Quantifying surface faulting hazards for lifelines crossing active faults

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Abstract: Lifelines crossing active faults are vulnerable to breakage during surface faulting earthquakes. Mitigation measures to counter surface rupture damage include the placement of seismic shut-off valves outside the zone of faulting or flexible joints that accommodate the expected fault movement. The design and decisions regarding location of these mitigation measures requires detailed knowledge of the location of the active fault traces, the width of the fault zone, and the distribution of strain within the fault zone. Unfortunately, due to a lack of detailed documentation of historical surface faulting events, there are few empirical data with which to characterize the distribution of strain during surface faulting events. Therefore, either we are required to perform expensive, invasive, site-specific fault investigations to characterize each fault crossing, or in the absence of detailed understanding of the characteristics of fault rupture, we generally have to adopt overly conservative and costly approaches to mitigation. This paper evaluates current fault investigation practice and describes an alternative approach to defining potential surface rupture zones using existing geologic data to develop predictive models for surface fault deformation. This approach provides a cost-effective, reasonable and rational basis for estimating the location and width of potential surface faulting accompanying a large earthquake. Either approach allows the creation of maps depicting the potential distribution of deformation from surface faulting. These maps assist the engineering community in addressing mitigation issues and in developing effective post-earthquake repair strategies.

Résumé: Les infrastructures linéaires traversant des failles actives sont vulnérables pendant les tremblements de terre causant des failles superficielles. En mesure de prévention contre les dommages de rupture superficielle on peut placer des soupapes d'isolation sismique hors de la zone de failles ou bien des joints flexibles pour mitiger les mouvements anticipés de lafaille. Afin de concevoir et décider où placer ces mesures préventives on doit connaître de façon détaillée la position des failles actives, la largeur de la zone de failles, et la distribution des déformations dans la zone. Malheureusement, le manque de documentation détaillée sur les évènements historiques de failles superficielles fait qu'il y a peu de données permettant de caractériser la distribution de déformations pendant ces évènements. En conséquence, on doit soit faire des recherches chères, invasives et pour chaque site pour caractériser chaque intersection d'infrastructure linéaire avec une faille, soit, en l'absence de données sur les caratéristiques spécifiques de la faille, on doit entreprendre des mesures de prévention conservatrices et coûteuses. Cet article présente une évaluation de la pratique courante pour rechercher les failles et décrit une approche alternative pour définir les zones de rupture superficielle potentielles au moyen de données géologiques existantes, afin de développer des modèles de prédiction pour les déformations de failles superficielles. Cette approche pourvoit une base efficace, raisonable et rationelle pour évaluer la position et largeur des zones de failles superficielles accompagnant un tremblement de terre important. Elle permet de créer des cartes montrant la distribution potentielle des déformations résultant de failles superficielles, aidant la communauté ingénieure à résoudre les problèmes de prévention et à développer des stratégies de réparation efficaces suivant un tremblement de terre.

Keywords: earthquakes, seismic risk, geological hazards, engineering geology maps.

INTRODUCTION

Lifelines, both buried and on the surface, are particularly vulnerable to breakage during surface faulting earthquakes. Pipelines are particularly prone to failure when fault movement puts them in compression (Figure 1). Mitigation measures to counter surface faulting damage either involve total avoidance of the fault zone (not always a viable option) or include the placement of seismic shut-off valves outside the zone of faulting or flexible joints that accommodate the expected fault movement and designing a crossing that keeps the utility corridor in tension. The location and design of these mitigation measures requires detailed knowledge of the location of active fault traces, the width of the fault zone, and the distribution of deformation within the fault zone. Usually these data are obtained by detailed site-specific geologic investigations, including shallow geophysical profiling, soil borings, and fault trenching (CGS, 2002). This paper evaluates current fault investigation practice and describes an alternative approach to defining potential surface rupture zones using existing geologic data to develop predictive models for surface fault deformation. The latter approach is illustrated by examples from northern California. In well-studied regions such as the San Francisco Bay Area, there is a preponderance of existing data making the following approach a cost-effective method for evaluating fault rupture hazard.

