California High-Speed Train Project

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TECHNICAL MEMORANDUM

Fault Rupture Analysis and Mitigation
TM 2.10.6

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for the California High-Speed Rail Authority

System Level Technical and Integration Reviews

The purpose of the review is to ensure:

- Technical consistency and appropriateness
- Check for integration issues and conflicts

System level reviews are required for all technical memoranda. Technical Leads for each subsystem are responsible for completing the reviews in a timely manner and identifying appropriate senior staff to perform the review. Exemption to the system level technical and integration review by any subsystem must be approved by the Engineering Manager.

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ABSTRACT

The California High-Speed Train (CHST) system shall be designed to accommodate substantial seismic hazards in California including faults capable of rupture during the life expectancy of the CHST project. Faults located beneath and/or immediately adjacent to HST system elements may rupture during the lifetime of this project, and must be considered during the project development. This Technical Memorandum (TM) provides guidelines for the identification of such fault hazard zones requiring consideration, methods to determine the rupture displacement characteristics, and mitigation measures to meet project performance requirements.

Crossing of fault hazard zones shall be avoided where feasible. Where crossing fault hazard zones cannot be avoided, the primary mitigating strategy is to place the alignment at-grade with ballasted track, oriented as near to perpendicular as feasible to the fault trace, in order to minimize the fault zone length beneath the HST footprint. The system will be developed with the intent of satisfying the Seismic Performance Criteria as defined in the TM 2.10.4 Interim Seismic Design Criteria.

Since buildings for the HST system are subject to the design requirements of the California Building Code (CBC) which requires fulfillment of Alquist-Priolo (A-P) regulations, buildings cannot be designed over or immediately adjacent to active faults.

Where at-grade tracks are infeasible, such as at congested sites, water crossings, or mountainous terrain, then elevated or underground structures may be unavoidable. For such scenarios, this TM provides guidelines for the following:

- Fault displacements analysis including:
    - Probability of fault rupture
    - Fault displacement magnitude
    - Orientation and direction of displacement
- Seismic Performance Criteria evaluation
- Secondary mitigation strategies
- System mitigation classifications
    - **Class A systems** can tolerate expected fault displacements using either standard or special mitigation design in order to meet Seismic Performance Criteria.
    - **Class B systems** require special mitigation design, but cannot meet standard Seismic Performance Criteria, thus a variance to the standard criteria and operations is required.
    - **Class C systems** cannot meet Seismic Performance Criteria and cannot be feasibly mitigated with a variance. Thus, elevated and underground structures may not be used. Such Class C systems shall be comprised of at-grade ballasted track with no exceptions.
- Variances to seismic performance and standard design criteria

1.0 INTRODUCTION

1.1 PURPOSE OF TECHNICAL MEMORANDUM

Continuing revenue operation of the CHST system during and after a strong seismic event is a priority of the Authority. Because of the high likelihood of major seismic activity during the life of the system, preventive measures must be made to avoid long shut-down of the system after an earthquake. This technical memorandum establishes design guidelines for such scenarios since significant challenges exist where the HST alignment crosses or is in close proximity to capable fault zones.

This technical memorandum provides guidance on screening rupture locations, determining rupture severity and limits, and defining minimum levels of performance. It also provides guidance for determining expected displacements in terms of orientation, sense of movement, magnitude, displacement history, and rupture length/depth.

Applying these guidelines will result in consistent and appropriate fault displacements for use in the preliminary design. This technical memorandum does not address ground motion analysis or evaluation of geologic or other seismic hazards such as liquefaction or stability that are contained in other, separate documents.

At capable fault zones, the primary mitigating strategy is to place the alignment at-grade with ballasted track. The alignment shall be oriented as near to perpendicular (90°±30˚) as feasible to the fault trace, in order to minimize the fault zone length beneath the HST footprint, and reduce the damaging effects to the track system. Elevated and underground construction shall, to all practical extents, be avoided at capable fault zones.

Where at-grade tracks are infeasible, such as at congested sites, water crossings, or mountainous terrain, then elevated or underground structures may be unavoidable. This technical memorandum will address secondary mitigation strategies for such scenarios.

Once analyses have been made for structures subject to fault rupture, the structural systems shall be classified by the mitigation measures required, if any, to achieve acceptable performance. The mitigation classification highlights the potential impact to project alignment, design, and operation.

1.2 STATEMENT OF TECHNICAL ISSUE

Preventative measures must be made to avoid long shutdown of the high-speed train system after an earthquake. This technical memorandum establishes design guidelines for such scenarios since significant challenges exist where the HST alignment crosses or is in close proximity to capable fault zones.

Establishing guidelines and criteria for HST systems at or near capable fault zones provides appropriate assessment and mitigation of risk, provides a consistent basis for design, and will result in system-wide criteria applicable to HST.

1.3 GENERAL INFORMATION

1.3.1 Definition of Terms

The following technical terms and acronyms used in this document have specific connotations with regard to the California High-Speed Train system.

Capable Fault	A mapped or otherwise known Quaternary fault with evidence of Holocene displacement, structural relationship to related Holocene faults, and/or where data is not sufficient to rule out the presence of Holocene movement.
Holocene Fault	Fault with most recent movement within the past 11,000 years

Quaternary Fault	Fault with evidence of movement in the past 1.6 million years
Fault Hazard Zone	Overall zone within which deformations related to fault rupture may occur and should be considered in the design.

Acronyms

AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
AISC	American Institute of Steel Construction
AWS	Structural Welding Standards
CBDA	Caltrans Bridge Design Aids Manual
CBDD	Caltrans Bridge Design Details Manual
CBDM	Caltrans Bridge Design Manuals
CBDP	Caltrans Bridge Design Practice Manual
CBDS	Caltrans Bridge Design Specifications
CBC	California Building Code 2007
CDC	CHSTP Design Criteria
CGS	California Geological Survey
CHST	California High-Speed Train
CHSTP	California High-Speed Train Project
CMTD	Caltrans Bridge Memo to Designers Manual
CSDC	Caltrans Seismic Design Criteria ver. 1.5
DBE	Design Basis Earthquake
EEWDS	Earthquake Early Warning System
FHZ	Fault Hazard Zone
LDBE	Lower-level Design Basis Earthquake
MCE	Maximum Considered Earthquake
M_w	Moment Magnitude Scale of Earthquake
NCL	No Collapse Performance Level
OPL	Operability Performance Level
PMT	Program Management Team
RI	Return Interval
SPL	Safety Performance Level
SSPP	System Safety Program Plan

1.3.2 Units

The California High-Speed Train Project (CHSTP) is based on U.S. Customary Units consistent with guidelines prepared by the California Department of Transportation (Caltrans) and defined by the National Institute of Standards and Technology (NIST). U.S. Customary Units are officially used in the U.S. and are also known in the U.S. as “English” or “Imperial” units. In order to avoid any confusion, all formal references to units of measure should be made in terms of U.S. Customary Units.

2.0 DEFINITION OF TECHNICAL TOPIC

2.1 GENERAL

This technical memorandum establishes fault definitions, design parameters, fault effects, displacement analysis guidelines, system mitigation classifications, and primary and secondary mitigation strategies where at-grade track, elevated structures, or tunnels occur at capable fault zones.

The guidelines in this Technical Memorandum apply to all Primary Structures as defined in TM 2.10.4 Interim Seismic Design Criteria and include structures that directly support track and running trains.

