California High-Speed Train Project

TECHNICAL MEMORANDUM

Fault Hazard Analysis and Mitigation Guidelines
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.

System Level Technical Reviews by Subsystem:

Systems:	Not Required Bradley Banks, PE	 Date
Infrastructure:	*Signed document on file* Gene Lusherovich, PE	8 May 2014 Date
Operations and Maintenance:	*Signed document on file* Joseph Metzler	24 April 2014 Date
Safety:	*Signed document on file* John Cockle	23 April 2014 Date
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ABSTRACT

The California High-Speed Train Project (CHSTP) system shall be designed to accommodate displacement associated with faults and fault zones. This Technical Memorandum (TM) provides guidelines for the identification, characterization, and mitigation of fault displacement.

Attention is directed to California's Alquist-Priolo Earthquake Fault Zoning Act 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.

As part of the California Building Code (CBC), the Alquist-Priolo Act has jurisdiction over buildings for human occupancy. Therefore, CHST buildings such as stations, maintenance buildings, etc., shall be subject to requirements that do not allow placement of buildings on or immediately adjacent to Holocene faults.

Because no codes exist in California which regulate non-building structures subject to transient human occupancy, such as railway tracks and viaducts, this TM provides guidelines for analysis and mitigation that may not be consistent with Alquist-Priolo. The term "active" fault is specific to the Alquist-Priolo Act; in this TM the term "hazardous" fault is used.

This TM does not address vibratory ground motions; refer to TM 2.9.6: Interim Ground Motion Guidelines for motion development procedures.

For purposes of evaluating fault displacement hazard within this TM, faults and fault zones are defined as brittle failure of the ground surface having an elongated (miles) and uniform surface trend within a narrowly defined zone defined in tens to one-hundreds of feet in width. They are differentiated from tectonically induced landslides, and non-brittle surface and near surface deformation, such as folding or warping, which are addressed in TM 2.9.3: Geologic and Seismic Hazard Analysis.

Faults shall be identified and characterized as Non-Hazardous Faults, Potentially Hazardous Fault Zones (PHFZs) and Hazardous Fault Zones (HFZs) through a progressive process described in this TM.

PHFZs shall include all faults with known Holocene activity and shall include Quaternary faults where Holocene activity is suspected or cannot be reasonably disputed. <u>PHFZs shall be communicated early in the preliminary design process</u> since mitigations may be required to meet CHSTP performance objectives.

1.0 INTRODUCTION

1.1 PURPOSE OF TECHNICAL MEMORANDUM

This Technical Memorandum (TM) establishes design guidelines for fault hazard displacement analysis, and mitigation.

During and after strong vibratory ground motions and fault displacements, safe train operation and minimizing the probability of high-speed train derailment are the main concern of the Authority. Because of the high likelihood of large fault displacements during the life of the system, preventive measures will be made to guard against derailment, and to avoid long term system shut-downs.

1.2 STATEMENT OF TECHNICAL ISSUE

This TM provides the methodology for identifying faults that may pose a surface faulting hazard, estimating fault displacements, and presents some appropriate mitigation measures.

Preventative measures shall be made to minimize the probability of high-speed train derailment, and allow operation to continue during and after an Operating Basis Earthquake (OBE) event.

Preventative measures shall be made to prevent collapse, contain derailment, and avoid long shut-downs during and after a Maximum Considered Earthquake (MCE) event.

1.3 GENERAL INFORMATION

1.3.1 Definition of Terms

The following technical terms, acronyms, and abbreviations used in this document have specific connotations with regard to the CHST system.

Fault	A tectonically induced relative and measurable displacement between two crustal blocks nucleating at some depth within the earth’s crust; surface fault rupture is the surface expression of relative movement along the fault
Fault Hazard Zone	The overall zone within which deformations related to fault rupture may occur and shall be considered in the design, including both principal and distributive fault traces
Hazardous Fault	A potentially hazardous fault with documented evidence of displacement that meets any or all fault displacement criteria including slip rate (SR) and/or recurrence interval (RI)
Maximum Considered Earthquake (MCE) Fault Displacements	Fault displacements corresponding to the greater of (1) a mean probabilistic fault displacement based upon a 10% probability of exceedance in 100 years (i.e., a return period of 950 years); and (2) a deterministic assessment of the median estimate of the average displacement associated with the characteristic earthquake on the fault
Operating Basis Earthquake (OBE) Fault Displacements	Fault displacements corresponding to the greater of (1) a mean probabilistic fault displacement based upon an 86% probability of exceedance in 100 years (i.e., a return period of 50 years); and (2) ground deformation performance criteria that would lead to degradation of the rail alignment such that high speed running would not be possible because of the risk of derailment (e.g., horizontal ground offset of 12 inches or a total vertical ground offset of 4 inches over any 10-foot wide zone during a surface rupture event)

Potentially Hazardous Fault	A fault having mapped or otherwise known Holocene activity, including those faults structurally related to Holocene faults and including Quaternary faults with suspected Holocene activity and/or insufficient data to develop a reasonable dispute against such activity; faults whose most recent displacement is pre-Holocene are considered non-hazardous

Acronyms/Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
AISC	American Institute of Steel Construction, Manual of Steel Construction
AP	Alquist-Priolo Earthquake Fault Zoning Act of 1972
ASCE	American Society of Civil Engineers
AWS	Structural Welding Standards
BDS	Bridge Design Specifications
Caltrans	California Department of Transportation
CBC	California Building Code
CBDM	Caltrans Bridge Design Manuals
CGS	California Geological Survey
CHST	California High-Speed Train
CHSTP	California High-Speed Train Project
CSDC	Caltrans Seismic Design Criteria
EEWDS	Earthquake Early Warning Detection System
FHZ	Fault Hazard Zone
HF	Hazardous Fault
HFZ	Hazardous Fault Zone
MCE	Maximum Considered Earthquake
M_w	Moment Magnitude Scale of Earthquake
NCL	No Collapse Performance Level
OBE	Operating Basis Earthquake
OPL	Operability Performance Level
PMT	Program Management Team
PHF	Potentially Hazardous Fault
PHFZ	Potentially Hazardous Fault Zone
RI	Recurrence Interval
SDAP	Seismic Design and Analysis Plan
SR	Slip Rate
SSPP	System Safety Program Plan
TM	Technical Memorandum

1.3.2 Units

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

2.0 DEFINITION OF TECHNICAL TOPIC

2.1 GENERAL

This technical memorandum (TM) establishes fault definitions, design parameters, fault effects, fault displacement analysis guidelines, and presents some appropriate mitigation measures.

Refer to TM 2.10.4: Seismic Design Criteria for infrastructure design classifications, and definition of two design earthquakes along with classification specific seismic performance objectives and acceptable damage. Per TM 2.10.4, structures at HFZs are defined as “Complex” and subject to specific analytical requirements. Mitigation at HFZs shall aim to meet all performance requirements consistent with TM 2.10.4.

For purposes of evaluating fault displacement hazards, faults and fault zones are defined as brittle failure of the ground surface having an elongated (miles) and uniform surface trend within a narrowly defined zone defined in tens to one-hundreds of feet in width. Initial screening methods and assessment of other seismic and geologic hazards, such as tectonically induced landslides, non-brittle surface and near surface deformation such as folding or warping, are provided in TM 2.9.3: Geologic and Seismic Hazard Analysis.

This TM references an established methodology for conducting probabilistic fault displacement hazard analyses. Within that methodology, the displacement method is recommended over the earthquake method.

For mitigations at HFZs, general concepts were taken from a paper by Bray. For elevated structures, the basis of the following guidelines and criteria rely on information assembled by FIB (the International Federation for Structural Concrete) Task Group 7.4. For underground structures, a 2004 CHSTP EIR/EIS level “Tunneling Issues Report” was used for reference material.

2.1.1 CHSTP Design Considerations

Seismic design considerations can significantly influence operation, risk, performance, and cost of high-speed train facilities. The following design considerations are reflected in this TM:

- The maximum initial operating speed is 220 mph. The maximum design speed for the main tracks is 250 miles per hour; segments of the alignment may be designed to lesser speeds.
- Design and construction of high-speed train facilities shall comply with the approved and permitted environmental documents.

2.2 DESIGN VARIANCES TO SEISMIC DESIGN CRITERIA

Mitigation at HFZs shall aim to meet all performance requirements consistent with TM 2.10.4. However, this may be infeasible for large magnitude HFZ displacements.

Where design variances to performance and operational criteria are the only practical option, they shall be prepared according to TM 1.1.18: Design Variance Guidelines.

2.3 SEISMIC DESIGN AND ANALYSIS PLAN

As a requirement of TM 2.10.4, the Designer shall develop a Seismic Design and Analysis Plan (SDAP) for each infrastructure element.

The SDAP shall define the following:

- General Classification as Primary Type 1, Primary Type 2, or Secondary, as defined in TM 2.10.4
- Technical Classification as “Complex”, as defined in TM 2.10.4 (all infrastructure elements at HFZs are defined as “Complex” within TM 2.10.4)

The SDAP shall contain detailed commentary on seismic analysis for each design earthquake, including analysis during Operating Basis Earthquake (OBE) events as required per TM 2.10.10: Track-Structure Interaction.

For fault displacement design, the SDAP shall indicate the analysis software to be used, modeling assumptions and techniques to be employed.

The SDAP shall contain commentary as to the suitability of linear versus nonlinear analysis, considering the magnitude of fault displacement, the severity of vibratory ground motions, induced strains in the soil and structure, expected nonlinearities, and expected inelastic behavior.

The SDAP shall define the pre-determined mechanism for seismic response, and the regions of targeted inelastic response.

2.4 DESIGN REFERENCES AND CODES

The provisions within this TM shall govern the design. Provisions in the following documents shall also be considered as guidelines where applicable and when sufficient criteria are not provided by this TM.