However, this approach also is useful in less well-studied regions; rather than developing detailed fault rupture hazard maps, it can be used as a screening tool to focus any future fault investigations. Although the following discussions primarily refer to strike-slip faulting, for the most part they are equally applicable to dip-slip (both normal and reverse) faulting.

FACTORS AFFECTING SURFACE FAULTING COMPLEXITY

With the exception of a few rare examples, in tectonically active regions surface faulting occurs on existing faults that have been either, the source of historical surface faulting, are undergoing active creep, or have experienced surface faulting within late Pleistocene or Holocene time. The rupture pattern within a fault zone is usually complex. The majority of the offset occurs on a primary, often central rupture, whereas less intense, secondary ruptures occur in peripheral areas, several meters to several hundreds of meters away from the primary rupture (Figure 2). If fault displacement is accommodated over a broader area, then the deformation may be manifest as a zone of fracturing and ground cracking with minor amounts of slip on individual fractures. In addition to slip on discrete fault planes, some displacement may be accommodated as warping or distortion (Figure 1). Although the individual offsets in a zone of distributed faulting may be small; the cumulative offset across the entire zone can be significant.

The primary control of the style of surface faulting along strike-slip faults is the geometry of the fault (Figure 3). Fault bends are generally associated with a widening of the fault zone. If there is a component of vertical displacement, the pattern of surface faulting may be further complicated. Similarly, for normal faults and reverse faults, fault geometry is the primary control of the style of surface expression. Fault bends, step-over zones, relay ramps, and segment boundaries are all associated with more complex, broader fault zones (Figure 4). The dip of the fault plane, and changes in the fault plane dip, also control the complexity of surface rupture.

The material through which the fault propagates to reach the earth's surface also has a strong influence on the geometry of the surface rupture. Faulting through unconsolidated sediments is highly variable, and the resultant deformation zone is dependent on a number of factors, many of which are not yet fully understood (Bray *et al.*, 1994).

The geometry of faulting in bedrock is often controlled by the orientation of existing fractures. The amount of offset during repeated earthquakes is also important. Small fault offsets result in subdued, discontinuous surface fault features, while larger offsets generally result in more continuous, linear fault zones.

Figure 1. Damage to the 0.76 m diameter Goldfields Water Supply pipeline by the surface rupture from the 1968 ML 6.8 Meckering, Western Australia, earthquake. Reverse fault movement on the Meckering fault caused 2.11 m of crustal shortening. This resulted in 1.32 m of telescoping of the cast iron pipeline. The remaining deformation was accommodated by warping of the pipeline (From Gordon & Lewis, 1980).

