的 SM&I 辦公室，拜訪 Fracture Critical Inspection 的主管 Shujun

Wang，參觀 Special Inspection Team 的裝備，下圖為執行水下橋梁基礎檢測作業所需要的船，執行水下檢測作業的同仁需要經過嚴格的訓練並取得認證後方可執行業務。

圖 23 Caltrans 擁有水下檢測作業船隻

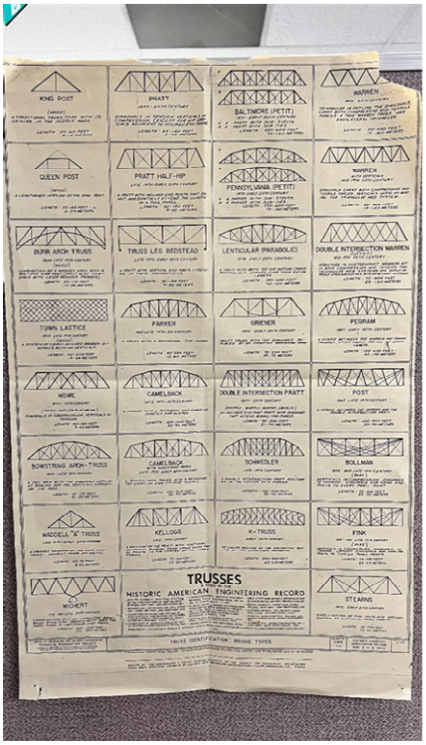


圖 24 需要做 Specail Inspection 橋梁分布圖及老舊桁架橋的檢查重點

圖 25 與 Shujun Wang 於 Frature Critical Inspection 現場合影

另外亦拜訪 SM&I 辦公室 Hydraulic Desgin 的 chief engineer Kevin Flora，Kevin 表示在 Hydraulic Desgin 部分，著重在關心橋梁基礎遭受河川沖刷特別嚴重的橋梁，Hydraulic Desgin 加以列管並每年前往巡檢及測量，重點在於橋梁上下游河道的變化，河床斷面及河川水位變化，還有受沖刷橋墩的沖刷情形，將以上情形紀錄成報告並繪製斷面圖以利比對，同時利用工程軟體進行 2 維水理分析，確認基礎安全度。若發現問題變嚴重，即著手設計改善工程。至於設計規範，目前仍沿用既有 FHWA 及 Caltrans 既有規範，針對河川沖刷問題，以下圖 FHWA 頒布的「橋梁沖刷及河川不穩定性之因應對策」作為聖經。

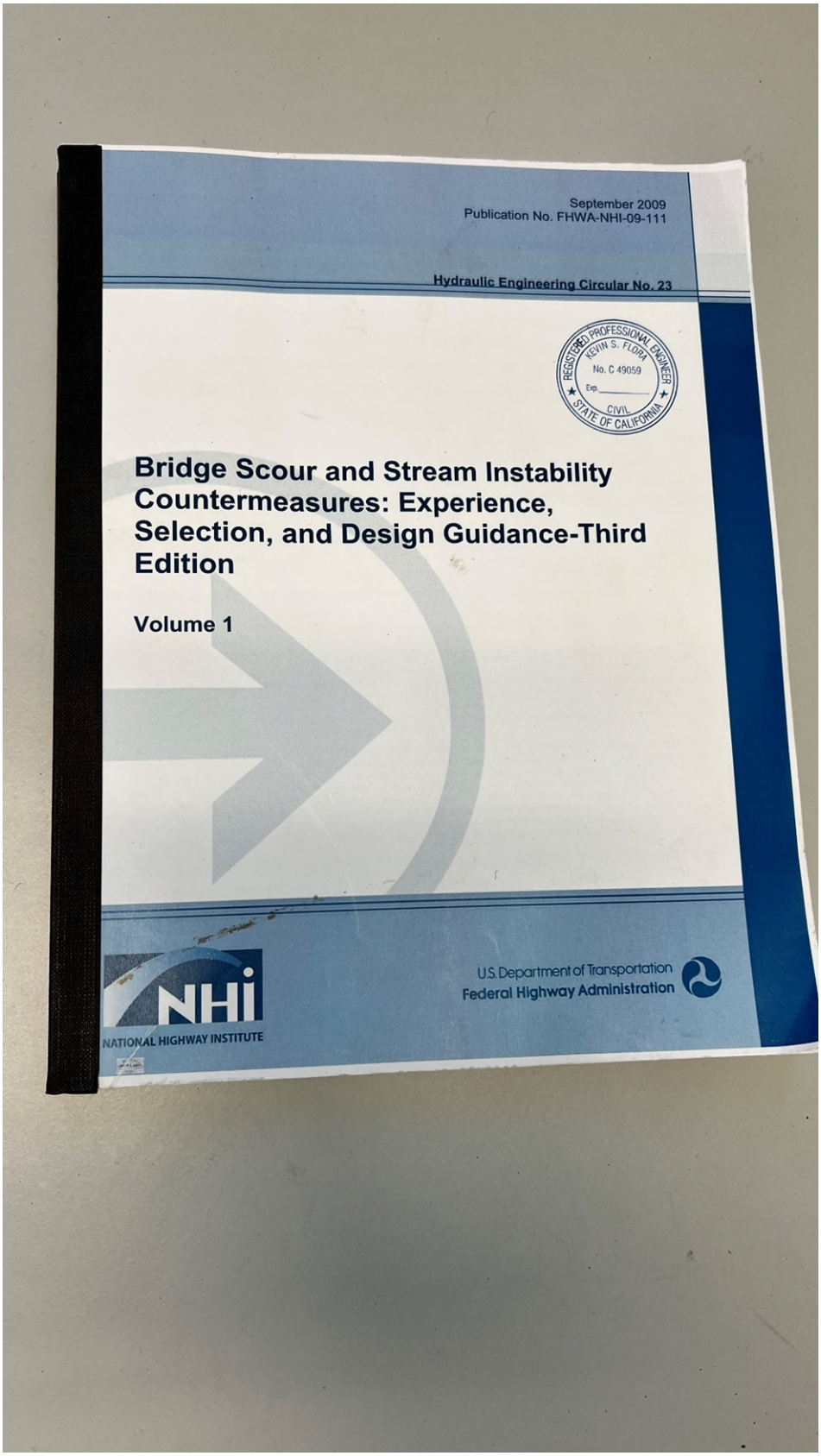


圖 26 FHWA「橋梁沖刷及河川不穩定性之因應對策」

(二) 道路及橋梁受極端氣候產生之災害及作為

研習期間，承蒙 Caltrans 人員熱心幫忙，帶筆者前往多處高速公路遭受極端氣候影響的位址參觀，顯示加州遭受極端氣候衝擊越來越明顯。

1.洛杉磯郡 State Route 39：此公路為洛杉磯東部地區往北越過山區連接 San Bernadino 郡北部的道路，因位於山區，受暴雨影響甚鉅，多處發生邊坡坍方及橋梁沖刷問題，目前正依據優先順序辦理修復或整治。