- American Concrete Institute (ACI)
  - ACI 318: Building Code Requirements for Structural Concrete [1]
  - ACI 350: Code Requirements for Environmental Engineering Concrete Structures and Commentary [2]
- American Welding Society (AWS) Codes
  - AWS D1.1/D1.1M: Structural Welding Code-Steel [3]
  - AWS D1.8/D1.8M: Structural Welding Code-Seismic Supplement [4]
- American Association of State Highway and Transportation Officials (AASHTO)
  - AASHTO/AWS D1.5M/D1.5: Bridge Welding Code [5]
  - AASHTO Guide Specifications for LRFD Seismic Bridge Design [6]
  - AASHTO Guide Specifications for Seismic Isolation Design [7]
  - AASHTO LRFD Bridge Construction Specifications [8]
- California Building Code (CBC) [9]
- American Railway Engineering and Maintenance-of-Way Association (AREMA)
  - Manual for Railway Engineering [10]
- American Society of Civil Engineers (ASCE)
  - ASCE 7: Minimum Design Loads for Buildings and Other Structures [11]
  - ASCE 41: Seismic Rehabilitation of Existing Buildings [12]
- American Institute of Steel Construction (AISC)
  - Steel Construction Manual [13]
- California Department of Transportation (Caltrans) Bridge Design Manuals (CBDM)
  - Caltrans Bridge Design Specification – AASHTO LRFD Bridge Design Specifications and California Amendments (to the AASHTO LRFD Bridge Design Specifications), hereafter referred to as "AASHTO LRFD BDS with California Amendments" [14,15]
  - Caltrans Bridge Memo to Designers Manual (CMTD) [16]
  - Caltrans Bridge Design Practices Manual (CBDP) [17]
  - Caltrans Bridge Design Aids Manual (CBDA) [18]
  - Caltrans Bridge Design Details Manual (CBDD) [19]
  - Caltrans Seismic Design Criteria (CSDC) [20]

Criteria for design elements not specific to high-speed rail 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 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 other agency standards.

Attention is directed to California's Alquist-Priolo Earthquake Fault Zoning Act of 1972, which is intended 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.

As part of the CBC, the Alquist-Priolo Act has jurisdiction over buildings for human occupancy. Therefore, CHST buildings such as stations, maintenance buildings, etc., shall be subject to requirements that do not allow placement of buildings on or immediately adjacent to Holocene faults.

Because no codes exist in California that regulate non-building structures subject to transient human occupancy, such as railway tracks and viaducts, this TM provides guidelines for analysis and mitigation of such structures that may not be consistent with the Alquist-Priolo Act. The term "active" fault is specific to the Alquist-Priolo Act; in this TM the term "hazardous" fault is used.

Guidelines within this TM are generally consistent with Caltrans Memo to Designer (CMTD) 20-10, which defines a methodology for surface fault rupture displacement determination. The CMTD 20-10 references California Geological Survey (CGS) guidelines for evaluating surface fault hazards, and the methodology by Wells and Coppersmith and Hecker et al. 2013 for estimating fault displacements.

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

3.0 ANALYSIS AND ASSESSMENT

3.1 GENERAL

This TM provides guidelines for identifying HFZs in terms of their fault displacements, recurrence rates, orientation, sense of slip, and other characteristics. The methodology for assessing fault hazard displacement includes both deterministic and probabilistic approaches to quantify the best estimates of fault displacements to be used in design.

Based upon the expected fault displacement magnitudes, some appropriate mitigation measures are presented.

The information included in this TM is to be used in conjunction with TM 2.10.4: Seismic Design Criteria, TM 2.9.6: Interim Ground Motion Guidelines, and TM 2.9.3: Geologic and Seismic Hazard Analysis Guidelines.

3.2 FAULT DISPLACEMENT DESIGN PARAMETERS

3.2.1 General

A three-tiered analysis is presented, which shall be used in defining and characterizing hazardous fault displacements. The analysis is illustrated in Figure 3-1.

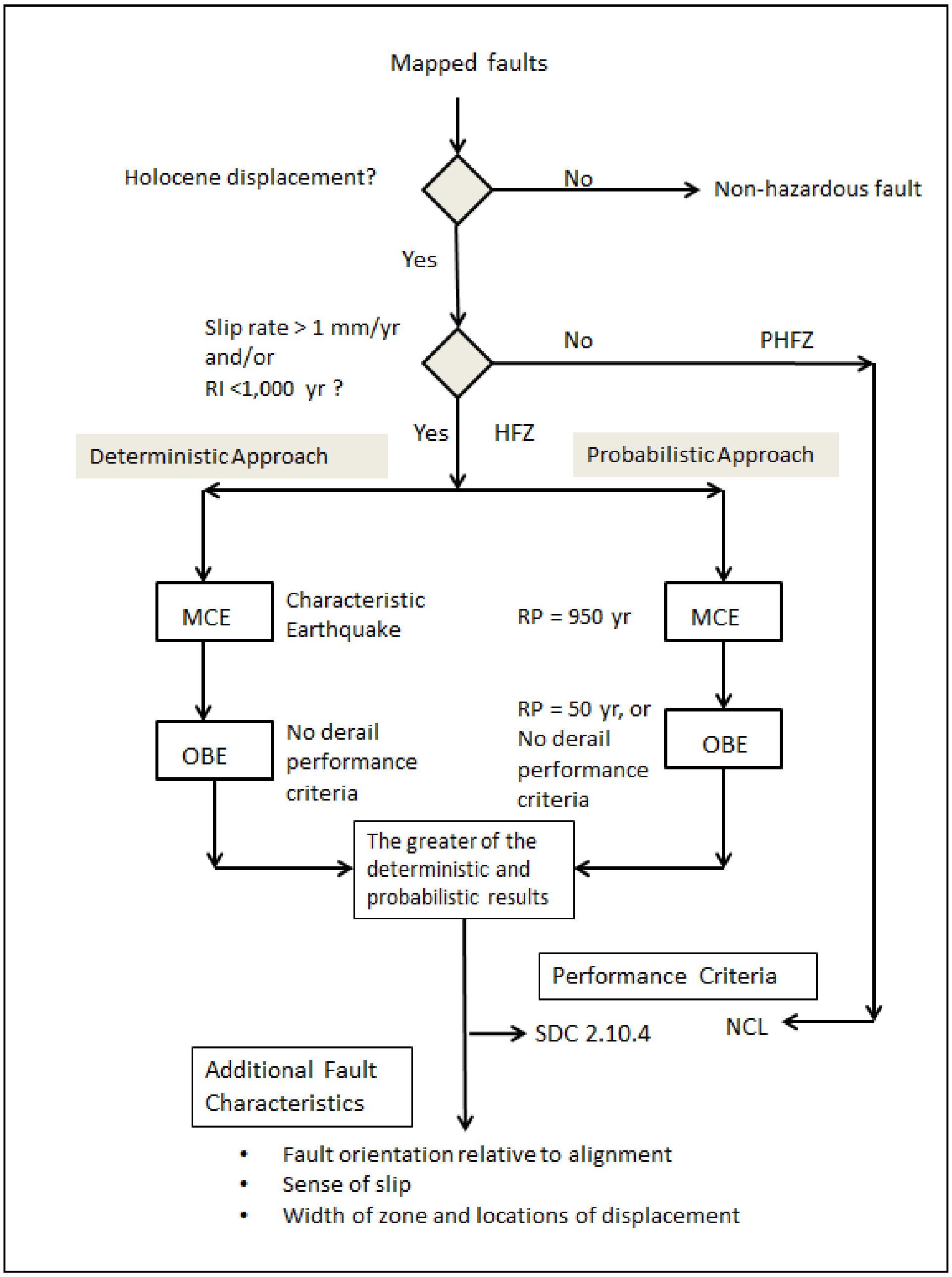
First, an initial screening of mapped faults shall be performed as part of the Geologic and Seismic Hazard Evaluation required by TM 2.9.3: Geologic and Seismic Hazard Analysis Guidelines. This screening will identify any PHFZs based on available information pertaining to the likelihood of Holocene fault activity. The screening analysis is described in section 3.2.2 of this TM.

Second, all PHFZs shall be evaluated relative to two hazard factors: recurrence interval (RI) and slip rate (SR). Any faults meeting or exceeding either of these criteria shall be considered HFZs and will need to be addressed in mitigation design. The process for identifying HFZs is given in section 3.2.3.

Third, estimates of fault displacement at HFZs for purposes of design will be made using deterministic and probabilistic analysis methods. In addition to the amount of displacement, a number of other characteristics of the fault crossing shall be assessed, including the orienation of faults, the sense of slip, and the width of the zone of faulting. The methods for assessing fault displacements and their characteristics is given in section 3.2.4.

This TM does not address development of vibratory ground motions, refer to TM 2.9.6: Interim Ground Motion Guidelines.

Figure 3-1: Tiered Process for Identifying Hazardous Fault Zones and Defining Design Basis Fault Displacements



3.2.2 Screening of Mapped Faults

Consistent with the guidance in TM 2.9.3: Geologic and Seismic Hazard Analysis Guidelines, available geologic data shall be compiled and evaluated with respect to the recency of displacement for purposes of screening. Mapped faults shall be evaluated with respect to the geologic evidence of the most recent displacement. If definitive data are not available, the evaluation shall include consideration of available geomorphic data, tectonic models, and possible connections with other faults whose recency is known. PHFZs include faults with documented evidence of Holocene activity and shall include Quaternary faults for which Holocene activity is suspected or cannot be reasonably disputed. The screening assessment is intended to identify Holocene faults, which are classified as PHFZs, and Non-Hazardous faults that are assessed to be older than Holocene and are, therefore, screened out.

3.2.3 Hazardous Fault Zone Definition

All faults having known or suspected Holocene activity (i.e., PHFZs) shall be evaluated based on available information related to their recurrence rates and their geologic slip rates. Should either or both of the following criteria be met or exceeded, the PHFZ shall be classified as a HFZ:

- Recurrence interval (RI) ≤ 1,000 years
- Slip rate (SR) ≥ 1 mm/year

The evaluation of faults relative to these criteria will entail the evaluation of all available geologic data related to the paleoseismic history of the fault. If no such data exist, it may be necessary to conduct limited geologic investigations designed to address these criteria (e.g., geomorphic analyses, geologic mapping, age-dating, Quaternary geologic studies) within reasonable ranges of uncertainty.

As depicted in Figure 3-1, if it is determined that the fault does not meet or exceed the criteria described above, then the fault shall be classified as a PHFZ and will require estimation of possible displacement based on existing data. The displacement estimated shall be that assessed to be associated with the MCE event. This displacement shall be considered in meeting the No Collapse Limit (NCL) performance criteria under the MCE event, which is defined in section 3.2.4.1.