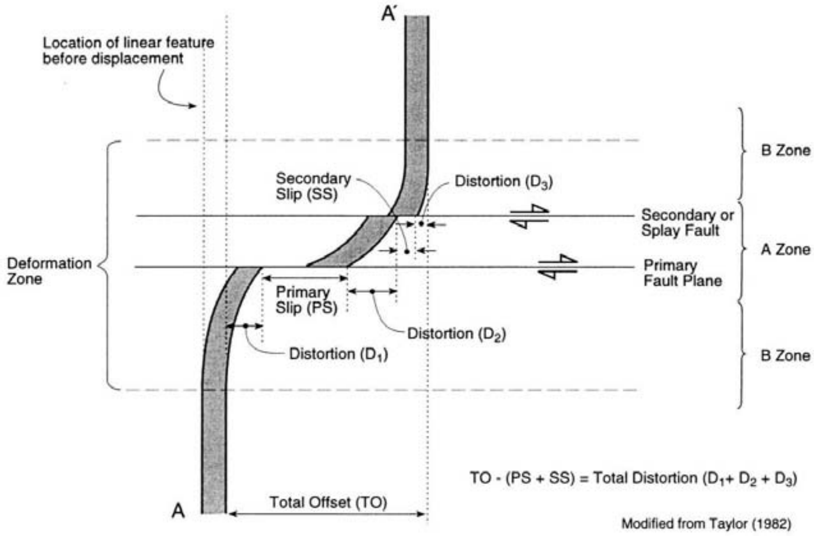

Figure 2. Map view of a schematic strike-slip fault zone showing variation in displacement of a marker horizon (A-A') across the width of the fault zone. This schematic also represents a section view of a dip-slip fault (Modified from Taylor, 1982). A and B Zones are described in the text; also see Figure 8.

FAULT INVESTIGATIONS

The majority of active fault investigations follow a similar path, regardless of the tectonic environment within which they are performed. Initial investigations are carried out using remote sensing tools, either satellite imagery or stereoscopic aerial photographs, to identify geomorphic features indicative of the presence of active surface faulting (Allen, 1975). The ease of recognition of active faults is dependent on the style of faulting, degree and recency of activity, and on the preservation of fault-line geomorphology. In areas with high erosion and/or weathering rates, or where sedimentation rates are high across the fault trace, some or all indicators of recent fault activity may be lost or obscured.

Once an active fault zone is identified, reconnaissance investigations, either ground-based or aerial, are used to confirm the interpretations made from remote-sensing imagery and to select sites for further investigation. Depending on the nature of the engineering project, the location of sites for further investigation may be dictated by facilities layout. Otherwise sites for more detailed investigation are chosen on the basis of providing as complete a stratigraphic record as possible. Often this will not be the section of the fault with the most dramatic surface expression.

Site-specific fault investigations fall into three general categories: 1) surface; 2) non-invasive subsurface; and 3) invasive subsurface. Surface investigations usually involve detailed geomorphic mapping and scarp profiling in order to determine the amount and nature of recent displacement along the fault. Such investigations usually only provide information on the most recent faulting episodes and often cannot discriminate between the effects of multiple surface faulting events. In addition, these investigations do not provide a detailed picture of the fault zone geometry. Non-invasive subsurface investigations involve geophysical surveying methods, including reflection and refraction seismic profiling, ground probing radar, and electromagnetic profiling. Although these techniques can be useful in detecting the presence of shallow faults, they do not provide a detailed picture of the fault zone itself. To obtain a detailed understanding of the geometry of an active fault zone, we generally have to perform invasive subsurface investigations, namely fault trench excavations (Figure 5).