圖 27 Route 39 橋梁因沖刷問題，須辦理改建

圖 28 Route 39 邊坡土石崩落

圖 29 Route 39 道路下邊坡遭沖刷淘空

圖 30 Route 39 邊坡保護工法，於坡度過於陡峭且高度甚高的裸露邊坡，採以直升機吊掛掛網方式進行施工

圖 31 與 Caltrans 同仁於 Route 39 邊坡整治工程現場合影

圖 32 Route 39 邊坡掛網保護完成情形

圖 33　Route 39 局部路段因損壞情形嚴重，修復不符合經濟效益，故暫不進行修復工程，道路封閉

2.Ventura 郡與 Santa Barbara 郡 ： 多處河川遭受暴雨帶來的洪水夾帶上游石塊衝擊橋墩及護岸，造成損壞

圖 34　Route 150 橋梁遭沖刷河床侵蝕、邊坡護岸遭沖毀

圖 35　Route 150 橋梁下方河道堆積土石，通水斷面減少，橋墩及橋台有被衝撞之虞

圖 36　Route 150 橋梁墩柱遭沖刷及撞擊，河床面下降

圖 37　Route 1 附近地方道路橋梁下方河道堆積洪水夾帶雜物

圖 38 Route 33 橋梁橋台邊坡遭沖刷裸露

圖 39 Route 192 橋梁旁邊坡嚴重沖刷裸露

圖 40 Route 1 旁海岸侵蝕

圖 41 Route 1 位於海邊橋梁，鋼構鏽蝕嚴重需要改建

3. Orange Couty：多處公路邊坡及橋梁遭受暴雨侵襲造成災害，另有野火造成邊坡裸露而坍方及設施遭焚毀需改建

圖 42 Route 1 位於海邊，下邊坡遭沖蝕崩坍，進行保護

圖 43 Route 1 位於海邊之下邊坡遭海浪侵蝕

圖 44 Route 241 路側野生動物逃脫通道，原木構架支撐遭野火焚

毀，復舊改採金屬支撐架

圖 45 Route 91 邊坡植生遭野火焚毀導致邊坡坍滑

4.San Bernadino 郡：位於沙漠中的 I-40 ，橋梁遭到暴雨帶來的洪水侵襲，橋墩遭嚴重沖刷，結構亦遭撞擊，已規劃改建

圖 46　I-40 位於沙漠中的橋梁受洪水侵襲損壞

5.北加州高速公路 ：著名的海岸公路 Route 1 沿線有多處災害發生，沙加緬度附近河川橋也有多處橋梁在改建後 2~3 年間橋墩即發生沖刷問題

圖 47　Route 1 受海岸侵蝕影響，原路線飽受威脅，故更改路線往內陸移動並改為高架橋，花費 2500 萬美金

圖 48　Route 1 新建橋梁的前方受海岸侵蝕影響，圖中臨海的山崖已被海水侵蝕後退，數戶房子已掉入海中

圖 49　Route 1 公路下邊坡坍方，施作保護工

圖 50　Route 1 邊坡修復整治工程施作中，需交維封閉車道，現場僅餘 1 車道，交維人員指揮輪流放行

圖 51　Route 99 橋梁於 2020 年改建完成，3 年時間即發生橋墩沖刷

圖 52　Route 99 橋梁橋墩沖刷

圖 53 Hydraulic Design 人員至重點監測橋梁進行河道調查

圖 54 Hydraulic Design 人員至重點監測橋梁進行河道調查

(三) 橋梁及拓寬工程參觀

1. 筆者於 2018 年至 Caltrans 參訪時尚在興建的第 6 街高架橋，現已完工通車

圖 55　第 6 街高架橋

2. 筆者於 2018 年至 Caltrans 參訪時尚在興建的 Gerald Desmond Bridge，現已完工通車，為加州第一座斜張橋。

圖 56　Gerald Desmond Bridge

圖 57 Gerald Desmond Bridge 橋塔內設有維護電梯

3. Santa Barbara County Route 154 上的 Cold Spring Canyon Arch Bridge，於 1964 年完工通車，為加州最大及最高的鋼拱橋。

圖 58　Cold Spring Canyon Arch Bridge

4. 位於聖地牙哥的 Coronado Bridge，連接聖地牙哥市和 Coronado Island，於 1969 年完工通車，並在 2003 年完成耐震補強。長度 2.1 英里，主跨度為 3 跨，跨度為 660 英尺及 550 英尺，主跨度航道淨高最高 200 英尺，其餘尚有 26 跨，為鋼箱梁橋。

圖 59　Coronado Bridge，主航道橫跨 3 跨，橋墩設有保護防撞設施

圖 60 Coronado Bridge 設置大型的 DIS 動態隔震支承

圖 61　Coronado Bridge 鋼梁間維修走道

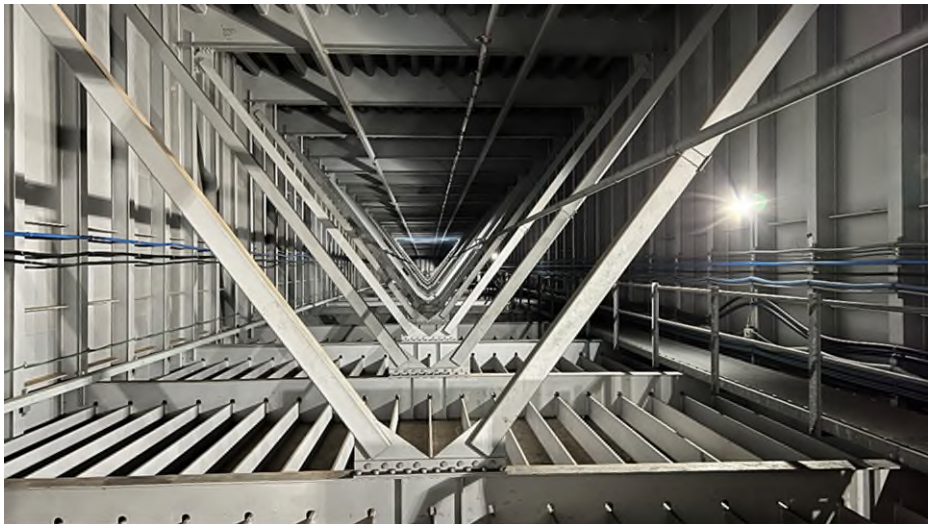


圖 62　Coronado Bridge 主橋跨巨型鋼箱梁內部及其維修走道

圖 63　Coronado Bridge 鋼橋油漆工程搭設臨時維修平台

圖 64　Coronado Bridge 設置活動式中央分隔島，可快速移動護欄位置，調整雙向車道數

圖 65　Route 71 拓寬工程施作 Soldier Pile 擋土

圖 66　Route 134 橋梁更新混凝土護欄及橋面板

(四) 橋檢觀摩

本次研習由 Caltrans SM&I 人員帶筆者參加橋樑檢測作業，其中包含鋼橋的 Fracture Critical Inspection。

圖 67　I-5 與 I-10 交會之系統交流道橋樑檢測作業，位於車流量極為繁忙的路段執行業務十分危險，需高度集中精神

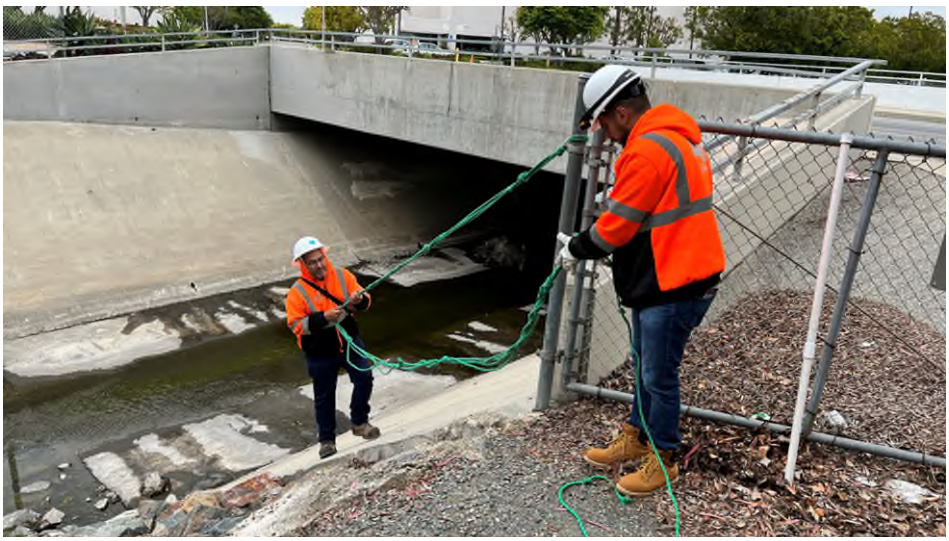


圖 68　跨越渠道橋梁，檢測人員固定繩索以類似垂降的方式下至渠道進行檢查

圖 69　San Diego 市區 I-5 單向即有 5 車道，車流量又高，檢查人員僅能在路肩巡檢剛性鋪面狀況，即便在路肩亦十分危險

圖 70　Route 174 橋梁利用橋檢車進行 Fracture Critical Inspection，封閉 1 車道後僅餘 1 車道供雙向通行，交維工作極為重要，利用前導車引導車流確保安全

圖 71　Route 174 橋梁利用橋檢車進行 Fracture Critical Inspection，並以超音波儀器檢查 Fracture Critical Elements 的完整性

六、Caltrans 其他制度觀摩

(一) 震後橋梁巡檢制度

根據 Caltrans 制定的「公路維護指南（Maintenance Manual）」第 H 章規定，地震過後，需由分區辦公室維護人員進行道路和結構檢查。檢查範圍取決於地震規模、與地震震央的接近程度和測量到的地表震動程度。

地震後「道路」檢查應由分區辦公室維護人員和地區道路工作人員負責。「橋梁」檢查將視損壞的強度和程度，在分區辦公室維護主管、隸屬於署本部的結構維護檢查部門（Structure Maintenance &Inspection，以下簡稱 SM&I）的地區橋梁維護工程師（Area Bridge Maintenance Engineer，以下簡稱 ABME） 和分區辦公室結構施工工程師的指導下進行。

1. 芮氏規模小於 5.5：

道路：

地區辦公室將視情形決定是否派維修人員前往受影響地區進行檢查，取決於該受影響地區在過往地震中的道路損壞情況。預計除非同時發生大雨和其他可能導致邊坡滑動的情況，否則道路損壞程度應不大。

如果發現損壞，例如道路沉陷、護欄損壞等，地區維護人員應檢查受影響區域內的所有道路。如果檢查到嚴重損壞，則應將檢查半徑增加到 10 英里。

橋梁：

小於 5.5 級的地震被認為太低，不會造成任何橋樑損壞。但若地區維護人員發現的任何與地震相關的損壞，應回報 SM&I。

2. 芮氏規模介於 5.5 至 6.2：

道路：

由分區辦公室派遣維護人員在最高地表震動點或震央 5 英里半徑內的區域進行檢查。可能會出現道路輕微損壞或沉陷。如果維護人員發現任何嚴重的道路地震損壞，則檢查半徑應增加到 10 英里。

橋梁：

在本地震級距內，預計橋梁只會發生輕微損壞。惟在特定的條件下，可能有較大程度損壞。

分區辦公室維護主管人員應檢查震央 5 英里半徑內的所有橋梁。如果檢查到嚴重損壞，則檢查半徑應增加到 10 英里。若有任何地震相關損壞，分區辦公室應立即回報給 SM&I。

3. 芮氏規模大於 6.2：

芮氏規模大於 6.2 以上地震，對道路和橋梁皆可能造成損壞。雖然道路會受到破壞，但橋梁結構破壞對用路人造成最直接危險。根據加州歷史地震損壞評估，當地震規模在 6.2 至 6.5 時，橋梁會出現輕微至中度損壞。當規模大於 6.6 時，損壞程度會危害橋梁的整體安全。

道路：

規模大於 6.2 的地震後，每個分區辦公室應派遣維護人員在最高地表震動點或震央 10 英里半徑內的區域進行檢查。預計道路將出輕微到嚴重損壞或沉陷。 如果維護人員發現任何重大道路地震損壞，則檢查半徑應增加到 25 英里。

橋梁：

在此規模地震下橋梁預期會發生損壞。特定的條件下可能會有重大損壞。橋樑損壞的範圍可能從輕微到災難性，取決於結構類型和與震央之距離。

分區辦公室維護主管應檢查震央 5 英里半徑內的所有橋梁。如果檢查到嚴重損壞，則檢查半徑應增加到 10 英里。若有發現任何地震相關損壞，分區辦公室應立即回報給 SM&I。