If the PHFZ meets or exceeds the RI or SR criteria set forth above, the fault shall be classified as a HFZ and the amounts of displacement for design shall be determined, other important fault characteristics assessed, and mitigation measures, variances to the seismic design criteria, and/or avoidance of the HFZ shall be considered, as discussed in section 3.2.4.

3.2.4 Hazardous Fault Displacement Analysis Methods

Estimated fault displacement at HFZs shall be evaluated based on available information and investigative data, as needed. Site investigations shall be made at HFZs to evaluate the displacement characteristics where the HFZ intersects the high-speed track alignment. At HFZs, geologic site investigations may be necessary to provide the data required as input to fault displacement hazard assessments. Such investigations are likely to include geologic mapping, geomorphic studies, age-dating analyses, and paleoseismic trenching. Geologic site investigations shall be performed with necessary approved and permitted environmental documents.

Using the information developed as part of the geologic investigations, both a deterministic and a probabilistic methodology shall be used to assess the fault displacement hazard, and the larger fault displacement estimate shall be used for design (refer to Figure 3-1).

The deterministic approach shall be conducted by assessing the median estimate of the average displacement (not maximum fault displacement) associated with the “characteristic earthquake” on the fault as defined from geologic data (Schwartz and Coppersmith, 1984; Hecker et al., 2013). Magnitudes and displacements associated with the characteristic earthquake shall be assessed based on empirical relationships, such as those developed by Wells and Coppersmith and Petersen et al..

The probabilistic approach shall use an accepted probabilistic fault displacement hazard analysis (PFDHA) approach to arrive at fault displacement hazard curves at the fault crossings (i.e., Youngs et al., 2003). As noted in Youngs et al. (2003), it is suggested that the “displacement” approach be used that relies on single-site data on the amount of displacement associated with past events. If this type of paleo-displacement data can be developed from field investigations, then displacement per event can be assessed directly rather than by first estimating magnitudes from rupture segment length. The displacement per event and slip rate developed from local geologic data will provide the input needed for the PFDHA. Otherwise, the analysis shall use the “earthquake approach” in Youngs et al. (2003) that uses information on slip rate and assessments of the recurrence rates of various magnitudes and their associated displacements per event. Once the mean hazard curve is developed at the fault crossing, it can be entered at the return periods of interest (e.g., return periods of 50 or 950 years) to get the design displacement value. Note that lower activity faults may have zero fault displacement hazard at short return periods, and this should be expected.

The larger of the displacements derived from the probabilistic and deterministic approaches shall be used for design. In cases where significant differences exist between these two approaches and there are significant cost implications, a variance can be applied for to justify a lower displacement value.

3.2.4.1 Design Basis Fault Displacements

As illustrated in Figure 3-1, the fault displacements derived from both the deterministic and probabilistic analyses are used to define design basis fault displacements for two levels: the Maximum Considered Earthquake (MCE) and the Operating Basis Earthquake (OBE).

For the deterministic approach, the MCE fault displacement is defined by the median estimate of the average displacement associated with the “characteristic earthquake” on the fault, as defined above in section 3.2.4. The OBE fault displacement is defined by the ground deformation performance criteria that would lead to degradation of the rail alignment such that high-speed running would not be possible because of the risk of derailment (e.g., horizontal ground offset of 12 inches or a total vertical ground offset of 4 inches over any 10-foot wide zone during a surface rupture event).

For the probabilistic approach, the MCE fault displacement is defined by the mean probabilistic fault displacement based upon a 10% probability of exceedance in 100 years (i.e., a return period of 950 years). The OBE fault displacement is defined by the greater of a mean probabilistic fault displacement based upon an 86% probability of exceedance in 100 years (i.e., a return period of 50 years) and the deterministically-defined OBE fault displacement.

PHFZs will also require estimation of possible displacement based on existing data. The displacement estimated shall be that assessed to be associated with the MCE event, as defined in the deterministic approach. This displacement shall be considered in meeting the No Collapse Limit (NCL) performance criteria under the MCE event.

In addition to the amount of fault displacement, a HFZ shall also be characterized according to other parameters that are important to design, as discussed in section 3.2.4.2.

3.2.4.2 Characteristics of a Hazardous Fault Zone

The characteristics of HFZs of importance to fault displacement design shall be defined and consist of the following:

- Fault orientation relative to alignment (direction of strike and dip)
- Sense of slip (rake, horizontal and vertical components)
- Width of zone and locations of displacement (primary, secondary traces, buffer zone)

Each of these characteristics is discussed below.

Fault Orientation Relative to Alignment

The orientation of the fault is defined as the direction of the strike and dip of the fault plane. The orientation shall be presented as a fault strike value relative to north and shall be described in degrees of rotation relative to the CHST alignment at that location, where applicable. To minimize fault displacement hazards, the alignment of the at-grade CHST track shall be nearly perpendicular (90° ± 30°) to the strike of the fault. This will reduce the fault zone length beneath the CHST footprint.

Sense of Slip

The sense of slip on a fault is defined as being primarily horizontal (strike slip) or vertical (dip slip). 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 components of horizontal and vertical slip on a fault of interest shall be defined by the rake or the slip vector along the fault surface.

The sense of slip and rake of potential ruptures shall be based on 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 the actual orientation.

Width of Zone and Locations of Displacement

A HFZ is characterized as the overall zone within which deformations related to fault rupture may occur and shall be considered in the design.

A HFZ consists of three components:

1. The primary zone of faulting
2. A secondary zone of faulting within which secondary or subsidiary displacement may occur
3. A safety or buffer zone surrounding the primary and secondary zones of faulting, which represents the uncertainty in the location of future deformations

For the primary zone of faulting, all information from compiled literature, remote sensing, and field investigations, including both surface mapping and paleoseismic trench observations, shall be used. All reasonable mapped fault locations shall be considered as part of the primary zone of faulting. In order to minimize uncertainty, the identification of primary zones of faulting shall be based on field observations made at the location where the rail alignment crosses the fault to the extent possible.

The secondary rupture zone shall take into consideration secondary or subsidiary displacements, which are typically smaller than the primary zone displacements. The width of this zone shall be based on field observations of secondary displacement at or near the alignment's fault crossing and, if fault-specific data cannot be developed, using empirical information from similar fault zones and their breadth of secondary faulting. To minimize uncertainty regarding the width of this zone, field observations shall be made at the location where the rail alignment crosses the fault.

The recommended safety or buffer zone width shall be a minimum of 50 feet, but may be greater based on field evidence. The final buffer zone width is left to the design team's discretion; however, it must be shown to adequately bracket the uncertainty of future displacements.

3.3 FAULT DISPLACEMENT DESIGN STRATEGIES

3.3.1 General

The design basis fault displacement obtained from the procedures above shall be used to evaluate the performance of the structures in meeting the seismic performance objectives as described in TM 2.10.4.

3.3.2 Analysis Requirements

As stated in TM 2.10.4, structures at HFZs are defined as Complex. Refer to TM 2.10.4 for analysis requirements for both preliminary and final design of Complex structures.

3.3.3 Design Process for Hazardous Fault Zone Structures

For the preliminary design, the design process at HFZs shall include the following:

- Identify HFZs, evaluate site conditions, classify and characterize the fault displacements for the design earthquakes.
- Determine the vibratory ground motions for the design earthquakes.
- Prepare preliminary design concepts and mitigation strategies. Submit SDAP (refer to section 2.3) for review and approval.
- Perform preliminary design per the SDAP and TM 2.10.4.
- Where design variances to performance and operational criteria are necessary, submit design variance according to TM 1.1.18.
- Provide preliminary design cost estimates.

For final design, the design process at HFZs shall include:

- Identify HFZs, evaluate site conditions, and classify and characterize the fault displacements for the design earthquakes.
- Determine the vibratory ground motions for the design earthquakes.
- Prepare final design concepts and mitigation strategies. Submit SDAP (refer to section 2.3) for review and approval.
- Perform final design per the SDAP and TM 2.10.4. Prepare final design drawings and specifications.
- Where design variances to performance and operational criteria are necessary, submit design variance according to TM 1.1.18.
- Provide final design cost estimate.
- Develop a HFZ hazard mitigation plan; refer to section 3.4.6.
- Develop a HFZ structural health monitoring plan; refer to section 3.4.7.

3.4 MITIGATION STRATEGIES AT HAZARDOUS FAULT ZONES

3.4.1 General

When a significant fault surface ruptures, it is likely that local track alignment will degrade to such an extent that a train running at high speed will derail. Thus, at all HFZs, derailment mitigation features shall be provided for within the design.

Refer to TM 2.1.7 Rolling Stock and Vehicle Intrusion Protection for High-Speed Rail and Adjacent Transportation Systems for additional commentary of derailment mitigation.

Generally, HFZ mitigation designs which facilitate track repair and realignment, and minimize the potential for the HST to leave the right-of-way shall be pursued. The appropriate HFZ mitigation strategy depends upon whether the dominant direction of fault displacement is lateral or vertical.

3.4.2 Mitigation Strategy Where Dominant Fault Displacement is Lateral

Where the alignment crosses a HFZ and the dominant direction of fault displacement is in the lateral direction (i.e., strike-slip), the appropriate mitigation 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 CHST footprint.

At-grade track refers to ballasted track supported directly off engineered or native grades, on embankments, or on cut slopes, refer to TM 2.1.5: Track Design for track design criteria.

3.4.2.1 Increased Width of Right-of-Way

When designing at-grade track at HFZs, consideration shall be made for an increased width of right-of-way with large widths of level ground on each side of the tracks.

The increased width shall be used to provide separation between the tracks and improvements, provides access for emergency rescue, and adds flexibility for post-event track realignment and reconstructive work.

3.4.2.2 Increased Length of Level Ground within and beyond the HFZ

When designing at-grade track at HFZs, consideration shall be made for an increased length of level ground within and beyond the HFZ. The increased length will provide a “runout” section for the derailment mitigation features, so the train can come to a standstill while remaining upright.