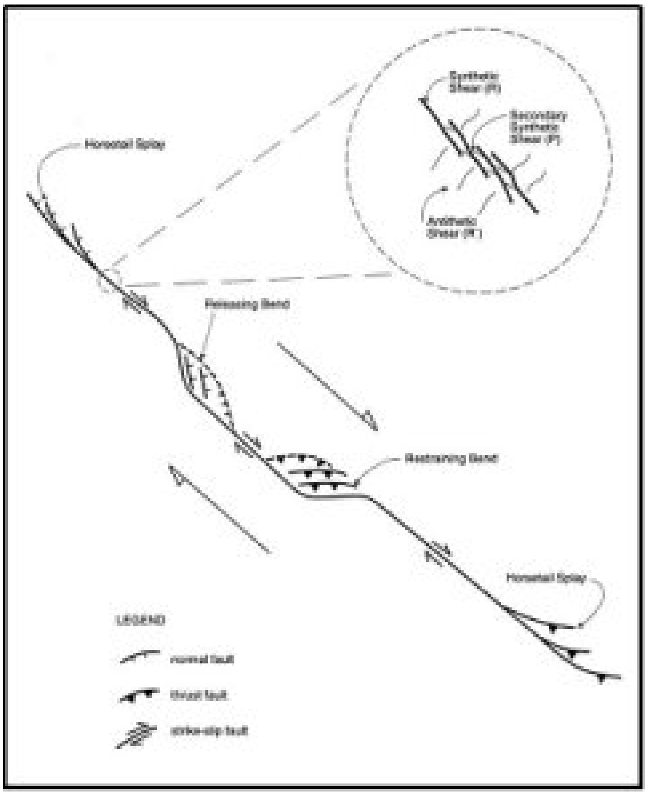

Figure 3. A schematic map view of fault bend complexity along a strike-slip fault. In areas of compressional bends broader zones of folding and secondary thrust faulting develop. Extensional fault bends develop secondary normal fault splays. Similar complexities occur along bends in both normal and reverse faults. See also Figure 4.

Detailed fault trenching, with careful stratigraphic logging of the trench walls, provides a clear, albeit 2-D image of the fault zone at any particular site. Multiple or serial trench excavations or larger pit-style trenches, especially when excavated downward stages, can provide a more complete, 3-D picture of the fault zone architecture (Wesnousky *et al.*, 1991). Although fault trenching provides our best view of fault zone structure, we have to be aware of potential problems. Erosion and/or periods of non-deposition can lead to a lack of preservation of some faulting events, therefore providing only a partial picture of recent fault activity. However, the fact that many fault appear to rupture in a similar manner in repeated events (Hecker & Abrahamson, 2004; Schwartz & Coppersmith, 1984) indicates that non-preservation of some surface rupturing events is not a major problem to understanding the details of rupture style.

Although fault trenching provides the most detailed picture of a fault zone, it is a relatively expensive and time-consuming investigative technique. The costs of investigation each fault crossing may be come prohibitive and not possible within a tight project schedule, especially when dealing with a lifeline corridor or network of lifelines that may have multiple fault crossings. In such circumstances, a cost-benefit analysis has to evaluate the value of numerous site-specific fault investigations as opposed to performing less-detailed reconnaissance-level investigations and adopting more expensive mitigation measures to compensate for the uncertainty in fault location and fault rupture magnitude. In addition, in regions where the preservation of late Quaternary stratigraphy is incomplete or where trenching is impossible (*e.g.*, offshore marine environments), alternative methods for fault rupture characterisation are required. In an attempt to improve on reconnaissance-level fault rupture hazard investigations Fenton & Fuette (1999) developed a method of compiling all available fault data to develop predictive models of potential fault behaviour. Although not intended to replace detailed site-specific investigations, this approach provides a relatively rapid, cost-effective method of assessing fault rupture hazard. This approach is described in the following sections.