規模 6.2 至 6.6 的地震發生時，SM&I 和分區辦公室結構施工工程師將應根據分區辦公室回報告的損壞情況做好動員準備。如果發生大範圍的損壞，SM&I 的 ABME 和分區辦公室結構施工工程師將立即對橋梁進行獨立損壞檢查。SM&I 為檢查領導者，並系統性整合整個受影響區域的橋梁損壞評估結果。

SM&I 應將前述工作通知分區辦公室主管和結構施工部門，在 SM&I 完全動員之前，由分區辦公室主管和結構施工部門先行主導本項工作。

規模 6.7 以上的地震，SM&I 將分析預期的損害規模，然後動員南加州和北加州的團隊。分區辦公室維護主管應檢查震央 10 英里半徑內的所有橋梁。如果檢查到嚴重損壞，則檢查半徑應增加到 20 英里。SM&I 應立即收到任何與地震相關的損害通知，以便立即動員並準備進行相關工作。

(二) Shake Cast 地震預警系統

根據前段敘述，SM&I 在大地震發生後要分析預期的損害規模，並立即動員至受影響區域內之損害橋梁進行更詳細的橋梁檢查。如何能在震後最短時間內獲得充足資訊，加快動員速度，將有限的資源精準投入至最需要的地方，便顯得十分重要。

因應上述需求，美國地質調查所（USGS）於 2003 年開發 Shakecast 系統，其後 Caltrans 與 USGS 合作於 2008 年推出 ShakeCast 2.0，已被其他單位廣泛採用，現在已進版至 ShakeCast 3.0。

Shakecast 系統利用 USGS 建置的 ShakeMap 為基礎作發展，ShakeMap 是透過 USGS 建置在全國的地震感測器在大地震發生後收集到的資訊，自動產生出震後近乎即時的地表震動和震動強度地圖。以加州為例，有 1900 多個地震感測器組成的陣列可精準繪製 ShakeMap。

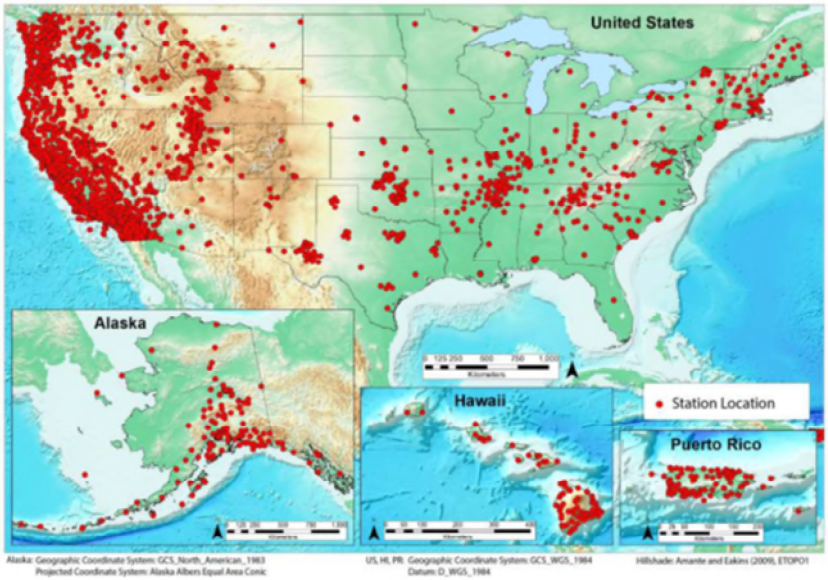


圖 72 全美國地震感測器分布圖

透過 Caltrans 在系統內建置的橋梁資料庫與 ShakeMap 結合，運算分析後評估可能受地震影響的橋梁數量、位置及其嚴重程度，定出橋梁等設施緊急檢查的優先順序。這些資訊彙整成 ShakeCast Report，在地震發生後 10 分鐘內向相關單位（橋梁管理單位、急救人員等）提供通知和信息，SM&I 的 ABME 即可立即掌握受災最嚴重的橋梁，在最短時間內做出動員決策並趕赴現場。同時該系統可持續檢索收集地震發生後幾分鐘內測量的震動資料，並可模擬地震發生情境，作為預先規劃之工具，評估橋梁系統性能和緊急應變能力。

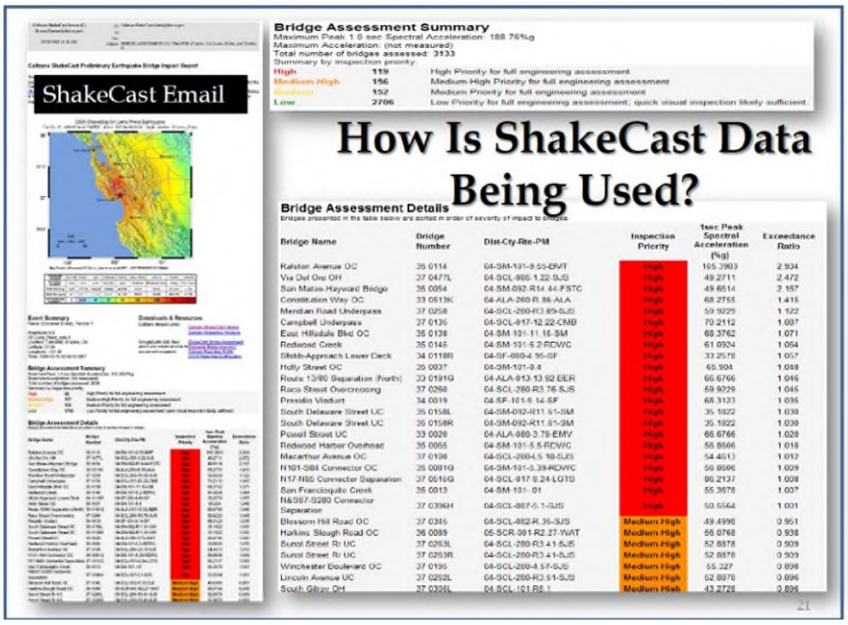


圖 73 ShakeCast 系統寄發受損橋梁優先排序資料給使用者

(三) 建設計畫開發制度

Caltrans 負責 SHS 新建、維護及營運，主要任務是確保 SHS 設施安全及永續營運，提供用路人安全及有效率的公路運輸系統。Caltrans 在公路建設計畫推動過程中，必須在確認開發和建造符合管理州和聯邦運輸資金使用的法律和法規等相關規定之前提下，進行完善的研究、規劃、設計及施工。

為達成上述目標，Caltrans 制定「計畫開發程序指南（Project Development Procedure Manual）」，使 Caltrans 員工在執行建設計畫開發業務能有準則得以依循。

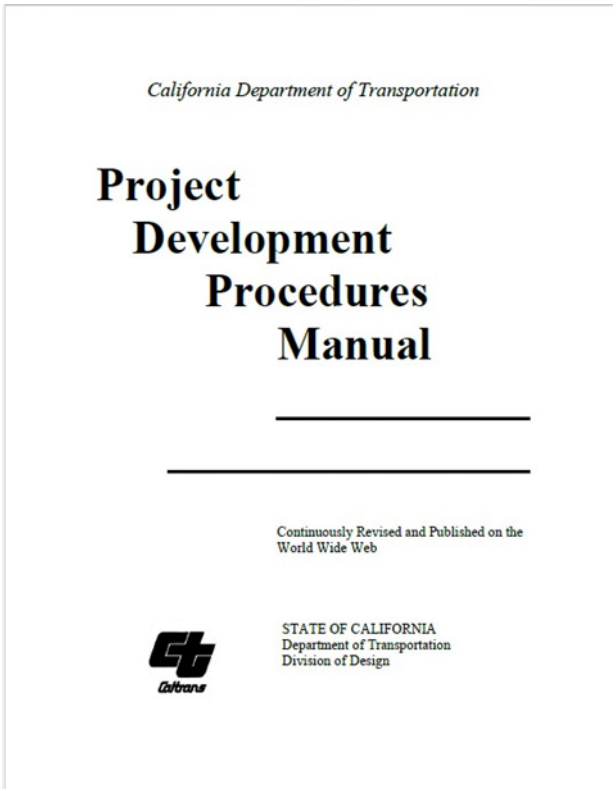


圖 74 計畫開發程序指南

本指南列出計畫開發的完整步驟，詳如下圖：

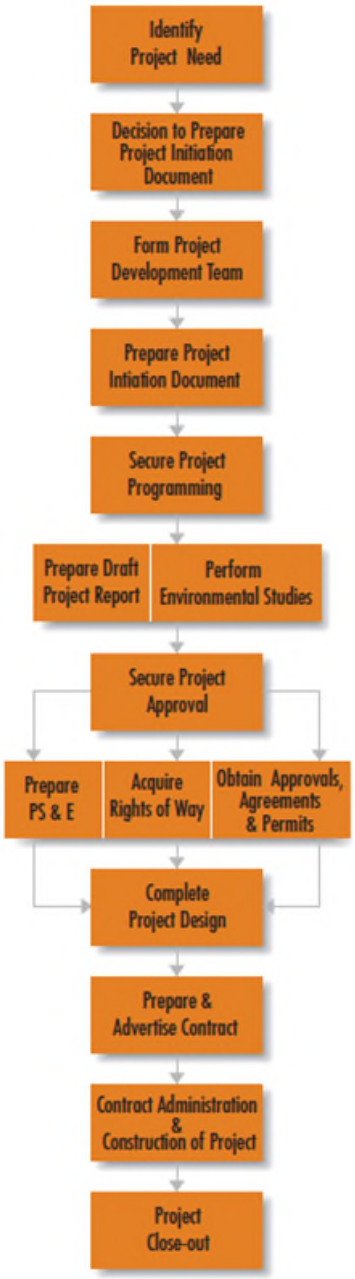


圖 75 計畫開發流程

內容概述如下：

1.確定計畫需求：

在建設計畫開發開始之前，Caltrans 需確認現有交通系統的結構或營運不足，或因區域發展變化衍生新的交通需求，導致需要新的建設計畫，必要時需結合地方交通主管機關及聯邦主管機關會同進行。計畫需求透過 Caltrans 管理系統、總體規劃、