3.4.2.3 Embankment Mitigations

At embankments, the use of engineered, compacted fill has been shown to be an effective means to mitigate fault displacement hazards. Three geotechnical design techniques are typically used to partially add ductility to the underlying ground, and absorb and spread out the underlying bedrock fault displacement:

- Increasing the height of compacted fill
- Increasing the ductility of compacted fill
- Installing geosynthetic reinforcement

Refer to the Geotechnical Data Report for embankment design and stability analysis criteria.

3.4.2.4 Cut Slope Mitigations

Increased right-of-way width provisions mitigate the potential for a derailed train to ride up adjacent cut slopes and overturn. Refer to the Geotechnical Data Report for cut slope design and stability analysis criteria.

3.4.2.5 Retaining Wall Mitigations

Where retaining walls are required for at-grade track placement, the walls shall be designed for ductile performance in order to avoid fracture and abrupt wall dislocation which will mitigate a blunt edge hazard for the derailed train.

Refer to the Geotechnical Data Report for fault displacement induced seismic wall pressures.

Consideration shall be made to using loose soil or collapsible backfill in order to reduce the lateral earth pressures on walls.

3.4.3 Mitigation Strategy Where Dominant Fault Displacement is Vertical

Where the alignment crosses a HFZ and the dominant direction of fault displacement is vertical (i.e., reverse or normal), the appropriate mitigation strategy is to provide a structural solution in the form of an elevated, earth-supporting, or at-grade structure.

3.4.3.1 Articulation at Piers

Where elevated structures cross HFZs, increased articulation at piers shall be considered in order to accommodate the expected displacements and rotations without inducing significant forces in the superstructure or piers. This requires joints to be designed to generously accommodate the necessary rotations and displacements, as well as careful ductile detailing of structural components.

3.4.3.2 Simple Spans and Elongated Bearing Seats

Simple span structures with attention to articulation at the pier shall be considered. Since such structures, when subject to large fault displacements, are at risk of girder unseating and potential collapse. For such structures, large and elongated bearing seats shall be considered to accommodate the necessary rotations and displacements without introducing significant damaging forces to the piers or girders.

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.

The following additional mitigation measures for these type of structures shall be considered:

- Enhanced derailment containment, considering derailment loads greater than those prescribed by TM 2.3.2: Structure Design Loads
- Built-in facilities for repositioning spans for post-event track realignment

3.4.3.3 Seismic Isolation and Dissipation Devices

For bridges, aerial structures and grade separations at HFZs, seismic isolation and response modification systems with attention to articulation at piers shall be considered. Isolation systems such as friction pendulum bearings, capable of resisting both the vibratory ground motions and fault displacements, have been successfully used on long viaducts. Other isolation systems may be equally viable.

Due to the high-speed train serviceability requirements, careful attention must be made when using isolation and response modification systems, especially when considering their response to service loads, and track-structure interaction requirements per TM 2.10.10: Track-Structure Interaction.

3.4.3.4 Large Diameter Monopile Foundations

Where the HFZ is not well defined, or is known to exist over a wide area, large diameter monopile foundations shall be considered for elevated structures. The use of monopiles minimizes the hazard of a fault rupture passing directly through a traditional multi-pile cap.

3.4.3.5 Thickened Reinforced Concrete Mat Foundations

For building type structures at HFZs, in order to resist the combined effects of angular distortion and tensile ground strain due to fault movement, the use of strong, ductile thickened reinforced concrete mat foundations shall be considered. Such foundations can accommodate some level of ground deformation without compromising the functionality of the structure. They also can satisfy more routine design issues such as static fill deformation and seismically induced settlement.

In some applications, the use of “slip layers” can serve to limit the transmittable ground strain and decouple ground movements from the foundation. Conceptually, these slip layers consist of providing a series of polyethylene (plastic) sheets overlaying a clean granular soil-bedding layer below the mat foundation.

3.4.3.6 Fault Chambers

Where tunnels cross HFZs, local use of a larger tunnel cross section shall be considered. The larger cross section shall be sized based upon the predicted direction and amount of offset in order to allow clear passage and realignment of the track after a surface rupture event.

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

3.4.3.7 Increased Width at U-Walls

Where U-walls exist at HFZs, 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 track realignment work.

U-walls shall be designed for ductile performance in order to avoid fracture and abrupt wall dislocation, which will mitigate a blunt edge hazard for the derailed train.

3.4.3.8 **Tunnel Lining System**

Where tunnels exist at HFZs, a tunnel lining system shall be considered that allows rapid repair. Shotcrete and dowel rock reinforcement systems have been used previously for this situation. If lining damage occurs, additional dowels and shotcrete can be installed post-earthquake to allow service resumption.

3.4.4 Mitigation Strategy Where Alignment is Parallel to the Fault Trace

In the case where alignment is oriented parallel to a fault trace with predominantly vertical displacement (i.e., reverse and normal faults), provisions shall be made to place the structure on the "footwall" side of the trace.

3.4.5 Additional Mitigation Strategies

At HFZs, the following additional mitigation strategies shall be considered.

3.4.5.1 **Safety Features**

Safety features per the requirements of TM 2.8.1: Safety and Security Design Requirements for Infrastructure Elements shall be included in the design.

3.4.5.2 **Excluded Track or Track-Side Features**

At HFZs, the following track features shall not be permitted:

- Switches or Crossings
- Structures crossing over tracks
- Track-side structures or improvements within the increased width of right-of-way

3.4.5.3 **Stockpile Track Materials**

Material required to quickly repair a track section that could be potentially damaged by surface faulting (e.g., rails, ties, componentry, ballast) should be made readily available and stored under controlled and secure conditions at nearby maintenance of infrastructure facilities. This will facilitate rapid repair in the aftermath of a fault rupture at a track section.

The use of unique design items that are not readily available and are difficult to store and maintain in the long term shall be avoided at HFZs.

3.4.5.4 **Duct Bank Fault Chambers**

Where duct banks cross HFZs, 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 amount 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.

3.4.5.5 **Service Loops**

Where fiber optic or other communication lines cross HFZs, service loops or extra lengths of line within duct banks shall be considered.

3.4.6 Hazard Mitigation Plan

A Site-Specific Hazard Analysis Report shall be developed for HFZs in conformance with the hazard management program identified in the CHSRP Safety and Security Management Plan and shall include the following:

- Definition of effect on the CHSRP including track displacement and structural damage
- Derailment containment measures
- Health monitoring system
- Earthquake Early Warning Detection System (EEWDS)
- Emergency access and evacuation plan

- Inspection protocol
- Methods of repair
- Estimated down time

3.4.7 Structural Health Monitoring Plan

Where structures are used at HFZs, a structural health monitoring plan shall be developed. Guidelines for this plan are under development and pending.

3.4.8 Earthquake Early Warning Detection System

A systemwide earthquake early warning detection system (EEWDS) is being considered and may include additional sensors at HFZs.

The goal would be a system integrated with train control, communications and signal systems capable of detecting early P-wave ground motions, calculating the expected magnitude of shaking, and triggering braking response for at-risk trains.

If implemented, EEWDS will be coordinated with maintenance and inspection protocols.

4.0 SUMMARY AND RECOMMENDATIONS

The California High-Speed Train Project (CHSTP) system shall be designed to accommodate displacement associated with faults and fault zones. Specific design criteria regarding the identification, characterization, and mitigation of fault displacement has been made.

Faults shall be identified and characterized as Non-Hazardous Faults, Potentially Hazardous Fault Zones (PHFZs) and Hazardous Fault Zones (HFZs) through a progressive process described in this TM.

PHFZs shall include all faults with known Holocene activity and shall include Quaternary faults where Holocene activity is suspected or cannot be reasonably disputed.

HFZs shall include all PHFZs in which either or both of the following criteria are met or exceeded:

- Slip Rate (SR) ≥ 1 mm/year
- Recurrence Interval (RI) ≤ 1,000 years

All HFZs shall have future potential displacement estimated based on the greater of probabilistic and deterministic values. Methods for computing each are described in this document. In addition to the amount of displacement, the characteristics of the fault zone shall also include the orientation relative to the alignment, sense of slip, width of the zone of deformation, and locations of slip within the zone of deformation (primary and secondary zones of faulting).

PHFZs will also require estimation of possible displacement based on existing data and will not be required to meet the performance requirements for HFZs, but shall be considered when developing vibratory ground motions.

This TM does not address vibratory ground motions; refer to TM 2.9.6: Interim Ground Motion Guidelines for motion development procedures.

Refer to TM 2.10.4: Seismic Design Criteria for infrastructure design classifications, and definition of two design earthquakes along with classification specific seismic performance objectives and acceptable damage. Per TM 2.10.4, structures at HFZs are defined as “Complex” and subject to specific analytical requirements.

Mitigation at HFZs shall aim to meet all performance requirements consistent with TM 2.10.4. However, for large magnitude HFZ displacements this may be infeasible. Where design variances to performance and operational criteria are the only option, they shall be prepared according to TM 1.1.18: Design Variance Guidelines.

When a significant fault surface ruptures, it is likely that local track alignment will degrade to such an extent that a train running at high speed will derail. Thus, at all HFZs, derailment mitigation features shall be provided for within the design.

Generally, HFZ mitigation designs that facilitate track repair and realignment, and minimize the potential for the HST to leave the right-of-way shall be pursued. At HFZs, the appropriate HFZ mitigation strategy depends upon whether the dominant direction of fault displacement is lateral or vertical.

Where the dominant fault displacement is lateral, the appropriate mitigation 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 CHST footprint. Although at-grade crossings are preferred, embankments, retaining walls, and cut slopes are allowed.

Where the dominant fault displacement is vertical, the appropriate mitigation strategy is to provide a structural solution in the form of an elevated, earth-supporting, or at-grade structure.