2.1.1 CHSTP Design Considerations

Design guidelines for high-speed facilities are under development and are defined in separate technical memoranda:

- Guidelines in this TM are largely based on three levels of performance criteria described in TM 2.10.4: Interim Seismic Design Criteria.
- Initial screening methods and assessment of other seismic and geologic hazards are provided in TM 2.9.3: Geologic and Seismic Hazard Analysis.
- This technical memorandum references two methods for probabilistic fault displacement hazard analysis [16, 17]. The displacement approach method [16] is recommended.
- For elevated structures, the basis of the following guidelines and criteria rely on information assembled by FIB (Internationale du Beton) Task Group 7.4 [18].
- For underground structures, a 2004 CHST EIR/EIS level "Tunneling Issues Report" [19] was used for reference material.

2.1.2 Design Parameters

- All structures carrying high-speed trains shall be designed to these requirements, and shall comply with the structure gauge and rail section adopted for the high-speed train system.
- The design life of fixed facilities shall be 100 years per TM 1.1.2 Design Life.
- The maximum design speed for the main tracks is 250 miles per hour; segments of the alignment may be designed to lesser speeds.
- Structural requirements require that bridges and aerial superstructures be designed as rigid and stiff in order to meet dynamic performance, traffic safety, rail-structure interaction, and passenger comfort requirements.
- Design and construction of high-speed train facilities shall comply with the approved and permitted environmental documents.
- The performance objectives may not be achievable at locations of significant fault rupture. For these cases, variances to the standard design criteria can be made, subject to approval by the Authority, or elevated and underground structures may be prohibited (e.g., tracks shall be at-grade, no exceptions).

2.2 LAWS AND CODES

Initial high-speed train (HST) design criteria will be issued in technical memoranda that provide guidance and procedures to advance the preliminary engineering. When completed, a Design Manual will present design standards and criteria specifically for the design, construction and operation of the high-speed railway.

Criteria for design elements not specific to HST operations will be governed by existing applicable standards, laws and codes. Applicable local building, planning and zoning codes and laws are to be reviewed for the stations, particularly those located within multiple municipal jurisdictions, state rights-of-way, and/or unincorporated jurisdictions.

In the case of differing values, the standard followed shall be that which results in the satisfaction of all applicable requirements. In the case of conflicts, documentation for the conflicting standard is to be prepared and approval is to be secured as required by the affected agency for which an exception is required, whether it be an exception to the CHSTP standards or another agency's standards.

Attention is specifically directed to California's Alquist-Priolo Earthquake Fault Zoning Act [13] of 1972, which was passed to mitigate the hazard of surface faulting. This Act stipulates that a geologic investigation be made to define the fault trace, in order to prevent buildings for human occupancy from being constructed over fault traces, as well as defining the required offset from the fault trace.

Since the Alquist-Priolo Act has jurisdiction over buildings via the California Building Code (CBC), design of buildings for the CHST system will be subject to these requirements that do not allow placement of buildings on or immediately adjacent to Holocene faults. Since no other codes exist in California that regulate non-building structures, project-specific criteria and guidelines are included in this document that provide alternative capable fault definitions and guidelines for analysis and mitigation that are not consistent with Alquist-Priolo. The term active faulting has definitions that are specific to the Alquist-Priolo, and thus the term capable fault is provided for these project-specific criteria.

These project-specific guidelines are generally consistent with Caltrans Memo to Designer (CMTD) 20-10, which defines a methodology for surface fault rupture displacement determination. CMTD 20-10 references California Geological Survey (CGS) guidelines [14] for evaluating surface fault hazards, and the methodology by Wells and Coppersmith [15] for estimating fault offset displacements.

3.0 ASSESSMENT / ANALYSIS

3.1 GENERAL

This technical memorandum provides guidelines for determining capable fault locations and expected displacements in terms of probability of fault rupture, fault displacement magnitude, and orientation and direction of displacement. These guidelines are to be used to establish fault displacements for use in preliminary design.

Since structures at or near capable faults are defined as complex, analysis requirements for the various stages of design are given.

Based upon the analysis results, mitigation measures required to achieve acceptable performance can be defined. A system mitigation classification is then determined based upon whether minimum CHSTP criteria may be met or whether a variance to the minimum criteria is required. The mitigation classification highlights the potential impact to project design, serviceability and operation.

The information included in this document is to be used in conjunction with TM 2.10.4: Interim Seismic Design Criteria and TM 2.9.3: Geologic and Seismic Hazard Analysis Guidelines.

3.2 DESIGN CODES AND SPECIFICATIONS

The structural design shall meet all applicable portions of the general laws and regulations of the State of California and of the respective local authorities.

Unless otherwise specified, HST facilities shall be designed in accordance with all applicable portions of the following standards and codes:

1. AREMA: American Railway Engineering and Maintenance-of-Way Association, Manual for Railway Engineering, 2009
2. ACI: American Concrete Institute, Building Code Requirements for Reinforced Concrete, ACI 318-05
3. AISC: American Institute of Steel Construction, Steel Construction Manual, 13th Edition
4. AWS D1.1/D1.1M:2008 Structural Welding Code-Steel
5. AASHTO/AWS D1.5M/D1.5:2008 Bridge Welding Code
6. AWS D1.8/D1.8M:2009 Structural Welding Code-Seismic Supplement
7. CBC: The 2007 California Building Code
8. California Department of Transportation (Caltrans) Bridge Design Manuals, latest edition
   - Bridge Design Specification (CBDS) - AASHTO LRFD Bridge Design Specification 4th Edition, 2007 with California Amendments
   - Bridge Memo to Designers Manual (CMTD)
   - Bridge Design Practices Manual (CBPD)
   - Bridge Design Aids Manual (CBDA)
   - Bridge Design Details Manual (CBDD)
   - Bridge Memo to Designers Manual (CMTD)
   - Standard Specifications
   - Standard Plans
   - Caltrans Seismic Design Criteria ver. 1.5 (CSDC)
9. ASCE/SEI 41-06: Seismic Rehabilitation of Existing Buildings. Reston, VA: American Society of Civil Engineers, 2007.

In the event of conflicting requirements between the CHSTP Design Criteria and other standards and codes of practice, the Design Criteria shall take precedence. For requirements that have not been included in the Design Criteria, the order of code adoption shall be: 1) local codes; 2) U.S. National Standards; 3) others.

3.3 FAULT DISPLACEMENT DESIGN PARAMETERS

3.3.1 General

Evaluation of fault rupture shall be provided for all three (3) performance criteria to be consistent with seismic design methods defined in TM 2.10.4: Interim Seismic Design Criteria for all faults that meet the capable fault definition as defined in Section 3.3.3. Displacement analyses shall provide designers with location, displacement magnitude, movement direction, and orientation and shall include a description of data uncertainty for consideration within the design process.

Methods of analysis are provided below and shall be implemented during the preliminary (15% design and 30% design), and final design. The fault displacement analysis for 15% design shall estimate the MCE-based displacement parameters in sufficient detail to preclude the need for realignment and/or revised footprint during subsequent 30% design. The 30% design shall implement fault displacement analysis methods for the MCE, DBE, and LDBE events in sufficient detail and reliability so that 30% design and cost estimate can be prepared for any required mitigations. The displacement methods are summarized in Section 3.3.5.

Additionally, local factors such as near-field effects and topographic amplification should be considered in estimating ground motions. These values shall be considered in assessing the required mitigation measures to meet the performance criteria.

These guidelines do not apply to buildings and facilities that do not carry high-speed train loadings. Buildings are subject to Alquist-Priolo requirements which state that buildings cannot be designed and built over Holocene faults.

3.3.2 Qualifications for Capable Fault Rupture Investigation

Geological investigations involving capable fault trace and displacement determination must be under the direct supervision of a current California licensed Engineering Geologist (CEG).

3.3.3 Capable Fault Definition

Faults subject to these criteria and guidelines are referred to as “capable faults”. Capable faults are defined as a mapped or otherwise known Quaternary fault with evidence of Holocene displacement, structural relationship to related Holocene faults, and/or where data is not sufficient to rule out the presence of Holocene movement.