系統和區域規劃以及優先流程來確定。建設計畫必須有效改善地區的交通缺陷以及符合潛在交通需求，並綜合考量環境、社會、文化、經濟社區、美學、歷史及景觀等因素。

2.決定準備計畫啟動文件(Project Initiation Document，以下簡稱 PID)：

類似我國的可行性研究。國道系統上的所有計畫都需要 PID 才能進行後續規劃設計。PID 旨在使利害關係人、決策者和 Caltrans 成員初步了解計畫需求。 PID 由計畫團隊在計畫經理的領導下制定。當 Caltrans 指派建設計畫專案負責主管並組成計畫團隊後，即正式展開計畫開發，包含 PID。

PID 內容包含計畫範圍、進度和成本估算的關鍵問題和假設。針對主要問題進行分析，例如施工可行性、資金來源、交通營運、運輸管理、環境問題、社區參與以及確認可能受計畫影響的個人和機構。 PID 報告是重要的工程文件，包含初步工程報告、詳細的替代方案分析以及成本、進度和範圍資訊。

3.組成計畫開發團隊(Project Development Teams，以下簡稱 PDT)：

PDT 負責從可行性研究到專案完成的整個計畫開發過程。PDT 細化計畫的目的和需求，透過各種分析評估（如價值分析）來開發和評估替代方案，協助計畫主持人指導研究、提出建議，並執行計畫開發工作。 PDT 需參加公開聽證會和社區參與等重要會議，進行研究和累積數據。大規模的建設計畫，PDT 成員需納入來自外部專業機構或個人，甚至可能包括社區團體代表。

4.準備專案啟動文件：

PID 的主要目的是確定計畫範圍、成本和進度，並由 Caltrans 核定。PDT 研提各種開發方案，以滿足計畫的目的和需求，這個過程的結果就是 PID。對每個方案的研究應至少包括：設計理念、環境影響、路權需求以及相關費用。PDT 從這些方案中選擇一個可行的方案，並經過分區辦公室主管批准後，對 PID 中提出的成本、設計概念或範圍以及進度表進行詳細規劃。成

本包括建設成本、路權用地取得和計畫開發與支援成本。

5.確保計畫資金及預算來源：

在開始詳細計畫研究之前，必需規確定計劃資，並經加州交通委員會（California Transportation Commission，CTC）核定。

6.準備計畫報告草稿（Draft Project Report，以下簡稱 DPR）：

該報告草稿基於初步工程分析，包含有關計畫背景、目的和需求、調查方案以及工程和環境調查中遇到的問題。遭遇問題可能包含環境問題，或有關各項許可、路權、交通管理的問題，及其他工程或資金問題。

此階段工作包括勘測和測繪、交通預測和模式建立、價值分析、水利研究、路權和公用事業需求及影響評估、材料和地質資訊以及替代方案研究。

7.進行環境研究：

在進行準備計畫報告草稿的同時，必需同步進行環境研究，以分析各種計畫方案的效果和影響。此研究必需符合加州環境品質法案 (CEQA) 和國家環境政策法案 (NEPA)規定。

研究結果為環境文件（Environmental Document ，以下簡稱 ED）。ED 的類型取決於影響的嚴重程度。 對環境影響很小或沒有的計畫，ED 可較簡單，而具有重大影響的較大、更複雜的計畫，可能需要詳細的環境影響聲明 (EIS) 或環境影響報告 (EIR)。法律規定 DPR 和 ED 需透過公開會議等正式程序以徵求公眾意見。ED 必須概述需求和目的以及不採取某些替代方案的原因，確定每個方案的所有重大不利影響以及針對每個影響的緩解措施，也需提供選擇首選替代方案的決策過程紀錄。ED 通常由相關機構審查確認。

8.計畫核准：

完成 ED 並獲得批准後，將 ED 與核准的 DPR 一併公布以徵求公眾意見。 確定不會產生重大環境影響的計畫通常不會徵求公眾意見。這些計畫不需要考慮替代方案，因此直接進入 PR 和 ED 階段，無需經過草案研提階段。

收集公眾意見，PDT 分析並適當回應公眾意見後選擇首選方案。將 ED 完成定稿並附在最終的 PR 中，其中應說明首選替代方案的選擇及根據公眾意見對計畫進行的修改。

分區辦公室主管核定 PR 及所附經核定的 ED 尚需得到聯邦公路管理署 (FHWA) 的核定或 FHWA 授權給 Caltrans 核定。核定後允許有一個月的等待期，以便為其他聯邦機構提出反對或項目反對者採取法律行動提供機會。如果計畫不包含聯邦資金，則由 Caltrans 核定。

此時，計畫範圍已詳細確定，並識別所有影響，計畫得以進入下一步，進行詳細設計。

9.進行詳細設計：

在此階段，進行設計調查和測量；完成包括交通數據、水文學和水力、大地工程設計、路面設計、結構設計以及材料和隔音牆設計等報告，並編製預算。在確定路權用地取得後，完成細部設計文件，啟動工程採購。在此階段若發現 PR 和 ED 未解決的問題，則需要辦理修訂。

10.取得路權用地：

通常路權用地取得在 DPR 完成後開始。Caltrans 必須以公平合理的市場價值購買房產。普通無爭議收購可能需要大約 8 個月的時間。地主若有爭議題請法院審理，可能會花費 2 年或更長時間。

11.獲得批准、協議和許可：

在計畫開發中，工程和環境研究、計畫核定和設計等各階段工作，都可能需要與其他機構進行協調和談判以期達成協議。其中一些協議是在 DPR 獲得批准時需要的，而另一些則是在詳細設計完成時需要的。

12.完成細部設計：

本階段需完成作為招標提供給投標廠商估算並投標的細部設計文件，包含細部設計圖、材料與施工技術規範、詳細施工項目及數量以及預算。完成後即可進行招標作業。

13.招標作業

14.施工監督管理與契約管理

參、心得及建議

一、心得

1. Caltrans 負責管理全加州的高速公路，幅員遼闊，業務繁重，然而加州政府給予 Caltrans 充分的資源，無論是人力、財力及機具設備等，都十分到位。Caltrans 在公路建設的全生命週期，自規劃、設計到施工監督、營運維護、設施檢測等工作均為自辦，因此在機關內的專業人才濟濟，有利於掌握業務執行進度及品質，更重要的是，可落實經驗傳承，讓機關專業人才不至產生斷層。在 Caltrans 北加辦公室看到 Underwater Inspection 用的船，真的十分震撼，不由得心生羨慕。
2. 研習期間 Caltrans 人員帶筆者走訪南加及北加多處公路設施，並與其交流，確實感受到近年來加州的高速公路設施（主要是邊坡和橋梁）受極端氣候影響甚鉅，發生災害的次數增加，分布地點也變廣泛。尤其是 I-40 那座需重新改建的橋梁，該地處於沙漠地帶，需要重建原因竟然是橋墩基礎嚴重冲刷，筆者覺得不可思議之餘，亦深切認知氣候變遷確實正在影響著我們。
3. Caltrans 十分重視面對極端氣候可能造成的衝擊，審慎應對，從最高階層制定政策宣示積極因應極端氣候開始，規劃嚴謹的步驟，並明確規定各部門應該負責的範疇與應達成的工作，以逐步完成各階段工作，並展望未來提出各項建議，指引 Caltrans 各部門人員重視極端氣候並於公路設施全生命週期各階段規劃各種因應策略並據以執行。

4. Caltrans 建議的適應策略中，需要將未來日益嚴重的極端氣候因子衝擊納入設計考量，並修正相關設計規範。惟與 Caltrans 人員交流討論，表示修正設計規範工作牽涉範圍極層面廣大，需要結合聯邦、各州相關單位及學術界各方努力並凝聚共識，方可成就。目前對於極端氣候造成公路設施衝擊及影響的論述均為定性，尚無法定量，且各界對於未來極端氣候的模擬情境也莫衷一是，故修正設計規範這項工作仍在現在進行式。目前比較常見的作法是把安全係數放大，例如排水設施或橋梁設計時，在預期發生洪水或淹水機率較高區域，提高洪水重現期距，提高出水高等方式進行調適設計。
5. Caltrans 建議的減輕災害或適應極端氣候的工程方法，多為既有之工程方法，尚未見有新的防制或改善工法。Caltrans 也很重視採用自然生態工法作為調適策略。
6. Caltrans 的設計部門建立相當完整的工程標準圖，讓工程設計的工作更易於執行且具有一致性，是相當好的作法。
7. Caltrans 橋檢人員在執行業務時十分注意交通安全，在 Route 174 橋樑進行 Fracture Critical Inspection 時因為出動橋檢車必須佔據 1 車道，現場僅餘 1 車道供雙向通行，Caltrans 交維人員除在橋梁兩端設置關卡進行輪流調撥車輛通行，更派出前導車（pilot car）導引車流行進，確保車輛速度布置於過快危及檢查安全，值得借鏡。
8. Caltrans 藉由 ShakeCast 系統可以快速掌握大地震後高速公路橋梁等公路設施的受影響狀況，減少緊急應變時間，有效投入資源，值得參考。

9.加州高速公路收費制度與台灣頗不相同，大洛杉磯地區的高速公路大部分採取的收費方式是將最內側車道設置為收費車道，其餘車道不收費。或許是因為不收費的關係，跟 Caltrans 人員交流時、表示