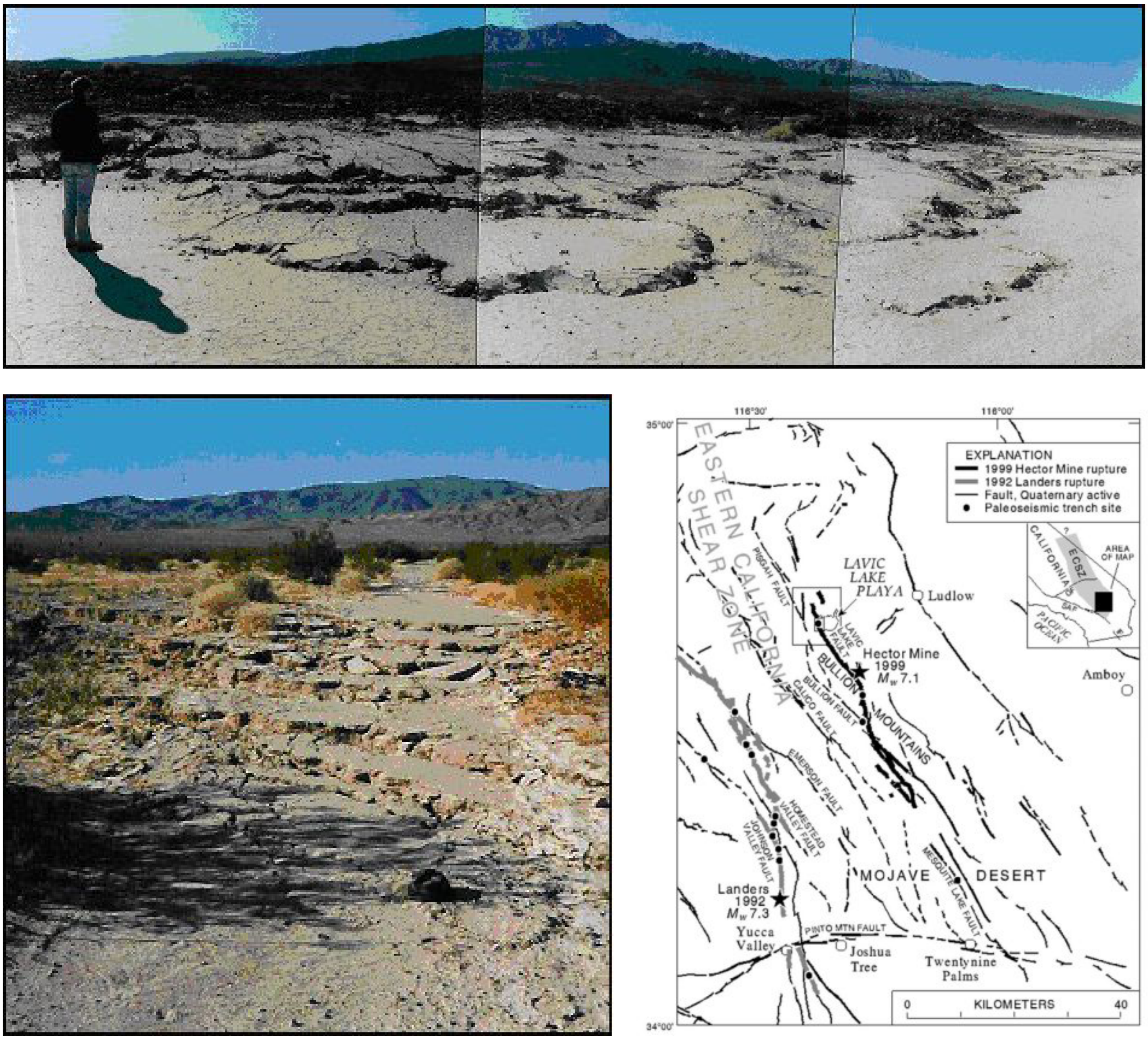

Figure 4. Geometric complexities along the Lavic Lake fault rupture, 1999 **M** 7.1 Hector Mine, Southern California, earthquake. Top: Low-angle thrust splays at a compressional bend. Left: Distributed normal-oblique fault displacements in an extensional fault bend. Location map (right) from Rymer *et al.* (2002).

Figure 5. Fault trench investigations along the Maacama fault, Mendocino County, Northern California. Main fault trace marked by dashed lines. Multiple trenches provide a picture of along-strike changes in fault rupture style.

DATA REQUIREMENTS FOR THE CHARACTERISATION OF SURFACE RUPTURE

In order to characterize the potential hazard from surface faulting, we need to understand certain aspects of the potential fault rupture. Not least is accurately locating the fault trace, determining the width of the fault rupture zone, and determining the amount of displacement and the style of faulting.

Location of Active Fault Traces

Faults that have had multiple surface ruptures in historic time generally rupture in a similar fashion, along the same fault trace (Hecker & Abrahamson, 2004). In addition, in a complex fault zone, surface ruptures are generally observed to occur along the youngest fault traces. In tectonically active areas, the vast majority of historic surface-rupturing earthquakes have occurred on existing faults that display geologic or geomorphic evidence for movement during Pleistocene or Holocene time. Thus, in order to locate the likely trace of the next surface rupture we need to identify the most recently active fault traces. The most useful tools for identifying and locating active faults are analysis of remote sensing imagery, aerial and ground reconnaissance, and morphotectonic mapping. Recently LIDAR has proven especially effective in locating fault traces in regions of dense vegetation cover (Harding & Berghoff, 2000).