Where the design of buildings is involved, the CBC definition of Active Faults shall be used and will be subject to all requirements of the Alquist–Priolo Act [13].

3.3.4 Seismic Performance Criteria and Probability

Fault rupture analysis shall be performed consistent with the Seismic Performance Criteria established in TM 2.10.4: Interim Seismic Design Criteria. There are three (3) performance levels and related design events to consider, which include:

NCL: The No Collapse Performance Level (NCL)

SPL: The Safety Performance Level (SPL)

OPL: The Operability Performance Level (OPL)

3.3.5 Fault Displacement Analysis Methods

This section provides guidance on the methodologies which shall be used to develop surface fault displacements consistent with TM 2.9.6: Interim Ground Motion Guidelines, for all three performance criteria.

The guidelines address the methodologies to be used for 15%, 30%, and final design.

3.3.5.1 Fault Hazard Zone Definition

The definition of the Fault Hazard Zone (FHZ) is defined as the overall zone within which deformations related to fault rupture may occur and should be considered in the design. This FHZ consists of three components; The primary zone of faulting, a surrounding zone within which secondary or sympathetic displacement has and/or may occur, and the safety zone which is a buffer zone surround the primary and secondary zones that represents the uncertainty of deformations in the future. The information from compiled literature, remote sensing, and field investigations (as required) shall be used to estimate the zone of potential primary rupture. All reasonable mapped fault locations shall be considered as part of the primary zone of fault rupture. The secondary rupture zone shall take into consideration sympathetic or secondary and typically lower displacements. The width of this zone shall encompass paleoseismic trench observations of secondary movement as well as empirical information for similar fault zones and their breadth of secondary movement. The safety zone breadth shall be left to the design team's discretion but will be demonstrated by the designer to be adequate to bracket the uncertainty of future movement(s).

The width of the distributive faulting shall also be assessed for the capable fault in question. That is, the nature of faulting within the overall capable fault zone shall differentiate between the potential for discrete faulting anywhere within the zone as opposed to the distribution of the displacement throughout this zone. A credible explanation will be needed for this differentiation and, in the absence of this substantiation, both shall be considered possible and considered within the design until additional data can be obtained to provide the necessary substantiation. The defined fault zone shall conservatively capture potential for future distributive faulting. In addition, the zone containing all mapped faults shall be used to evaluate this spatial variability and thus the overall breadth of this zone and the greater of the two zone widths shall be used for design purposes.

3.3.5.2 Fault Displacement Methodology

Fault rupture analysis and design shall be consistent with the Seismic Design Criteria and Interim Ground Motion Analysis methods. These guidelines require fault displacement definition for the MCE event for 15% Design. For 30% and Final Design, the fault displacement values for MCE, DBE, and LDBE events shall be determined and evaluated.

Prior to evaluation of displacement magnitude, the probability of rupture shall be assessed to further define the fault as capable. Contrary to Alquist-Priolo regulations for buildings, the HST system will not necessarily prohibit the construction of non-building facilities at or near known active faults. Buildings will remain subject to California Building Codes (CBC) and thus A-P requirements apply and preclude construction over a Holocene Fault. The probability of rupture shall be evaluated using the seismic performance criteria identified in TM 2.9.6 - Interim Ground Motion Guidelines. The probability of rupture shall be evaluated for all faults meeting the capable fault definition above. The probability of rupture shall be based on rupture frequency data (where available and reliable)

In general, capable faults that have higher slip rates and/or high frequency return periods will remain classified as capable. If a fault can be effectively demonstrated to have a sufficiently long Return Interval (RI), it may be declassified as capable and may not be subject to the evaluation and mitigation requirements herein. The RI shall be defined as the characteristic (average) return period of the fault and will be compared to the most recent large earthquake. If the return interval (RI) for the fault is approximately equal to or less than the time since the most recent event (RE) and is less than the seismic performance criteria return period (SPC) and these are reliable values, the fault will be remain classified as capable of rupture. This comparison of Return Interval to the most recent event and SPC criteria is expressed in the simple equation as:

If RI – RE < SPC, then rupture is probable and the magnitude of displacement must be evaluated.

If RI - RE ≥ SPC, then rupture is not probable in relation to the seismic performance criteria

Where: RI = fault return interval

RE = time since the most recent event

SPC = Seismic Performance Criteria Return Period

As an example, if a mapped Quaternary fault is not mapped as Holocene but is on strike with a potentially structurally related fault with evidence of Holocene movement, it shall be classified as capable. If reliable existing or acquired fault characteristic data is available to effectively demonstrate that this fault has a well-constrained RI value of 3,500 years and the most recent event (RE) was 1,500 years ago, the projected future event would be 2,000 years. Since this value exceeds both the LDBE (100 year) and DBE (950 year) return periods, it would not need to be mitigated for these performance levels. However, since the value is less than the MCE event (2,475 return period), the system needs to be evaluated and mitigated for the NCL (No Collapse Level) performance criteria. It is critical that these fault characteristics be identified as early as possible and communicated to the PMT.

3.3.5.3 Fault Displacement Magnitude

The fault displacement shall be assessed based on the best available data for all three design stages, 15% Design, 30% Design and Final Design. The displacement value for the MCE (2,475 year return period), the DBE (945 year return period), and LDBE (100 year return period) events shall be estimated unless the RI-RE value is greater than the SPC. The displacement magnitude shall be based on the earthquake magnitude (Mw) derived using the Interim Ground Motion (IGM) Analysis methodology, thus assuring consistency between the ground motion value and the ground rupture displacement value for the same fault. Since the IGM methodology appropriately includes the affects of other nearby faults including a background event, the Mw for the fault shall be deaggregated to be representative of movement for only the subject capable fault.

During the 15% design, only the MCE ground motion is required and thus only an MCE-based Mw value will be available. While this is appropriate for ground motion analysis, the LDBE and/or the DBE level ground rupture and performance criteria may dictate design and may have significant influence on the HST alignment and/or feasibility. In this instance, the DBE-based Mw value shall be obtained using existing USGS and CGS data for that fault. In the absence of any existing fault data, the LDBE-based Mw value shall be assumed to be equal to the DBE-based Mw value.

The displacement value shall be computed using the empirical magnitude-displacement correlations developed by Wells and Coppersmith [15]. An alternative correlation can be used if it can be substantiated as being more applicable for the fault characteristics for the evaluated fault. The Youngs et al. [16] probabilistic fault displacement model shall then be used to independently assess the magnitude of fault displacement (principal and distributive). These values will be compared to the displacement estimated using the Wells and Coppersmith [15] values. The larger of the two values will be used in the design unless an effective argument can be provided which demonstrates that a certain method is more reliable for the evaluated fault.

Where the subject fault is a “creeping” fault with a high frequency of ruptures, the design will need to accommodate the total displacement during the life expectancy of the HST system by assuring that adequate right-of-way exists and that the cumulative strain can meet or exceed the performance criteria. The displacement analysis shall provide the frequency of displacements, displacement for each event, and the expected cumulative displacement.

3.3.5.4 Orientation and Direction of Displacement

The orientation of the fault is defined as the alignment and inclination of the fault plane. The direction of displacement is defined as the direction of slip along that plane represented by a vector along the planar surface. The orientation shall be presented as a fault strike value relative to north, and shall be described in degrees of rotation relative to the HST alignment at that location, where applicable. The fault orientation value shall be nearly perpendicular (90°±30˚) to HST alignment, in order to reduce fault zone length beneath the HST footprint.

The displacement direction for dip-slip faults shall be characterized as being either normal or reverse. Strike-slip faults shall be identified as being either left-lateral or right-lateral. For oblique-slip faults, the displacement of both dip-slip and strike-slip components shall be quantified.