即便鋪面大多為剛性鋪面，且需養護鋪面實在太廣，無法及時修補損壞的鋪面，導致行車舒適感不甚佳，但不常收到路面品質不佳的陳情。

二、建議

1.Caltrans 內部專業人才濟濟，業務得以自行辦理，本局宥於人力編制及預算問題，恐無法達到如 Caltrans 的規模，本局現階段在工程監造及橋梁檢測已有部分自辦，建議可持續辦理。建議亦可透過辦理教育訓練，增加同仁的專業本質學能，亦有利於經驗傳承。

2. Caltrans 面對氣候變遷議題，已積極因應，並已有階段性成果，已完成盤點評估公路設施受極端氣候影響的脆弱性並加以優先排序。Caltrans 充分了解氣候變遷議題影響層面極廣，需要與其他外部機構合作方可達成目標，例如在製作前述報告的過程中，就需要氣象單位收集的歷史氣候紀錄做為基礎加以分析評估。建議本局若要評估公路設施的脆弱性，可比照 Caltrans 模式逐步建立。

3. 自辦設計部分，Caltrans 在設計方面，有建立完整的工程施工標準圖，範圍涵蓋大部分公路工程內容，使同仁易於進行自辦設計（特別是規模不大且無特殊性的工程），亦可建立公路設施的統一性。建議本局亦可朝此方向辦理，即便是委外設計，亦可要求設計顧問在大部分的工程內容依據本局工程標準圖辦理設計。，

4. Caltrans 為降低溫室氣體排放，已將大部分的公務車換成電動車，為氣候變遷盡一份心力，建議本局亦可參考辦理。

肆、附錄

Caltrans：Adaptation Strategies for Transportation Infrastructure，May 2023

Adaptation Strategies for Transportation Infrastructure

EDUCATIONAL RESOURCE

May 2023

INTRODUCTION

This educational-only resource describes the types of hazards and/or threats represented by different climate stressors and lists the types of adaptation actions or strategies that could be considered to avoid or minimize impacts. **This document should be used as an educational tool for planners that provides an initial look into how to consider project-level strategies to adapt to more extreme risks.** The document does not consider feasibility for permitting conditions or other site-specific considerations. Any planning of actual projects, for PID phase or other purposes, should be done so in consultation with Design and other relevant district expertise. Furthermore, the document does not include maintenance strategies that could prevent or reduce the impacts of extreme events to the state transportation system. Please reach out to your district's maintenance division to discuss these strategies. DOTP will consider adding a section on maintenance strategies in a future iteration of this document.

The intended users of this document are district planners, and for consultation with Project Development Teams (PDTs) at early project scoping stages. For more information on how the strategies described in this document may be incorporated into the planning process, please refer to the Climate Change Emphasis Area Guidance for Corridor Planning.

The adaptation actions or strategies provided in this guide are generally organized into traditional engineered protection approaches, natural and nature-based solutions, and a hybrid of these approaches. Engineered solutions include the use of constructed structures like levees, armoring, or Rock Slope Protection (RSP). Natural, or nature-based solutions include approaches that work with and enhance nature to build climate resilience and/or contribute to carbon neutrality. A priority emphasized by California's 2022 Climate Adaptation Strategy, the State's commitment to advancing multi-benefit, nature-based solutions seeks to ensure that California's communities and natural systems continue to thrive together in the face of climate change—and also reflects the opportunity to avoid ***maladaptation***—or the concept of constructing protective infrastructure in some of our most hazard-prone areas that can increase vulnerabilities and provide a false sense of security (IPCC AR6, 2022). Natural or nature-based solutions should be prioritized wherever feasible, particularly in areas that could be flooded or eroded from tidal or fluvial processes like riverine or coastal areas. Hybrid approaches are a combination of at least two strategies that are used together on a single site to address different levels of risk, or different strategies may be phased and implemented over time to address changing conditions.

This guide includes strategies to address potential climate change impacts to transportation infrastructure including those analyzed in the Caltrans District Climate Change Vulnerability Assessments, and Adaptation Priority Reports.

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ADDRESSING CHANGES IN PRECIPITATION

Climate-driven changes in precipitation may cause a rapid increase in peak flows along streams, potentially leading to pooling or riverine flooding. Flooding events can heavily impact transportation assets passing nearby or over these streams, whether by disrupting traffic or damaging infrastructure. The section below provides adaptation strategies to address impacts on the transportation system from changes in precipitation.

Although not included in this section, depending on flooding levels, frequency of flooding events, and other drainage features, elevation of the roadway may be needed.

RIVERINE FLOODING

Three main strategies can be pursued to address riverine flooding. They are not exclusive of each other and could be pursued in tandem depending on the project or application and are as follows:

- **Floodplain Conservation and Restoration (Nature Based):** Floodplain creation and restoration can be an effective option for reducing flood risk where the transportation system is protected from riverine floods by levees. As increased flows in waterways are given an opportunity to re-connect with the floodplain and slow down—the risk of levee failures are reduced. Wetland and riparian habitat restoration on the floodplains can further slowdown the flow of floodwaters, enable groundwater recharge, and hold soil in place. Coordination with state, local, and regional partners is an important aspect of use of this strategy.
- **Drainage Improvements:** Drainage improvements may assist in mitigating events where transportation facilities are overwhelmed by high flows from precipitation or runoff. Drainage can be improved through a variety of methods including widening the capacity of culverts, elevating road surfaces, bioswales, retention/detention ponds, and improving permeability. Designing and building with less-permeable surfaces can cause a significant increase in surface runoff, so incorporating permeable surfaces into design may improve the overall drainage capabilities of facilities.
- **Accommodate:** Roadway inundation from flood zones can occur when roadways are built parallel to rivers and streams or transect river floodplains. Elevating roads in at-risk flood zones (taking into account future flood events) above a certain flood level can protect roads from routine flooding.

Sources used for this section:

- California Natural Resources Agency (Resources) California Climate Adaptation Strategy (2022)
- Caltrans Highway Design Manual - Chapter 890
- Caltrans, Hybrid Streambank Revetments: Vegetated Rock Slope Protection (DIB-87-01)
- Caltrans Landscape Architecture Program (Intranet Links)

- Model Water Efficient Landscape Ordinance
- Erosion Control Design
- Low Impact Development

- EPA Wetlands Restoration Definitions and Distinctions
- FHWA Highways in the River Environment-Floodplains, Extreme Events, Risk, and Resilience (2nd Edition, 2016)

Example Strategies for Flooding and Riverine Flooding

Strategy	Project	Project Details
Floodplain Preservation and Restoration	Levee set-back and Wetland/ Riparian Habitat Restoration (Nature Based)	• Restoration of the floodplain and connectivity with the river system increases residence time of flood flows, and reduces the potential of levee failure • Wetland and riparian restoration can further slowdown river flows by restoring habitat through placement of imported sediment, removal of invasive vegetation and other foreign materials, and planting of native marshland vegetation that stabilizes soils, and increases sediment retention. • Re-establishment of wetlands consists of modifying the physical, chemical, or biological characteristics of a site with a goal of returning natural/historic functions to former or degraded wetland.
Drainage Improvements	Bioswales/ Bioretention Basins (Nature Based)	• These strategies mitigate stormwater flooding impacts by serving as an absorbent catchment for the stormwater. Plants act to attenuate water flows and hold soil in place, while the permeable groundcover allows infiltration into the soil. • Can assist with ground water recharge – addressing ground subsidence issues in the area which may help protect the facility. In dry and arid areas, dry swales may be more appropriate. Bioswales can improve water quality of runoff compared to other strategies by catching and breaking down pollutants in stormwater, such as heavy metals. • These facilities require regular upkeep to maintain their beneficial functions over long periods of time.
	Retention Ponds	• Retention ponds consist of a permanent pond area with landscaped banks and serves to control the quantity of runoff discharged to receiving waters.
	Detention Ponds	• Typically, these are engineered with hardened, less permeable shorelines. These ponds act as a temporary water storage to reduce peak flow periods and allow for more gradual runoff when flow levels recede.

Drainage Improvements	Culvert Expansion/ Bridge Elevation	• The redesign of a culvert or bridge to allow for higher peak flow levels. • Current design standards are for 100-year flood standards, however, with projected shorter and more intense wet seasons, this may result in an underestimation for potential flows if climate change projections are not considered in design.
Accommodate	Elevate	• If necessary, given projected flood levels and/or subsidence, roads, bridges, and other transportation facilities can be elevated above a certain flood level (such as through bridge abutment lengthening, increases in bridge freeboard, or a viaduct or causeway), generally to protect against storm conditions or future routine flooding. • Elevating individual components is costly and elevating or constructing new roadways can be both complex and expensive; however, those costs should be balanced against on-going maintenance costs associated with repeated damages from flood events and environmental mitigation costs.

STREAM EROSION & FLOW ALTERATION

Strategies to address stream erosion and stream flow alteration are grouped into the following three categories:

- **Stabilization:** Stabilization by either a nature-based, structural, or hybrid approach may assist in protecting streambanks. These methods include bulkheads made of concrete, masonry or steel, and vegetation which is the most natural method for stabilization of embankments and channel bank protection.
- **Armor Protection:** Armor is the artificial surfacing of bed, banks, shore, or embankment to resist erosion or scour. Armor devices can be flexible (self-adjusting) or rigid. Flexible types include rock slope protection, gabions, and precast concrete articulated blocks. Rigid types include concreted-rock slope protection, sacked concrete slope protection, and concrete filled cellular mats.
- **Training Systems/Redirection of Flows:** Structures, usually within a channel, that act as countermeasures to control the direction, velocity, or depth of flowing water. When training systems are used, they generally straighten the channel, shorten the flow line, and increase the local velocity within the channel. In the case of a stream attack, a new channel can be created, or the stream can be diverted away from the embarkment by the use of baffles, deflectors, or spurs.