Determination of Fault Zone Width

Fully characterizing the hazard from surface faulting requires an estimation of the width of the active fault zone. For this purpose, all available data on the deformation along a fault including: existing detailed mapping of both geology and geomorphology; mapping from aerial photography; any subsurface information, including trench logs and boring profiles; and any maps of historical surface rupture distribution need to be compiled. In the absence of existing site-specific data, analysis of high quality aerial photographs is usually sufficient to identify geomorphic features that may indicate the potential width of the fault zone. Alternatively, in areas where there is sufficient empirical data, a statistical approach, such as that of Petersen *et al.* (2004) is useful in providing a first order estimate of the width of the zone of potential faulting.

Distribution of Deformation

Once the width of the fault rupture zone is defined, it is also important to determine the distribution of deformation across this zone. Although the majority of fault offset occurs as slip on the primary fault plane, a potentially significant amount of offset is often accommodated as slip on subsidiary or secondary faults, or as distortion and distributed shear in a zone flanking the main fault trace (Figure 4). Using empirical geologic data, in particular, fault displacement measurements from trench exposures, displacement distribution profiles (Figure 6) can be developed for each fault zone (Fenton & Dober, 2000; Lazarte *et al.*, 1994). However, the lack of sufficiently detailed trenching along the majority of faults worldwide means that there is generally insufficient data with which to construct meaningful displacement distribution profiles. From previous studies in California, Fenton and Fuette (1999) show that within the same tectonic regime, we can use data from faults with the same style of displacement to provide a reliable measure of the distribution of displacement.

Amount of Displacement

If there is no detailed paleoseismic displacement data for a fault, relationships among fault length, earthquake magnitude, and surface displacement (Stirling *et al.*, 2002; Wells and Coppersmith, 1994) provide an estimate of the amount of displacement across the fault zone. These relationships do not provide discrete values of displacement along the faults; rather they provide a range of values (average and maximum) of displacement for the entire fault. A measure of maximum displacement is usually sufficient for design of retrofit measures. In an region where there is a large population of faults, fault displacement data can be used to develop probability of exceedence curves for both average and maximum displacement (Youngs *et al.*, 2003).

DEVELOPMENT OF FAULT RUPTURE HAZARD MAPS

The development of fault rupture hazard maps uses data for the location of active fault traces and the width of the fault zones and distribution of deformation within the fault zones to depict areas of relative fault rupture hazard (Fenton & Fuette, 1999). An inner 'A' zone is the most probable location within which primary fault slip will occur. This zone will accommodate the majority of fault offset, possibly as much as 80 to 90% of the total displacement across the entire fault zone width (Figure 2). The width of this zone represents the uncertainty in the location of the primary active fault trace. The 'A' zones are determined from the width of the fault rupture zones exposed in trench exposures, the width of the geomorphic fault trace, as interpreted from aerial photographs, and on the width of contemporary creep zones. For a mature strike-slip fault without major geometric complexities, this zone could be less than 10 m wide. An outer 'B' zone that accommodates any secondary and distributed deformation flanks the zone of primary rupture (Figure 2). Deformation within the ‘B’ zone includes distributed minor faulting and warping. Although individual fault slip in this zone may be small, the cumulative displacement may be significant. The width of these zones is a function of both certainty of the fault location, and the geometric complexity of the fault zone. This zone may extend from a few tens of metres to several hundred metres in width (Figure 6).