The orientation and direction of displacement of potential ruptures shall be based on all available geologic evidence of fault behavior in the past. If multiple orientations are possible, each shall be considered in design until additional data can be obtained to better constrain this finding. Similarly, the direction of displacement shall be based on geologic data available and any uncertainties or contradictions in data shall be considered in the design until additional data can better define the displacement direction.

3.4 FAULT DISPLACEMENT DESIGN STRATEGIES

3.4.1 General

The displacement obtained from the procedures above shall be used to evaluate the performance of the structures in meeting the Seismic Performance Criteria as defined in TM 2.10.4 Interim Seismic Design Criteria.

3.4.2 Analysis Requirements

Per TM 2.10.4: Interim Seismic Design Criteria, structures at or near capable faults are defined as complex.

Per TM 2.10.5: 15% Seismic Design Benchmarks, Equivalent Static Seismic Analysis is required for complex structures for 15% design. The equivalent static response from the dynamic component and fault offset component of motions may be added together by superposition.

At 30% and final design, (TM 2.10.4, Table 6.1), complex structures require either non-linear time history analysis or linear response spectra analysis, based upon the importance classification.

For non-linear time history analysis, the dynamic motions and permanent displacements are to be quantified in separate hazard assessments then combined into a single time history for design.

For linear response spectra analysis, the dynamic spectral response of the structure may be determined separately without consideration of fault displacement. The fault displacement response is then determined statically and added to the dynamic response by superposition.

3.4.3 Mitigation Classification

Once analyses have been made for structures subject to fault rupture, the systems shall be classified by the mitigation measures required to achieve acceptable performance.

System classification highlights the potential impact to project alignment, design and operation.

- **Class A systems** can tolerate expected fault displacements using either standard or special mitigation design in order to meet Seismic Performance Criteria.
- **Class B systems** require special mitigation design, but cannot meet standard Seismic Performance Criteria, thus a variance to the minimum criteria and operation is required.
- **Class C systems** cannot meet Seismic Performance Criteria and cannot be feasibly mitigated with a variance. Thus, elevated and underground structures may not be used. Such Class C systems shall be comprised of at-grade ballasted track with no exceptions.

3.4.4 Variances to Standard Criteria

Damage of systems near or at fault hazard zones is a substantial risk to the HST system. If large fault offsets occur, unavoidable track or structural damage may occur, increasing the risk of train derailment. This is recognized in TM 2.10.4, which states “it is recognized that where the alignment crosses active faults, system seismic performance criteria may be impractical due to expected large offset displacements each side of the fault.”

Thus, for systems with Class B mitigation classification, variances to standard CHSTP performance and operational criteria will be required. Such variances must be specified in writing, and are subject to approval by the Authority.

Examples of performance criteria variances for Class B systems include:

- Exceedence of allowable strain limits for structural components (i.e., variance to TM 2.10.4: Interim Seismic Design Criteria)
- Exceedence of allowable deformation limits for the track and structure or exceedence of allowable rail stresses, under an LDBE event (i.e.: variance to TM 2.10.10: High-Speed Train and Track Structure Compatibility)

Examples of operational criteria variances for Class B systems include:

- Reduced train speeds near the fault crossing
- Reduced train service near the fault crossing
- Temporary closure for repairs following an LDBE event
- Extended closures for repairs following a DBE event

For each Class B mitigation scenario, it is the responsibility of the designer to determine what variances to standard design criteria are needed, and submit a Variance Request for approval by the Authority.

3.4.5 Typical Design Process for Fault Hazard Zone Structures

Typical design for elevated or underground structures at fault hazard zones shall consist of [18]:

- Evaluation of site conditions: fault classification and characterization for the three design earthquakes.
- Determination of near fault dynamic ground motions, and permanent (i.e.: fault offset) displacements.
- Preparation of preliminary design concepts.
- Preliminary design based upon the near fault dynamic ground motions and permanent (i.e.: fault offset) motions, in order to determine structural demands, and necessary expansion joint displacement and rotational demands.
- Submittal and approval of mitigation Class B system variances to CHST performance and operational criteria.
- Development of a bridge or tunnel hazard mitigation plan (final design).
- Development of a bridge or tunnel health monitoring system (final design).

For the 15% design level, the design submittal at fault crossings shall include:

- Identification of fault hazard zones.
- Estimate expected fault displacement demands for the MCE event.
- Preliminary design concepts.
- 15% design Equivalent Static Analyses.
- Determination of the preliminary Mitigation Classification.
- Mitigation Class B system variances to the Authority.
- At-grade alignments for Class C systems.
- Documentation of mitigations and provide 15% level cost estimate.

For the 30% design level, the design submittal at fault crossings shall include:

- Final identification of fault hazard zones.
- Determination of expected fault displacement demands for LDBE, DBE, and MCE events.
- 30% design non-linear time history analysis or linear response spectra analysis, based upon the Structural Classification as defined in TM 2.10.4: Interim Seismic Design Criteria.

- Final Mitigation Classification for the system.
- Approved Mitigation Class B variances.
- At-grade alignments for Class C systems.
- Documentation of the design, mitigations, and 30% design cost estimate.

3.5 PRIMARY MITIGATING STRATEGY AT FAULT HAZARD ZONES

At fault hazard zones, the primary mitigating strategy is to place the alignment at-grade with ballasted track, oriented as near to perpendicular (90°±30˚) as feasible to the fault trace, in order to minimize the fault zone length beneath the HST footprint, and allow timely inspections and repairs after an earthquake event.

Elevated and underground construction at fault hazard zones shall, to all practical extents, be avoided.

In order to place the track at-grade, structural improvements such as embankments and retaining walls may be necessary. Where embankments and retaining walls are needed, consideration shall be made for an increased width of right-of-way. This is in recognition of anticipated damage to the embankments and retaining walls. The increased width shall provide more separation between the tracks and improvements, and add flexibility for realignment work.

For fault offset induced seismic pressures for retaining walls, and modified stability analyses for embankments, refer to the Geotechnical Data Report.

The primary mitigating strategy for trackside Systems facilities, including traction power, train control, communications, and other significant equipment, buildings, huts, and enclosures, is to locate these facilities outside all fault hazard zones.

3.5.1 At-Grade Track

Track Structure Compatibility Criteria is under development.

3.5.2 Earthquake Early Warning Detection System

An earthquake early warning detection system (EEWDS) shall be developed and used system-wide, including additional sensors at fault hazard zone regions. The detection system shall be integrated with the train control, communications and signals systems, and be capable of triggering an appropriate response for at risk trains to bring them to a safe stop as soon as p-waves are detected.

The EEWDS will not be effective if a train is near or at the fault zone due to the short time lapse between the p-wave and s-wave generation. For trains within a few miles of the fault zone, the EEWDS shall be designed to precipitate the braking of trains to a safe stop before they cross potentially damaged track.

Additionally, the EEWDS implementation shall be coordinated with maintenance and inspection protocols.

3.6 SECONDARY MITIGATING STRATEGIES FOR ELEVATED STRUCTURES

Where at-grade tracks are infeasible, such as at congested sites, water crossings, or mountainous terrain, then elevated structures may be unavoidable.

For mitigation to Class B systems, variances to standard HST performance and operational criteria will be required. Such variances must be specified in writing, and are subject to approval by the Authority.

Realizing the potential for fault rupture damage, mitigating designs which allow rapid track realignment and structural repair shall be pursued. Some secondary mitigating strategies for elevated structures at fault hazard zones follow.

3.6.1 Simple Spans and Elongated Bearing Seats

In order to cost effectively meet train performance requirements, relatively short, simple span structures shall be used. Since such structures, when subject to large fault displacements, are at risk of girder unseating and potential collapse, large and elongated bearing seats shall be used to accommodate the necessary rotations and displacements without introducing significant damaging forces to the piers or girders [18].