Sources used for this section:

- Caltrans Construction Manual – Chapter 4
- Caltrans Highway Design Manual – Chapter 870
- Caltrans Hybrid Streambank Revetments: Vegetated Rock Slope Protection (DIB-87-01)
- Caltrans Standard Plans

Example Strategies for Stream Erosion

Strategy	Project	Project Details
Stabilization	Vegetation Stabilization (Nature Based)	• The most natural method for stabilization of embankments and channel bank protection. It can be relatively easy to maintain, visually attractive and environmentally desirable. • The root system forms a binding network that helps hold the soil. • Grass and woody plants above ground provide resistance to the near bank water flow causing it to lose some of its erosive energy.
	Bulkheads	• A steep or vertical structure supporting a natural slope or constructed embankment which include the following: gravity or pile supported concrete or masonry walls, and sheet piling. • As bank protection structures, bulkheads serve to secure the bank again erosion as well as retaining it against sliding.
Armor Protection (Flexible)	Rock Slope Protection (RSP)	• Streambank Rock Slope Protection, commonly referred to as riprap, consists of rock courses placed upon the embarkment or the natural slope along a stream. • Rock Slope protection has the following advantages: it is flexible, local damage is easily repairable, construction is not complicated, appearance is natural, it is salvageable (may be stockpiled and reused if necessary). • Adding vegetation to create Vegetated Rock Slope Protection has positive attributes on stream integrity such as improving stream ecology, increasing soil strength, and providing flow resistance. However, vegetation can also increase slope failure potential under saturated conditions.
	Gabion	• Consist of rectangular wire mesh baskets filled with stone. • Wall Type: Empty cells are positioned and filled in place to form walls in a stepped fashion. Not fully self-adjusting but has some flexibility. • Mattress Type: Baskets are positioned on the slope and filled. This type is very flexible, and well suited for man-made roadside channels (with uniform flow), and as overside drains that are constructed on steep and unstable slopes.
Armor Protection (Rigid)	Concreted-Rock Slope Protection	• Consists of rock slope protection with interior voids filled with plain cement concrete to form a monolithic armor. • This method has application in areas where rock of sufficient size for ordinary rock slope protection is not economically available.
	Partially Grouted Rock Slope Protection	• A form of smaller rock held together with a cementitious material. • A viable alternative to larger rock or concreted rock slope protection where either the availability of large materials is limited, or there are site limitations regarding the placement of large materials.

Armor Protection (Rigid)	Sacked-Concrete Slope Protection	• Consists of facing the embankment with sacks filled with concrete. • Use of this method is generally limited to replacement or repair of existing sacked concrete facilities, as it is both a cost- and labor-intensive approach.
Training Systems	Bendway Weirs	• Bendway Weirs, also referred to as steam barbs, bank barbs, and reverse sills, are low-elevation stone sills used to improve lateral stream stability and flow alignment problems at river bends and highway crossings on streams and smaller rivers. • They also encourage deposition of bed material and growth of vegetation.
	Spurs	• Can be a pervious or impervious structure projecting from the streambank into the channel. • The main function of spurs is to reduce flow velocities near the bank, which in turn, encourages sediment deposition due to the reduced velocities. Increased protection of banks can be achieved over time, as more sediment is deposited behind the spurs. • Deflectors and Baffles can also be used to control direction and velocity of flow.
	Guide Dikes/Banks	• Guide banks are appendages to the highway embankment at bridge abutments, they are smooth extensions of the fill slope on the upstream side, and can be used on both sand and gravel-bed streams. • The two major enhancements guide banks bring to bridge design are (1) reduce the separation of flow at the upstream abutment face and thereby maximize the use of the total bridge waterway area, and (2) reduce the abutment scout due to lessening turbulence at the abutment face.

ADDRESSING SEA LEVEL RISE

Over the past century, increases of average global temperatures have already caused sea levels to rise from thermal expansion of warming ocean water, as well as through land ice melt. While the California coast already regularly experiences erosion, flooding, and significant storm events, future sea level rise will exacerbate these natural forces, leading to an increase in the potential for flooding and erosion of Caltrans roadways and infrastructure. Adaptation strategies that are most appropriate for a particular asset or segment within a transportation corridor will depend on the specific circumstances for each location. Each type of adaptation strategy—including protection, accommodation, retreat, or a hybrid of these—are associated with benefits and impacts that should be considered in decision-making around when each one should be used.

As a guiding principle when considering which adaptation strategy might be most appropriate to use—as the transportation system generally provides critical infrastructure services for Californians in terms of national or regional economic security, national or regional energy security, and national or regional public health or safety—**accommodation strategies should be prioritized that relocate or elevate transportation infrastructure to safe areas to avoid the need for hard shoreline protection that harms coastal resources and could have expensive ongoing maintenance costs**.

- More specifically, adaptation strategies for *new* transportation infrastructure should seek to avoid areas where sea level rise could affect the infrastructure over the entire expected service life of the asset or project. For transportation infrastructure that is *already established*, a combination of adaptation strategies may be necessary that clearly relate how short, medium, and long-term choices—or a "phased" or "adaptation pathways" approach—will collectively deliver long-term resiliency over time. For example, short-term protection through armoring may be necessary to maintain transportation services while a longer-term solution is planned or constructed which realigns the roadway.
- In general, it is well understood through the Intergovernmental Panel on Climate Change (IPCC) that reliance on traditional engineered protective approaches like sea walls can facilitate long-term commitments that "lock in" vulnerability, asset exposure, and risks that are difficult and costly to change and are "maladaptive" (IPCC AR6, 2022); therefore, use of these approaches should be thoughtfully considered such that options remain open for longer-term adaptation pathways that avoid and relocate transportation infrastructure away from sea level rise risks in the future.

For additional guidance on addressing sea level rise in terms of State policy, guidance, resources, science, and tools, visit the Sea Level Rise and the Transportation System in the Coastal Zone webpage developed by the Division of Environmental Analysis. The section below provides a summary of adaptation strategies to address impacts on the transportation system from changes in sea level rise.

COASTAL FLOODING AND EROSION

Adaptation strategies which address sea level rise hazards for the purposes of this guide can generally be organized into those which address flooding and erosion, while the specific adaptation approach should be selected given the project location (i.e., open coast, beach, or sheltered bay). Examples are organized according to four main adaptation strategies as follows:

- **Retreat:** Retreat strategies are those in which assets are moved out of harm's way. This includes removing or relocating existing structures that are in danger from hazards, as well as siting new development to avoid hazardous areas so that it will be safe over its anticipated lifetime without requiring additional adaptation measures. Examples include highway realignment or deliberate use of detours.

- **Soft Shoreline Protection:** Can be referred to as "green" or "nature-based" strategies and considers features that rely on natural components and processes to provide protection, such as constructed or restored dunes, beach nourishment, vegetation, oyster beds, and the like.

- **Engineered Shoreline Protection:** Strategies in which a physical barrier is constructed to essentially keep water (either from flooding or erosion) away from a structure. Examples include Rock Slope Protection (RSP), secant walls, and seawalls.

- **Accommodate:** Accommodation strategies are those in which the asset itself is designed to accommodate impacts from coastal hazards and enable current and future oceanic hydraulic (stillwater levels, wave run-up, storms, scour, groundwater) processes in conjunction with the companion geological and environmental setting of the project location within the littoral cell. Examples include bridge abutment lengthening, causeways, culvert conversions to bridges, and viaducts.

- **Hybrid Approach:** A solution that combines any of the above strategies for an asset or collection of assets along a transportation corridor including natural (nature-based) and constructed (structural) elements.

Sources used for this section:

- California Coastal Commission Sea Level Rise Policy Guidance: Interpretative Guidelines for Addressing Sea Level Rise in Local Coastal Programs and Coastal Development Permits (2018)
- California Coastal Commission Critical Infrastructure at Risk: Sea Level Rise Planning Guidance for California's Coastal Zone (November 2021)
- California Natural Resources Agency Report for Fourth Climate Change Assessment: Toward Natural Shoreline Infrastructure to Manage Coastal Change in California
- Caltrans Design Manual for Hybrid Coastal Protection Strategies (2022)
- Caltrans Drainage References (intranet link)
- FHWA HEC-25 Highways in the Coastal Environment
- FHWA Nature-Based Solutions for Coastal Highway Resilience: An Implementation Guide
- Governor's Office of Planning and Research (OPR) Planning and Investing for a Resilient California: A Guidebook for State Agencies (2018)
- Ocean Protection Council State of California Sea-Level Rise Guidance: 2018 Update (2018)

Example Strategies for Coastal Flooding and Erosion

Strategy	Project	Project Description	Coastal Flooding	Coastal Erosion
Retreat (Nature Based)	Realignment/ Relocation	• Realignment away from the at-risk location is a potential strategy that may be most appropriately explored as part of long-term adaptation of the transportation system. • Planned retreat can be utilized by predicting sea level rise through scientific models, though this option is often highly costly—however, it is also understood that evidence suggests that in vulnerable areas, the cumulative costs of keeping infrastructure safely in place could eventually outweigh the costs of relocation.	X	X

Soft Shoreline Protection (Nature Based)	Sand Dunes	• Coastal dunes are mounds or hills of sand and native vegetation often situated landward of the wave run-up zone of a beach. • Dunes can act as a sand supply reservoir that helps re-nourish the beach when erosion from coastal storms and waves may deplete the sediment. Coastal dunes provide protection by reducing wave overtopping events and inhibiting saltwater surface intrusion in the backshore environment. • Dunes with plantings are more stable and more resilient and offer important habitat for many rare and unique species.	**X**	**X**
	Sand Nourishment	• Sometimes referred to as beach nourishment, sand nourishment is the placement of sand onto a beach. • The additional sediment gets redistributed either by waves and currents or through human manipulation until it reaches an equilibrium profile. • Sand nourishment helps maintain the beach zone, acts as a buffer between upland areas to reduce the impacts of coastal hazards and supports beach ecosystems.	**X**	**X**
	Regional Sediment Management	• The systematic approach to addressing sediment supply imbalances at a regional scale. • Includes the restoration of natural processes as much as possible throughout the sediment system and encourages the use of clean sediment as a resource at sediment-starved locations.		**X**
	Sand Berm	• Often constructed out of existing sand to create temporary flood protection, and a high relief structure that reduces wave overtopping. • Sand berms can be eroded during large storms or regarded into the beach. Sand can also be imported to create berms or "dune embankments" that may have vegetation.	**X**	
	Oyster Bed	• Low-relief structures that consist of native oyster aggregates located in intertidal and subtidal zones. • They provide protection by buffering storm surges, attenuating waves, reducing shore erosion, and encouraging sediment accretion.	**X**	**X**
	Eelgrass Bed	• Communities of eelgrass on soft bottom substrates at lower intertidal and subtidal areas that provide high levels of primary productivity, high biodiversity, and high species density. • Eelgrass beds can provide protection by dissipating wave energy and slowing tidal currents at low tide.	**X**	**X**