5.0 SOURCE INFORMATION AND REFERENCES

1. ACI 318: American Concrete Institute, Building Code Requirements for Structural Concrete
2. ACI 350: American Concrete Institute, Code Requirements for Environmental Engineering Concrete Structures and Commentary
3. AWS D1.1/D1.1M: American Welding Society, Structural Welding Code-Steel
4. AWS D1.8/D1.8M: American Welding Society, Structural Welding Code Seismic Supplement
5. AASHTO/AWS D1.5M/D1.5: American Association of State Highway and Transportation Officials and American Welding Society, Bridge Welding Code,
6. AASHTO Guide Specifications for LRFD Seismic Bridge Design: American Association of State Highway and Transportation Officials
7. AASHTO Guide Specifications for Seismic Isolation Design: American Association of State Highway and Transportation Officials
8. AASHTO LRFD Bridge Construction Specifications: American Association of State Highway and Transportation Officials
9. California Building Code, Title 24 Part 2, Volumes 1 and 2
10. AREMA: American Railway Engineering and Maintenance-of-Way Association, Manual for Railway Engineering
11. ASCE 7: Minimum Design Loads for Buildings and Other Structures, American Society of Civil Engineers
12. ASCE 41: Seismic Rehabilitation of Existing Buildings, American Society of Civil Engineers
13. AISC: Steel Construction Manual, American Institute of Steel Construction
14. AASHTO LRFD Bridge Design Specifications: American Assocations of State Highway and Transportation Officials
15. California Amendments to AASHTO LRFD Bridge Design Specification, California Department of Transportation
16. Caltrans Bridge Memo to Designers Manual, California Department of Transportation
17. Caltrans Bridge Design Practice Manual, California Department of Transportation
18. Caltrans Bridge Design Aids Manual, California Department of Transportation
19. Caltrans Bridge Design Details Manual, California Department of Transportation
20. Caltrans Seismic Design Criteria, California Department of Transportation
21. California Geological Survey, Fault Rupture Hazard Zones, Special Publication 42, 47 pages, 2003, http://www.conservation.ca.gov/CGS/rghm/ap/Pages/Index.aspx
22. California Geological Survey, Guidelines for evaluating the hazard of surface fault rupture, CGS Note 49, 4 pp, 1996, http://www.conservation.ca.gov/cgs/information/publications/cgs_notes/note_49/Documents/note_49.pdf
23. Wells, D., and Coppersmith K., "New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement", Bulletin of the Seismological Society of America, Vol. 84, pp. 974-1002, 1994.
24. Petersen, M.D, Dawson, T.E, Chen, R., Cao, T., Wills, C.J., Schwartz, D.P., and Frankel, A.D., "Fault displacement hazard for strike-slip faults," Bulletin of the Seismological Society of America, Vol. 101, No. 2, pp. 805–825, April 2011.
25. Youngs, R.R., Arabasz, W.J., Anderson, R.E., Ramelli, A.R., Ake, J.P., Slemmons, D.B., McCalpin, J.P., Doser, D.I., Fridrich, C.J., Swan III, F.H., Rogers, A.M., Yount, J.C., Anderson, L.W., Smith, K.D., Bruhn, R.L., Knuepfer, P.L.K., Smith, R.B., dePolo, C.M., O'Leary, D.W., Coppersmith, K.J., Pezzopane, S.K., Schwartz, D.P., Whitney, J.W., Olig, S.S., and Toro, G.R., A Methodology for Probabilistic Fault Displacement Hazard Analysis (PFDHA), Earthquake Spectra, The Professional Journal of the Earthquake Engineering Institute, vol. 19, no. 1, p. 191-219, 2003.

26. FIB (the International Federation for Structural Concrete) Task Group 7.4, Seismic Design and Assessment Procedures for Bridges, Chapter 8: Design for Active Fault Crossings, primary author Ian Billings, 2003.
27. California High-Speed Train Program EIR/EIS, Task 1.11.a – Tunneling Issues Report, by Parsons Brinckerhoff, Inc., January, 2004.
28. Wesnousky, S., "Displacement and geometrical characterization of earthquake surface rupture: Issues and implications for seismic hazard analysis and the process of earthquake rupture", Bulletin of the Seismological Society of America, Vol. 98, No. 4, pp. 1609, 2008.
29. Ghasemi, H., “Bolu Viaduct: Damage assessment and retrofit strategy”, The 36th Joint Meeting of the US-Japan Panel on Wind and Seismic Effects (UJNR), Session 1, National Institute of Standards and Technology, Gaithersburg, Maryland, 2004.
30. 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.
31. Empelmann M., Whittaker D., Los E. and Dorgarten H., “Taiwan High Speed Rail Project – Seismic design of bridges across the Tuntzuchiao active fault”, 13th World Conference on Earthquake Engineering, Paper No. 140, Vancouver, B.C., Canada, 2004.
32. Bray, J. D., “Developing mitigation measures for the hazards associated with earthquake surface fault rupture,” Workshop on Seismic Fault-Induced Failures – Possible Remedies for Damage to Urban Facilities, Research Project 2000 Grant-in-Aid for Scientific Research (No. 12355020), Japan Society for the Promotion of Science, Workshop leader: Kazuo Konagai, University of Tokyo, Japan, pp. 55-79, January 11-12, 2001.
33. Anastasopoulos, I. and Gazetas, G., “Foundation-Structure Systems over a Rupturing Normal Fault: Part I. Observations after the Kocaeli 1999 Earthquake, 2007
34. Anastasopoulos, I. and Gazetas, G., “Behavior of Structure–Foundation Systems over a Rupturing Normal Fault: Part II. Analysis of the Kocaeli Case Histories, 2007
35. Bray, J.D. “Designing Buildings to Accommodate Earthquake Surface Fault Rupture, ATC and SEI 2009 Conference on Improving the Seismic Performance of Existing Buildings and Other Structures, 2009
36. Goel, R.K. and Chopra, A.K., “Analysis of Ordinary Bridges Crossing Fault Rupture ‘Zones,” EERC Report No. UCB/EERC-2008/01, 2008
37. NCHRP Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features, National Cooperative Highway Research Program, 1993
38. European Standard EN 12767: Passive Safety of Support Structures for read equipment. Requirements, classification and test methods.
39. Schwartz, D.P., and Coppersmith, K.J., “Fault Behavior and Characteristic Earthquakes: Examples From the Wasatch and San Andreas Fault Zones,” Journal of Geophysical Research, v. 89, no. B7, 5681-5698, 1984.
40. Hecker, S., Abrahamson, N.A., and Wooddell, K.E., “Variability of Displacement at a Point: Implications for Earthquake-Size Distribution and Rupture Hazard on Faults,” Bulletin of the Seismological Society of America, Vol. 103, No. 2A, pp. 651–674, April 2013.

6.0 DESIGN MANUAL CRITERIA

6.1 GENERAL

This technical memorandum (TM) establishes fault definitions, design parameters, fault effects, fault displacement analysis guidelines, and presents some appropriate mitigation measures.

Refer to TM 2.10.4: Seismic Design Criteria for infrastructure design classifications, and definition of two design earthquakes along with classification specific seismic performance objectives and acceptable damage. Per TM 2.10.4, structures at HFZs are defined as "Complex" and subject to specific analytical requirements. Mitigation at HFZs shall aim to meet all performance requirements consistent with TM 2.10.4.

For purposes of evaluating fault displacement hazards, faults and fault zones are defined as brittle failure of the ground surface having an elongated (miles) and uniform surface trend within a narrowly defined zone defined in tens to one-hundreds of feet in width. Initial screening methods and assessment of other seismic and geologic hazards, such as tectonically induced landslides, non-brittle surface and near surface deformation such as folding or warping, are provided in TM 2.9.3: Geologic and Seismic Hazard Analysis.

This TM references an established methodology for conducting probabilistic fault displacement hazard analyses. Within that methodology, the displacement method is recommended over the earthquake method.

For mitigations at HFZs, general concepts were taken from a paper by Bray. For elevated structures, the basis of the following guidelines and criteria rely on information assembled by FIB (the International Federation for Structural Concrete) Task Group 7.4. For underground structures, a 2004 CHSTP EIR/EIS level "Tunneling Issues Report" was used for reference material.

6.2 DESIGN VARIANCES TO SEISMIC DESIGN CRITERIA

Mitigation at HFZs shall aim to meet all performance requirements consistent with TM 2.10.4. However, this may be infeasible for large magnitude HFZ displacements.

Where design variances to performance and operational criteria are the only practical option, these shall be prepared according to TM 1.1.18: Design Variance Guidelines.

6.3 SEISMIC DESIGN AND ANALYSIS PLAN

As a requirement of TM 2.10.4, the Designer shall develop a Seismic Design and Analysis Plan (SDAP) for each infrastructure element.

The SDAP shall define the following:

- General Classification as Primary Type 1, Primary Type 2, or Secondary, as defined in TM 2.10.4
- Technical Classification as "Complex", as defined in TM 2.10.4 (i.e., all infrastructure elements at HFZs are defined as "Complex" within TM 2.10.4)

The SDAP shall contain detailed commentary on seismic analysis for each design earthquake, including analysis during Operating Basis Earthquake (OBE) events as required per TM 2.10.10: Track-Structure Interaction.

For fault displacement design, the SDAP shall indicate the analysis software to be used, modeling assumptions and techniques to be employed.

The SDAP shall contain commentary as to the suitability of linear versus nonlinear analysis, considering the magnitude of fault displacement, the severity of vibratory ground motions, induced strains in the soil and structure, expected nonlinearities, and expected inelastic behavior.

The SDAP shall define the pre-determined mechanism for seismic response, and the regions of targeted inelastic response.

6.4 DESIGN REFERENCES AND CODES

The provisions within this TM shall govern the design. Provisions in the following documents shall also be considered as guidelines where applicable and when sufficient criteria are not provided by this TM.