Elongated bearing seats not only provide increased displacement capacity, but also allow for possible post-earthquake realignment capability, thus avoiding costly and time-consuming demolition and reconstruction.

Note that temporary closure, track realignment, and repair reconstruction may be unavoidable, even for the most effective designs.

3.6.2 Seismic Isolation and Dissipation Devices

For longer and continuous span bridges at fault hazard zones, seismic isolation and response modification systems shall be considered [18]. Isolation systems such as friction pendulum bearings, capable of resisting both the dynamic and permanent offset displacements, have been successfully used on long viaducts [21, 22]. Other isolation systems may be equally viable.

Due to the stringent high-speed train serviceability requirements, careful attention must be made when using isolation and response modification systems, especially when considering their response to normal service loads.

3.6.3 Large Diameter Monopile Foundations

Where the fault zone is well defined, and the designer has confirmed that fault rupture will not rupture through the piers, traditional multi pile caps may be used.

Where the fault zone is not well defined, or is known to exist over a wide area, then large diameter monopile foundations shall be considered [23]. The use of this type system will minimize the risk of damage due to a fault rupture passing directly through a traditional multi pile cap.

3.6.4 Self Centering Columns

For near fault regions, where dynamic motions may be very intense, the use of self-centering columns [24] founded upon a traditional multi pile cap shall be considered. Self-centering columns have been shown to be capable of reducing post-earthquake residual displacements.

Self-centering columns are concrete columns with vertical, concentric unbonded post-tensioned tendons. Research has shown that the tendons effectively apply a restoring force, thus limiting residual post-earthquake displacements. The use of unbonded vertical reinforcement, and steel jackets at the plastic hinge zones, further add to self-centering column performance.

3.7 SECONDARY MITIGATING STRATEGIES FOR UNDERGROUND STRUCTURES

Where at-grade tracks are infeasible, such as at congested sites, water crossings, or mountainous terrain, underground structures may be unavoidable.

For mitigation Class B systems, variances to HST performance and operational criteria will be required. Such variances must be specified in writing, and are subject to approval by the Authority.

Secondary mitigating designs for underground structures which allow rapid track realignment and structural repair shall be pursued. Some secondary mitigating strategies for underground structures at fault hazard zones follow.

3.7.1 Fault Chambers

Where tunnels cross known faults with large offset displacements, local use of a larger tunnel cross section shall be considered [19]. The larger cross section shall be sized based upon the predicted direction and magnitude of offset in order to allow clear passage and realignment of track post-earthquake.

It may be necessary to extend the length of the larger cross section beyond the fault zone length for track realignment purposes.

3.7.2 Increased Width at U-Walls

Where U-walls exist at known fault crossings, consideration shall be made for increased width in recognition of anticipated damage to the walls. The increased width will provide more separation between the tracks and damaged walls, allow room for construction access, and provide additional flexibility for realignment work.

3.7.3 Tunnel Lining System at Lesser Faults

Where tunnels cross known lesser faults with smaller offset displacements, a tunnel lining system shall be considered which allows rapid repair. Shotcrete and dowel rock reinforcement systems have been used previously for this situation [19]. If lining damage occurs, then additional dowels and shotcrete can be installed post-earthquake to allow service resumption.

3.8 OTHER PRIMARY STRUCTURES

3.8.1 Duct Bank Fault Chambers

Where duct banks cross known faults with large offset displacements, the use of an oversized buried containment structure to house the duct bank shall be considered. The size of the containment structure shall be based upon the predicted direction and magnitude of offset in order to maintain service.

It may be necessary to extend the length of the duct bank containment structure beyond the fault zone to maintain serviceability.

3.8.2 Service Loops

Service loops or extra lengths of fiber optic or other communication lines in duct banks shall be provided within fault zones.

3.9 HAZARD MITIGATION PLAN

When design solutions to minimize risk levels at fault hazard zones are not possible, mitigation measures shall be developed in accordance with the Hazard Management and Resolution Process prescribed by the project-wide System Safety Program Plan (SSPP) and may include the following:

- Definition of expected structural damage
- Health monitoring system
- Earthquake Early Warning Detection system
- Emergency access and evacuation plan
- Inspection Protocol
- Methods of repair
- Estimated down time
- Alternative routes, if any.

4.0 SUMMARY AND RECOMMENDATIONS

Guidance for fault definitions, design parameters, fault effects, displacement analysis, system mitigation classifications, and primary and secondary mitigation strategies where at-grade track, elevated structures, or tunnels occur at capable fault zones are presented in Section 6.0.

5.0 SOURCE INFORMATION AND REFERENCES

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2. AASHTO LRFD: AASHTO LRFD Bridge Design Specifications 4th Edition, 2007 published by the American Association of State Highway and Transportation Officials.
3. American Concrete Institute, Building Code Requirements for Reinforced Concrete, ACI 318.
4. American Institute of Steel Construction, Steel Construction Manual, Thirteenth Edition.
5. American Society of Civil Engineers, Minimum Design Loads for Buildings and Other Structures, ASCE/SEI 7-05.
6. Structural Welding Code, Steel, 1996 ANSI/AWS D1.1-96.
7. Bridge Welding Code ANSI/AASHTO/AWSD1.5-95
8. The California Building Code.
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    - Bridge Design Specification (BDS) - AASHTO LRFD Bridge Design Specification, 2005, with Caltrans Interim Revisions
    - Bridge Memo to Designers Manual (MTD)
    - Bridge Design Practices Manual (BPD)
    - Bridge Design Aids Manual (BDA)
    - Bridge Design Details Manual (BDD)
    - Standard Specifications
    - Standard Plans
    - Seismic Design Memorandum
    - CSDC: Caltrans Seismic Design Criteria ver. 1.4
10. European Standard EN 1991-2:2003 Traffic Loads on Bridges
11. European Standard EN 1990 annex A2: Application to Bridges
12. Taiwan High Speed Rail (THSR) Corporation: Volumes 1 and 3
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19. California High-Speed Train Program EIR/EIS, Task 1.11.a – Tunneling Issues Report, by Parsons Brinckerhoff, Inc., January, 2004.
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22. Priestley, M.J.N. and Calvi, G.M., “Strategies for Repair and Seismic Upgrading of Bolu Viaduct 1, Turkey”, Journal of Earthquake Engineering, Vol. 6, Special Issue 1, pp. 157-184, 2002
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24. Mahin, Sakai, and Jeong, “Use of Partially Prestressed Reinforced Concrete Columns to Reduce Post-Earthquake Residual Displacements of Bridges”, Paper No. B25, 5th National Seismic Conference on Bridges & Highways, San Francisco, CA, Sept 18-20, 2005

6.0 DESIGN MANUAL CRITERIA

6.1 FAULT RUPTURE ANALYSIS AND MITIGATION

This section provides guidelines for determining capable fault locations and expected displacements in terms of probability of fault rupture, fault displacement magnitude, and orientation and direction of displacement. These guidelines are to be used to establish fault displacements for use in preliminary design.

Since structures at or near capable faults are defined as complex, analysis requirements for the various stages of design are given.

Based upon the analysis results, mitigation measures required to achieve acceptable performance can be defined. A system mitigation classification is then determined based upon whether minimum CHSTP criteria may be met or whether a variance to the minimum criteria is required. The mitigation classification highlights the potential impact to project design, serviceability and operation.

The information included in this document is to be used in conjunction with TM 2.10.4: Interim Seismic Design Criteria and TM 2.9.3: Geologic and Seismic Hazard Analysis Guidelines.

6.2 DESIGN CODES AND SPECIFICATIONS

The structural design shall meet all applicable portions of the general laws and regulations of the State of California and of the respective local authorities.