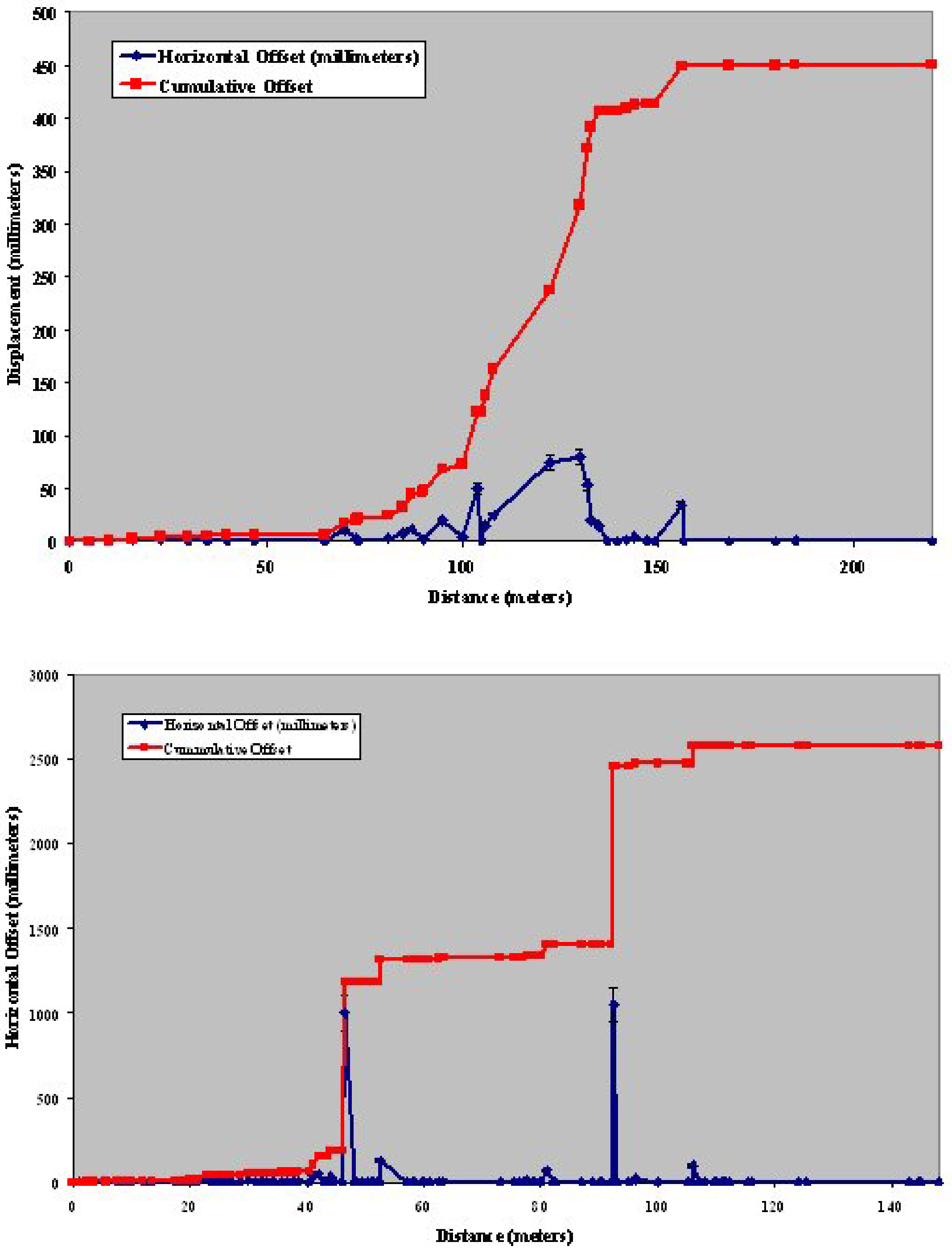

Figure 6. Cumulative displacement plots for traverses across the Bullion (top) and Lavic Lake (bottom) fault ruptures, 1999 M 7.1 Hector Mine, California, earthquake (From Fenton and Dober, 2000).