- American Concrete Institute (ACI)
  - ACI 318: Building Code Requirements for Structural Concrete [1]
  - ACI 350: Code Requirements for Environmental Engineering Concrete Structures and Commentary [2]
- American Welding Society (AWS) Codes
  - AWS D1.1/D1.1M: Structural Welding Code-Steel [3]
  - AWS D1.8/D1.8M: Structural Welding Code-Seismic Supplement [4]
- American Association of State Highway and Transportation Officials (AASHTO)
  - AASHTO/AWS D1.5M/D1.5: Bridge Welding Code [5]
  - AASHTO Guide Specifications for LRFD Seismic Bridge Design [6]
  - AASHTO Guide Specifications for Seismic Isolation Design [7]
  - AASHTO LRFD Bridge Construction Specifications [8]
- California Building Code (CBC) [9]
- American Railway Engineering and Maintenance-of-Way Association (AREMA)
  - Manual for Railway Engineering [10]
- American Society of Civil Engineers (ASCE)
  - ASCE 7: Minimum Design Loads for Buildings and Other Structures [11]
  - ASCE 41: Seismic Rehabilitation of Existing Buildings [12]
- American Institute of Steel Construction (AISC)
  - Steel Construction Manual [13]
- California Department of Transportation (Caltrans) Bridge Design Manuals (CBDM)
  - Caltrans Bridge Design Specification – AASHTO LRFD Bridge Design Specifications and California Amendments (to the AASHTO LRFD Bridge Design Specifications), hereafter referred to as “AASHTO LRFD BDS with California Amendments” [14,15]
  - Caltrans Bridge Memo to Designers Manual (CMTD) [16]
  - Caltrans Bridge Design Practices Manual (CBDP) [17]
  - Caltrans Bridge Design Aids Manual (CBDA) [18]
  - Caltrans Bridge Design Details Manual (CBDD) [19]
  - Caltrans Seismic Design Criteria (CSDC) [20]

Criteria for design elements not specific to high-speed rail 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 other agency standards.

Attention is directed to California’s Alquist-Priolo Earthquake Fault Zoning Act of 1972, which is intended 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.

As part of the CBC the Alquist-Priolo Act has jurisdiction over buildings for human occupancy. CHST buildings such as stations, maintenance buildings, etc., shall be subject to requirements that do not allow placement of buildings on or immediately adjacent to Holocene faults.

Because no codes exist in California that regulate non-building structures subject to transient human occupancy, such as railway tracks and viaducts, this TM provides guidelines for analysis and mitigation of such structures that may not be consistent with the Alquist-Priolo Act. The term “active” fault is specific to the Alquist-Priolo Act; in this TM the term “hazardous” fault is used.

Guidelines within this TM are generally consistent with Caltrans Memo to Designer (CMTD) 20-10, which defines a methodology for surface fault rupture displacement determination. The CMTD 20-10 references California Geological Survey (CGS) guidelines for evaluating surface fault hazards, and the methodology by Wells and Coppersmith and Hecker et al. 2013 for estimating fault displacements.

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

6.5 ANALYSIS AND ASSESSMENT

6.5.1 General

This TM provides guidelines for identifying HFZs in terms of their fault displacements, recurrence rates, orientation, sense of slip, and other characteristics. The methodology for assessing fault hazard displacement includes both deterministic and probabilistic approaches to quantify the best estimates of fault displacements to be used in design.

Based upon the expected fault displacement magnitudes, some appropriate mitigation measures are presented.

The information included in this TM is to be used in conjunction with TM 2.10.4: Seismic Design Criteria, TM 2.9.6: Interim Ground Motion Guidelines, and TM 2.9.3: Geologic and Seismic Hazard Analysis Guidelines.

6.6 FAULT DISPLACEMENT DESIGN PARAMETERS

6.6.1 General

A three-tiered analysis is presented which shall be used in defining and characterizing hazardous fault displacements. The analysis is illustrated in Figure 6-1.

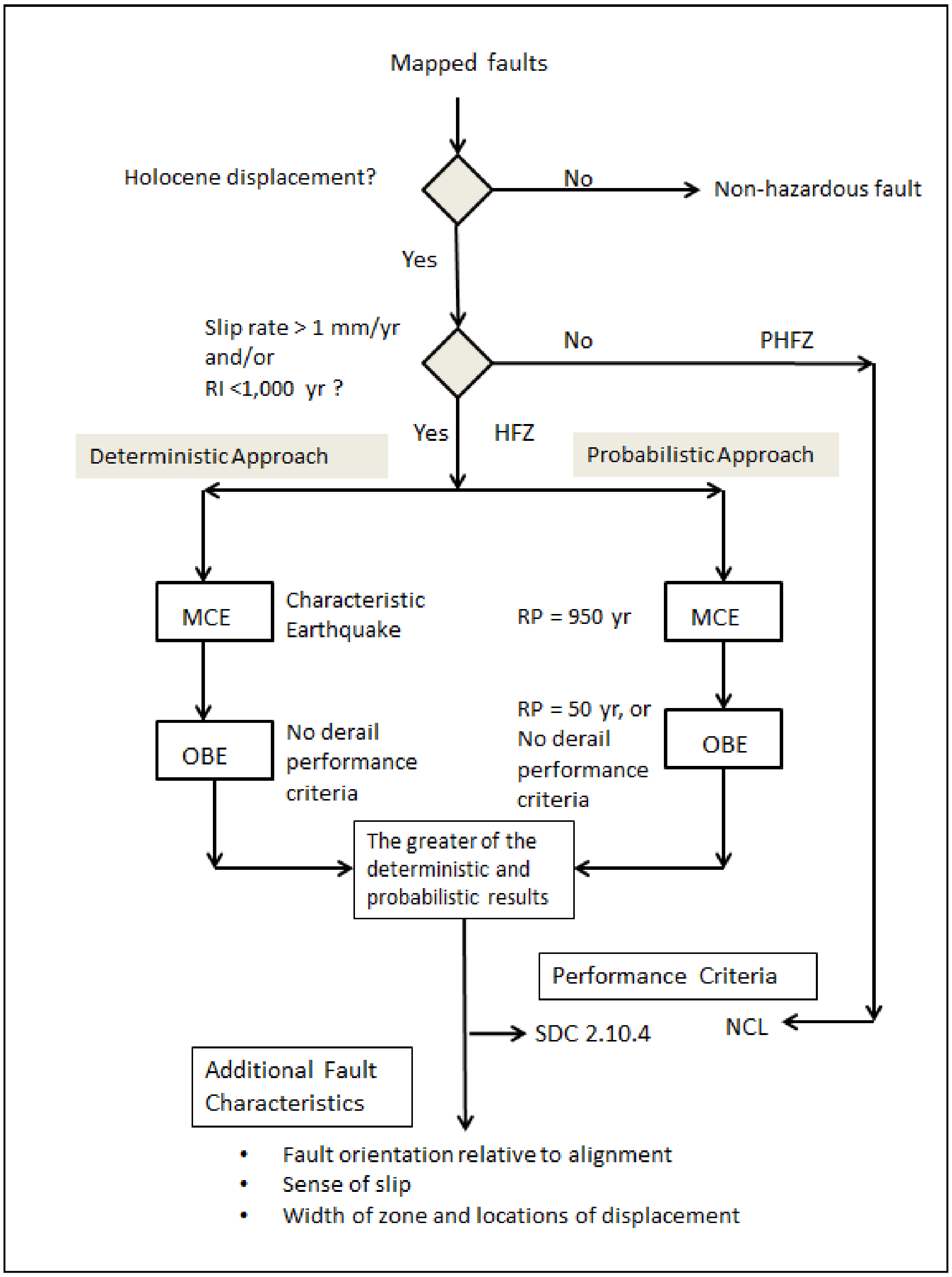
First, an initial screening of mapped faults shall be performed as part of the Geologic and Seismic Hazard Evaluation required by TM 2.9.3: Geologic and Seismic Hazard Analysis Guidelines. This screening will identify any PHFZs based on available information pertaining to the likelihood of Holocene fault activity. The screening analysis is described in section 6.2.2 .

Second, all PHFZs shall be evaluated relative to two hazard factors: recurrence interval (RI) and slip rate (SR). Any faults meeting or exceeding either of these criteria shall be considered HFZs and will need to be addressed in mitigation design. The process for identifying HFZs is given in section 6.6.3.

Third, estimates of fault displacement at HFZs for purposes of design will be made using deterministic and probabilistic analysis methods. In addition to the amount of displacement, a number of other characteristics of the fault crossing shall be assessed, including the orienation of faults, the sense of slip, and the width of the zone of faulting. The methods for assessing fault displacements and their characteristics is given in section 6.6.4.

This TM does not address development of vibratory ground motions; refer to TM 2.9.6: Interim Ground Motion Guidelines.

Figure 6-1: Tiered Process for Identifying Hazardous Fault Zones and Defining Design Basis Fault Displacements



6.6.2 Screening of Mapped Faults

Consistent with the guidance in TM 2.9.3: Geologic and Seismic Hazard Analysis Guidelines, available geologic data shall be compiled and evaluated with respect to the recency of displacement for purposes of screening. Mapped faults shall be evaluated with respect to the geologic evidence of the most recent displacement. If definitive data are not available, the evaluation shall include consideration of available geomorphic data, tectonic models, and possible connections with other faults whose recency is known. PHFZs include faults with documented evidence of Holocene activity and shall include Quaternary faults for which Holocene activity is suspected or cannot be reasonably disputed. The screening assessment is intended to identify Holocene faults, which are classified as PHFZs, and Non-Hazardous faults that are assessed to be older than Holocene and are, therefore, screened out.

6.6.3 Hazardous Fault Zone Definition

All faults having known or suspected Holocene activity (i.e., PHFZs) shall be evaluated based on available information related to their recurrence rates and their geologic slip rates. Should either or both of the following criteria be met or exceeded, the PHFZ shall be classified as a HFZ:

- Recurrence interval (RI) ≤ 1,000 years
- Slip rate (SR) ≥ 1 mm/year

The evaluation of faults relative to these criteria will entail the evaluation of all available geologic data related to the paleoseismic history of the fault. If no such data exist, it may be necessary to conduct limited geologic investigations designed to address these criteria (e.g., geomorphic analyses, geologic mapping, age-dating, Quaternary geologic studies) within reasonable ranges of uncertainty.

As depicted in Figure 6-1, if it is determined that the fault does not meet or exceed the criteria described above, then the fault shall be classified as a PHFZ and will require estimation of possible displacement based on existing data. The displacement estimated shall be that assessed to be associated with the MCE event. This displacement shall be considered in meeting the No Collapse Limit (NCL) performance criteria under the MCE event, which is defined in section 6.6.4.1.

If the PHFZ meets or exceeds the RI or SR criteria set forth above, the fault shall be classified as a HFZ and the amounts of displacement for design shall be determined, other important fault characteristics assessed, and mitigation measures, variances to the seismic design criteria, and/or avoidance of the HFZ shall be considered, as discussed in section 6.6.4.