Unless otherwise specified, HST facilities shall be designed in accordance with all applicable portions of the following standards and codes:

1. AREMA: American Railway Engineering and Maintenance-of-Way Association, Manual for Railway Engineering, 2009
2. ACI: American Concrete Institute, Building Code Requirements for Reinforced Concrete, ACI 318-05
3. AISC: American Institute of Steel Construction, Steel Construction Manual, 13th Edition
4. AWS D1.1/D1.1M:2008 Structural Welding Code-Steel
5. AASHTO/AWS D1.5M/D1.5:2008 Bridge Welding Code
6. AWS D1.8/D1.8M:2009 Structural Welding Code-Seismic Supplement
7. CBC: The 2007 California Building Code
8. California Department of Transportation (Caltrans) Bridge Design Manuals, latest edition
    - Bridge Design Specification (CBDS) - AASHTO LRFD Bridge Design Specification 4th Edition, 2007 with California Amendments
    - Bridge Memo to Designers Manual (CMTD)
    - Bridge Design Practices Manual (CBPD)
    - Bridge Design Aids Manual (CBDA)
    - Bridge Design Details Manual (CBDD)
    - Bridge Memo to Designers Manual (CMTD)
    - Standard Specifications
    - Standard Plans
    - Caltrans Seismic Design Criteria ver. 1.5 (CSDC)
9. ASCE/SEI 41-06: Seismic Rehabilitation of Existing Buildings. Reston, VA: American Society of Civil Engineers, 2007.

In the event of conflicting requirements between the CHSTP Design Criteria and other standards and codes of practice, the Design Criteria shall take precedence. For requirements that have not been included in the Design Criteria, the order of code adoption shall be: 1) local codes; 2) U.S. National Standards; 3) others.

6.3 FAULT DISPLACEMENT DESIGN PARAMETERS

6.3.1 General

Evaluation of fault rupture shall be provided for all three (3) performance criteria to be consistent with seismic design methods defined in TM 2.10.4: Interim Seismic Design Criteria for all faults that meet the capable fault definition as defined in Section 6.3.3. Displacement analyses shall provide designers with location, displacement magnitude, movement direction, and orientation and shall include a description of data uncertainty for consideration within the design process.

Methods of analysis are provided below and shall be implemented during the preliminary (15% design and 30% design), and final design. The fault displacement analysis for 15% design shall estimate the MCE-based displacement parameters in sufficient detail to preclude the need for realignment and/or revised footprint during subsequent 30% design. The 30% design shall implement fault displacement analysis methods for the MCE, DBE, and LDBE events in sufficient detail and reliability so that 30% design and cost estimate can be prepared for any required mitigations. The displacement methods are summarized in Section 6.3.5.

Additionally, local factors such as near-field effects and topographic amplification should be considered in estimating ground motions. These values shall be considered in assessing the required mitigation measures to meet the performance criteria.

These guidelines do not apply to buildings and facilities that do not carry high-speed train loadings. Buildings are subject to Alquist-Priolo requirements which state that buildings cannot be designed and built over Holocene faults.

6.3.2 Qualifications for Capable Fault Rupture Investigation

Geological investigations involving capable fault trace and displacement determination must be under the direct supervision of a current California licensed Engineering Geologist (CEG).

6.3.3 Capable Fault Definition

Faults subject to these criteria and guidelines are referred to as “capable faults”. Capable faults are defined as a mapped or otherwise known Quaternary fault with evidence of Holocene displacement, structural relationship to related Holocene faults, and/or where data is not sufficient to rule out the presence of Holocene movement.

Where the design of buildings is involved, the CBC definition of Active Faults shall be used and will be subject to all requirements of the Alquist-Priolo [13].

6.3.4 Seismic Performance Criteria and Probability

Fault rupture analysis shall be performed consistent with the Seismic Performance Criteria established in TM 2.10.4: Interim Seismic Design Criteria. There are three (3) performance levels and related design events to consider, which include:

- **NCL**: The No Collapse Performance Level (NCL)
- **SPL**: The Safety Performance Level (SPL)
- **OPL:** The Operability Performance Level (OPL)

6.3.5 Fault Displacement Analysis Methods

This section provides guidance on the methodologies which shall be used to develop surface fault displacements consistent with TM 2.9.6: Interim Ground Motion Guidelines, for all three performance criteria.

The guidelines address the methodologies to be used for 15%, 30%, and final design.

6.3.5.1 Fault Hazard Zone

The definition of the Fault Hazard Zone (FHZ) is defined as the overall zone within which deformations related to fault rupture may occur and should be considered in the design. This FHZ consists of three components; The primary zone of faulting, a surrounding zone within which secondary or sympathetic displacement has and/or may occur, and the safety zone which is a buffer zone surround the primary and secondary zones that represents the uncertainty of deformations in the future. The information from compiled literature, remote sensing, and field investigations (as required) shall be used to estimate the zone of potential primary rupture. All reasonable mapped fault locations shall be considered as part of the primary zone of fault rupture. The secondary rupture zone shall take into consideration sympathetic or secondary and typically lower displacements. The width of this zone shall encompass paleoseismic trench observations of secondary movement as well as empirical information for similar fault zones and their breadth of secondary movement. The safety zone breadth shall be left to the design team's discretion but will be demonstrated by the designer to be adequate to bracket the uncertainty of future movement(s).

The width of the distributive faulting shall also be assessed for the capable fault in question. That is, the nature of faulting within the overall capable fault zone shall differentiate between the potential for discrete faulting anywhere within the zone as opposed to the distribution of the displacement throughout this zone. A credible explanation will be needed for this differentiation and in the absence of this substantiation, both shall be considered possible and considered within the design until additional data can be obtained to provide the necessary substantiation. The defined fault zone shall conservatively capture potential for future distributive faulting. In addition, the zone containing all mapped faults shall be used to evaluate this spatial variability and thus the overall breadth of this zone and the greater of the two zone widths shall be used for design purposes.

6.3.5.2 Fault Displacement Methodology

Fault rupture analysis and design shall be consistent with the Seismic Design Criteria and Interim Ground Motion Analysis methods. These guidelines require fault displacement definition for the MCE event for 15% Design. For 30% and Final Design, the fault displacement values for MCE, DBE, and LDBE events shall be determined and evaluated.

Prior to evaluation of displacement magnitude, the probability of rupture shall be assessed to further define the fault as capable. Contrary to Alquist-Priolo regulations for buildings, the HST system will not necessarily prohibit the construction of non-building facilities at or near known active faults. Buildings will remain subject to California Building Codes (CBC) and thus A-P requirements apply and preclude construction over a Holocene Fault. The probability of rupture shall be evaluated using the seismic performance criteria identified in TM 2.9.6 - Interim Ground Motion Guidelines. The probability of rupture shall be evaluated for all faults meeting the capable fault definition above. The probability of rupture shall be based on rupture frequency data (where available and reliable)

In general, capable faults that have higher slip rates and/or high frequency return periods will remain classified as capable. If a fault can be effectively demonstrated to have a sufficiently long Return Interval (RI), it may be declassified as capable and may not be subject to the evaluation and mitigation requirements herein. The RI shall be defined as the characteristic (average) return period of the fault and will be compared to the most recent large earthquake. If the return interval (RI) for the fault is approximately equal to or less than the time since the most recent event (RE) and is less than the seismic performance criteria return period (SPC) and these are reliable values, the fault will be remain classified as capable of rupture. This comparison of Return Interval to the most recent event and SPC criteria is expressed in the simple equation as:

If RI – RE < SPC, then rupture is probable and the magnitude of displacement must be evaluated.