Soft Shoreline Protection (Nature Based)	Wetland Restoration	• Helps reduce erosion by restoring habitat through placement of imported sediment, removal of invasive vegetation and other foreign materials, and planting of native marshland vegetation that absorbs wave energy, stabilizes soils, increases sediment retention, and dampens incoming waves and coastal turbulence.	**X**	**X**
	Tidal Bench	• Gently sloping benches that typically extend from the mean tide level (MTL) or lower toward the backshore. • Tidal benches are constructed with fill material and vegetation and provide habitat and protection by dissipating wave energy and encouraging sediment accretion.	**X**	**X**
	Native Vegetation Stabilization	• Removal of invasive vegetation like iceplant (carpobrotus edulis) and planting of native vegetation that does not require irrigation can help stabilize the surface of the bluff face and reduce erosion.		**X**
	Artificial / Constructed Reef	• A submerged breakwater that aims to dissipate waves and provide habitat for hard-substrate ecological communities in the surf zone.	**X**	**X**
	Cobble berm	• Sometimes referred to as a dynamic revetment, cobble berms are constructed out of smaller, typically rounded rocks. • The cobble can be moved by larger waves during storms to create berms that dissipate wave energy and stabilize the shoreline.	**X**	**X**
	Ecotone Levee	• Also referred to as horizontal levees, ecotone levees are wide, and have a gently sloped footprint that extends from the subtidal zone to above mean higher high water (MHHW) to include the upland transition zone. • Ecotone levees provide for extended zoning of ecological resources while simultaneously creating textured surfaces through the use of vegetation and substrates that dissipate wave energy.	**X**	
	Marsh Sill	• Shore parallel structures that combine a low-profile stone "sill" with wetland vegetation. • The structural component provides protection to the marsh vegetation, allowing time for the plants to establish as well as the upland environment by dissipating wave energy and reducing shoreline erosion.	**X**	**X**
Engineered Shoreline Protection	Bulkhead	• A structure or partition to retain or prevent sliding of the land, and to protect the upland against erosion from wave action.	**X**	

Engineered Shoreline Protection	Seawall	• A structure, often concrete or stone, built along a portion of a coast to prevent erosion and other damage by wave action. It often retains earth against its shoreward face. • Typically, more capable of resisting greater wave forces than a bulkhead.	**X**	**X**
	Flood Barrier	• Temporary flood barriers may include the use of sandbags, plywood, and/or rubber bladders.	**X**	**X**
	Rock Slope Protection (RSP)	• Commonly referred to as riprap, RSP consists of rock courses placed upon the embankment or shore to prevent erosion.	**X**	**X**
Accommodate (Nature-based)	Elevate	• Roads, bridges, and other transportation facilities can be elevated above a certain flood level (such as through bridge abutment lengthening, increases in bridge freeboard, or a viaduct or causeway), generally to protect against storm conditions or extreme tides. • Elevating individual components is costly and elevating or constructing new roadways can be both complex and expensive; however, those costs should be balanced against on-going maintenance costs associated with repeated damages from wave exposure and environmental mitigation costs.	**X**	**X**
Hybrid Approach	Combination of nature-based and structural solutions	• A solution that combines any of the above strategies for an asset or collection of assets along a transportation corridor including natural (nature-based) and constructed (structural) elements. Additional guidance on hybrid approaches can be found in the Caltrans Design Manual for Hybrid Coastal Protection Strategies (2022)	**X**	**X**

ADDRESSING CHANGES IN TEMPERATURES

Extreme heat events are projected to become more frequent and severe in the future, affecting both the transportation infrastructure and its users. In hot weather, unshaded roofs and pavements in urban and heavily paved locations can be heated to temperatures far above that of the surrounding air, creating what is called a "heat island." Heat islands increase summertime peak energy demands, air conditioning costs, GHG emissions, and heat related illnesses. Wherever feasible, planners should consider these conditions when planning for streetscapes at a human scale.

High and low temperatures can cause pavements to buckle or crack. However, *pavement heat considerations are not included in this document; planners should consult the Division of Maintenance to consider the types of pavements that may be necessary to maintain efficiency of the roadway*. For more information, please review and reach out to the Caltrans Pavement Program.

Increases in snowpack coupled with warmer temperatures later in the year can result in rapid runoff events to communities along rivers and streams, as well as contribute to debris on the roadway and drainage facilities, please refer to the section on "Change in Precipitation" for strategies related to flooding, erosion, and flood alteration.

The section below provides adaptation strategies to address impacts on the transportation system other than pavements from changes in temperatures.

EXTREME HEAT EVENTS

Complete Streets and Improved Transit: Designing transportation facilities that remain usable for a variety of modes of transportation events would be an equitable approach for addressing impacts to non-auto users. Extreme heat is known to contribute to a variety of health risks that can affect non-vehicular travelers who have limited access to travel options that feature air conditioning. When considering complete streets projects, coordinate with active transportation representatives and partner agencies to consider complete street options that incorporate strategies for extreme temperatures.

Sources used for this section

- Caltrans Complete Streets Elements Toolbox Version 2.0

Example Strategies for Extreme Heat Events

Strategy	Project	Project Description
Complete Streets	Street Trees	• Trees shade pavement and rooftops, which helps maintain more comfortable summertime temperatures. • Trees also cool the air via evaporation, which alone or in combination with shading, can help reduce peak summer air temperatures and heat islands.
	Cooling Pavements	• Cooling Pavements reflect more solar radiation (thereby absorbing less heat) and are used in lieu of conventional black asphalt. • Decreasing the amount of heat absorbed by pavements can be achieved by using lighter materials such as concrete or using a lighter colored aggregate in asphalt paving mixes.
	Improved Active Transportation Safety	• Protected active transportation infrastructure that allows cyclists to move at slower, safer speeds during extreme heat events rather than higher speeds when sharing the road with cars. • Reduces the potential risk of exhaustion during extreme heat events.
Improved Transit	Transit Shelters	• Shaded areas where transit users can wait for transit in more comfortable conditions during extreme hear events.

Improved Transit	Increased Transit Service	• Reducing wait times for transit service to reduce exposure to extreme heat conditions and provide improved service.

ADDRESSING DROUGHT

Drought is a constant issue for the State, warmer temperatures, variable snowpack and precipitation, and earlier snowmelt caused by climate change make for longer and more intense dry seasons. Moisture loss from soils and vegetation contribute to drier conditions overall. This may lead to increased plant mortality, shifts in habitat, and increased wildfire risk. Using drought-tolerant plants not only contribute to water conservation, but also benefit fire-resistant landscaping, as plants that are drought-tolerant natives are also fire-resistant. This section provides adaptation strategies to address impacts on the transportation system from drought.

DROUGHT

Strategies to address drought are as follows:

- **Drought Resistant Landscaping:** This strategy involves the use of regionally appropriate, drought tolerant, and/or native plant material that may provide aesthetic, safety, environmental mitigation, stormwater pollution prevention, and erosion control benefits.

Sources used for this section

- Caltrans Division of Design – Highway Planting webpage
- Caltrans Climate Change Adaptation Strategy Report

Example Strategies for Drought

Strategy	Project	Project Description
Drought Resistant Landscaping	Highway Planting	• Good planting design provides functional and aesthetic benefits, require little supplemental potable water, and requires minimal resources to maintain. • Functionally, highway planting provides safety benefits such as headlight glare reduction and windbreaks. • Aesthetically, planning helps integrate the highway within its natural or guild environment to provide human scale and maintain an area's unique visual context.

ADDRESSING INCREASED WILDFIRE RISK

Wildfire is a very rapidly and costly climate-driven hazard affecting Californians every year. While many fires are preventable all together, project increases in temperature coupled with decreased in precipitation will likely generate more sever annual wildfire seasons in California in the future. Some measures can be taken to prevent the generation and uncontrollable spread of wildfire and mitigate potential damage to transportation facilities and their surrounding communities. This section provides adaptation strategies to address impacts on the transportation system from increased wildfire risk.

Caltrans Maintenance Division runs a robust Vegetation and Wildfire Management Program. Information on the needs identified and projects planned can be found here. Please reach out to Lisa Worthington (lisa.worthington@dot.ca.gov) with questions on vegetation management in your district.

INCREASED WILDFIRE RISK

Strategies to address increased wildfire around transportation infrastructure are grouped into the following three categories:

Defensible Space: Defensible space is a buffer that is created between a building and vegetation surrounding it. This space slows or stops the spread of wildfire and additionally protects the building from reactive heat impacts.

Fire-Resistant Landscaping: Fire-Resistant landscaping may prevent fire ignition, and slow or stop the spread of an existing wildfire.

Hardening: The use of ember- and heat-resistant materials may assist in preventing ignition and damage to Caltrans buildings and assets.