6.6.4 Hazardous Fault Displacement Analysis Methods

Estimated fault displacement at HFZs shall be evaluated based on available information and investigative data, as needed. Site investigations shall be made at HFZs to evaluate the displacement characteristics where the HFZ intersects the high-speed track alignment. At HFZs, geologic site investigations may be necessary to provide the data required as input to fault displacement hazard assessments. Such investigations are likely to include geologic mapping, geomorphic studies, age-dating analyses, and paleoseismic trenching. Geologic site investigations shall be performed with necessary approved and permitted environmental documents.

Using the information developed as part of the geologic investigations, both a deterministic and a probabilistic methodology shall be used to assess the fault displacement hazard, and the larger fault displacement estimate shall be used for design (refer to Figure 6-1).

The deterministic approach shall be conducted by assessing the median estimate of the average displacement (not maximum fault displacement) associated with the “characteristic earthquake” on the fault as defined from geologic data (Schwartz and Coppersmith, 1984; Hecker et al., 2013). Magnitudes and displacements associated with the characteristic earthquake shall be assessed based on empirical relationships, such as those developed by Wells and Coppersmith and Petersen et al..

The probabilistic approach shall use an accepted probabilistic fault displacement hazard analysis (PFDHA) approach to arrive at fault displacement hazard curves at the fault crossings (i.e., Youngs et al., 2003). As noted in Youngs et al. (2003), it is suggested that the "displacement" approach be used that relies on single-site data on the amount of displacement associated with past events. If this type of paleo-displacement data can be developed from field investigations, then displacement per event can be assessed directly rather than by first estimating magnitudes from rupture segment length. The displacement per event and slip rate developed from local geologic data will provide the input needed for the PFDHA. Otherwise, the analysis shall use the "earthquake approach" in Youngs et al. (2003) that uses information on slip rate and assessments of the recurrence rates of various magnitudes and their associated displacements per event. Once the mean hazard curve is developed at the fault crossing, it can be entered at the return periods of interest (e.g., return periods of 50 or 950 years) to get the design displacement value. Note that lower activity faults may have zero fault displacement hazard at short return periods, and this should be expected.

The larger of the displacements derived from the probabilistic and deterministic approaches shall be used for design. In cases where significant differences exist between these two approaches and there are significant cost implications, a variance can be applied for to justify a lower displacement value.

6.6.4.1 Design Basis Fault Displacements

As illustrated in Figure 6-1, the fault displacements derived from both the deterministic and probabilistic analyses are used to define design basis fault displacements for two levels: the Maximum Considered Earthquake (MCE) and the Operating Basis Earthquake (OBE).

For the deterministic approach, the MCE fault displacement is defined by the median estimate of the average displacement associated with the "characteristic earthquake" on the fault, as defined in section 6.6.4. The OBE fault displacement is defined by the ground deformation performance criteria that would lead to degradation of the rail alignment such that high-speed running would not be possible because of the risk of derailment (e.g., horizontal ground offset of 12 inches or a total vertical ground offset of 4 inches over any 10-foot wide zone during a surface rupture event).

For the probabilistic approach, the MCE fault displacement is defined by the mean probabilistic fault displacement based upon a 10% probability of exceedance in 100 years (i.e., a return period of 950 years). The OBE fault displacement is defined by the greater of a mean probabilistic fault displacement based upon an 86% probability of exceedance in 100 years (i.e., a return period of 50 years) and the deterministically-defined OBE fault displacement.

PHFZs will also require estimation of possible displacement based on existing data. The displacement estimated shall be that assessed to be associated with the MCE event, as defined in the deterministic approach. This displacement shall be considered in meeting the No Collapse Limit (NCL) performance criteria under the MCE event.

In addition to the amount of fault displacement, a HFZ shall also be characterized according to other parameters that are important to design, as discussed in section 6.6.4.2.

6.6.4.2 Characteristics of a Hazardous Fault Zone

The characteristics of HFZs of importance to fault displacement design shall be defined and consist of the following:

- Fault orientation relative to alignment (direction of strike and dip)
- Sense of slip (rake, horizontal and vertical components)
- Width of zone and locations of displacement (primary, secondary traces, buffer zone)

Each of these characteristics is discussed below.

Fault Orientation Relative to Alignment

The orientation of the fault is defined as the direction of the strike and dip of the fault plane. The orientation shall be presented as a fault strike value relative to north and shall be described in degrees of rotation relative to the CHST alignment at that location, where applicable. To minimize fault displacement hazards, the alignment of the at-grade CHST track shall be nearly perpendicular (90° ± 30°) to the strike of the fault. This will reduce the fault zone length beneath the CHST footprint.

Sense of Slip

The sense of slip on a fault is defined as being primarily horizontal (strike slip) or vertical (dip slip). 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 components of horizontal and vertical slip on a fault of interest shall be defined by the rake or the slip vector along the fault surface.

The sense of slip and rake of potential ruptures shall be based on 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 the actual orientation.

Width of Zone and Locations of Displacement

A HFZ is characterized as the overall zone within which deformations related to fault rupture may occur and shall be considered in the design.

A HFZ consists of three components:

1. the primary zone of faulting
2. a secondary zone of faulting within which secondary or subsidiary displacement may occur
3. a safety or buffer zone surrounding the primary and secondary zones of faulting which represents the uncertainty in the location of future deformations

For the primary zone of faulting, all information from compiled literature, remote sensing, and field investigations, including both surface mapping and paleoseismic trench observations, shall be used. All reasonable mapped fault locations shall be considered as part of the primary zone of faulting. In order to minimize uncertainty, the identification of primary zones of faulting shall be based on field observations made at the location where the rail alignment crosses the fault to the extent possible.

The secondary rupture zone shall take into consideration secondary or subsidiary displacements, which are typically smaller than the primary zone displacements. The width of this zone shall be based on field observations of secondary displacement at or near the alignment's fault crossing and, if fault-specific data cannot be developed, using empirical information from similar fault zones and their breadth of secondary faulting. To minimize uncertainty regarding the width of this zone, field observations shall be made at the location where the rail alignment crosses the fault.

The recommended safety or buffer zone width shall be a minimum of 50 feet, but may be greater based on field evidence. The final buffer zone width is left to the design team's discretion; however, it must be shown to adequately bracket the uncertainty of future displacements.

6.7 FAULT DISPLACEMENT DESIGN STRATEGIES

6.7.1 General

The design basis fault displacement obtained from the procedures above shall be used to evaluate the performance of the structures in meeting the seismic performance objectives as described in TM 2.10.4.

6.7.2 Analysis Requirements

As stated in TM 2.10.4, structures at HFZs are defined as Complex. Refer to TM 2.10.4 for analysis requirements for both preliminary and final design of Complex structures.

6.7.3 Design Process for Hazardous Fault Zone Structures

For the preliminary design, the design process at HFZs shall include the following:

- Identify HFZs, evaluate site conditions, classify and characterize the fault displacements for the design earthquakes
- Determine the vibratory ground motions for the design earthquakes.
- Prepare preliminary design concepts and mitigation strategies. Submit SDAP (refer to section 6.3) for review and approval.
- Perform preliminary design per the SDAP and TM 2.10.4.
- Where design variances to performance and operational criteria are necessary, submit design variance according to TM 1.1.18.
- Provide preliminary design cost estimates.

6.8 MITIGATION STRATEGIES AT HAZARDOUS FAULT ZONES

6.8.1 General

When a significant fault surface ruptures, it is likely that local track alignment will degrade to such an extent that a train running at high speed will derail. Thus, at all HFZs, derailment mitigation features shall be provided for within the design.

Refer to TM 2.1.7 Rolling Stock and Vehicle Intrusion Protection for High-Speed Rail and Adjacent Transportation Systems for more detailed commentary of derailment mitigation .

Generally, HFZ mitigation designs which facilitate track repair and realignment, and minimize the potential for the HST to leave the right-of-way shall be pursued. The appropriate HFZ mitigation strategy depends upon whether the dominant direction of fault displacement is lateral or vertical.

6.8.2 Mitigation Strategy Where Dominant Fault Displacement is Lateral

Where the alignment crosses a HFZ and the dominant direction of fault displacement is in the lateral direction (i.e., strike-slip), the appropriate mitigation 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 CHST footprint.

At-grade track refers to ballasted track supported directly off engineered or native grades, on embankments, or on cut slopes, refer to TM 2.1.5: Track Design for track design criteria.

6.8.2.1 **Increased Width of Right-of-Way**

When designing at-grade track at HFZs, consideration shall be made for an increased width of right-of-way with large widths of level ground on each side of the tracks.

The increased width shall be used to provide separation between the tracks and improvements, provides access for emergency rescue, and adds flexibility for post-event track realignment and reconstructive work.

6.8.2.2 **Increased Length of Level Ground within and beyond the HFZ**

When designing at-grade track at HFZs, consideration shall be made for an increased length of level ground within and beyond the HFZ. The increased length will provide a “runout” section for the derailment mitigation features, so the train can come to a standstill while remaining upright.

6.8.2.3 **Embankment Mitigations**

At embankments, the use of engineered, compacted fill has been shown to be an effective means to mitigate fault displacement hazards. Three geotechnical design techniques are typically used to partially add ductility to the underlying ground, and absorb and spread out the underlying bedrock fault displacement:

- Increasing the height of compacted fill

- Increasing the ductility of compacted fill
- Installing geosynthetic reinforcement

Refer to the Geotechnical Data Report for embankment design and stability analysis criteria.

6.8.2.4 Cut Slope Mitigations

Increased right-of-way width provisions mitigate the potential for a derailed train to ride up adjacent cut slopes and overturn. Refer to the Geotechnical Data Report for cut slope design and stability analysis criteria.

6.8.2.5 Retaining Wall Mitigations

Where retaining walls are required for at-grade track placement, the walls shall be designed for ductile performance in order to avoid fracture and abrupt wall dislocation which will mitigate a blunt edge hazard for the derailed train.

Refer to the Geotechnical Data Report for fault displacement induced seismic wall pressures.

Consideration shall be made to using loose soil or collapsible backfill in order to reduce the lateral earth pressures on walls.

6.8.3 Mitigation Strategy Where Dominant Fault Displacement is Vertical

Where the alignment crosses a HFZ and the dominant direction of fault displacement is vertical (i.e., reverse or normal), the appropriate mitigation strategy is to provide a structural solution in the form of an elevated, earth-supporting, or at-grade structure.