If RI - RE ≥ SPC, then rupture is not probable in relation to the seismic performance criteria

Where: RI = fault return interval

RE = time since the most recent event

SPC = Seismic Performance Criteria Return Period

As an example, if a mapped Quaternary fault is not mapped as Holocene but is on strike with a potentially structurally related fault with evidence of Holocene movement, it shall be classified as capable. If reliable existing or acquired fault characteristic data is available to effectively demonstrate that this fault has a well-constrained RI value of 3,500 years and the most recent event (RE) was 1,500 years ago, the projected future event would be 2,000 years. Since this value exceeds both the LDBE (100 year) and DBE (950 year) return periods, it would not need to be mitigated for these performance levels. However, since the value is less than the MCE event (2,475 return period), the system needs to be evaluated and mitigated for the NCL (No Collapse Level) performance criteria. It is critical that these fault characteristics be identified as early as possible and communicated to the PMT.

6.3.5.3 Fault Displacement Magnitude

The fault displacement shall be assessed based on the best available data for all three design stages, 15% Design, 30% Design and Final Design. The displacement value for the MCE (2,475 year return period), the DBE (945 year return period), and LDBE (100 year return period) events shall be estimated unless the RI-RE value is greater than the SPC. The displacement magnitude shall be based on the earthquake magnitude (Mw) derived using the Interim Ground Motion (IGM) Analysis methodology, thus assuring consistency between the ground motion value and the ground rupture displacement value for the same fault. Since the IGM methodology appropriately includes the affects of other nearby faults including a background event, the Mw for the fault shall be deaggregated to be representative of movement for only the subject capable fault.

During the 15% design, only the MCE ground motion is required and thus only an MCE-based Mw value will be available. While this is appropriate for ground motion analysis, the LDBE and/or the DBE level ground rupture and performance criteria may dictate design and may have significant influence on the HST alignment and/or feasibility. In this instance, the DBE-based Mw value shall be obtained using existing USGS and CGS data for that fault. In the absence of any existing fault data, the LDBE-based Mw value shall be assumed to be equal to the DBE-based Mw value.

The displacement value shall be computed using the empirical magnitude-displacement correlation developed by Wells and Coppersmith [15]. An alternative correlation can be used if it can be substantiated as being more applicable for the fault characteristics for the evaluated fault. The Youngs et al. [16] probabilistic fault displacement model shall then be used to independently assess the magnitude of fault displacement (principal and distributive). These values will be compared to the displacement estimated using the Wells and Coppersmith [15] values. The larger of the two values will be used in the design unless an effective argument can be provided which demonstrates that a certain method is more reliable for the evaluated fault.

Where the subject fault is a “creeping” fault with a high frequency of ruptures, the design will need to accommodate the total displacement during the life expectancy of the HST system by assuring that adequate right-of-way exists and that the cumulative strain can meet or exceed the performance criteria. The displacement analysis shall provide the frequency of displacements, displacement for each event, and the expected cumulative displacement.

6.3.5.4 Orientation and Direction of Displacement

The orientation of the fault is defined as the alignment and inclination of the fault plane. The direction of displacement is defined as the direction of slip along that plane represented by a vector along the planar surface. The orientation shall be presented as a fault strike value relative to north, and shall be described in degrees of rotation relative to the HST alignment at that location, where applicable. The fault orientation value shall be nearly perpendicular (90°±30˚) to HST alignment, in order to reduce fault zone length beneath the HST footprint.

The displacement direction for dip-slip faults shall be characterized as being either normal or reverse. Strike-slip faults shall be identified as being either left-lateral or right-lateral. For oblique-slip faults, the displacement of both dip-slip and strike-slip components shall be quantified.

The orientation and direction of displacement of potential ruptures shall be based on all available geologic evidence of fault behavior in the past. If multiple orientations are possible, each shall be considered in design until additional data can be obtained to better constrain this finding. Similarly, the direction of displacement shall be based on geologic data available and any uncertainties or contradictions in data shall be considered in the design until additional data can better define the displacement direction.

6.4 FAULT DISPLACEMENT DESIGN STRATEGIES

6.4.1 General

The displacement obtained from the procedures above shall be used to evaluate the performance of the structures in meeting the Seismic Performance Criteria as defined in TM 2.10.4 Interim Seismic Design Criteria.

6.4.2 Analysis Requirements

Per TM 2.10.4: Interim Seismic Design Criteria, structures at or near fault hazards are defined as complex.

Per TM 2.10.5: 15% Seismic Design Benchmarks, Equivalent Static Seismic Analysis is required for complex structures for 15% design. The equivalent static response from the dynamic component and fault offset component of motions may be added together by superposition.

At 30% and final design, (TM 2.10.4, Table 6.1), complex structures require either non-linear time history analysis or linear response spectra analysis, based upon the importance classification.

For non-linear time history analysis, the dynamic motions and permanent displacements are to be quantified in separate hazard assessments then combined into a single time history for design.

For linear response spectra analysis, the dynamic spectral response of the structure may be determined separately without consideration of fault displacement. The fault displacement response is then determined statically and added to the dynamic response by superposition

6.4.3 Mitigation Classification

Once analyses have been made for structures subject to fault rupture, the systems shall be classified by the mitigation measures required to achieve acceptable performance.

System classification highlights the potential impact to project alignment, design and operation.

- **Class A systems** can tolerate expected fault displacements using either standard or special mitigation design in order to meet Seismic Performance Criteria.
- **Class B systems** require special mitigation design, but cannot meet standard Seismic Performance Criteria, thus a variance to the minimum criteria and operation is required.
- **Class C systems** cannot meet Seismic Performance Criteria and cannot be feasibly mitigated with a variance. Thus, elevated and underground structures may not be used. Such Class C systems shall be comprised of at-grade ballasted track with no exceptions.

6.4.4 Variances to Standard Criteria

Damage of systems near or at fault hazard zones is a substantial risk to the HST system. If large fault offsets occur, unavoidable track or structural damage may occur, increasing the risk of train derailment. This is recognized in TM 2.10.4, which states “it is recognized that where the alignment crosses active faults, system seismic performance criteria may be impractical due to expected large offset displacements each side of the fault.”

Thus, for systems with Class B mitigation classification, variances to standard CHSTP performance and operational criteria will be required. Such variances must be specified in writing, and are subject to approval by the Authority.

Examples of performance criteria variances for Class B systems include:

- Exceedence of allowable strain limits for structural components (i.e., variance to TM 2.10.4: Interim Seismic Design Criteria)
- Exceedence of allowable deformation limits for the track and structure or exceedence of allowable rail stresses, under an LDBE event (i.e.: variance to TM 2.10.10: High-Speed Train and Track Structure Compatibility)

Examples of operational criteria variances for Class B systems include:

- Reduced train speeds near the fault crossing
- Reduced train service near the fault crossing
- Temporary closure for repairs following an LDBE event
- Extended closures for repairs following a DBE event

For each Class B mitigation scenario, it is the responsibility of the designer to determine what variances to standard design criteria are needed, and submit a Variance Request for approval by the Authority.

6.4.5 Typical Design Process for Capable Fault Zone Structures

Typical design for elevated or underground structures at fault hazard zones shall consist of [18]:

- Evaluation of site conditions: fault classification and characterization for the three design earthquakes.
- Determination of near fault dynamic ground motions, and permanent (i.e.: fault offset) displacements.
- Preparation of preliminary design concepts.
- Preliminary design based upon the near fault dynamic ground motions and permanent (i.e.: fault offset) motions, in order to determine structural demands, and necessary expansion joint displacement and rotational demands.
- Submittal and approval of mitigation Class B system variances to CHST performance and operational criteria.
- Development of a bridge or tunnel hazard mitigation plan (final design).
- Development of a bridge or tunnel health monitoring system (final design).