Sources used for this section:

- CALFIRE – Defensible Space webpage
- Caltrans Climate Change Adaptation Strategy Report
- Caltrans Roadside Design Strategies for Fire Suppression: Survey of Practice

Example Strategies for Wildfires

Strategy	Project	Project Description
Defensible Space	Fuels Reduction	• Clearing of vegetation long the SHS to protect SHS users from approaching wildfire, as well as protection from the ignition of fuels by SHS activity. • Allows for the SHS to act as a firebreak in wildfire events, potentially slowing the advance of wildfire and improving conditions for fire suppression in such wildfire events. *FYI: Caltrans runs a statewide Vegetation and Wildfire Management Program in the Maintenance Division.*

Fire-Resistant Landscaping	Landscape Management	• Planning and maintaining vegetation that is known to be tolerant to fire, or less likely to die off from higher projected temperatures, and prolonged period of drought. • Use of concrete weed mats (for example in center median) to reduce fuels/vegetation • Water conservation is another benefit to using fire-resistant landscaping, as plants that are fire-resistant are typically drought-tolerant natives.
Hardening	Culvert Replacement	• Replacement plastic culverts with culverts made from inert materials such as corrugated steel pipe (CSP). • Culverts made from inert materials are more resistant to wildfire conditions and can be expected to maintain intended function both during, and after wildfires take place. • In hilly areas that are prone to wildfires, replacement culverts should be wider to help accommodate for landslides that may block drainage systems.
	Guardrail and Signpost Replacement	• Replacement of wooden guardrail posts and signposts with metal or other inert material thar are less likely to be affected by wildfire. • Guardrail posts and signposts made from inert materials are more resistant to wildfire conditions can be expected to maintain intended function both during and after wildfires take place.

DEBRIS FLOW/EROSION

Debris flow generally occur during periods of intense rainfall or rapid snowmelt. Areas recently burned by a wildfire are especially susceptible to debris flow, including the areas downslope and outside of the burned area. Erosion may cause the loosening of soil, plant debris, rocks, and boulders, which can intensify the effects of debris flows. Keeping an area free of excess fuel for fires can also help in the mitigation of debris flows, as burned slopes become more vulnerable to the effects of debris-flow initiation and erosion. Loss of vegetation that holds soil in place and physical and chemical changes to the soil that result from intense heat and burning by fires make this soil more prone to debris flows.

Debris flow/erosion strategies are grouped into the following two categories:

- **Fire-Resistant Landscaping:** Fire-Resistant landscaping may prevent fire ignition, and slow or stop the spread of an existing wildfire.
- **Protection:** Involves measures such as debris-flow basins and retaining walls to protect travelers and highway features from the collateral damage resulting from landslide processes. Protection measures typically are used where the debris must be contained so that soil and debris are stopped from flowing to areas that are vulnerable to debris-flow damage.

Sources used for this section:

- USGS Appendix C. Introduction to Landslide Stabilization and Mitigation

Example Strategies for Debris Flow

Strategy	Project	Project Description
Fire-Resistant Landscaping	Landscape Management	• Keeping an area free of excess fuel for fires can help in the mitigation of debris flows, as burned slopes become more vulnerable to the effects of debris-flow initiation and erosion.
Protection	Debris-Flow Basins	• These catchment basins are commonly built at the base of slopes where debris flows are frequent. • Used especially in areas where debris must be contained so that soil and debris are stopped from flowing into sensitive ocean or river shoreline areas or where there are structures at the base of the slope that are vulnerable to debris-flow damage. • These basins will eventually fill with debris-flow deposits and must be emptied periodically, or they will overflow.
	Retaining Walls	• Designed to stop the progress or debris fall, either by blocking the flow or diverting it around a vulnerable area. • Retaining walls can be made out of steel, concrete, timbers, or other materials. • These structures should be carefully designed as any deflection of material may be unintentionally redirected into additional vulnerable areas.

ADDRESSING LANDSLIDE RISK

Landslides are a hazard that is typically driven by a combination of climate stressors. Precipitation, temperatures, and the occurrence of wildfire all have an influence on the probability that landslides may occur. This section provides adaptation strategies to address impacts on the transportation system from landslides.

LANDSLIDES

Landslide mitigation strategies are grouped into the following four categories:

- **Stabilization:** To be effective in stabilizing a slope, first one must identify the most important controlling process that is affecting the stability of the slope; secondly, one must determine the appropriate technique to be sufficiently applied to reduce the influence of that process. Stabilization involves measures such as earthwork, buttresses, dewatering, retaining walls, shoreline armor, anchor bolts, slope contouring, and drainage systems to preclude of minimize further landslide movement.

- **Protection/Mitigation:** Involves measures such as rock sheds, rockfall barriers, draperies, rockfall fences, and catchment ditches to protect travelers and highway features from the collateral damage resulting from landslide processes. Protection measures typically control rock and soil emanating from a landslide.
- **Avoidance/Relocation:** This strategy involves measures such as roadway realignments, bridges, viaducts, retaining walls, and tunnels to separate the highway from adverse impacts of a landslide. Avoidance allows the landslide movements to continue following mitigation, but those movements no longer affect the highway.
- **Slope Management:** Involves measures such as monitoring systems, patrols, planned road closures, signing, periodic maintenance, and minor rebuilding to allow operation of the highway within a tolerable amount movement and disruption. Management measures are often practical for large, slow-moving slides when the obstacles to other mitigation strategies prove insurmountable.

Sources used for this section:

- Caltrans Geotechnical Manual - Landslides
- USGS Appendix C. Introduction to Landslide Stabilization and Mitigation

Example Strategies for Landslide Risk

Strategy	Project	Project Details
Stabilization	Vegetation Stabilization (Nature Based)	• Seeding with grasses and legumes reduces surface erosion, planting with shrubs adds vegetative cover and stronger root systems will in turn enhance slope stability. • Dry seeding is usually less costly than hydraulic seeding but are limited to rough soil surfaces and gentler slopes. • Hydraulic seeding (hydroseeding) is more costly than dry seeding but is more effective for seeding steeper slopes.

	Bioengineered Stabilization
	
	(Hybrid)
		• This type of slope protection is used to reduce the environmental consequences of landslide-mitigation.
		• Consists of two elements:
		  ○ Biotechnical Stabilization: uses a combination of structures and plants to prevent and arrest slope failures and erosion.
		  ○ Soil Biotechnical Slope-Protection Systems: emphasize the use of natural, locally available materials such as soil, rock, timber, and vegetation, in contrast to manufactured materials such as steel and concrete.

Stabilization	Surface/Subsurface Drainage	• Surface draining can be implemented through either surface ditches or shallow subsurface drains. • Drainage is effective because it increases the stability of the soil and reduces the weight of the sliding mass.
	Earthwork	• The disturbance of soils associated with clearing, grading, or excavation activities such as removal of soil from the head of a slide, reducing the height of a slope, backfilling with lightweight material, benches, or flattening/reducing/other slope modification. • This strategy can be both costly and environmentally harmful if done incorrectly.
	Scaling and Trimming	• The removal or loose, unstable, and/or overhanging blocks of rock that includes the use of hand-held pry bars, drilling, and small explosive charges. • These operations can be time-consuming and expensive, and on active slopes may need to be repeated every few years, or as needed.
	Rock-fill Buttress/ Berm	• A berm or buttress of earthfill is deposited at the toe of a slope to increase its toe. This creates a counterforce that resists failure. • Broken rock or riprap instead of soil is preferable due to their greater frictional resistance to shear forces and easy draining, which reduced the problem of impeding ground-water flow.
	Plastic Mesh Reinforcement	• Reinforcement of plastic polymer stretched to form a lightweight, high-tensile-strength grid. This grid acts similarly to reinforcing mesh in concrete, adding strength to the shear strength of the soil. • This type of grid has a number of possible applications in slope stabilization, including soil strength reinforcement, soil drainage, improvement, and retaining-wall construction.
	Retaining Wall/Bulkhead	• A strong solid barrier that supports soil laterally, these structures are designed to harness soil to a slope that would otherwise naturally not exist. • Can be made from steel, concrete, timbers, or other materials. • Retaining walls used to separate water from land are called bulkheads.
	Reinforced Earth Wall	• A patented system for constructing fills at very steep vertical angles without the use of supporting structures at the face of the fill. • The system uses horizontal layers of flexible metal strips within the fill to form a composite earth-metal system with high strength.
	Shoreline Armor	• The use of physical structures to protect shorelines including seawalls, breakwaters, and riprap. • Armored shorelines can prevent sandy beaches, wetlands, and other intertidal areas from moving inland as the land erodes, but they also have the potential to eliminate habitat for marine organisms and beach front for the public by restricting the natural movement of sediments.

Stabilization	Anchor Bolts	• Composed of steel rods or cables that reinforce and tie together a rock face to • Anchors are post-tensioned members used to support large blocks of rock, whereas bolts are shorter and support surface rock.
Protection/Mitigation	Rock Sheds	• These shelters are built over roads, railways, and sometimes structures to shield the area from landslide activity such as rockfalls or rock avalanches. • Shed structures are either open ended or completely envelope the rockfall area in a concrete or steel structure that will deflect rockfall away.
	Barriers/Draperies/ Catchment Ditches	• Proactive mitigation method based on topographic contours to catch debris lifted and transported during an increased precipitation event. • Debris flow catchments can be implemented in burn scars that are susceptible to high amounts of runoff. These catchments prevent clogged culverts and subsequent damage to roads from water overflow. • Debris-flow retaining walls can also be used to stop the progress of debris fall either by blocking the flow or diverting it around a vulnerable area.
Avoidance/ Relocation	Roadway Realignments	• Rerouting the roadway to alignments that are less at risk from landslide or other geotechnical hazards.
	Bridge/Viaduct	• Separating a roadway from adverse impacts of potential landslides by raising or moving roadway to another location, allow landslide movements to continue but without affecting the highway.
	Tunnels	• Rerouting the roadway to travel below where the landslide movements may potentials affect the roadway. Known to be a very cost and labor-intensive project that would only be considered if there is no other strategy available.