6.8.3.1 Articulation at Piers

Where elevated structures cross HFZs, increased articulation at piers shall be considered in order to accommodate the expected displacements and rotations without inducing significant forces in the superstructure or piers. This requires joints to be designed to generously accommodate the necessary rotations and displacements, as well as careful ductile detailing of structural components.

6.8.3.2 Simple Spans and Elongated Bearing Seats

Simple span structures with attention to articulation at the pier shall be considered. Since such structures, when subject to large fault displacements, are at risk of girder unseating and potential collapse. For such structures, large and elongated bearing seats shall be considered to accommodate the necessary rotations and displacements without introducing significant damaging forces to the piers or girders.

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.

The following additional mitigation measures for these type of structures shall be considered:

- Enhanced derailment containment, considering derailment loads greater than those prescribed by TM 2.3.2: Structure Design Loads
- Built-in facilities for repositioning spans for post-event track realignment

6.8.3.3 Seismic Isolation and Dissipation Devices

For bridges, aerial structures and grade separations at HFZs, seismic isolation and response modification systems with attention to articulation at piers shall be considered. Isolation systems such as friction pendulum bearings, capable of resisting both the vibratory ground motions and fault displacements, have been successfully used on long viaducts. Other isolation systems may be equally viable.

Due to the high-speed train serviceability requirements, careful attention must be made when using isolation and response modification systems, especially when considering their response to service loads, and track-structure interaction requirements per TM 2.10.10: Track-Structure Interaction.

6.8.3.4 Large Diameter Monopile Foundations

Where the HFZ is not well defined, or is known to exist over a wide area, large diameter monopile foundations shall be considered for elevated structures. The use of monopiles minimizes the hazard of a fault rupture passing directly through a traditional multi-pile cap.

6.8.3.5 Thickened Reinforced Concrete Mat Foundations

For building type structures at HFZs, in order to resist the combined effects of angular distortion and tensile ground strain due to fault movement, the use of strong, ductile thickened reinforced concrete mat foundations shall be considered. Such foundations can accommodate some level of ground deformation without compromising the functionality of the structure. They also can satisfy more routine design issues such as static fill deformation and seismically induced settlement.

In some applications, the use of “slip layers” can serve to limit the transmittable ground strain and decouple ground movements from the foundation. Conceptually, these slip layers consist of providing a series of polyethylene (plastic) sheets overlaying a clean granular soil-bedding layer below the mat foundation.

6.8.3.6 Fault Chambers

Where tunnels cross HFZs, local use of a larger tunnel cross section shall be considered. The larger cross section shall be sized based upon the predicted direction and amount of offset in order to allow clear passage and realignment of the track after a surface rupture event.

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

6.8.3.7 Increased Width at U-Walls

Where U-walls exist at HFZs, 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 track realignment work.

U-walls shall be designed for ductile performance in order to avoid fracture and abrupt wall dislocation which will mitigate a blunt edge hazard for the derailed train.

6.8.3.8 Tunnel Lining System

Where tunnels exist at HFZs, a tunnel lining system shall be considered that allows rapid repair. Shotcrete and dowel rock reinforcement systems have been used previously for this situation. If lining damage occurs, additional dowels and shotcrete can be installed post-earthquake to allow service resumption.

6.8.4 Mitigation Strategy Where Alignment is Parallel to the Fault Trace

In the case where alignment is oriented parallel to a fault trace with predominantly vertical displacement (i.e., reverse and normal faults), provisions shall be made to place the structure on the “footwall” side of the trace.

6.8.5 Additional Mitigation Strategies

At HFZs, the following additional mitigation strategies shall be considered.

6.8.5.1 Safety Features

Safety features per the requirements of TM 2.8.1: Safety and Security Design Requirements for Infrastructure Elements shall be included in the design.

6.8.5.2 Excluded Track or Track-Side Features

At HFZs, the following track features shall not be permitted:

- Switches or Crossings
- Structures crossing over tracks
- Track-side structures or improvements within the increased width of right-of-way

6.8.5.3 Stockpile Track Materials

Material required to quickly repair a track section that could be potentially damaged by surface faulting (e.g., rails, ties, componentry, ballast) should be made readily available and stored under controlled and secure conditions at nearby maintenance of infrastructure facilities. This will facilitate rapid repair in the aftermath of a fault rupture at a track section.

The use of unique design items that are not readily available and are difficult to store and maintain in the long term shall be avoided at HFZs.

6.8.5.4 Duct Bank Fault Chambers

Where duct banks cross HFZs, 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 amount 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.

6.8.5.5 Service Loops

Where fiber optic or other communication lines cross HFZs, service loops or extra lengths of line within duct banks shall be considered.

6.8.6 Hazard Mitigation Plan

A Site-Specific Hazard Analysis Report shall be developed for all HFZs in conformance with the hazard management program identified in the CHSRP Safety and Security Management Plan and shall include the following:

- Definition of effect on the CHSRP including track displacement and structural damage
- Derailment containment measures
- Health monitoring system
- Earthquake Early Warning Detection System (EEWDS)
- Emergency access and evacuation plan
- Inspection protocol
- Methods of repair
- Estimated down time

6.8.7 Structural Health Monitoring Plan

Where structures are used at HFZs, a structural health monitoring plan shall be developed. Guidelines for this plan are under development and pending.

6.8.8 Earthquake Early Warning Detection System

A systemwide earthquake early warning detection system (EEWDS) is being considered and may include additional sensors at HFZs.

The goal would be a system integrated with train control, communications and signal systems capable of detecting early P-wave ground motions, calculating the expected magnitude of shaking, and triggering braking response for at-risk trains.

If implemented, EEWDS will be coordinated with maintenance and inspection protocols.

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June 9, 2014 PB-CHSRA-04339

Mr. Jeff Morales
Chief Executive Officer
California High-Speed Rail Authority
770 L Street, Suite 800
Sacramento, CA 95814

Attn: Mr. Frank Vacca, Chief Program Manager

Re: Request for Authority Review and Concurrence of TM 2.10.6, Revision 1

Dear Mr. Morales:

The technical memo (TM) 2.10.6 Fault Hazard Analysis and Mitigation Guidelines, Revision 1 is attached for your review. It has been revised and re-organized in Revision 1 and presents updates to the fault displacement design parameters. Significant revisions include:

- A new flowchart showing the tiered process for identifying hazardous fault zones and defining the design basis fault displacements.
- A concise definition what delineates a hazardous fault zone (HFZ) from a potentially hazardous fault zone (PHFZ).
- The use of both deterministic and probabilistic methodologies to assess the fault displacement hazard, with the larger fault displacement to be used for design, which is consistent with the vibratory component of ground motions for typical (i.e., not at HFZ) regions system-wide.
- A concise method to characterize HFZs with regards to fault displacement design.
- An outline of the design process for structures at HFZs, for both preliminary and final design. The Rev 0 "mitigation classification" section was removed since it was redundant with the general and technical classifications already required by TM 2.10.4: Seismic Design Criteria.
- Where the dominant fault displacement is lateral, the strategy is to use at-grade ballasted track oriented as near to perpendicular (90° ± 30°) to the fault trace, in order to minimize the fault zone length beneath the CHST footprint.
- Where the dominant fault displacement is vertical, the strategy is to use a structure in the form of an elevated, earth-supporting, or at-grade structure. Mitigation strategies include:
    - Increased articulation at piers to accommodate the fault displacement demands.
    - Simple spans and elongated bearing seats, to provide displacement capacity as well as post-event realignment capability.
    - Seismic isolation and dissipation devices at bridges and aerial structures to better decouple the superstructure from the substructure, and lessen the demands on the foundations.
    - Large diameter monopole foundations where the HFZ is not well defined, or is known to

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exist over a wide area, which minimizes the hazard of fault rupture passing directly through traditional multi-pier caps.

- Thickened reinforced ductile concrete mat foundations for building structures that resist the combined effects of angular distortion and tensile ground strain at HFZs.
- Fault chambers where tunnels are needed at HFZs, which include local design of a larger cross section based upon the predicted direction and magnitude of fault displacement.
- Increase width at U-walls to allow separation between track and walls, which allows roof for construction access and track realignment.

- For the case where the alignment is parallel to the fault track, a mitigation strategy to place the track on the "footwall" side of the fault trace was introduced.

It is understood that this is a living document and will be updated as required. If this meets with your requirements, please sign below acknowledging your concurrence for adoption and use on the program.

Sincerely,

James R. Van Epps

James R. Van Epps
Senior Vice President, Parsons Brinckerhoff
Program Director, California High-Speed Rail Program

Attachments:
Technical memo (TM) 2.10.6 Fault Hazard Analysis and Mitigation Guidelines, Revision 1

California High-Speed Rail Authority Concurrence

Frank Vacca

Frank Vacca, Chief Program Manager

Date: 6/12/2014

CALIFORNIA High-Speed Rail Authority

DATE: 06/09/2014

SIGNATURE/APPROVAL ROUTING SHEET

DOCUMENT(S) INFORMATION

To: Jennifer Thommen

From: Kris Livingston

Subject: TM 2.10.6 – Fault Hazard Analysis and Mitigation Guidelines, Revision 1

Description of Enclosed Document(s):
The Technical Memo (TM) 2.10.6 – Fault Hazard Analysis and Mitigation Guidelines, Revision 1is attached for your review and concurrence. Detailed changes to the original TM are attached in a cover letter for your reference.

☐ Expedite Due Date:

REVIEWER INFORMATION

Reviewer #1 Name (Print): James R. Van Epps	Reviewer's Initial/Date: KDL for JVE	Comments:
Reviewer #2 Name (Print): Frank Vacca	Reviewer's Initial/Date: FAV 6/12/2014	Comments:
Reviewer #3 Name (Print):	Reviewer's Initial/Date:	Comments:
Reviewer #4 Name (Print):	Reviewer's Initial/Date:	Comments:
Reviewer #5 Name (Print):	Reviewer's Initial/Date:	Comments:

☐ Approval/Signoff (initials)

☒ Signature

☒ Hand Carry or Call for Pick up
Name: Kris Livingston Ext.: 384-9515

☐ Information

☐ Do Not Release – Call When Signed

☐ Release When Signed

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