For the 15% design level, the design submittal at fault crossings shall include:

- Identification of fault hazards.
- Estimate expected fault displacement demands for the MCE event.
- Preliminary design concepts.
- 15% design Equivalent Static Analyses.
- Determination of the preliminary Mitigation Classification.
- Mitigation Class B system variances to the Authority.
- At-grade alignments for Class C systems.
- Documentation of mitigations and provide 15% level cost estimate.

For the 30% design level, the design submittal at fault crossings shall include:

- Final identification of fault hazards.
- Determination of expected fault displacement demands for LDBE, DBE, and MCE events.
- 30% design non-linear time history analysis or llinear response spectra analysis, based upon Structural Classification as defined in TM 2.10.4: Interim Seismic Design Criteria.

- Final Mitigation Classification for the system.
- Approved Mitigation Class B variances.
- At-grade alignments for Class C systems.
- Documentation of the design, mitigations, and 30% design cost estimate.

6.5 PRIMARY MITIGATING STRATEGY AT CAPABLE FAULT ZONES

At fault hazard zones, the primary mitigating strategy is to place the alignment at-grade with ballasted track, oriented as near to perpendicular (90°±30˚) as feasible to the fault trace, in order to minimize the fault zone length beneath the HST footprint, and allow timely inspections and repairs after an earthquake event.

Elevated and underground construction at fault hazard zones shall, to all practical extents, be avoided.

In order to place the track at-grade, structural improvements such as embankments and retaining walls may be necessary. Where embankments and retaining walls are needed, consideration shall be made for an increased width of right-of-way. This is in recognition of anticipated damage to the embankments and retaining walls. The increased width shall provide more separation between the tracks and improvements, and add flexibility for realignment work.

For fault offset induced seismic pressures for retaining walls, and modified stability analyses for embankments, refer to the Geotechnical Data Report.

The primary mitigating strategy for trackside Systems facilities, including traction power, train control, communications, and other significant equipment, buildings, huts, and enclosures, is to locate these facilities outside all fault hazard zones.

6.5.1 At-Grade Track

Track Structure Compatibility Criteria is under development.

6.5.2 Earthquake Early Warning System

An earthquake early warning detection system (EEWDS) shall be developed and used system-wide, including additional sensors at fault hazard zone regions. The detection system shall be integrated with the train control, communications and signals systems, and be capable of triggering an appropriate response for at risk trains to bring them to a safe stop as soon as p-waves are detected.

The EEWDS will not be effective if a train is near or at the fault zone due to the short time lapse between the p-wave and s-wave generation. For trains within a few miles of the fault zone, the EEWDS shall be designed to precipitate the braking of trains to a safe stop before they cross potentially damaged track.

Additionally, the EEWDS implementation shall be coordinated with maintenance and inspection protocols.

6.6 SECONDARY MITIGATING STRATEGIES FOR ELEVATED STRUCTURES

Where at-grade tracks are infeasible, such as at congested sites, water crossings, or mountainous terrain, then elevated structures may be unavoidable.

For mitigation to Class B systems, variances to standard HST performance and operational criteria will be required. Such variances must be specified in writing, and are subject to approval by the Authority.

Realizing the potential for fault rupture damage, mitigating designs which allow rapid track realignment and structural repair shall be pursued. Some secondary mitigating strategies for elevated structures at fault hazard zones follow.

6.6.1 Simple Spans and Elongated Bearing Seats

In order to cost effectively meet train performance requirements, relatively short, simple span structures shall be used. Since such structures, when subject to large fault displacements, are at risk of girder unseating and potential collapse, large and elongated bearing seats shall be used to accommodate the necessary rotations and displacements without introducing significant damaging forces to the piers or girders [18].

Elongated bearing seats not only provide increased displacement capacity, but also allow for possible post-earthquake realignment capability, thus avoiding costly and time-consuming demolition and reconstruction.

Note that temporary closure, track realignment, and repair reconstruction may be unavoidable, even for the most effective designs.

6.6.2 Seismic Isolation and Dissipation Devices

For longer and continuous span bridges at fault hazard zones, seismic isolation and response modification systems shall be considered [18]. Isolation systems such as friction pendulum bearings, capable of resisting both the dynamic and permanent offset displacements, have been successfully used on long viaducts [21, 22]. Other isolation systems may be equally viable.

Due to the stringent high-speed train serviceability requirements, careful attention must be made when using isolation and response modification systems, especially when considering their response to normal service loads.

6.6.3 Large Diameter Monopile Foundations

Where the fault zone is well defined, and the design has confirmed that fault rupture will not rupture through the piers, traditional multi pile caps may be used.

Where the fault zone is not well defined, or is known to exist over a wide area, then large diameter monopile foundations shall be considered [23]. The use of this type system will minimize the risk of damage due to a fault rupture passing directly through a traditional multi pile cap.

6.6.4 Self Centering Columns

For near fault regions, where dynamic motions may be very intense, the use of self-centering columns [24] founded upon a traditional multi pile cap shall be considered. Self-centering columns have been shown to be capable of reducing post-earthquake residual displacements.

Self-centering columns are concrete columns with vertical, concentric unbonded post-tensioned tendons. Research has shown that the tendons effectively apply a restoring force, thus limiting residual post-earthquake displacements. The use of unbonded vertical reinforcement, and steel jackets at the plastic hinge zones, further add to self-centering column performance.

6.7 SECONDARY MITIGATING STRATEGIES FOR UNDERGROUND STRUCTURES

Where at-grade tracks are infeasible, such as at congested sites, water crossings, or mountainous terrain, underground structures may be unavoidable.

For mitigation Class B systems, variances to HST performance and operational criteria will be required. Such variances must be specified in writing, and are subject to approval by the Authority.

Secondary mitigating designs for underground structures which allow rapid track realignment and structural repair shall be pursued. Some secondary mitigating strategies for underground structures at fault hazard zones follow.

6.7.1 Fault Chambers

Where tunnels cross known faults with large offset displacements, local use of a larger tunnel cross section shall be considered [19]. The larger cross section shall be sized based upon the predicted direction and magnitude of offset in order to allow clear passage and realignment of track post-earthquake.

It may be necessary to extend the length of the larger cross section beyond the fault zone length for track realignment purposes.

6.7.2 Increased Width at U-Walls

Where U-walls exist at known fault crossings, consideration shall be made for increased width in recognition of anticipated damage to the walls. The increased width will provide more separation between the tracks and damaged walls, allow room for construction access, and provide additional flexibility for realignment work.

6.7.3 Tunnel Lining System at Lesser Faults

Where tunnels cross known lesser faults with smaller offset displacements, a tunnel lining system shall be considered which allows rapid repair. Shotcrete and dowel rock reinforcement systems have been used previously for this situation [19]. If lining damage occurs, then additional dowels and shotcrete can be installed post-earthquake to allow service resumption.

6.8 OTHER PRIMARY STRUCTURES

6.8.1 Duct Bank Fault Chambers

Where duct banks cross known faults with large offset displacements, the use of an oversized buried containment structure to house the duct bank shall be considered. The size of the containment structure shall be based upon the predicted direction and magnitude of offset in order to maintain service.

It may be necessary to extend the length of the duct bank containment structure beyond the fault zone to maintain serviceability.

6.8.2 Service Loops

Service loops or extra lengths of fiber optic or other communication lines in duct banks shall be provided within fault zones.

6.9 HAZARD MITIGATION PLAN

When design solutions to minimize risk levels at fault hazard zones are not possible, mitigation measures shall be developed in accordance with the Hazard Management and Resolution Process prescribed by the project-wide System Safety Program Plan (SSPP) and may include the following:

- Definition of expected structural damage
- Health monitoring system
- Earthquake Early Warning Detection system
- Emergency access and evacuation plan
- Inspection Protocol
- Methods of repair
- Estimated down time
- Alternative routes, if any.