SURFACE FAULTING ALONG THE HAYWARD AND CALAVERAS FAULTS

The Hayward and Calaveras faults are the two most active faults in the eastern San Francisco Bay region, northern California (Figure 7). Both faults have experienced damaging earthquakes during the last 150 years. The Working Group on California Earthquake Probabilities (2003) estimates that the probabilities of Moment Magnitude (**M**) 6.7 or larger earthquakes on the Hayward and Calaveras fault before 2031 (*i.e.*, within the next 25 years) are 27 % and 11%, respectively. A large earthquake on either fault has the potential to cause widespread damage throughout the San Francisco Bay region. In addition to strong shaking, a large earthquake on either fault will also generate surface rupture along part or all of the mapped fault traces. This has the potential to cause significant damage the regional lifeline network, greatly affecting any post-earthquake recovery effort. A better understanding of potential earthquake ruptures will enhance both mitigation measures and post-earthquake recovery strategies.

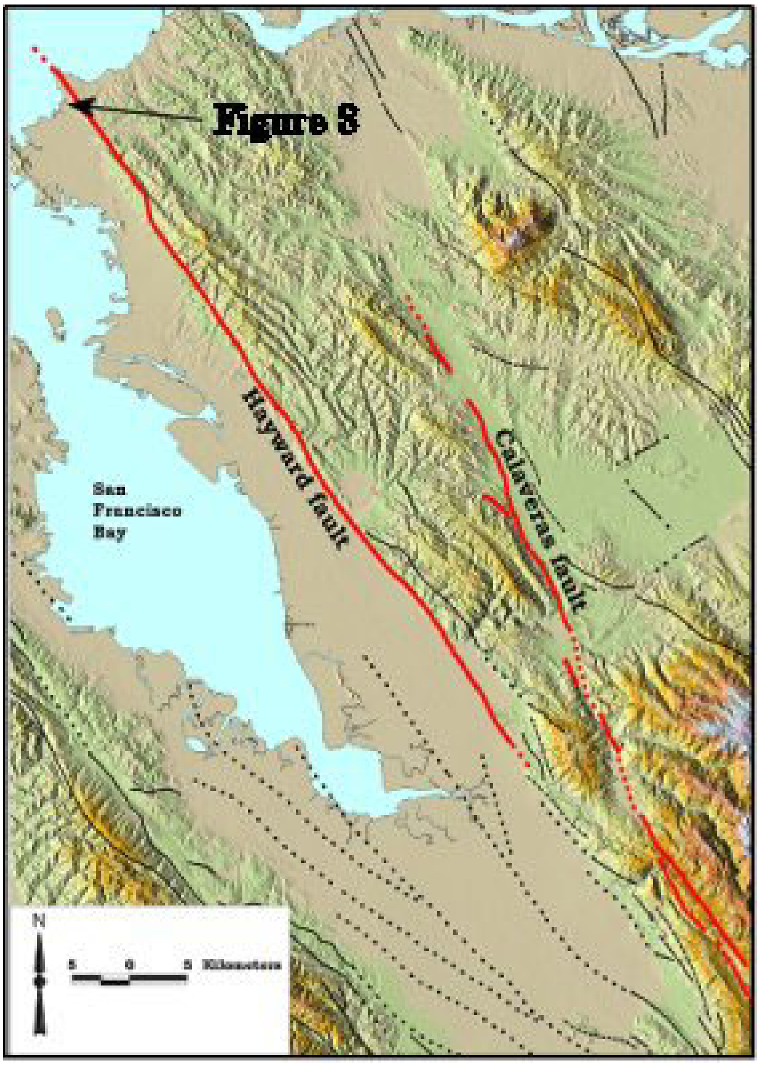

Figure 7. Map of the Eastern San Francisco Bay region. Active traces of the Hayward and Calaveras faults (heavy red lines). Fault traces from Jennings (1994).

One of the problems faced with determining the character of surface faulting along the Hayward and Calaveras faults is the comparative lack of detailed paleoseismic trenching investigations and the lack of well-documented historical surface faulting events. The accounts of the most recent earthquake ruptures on both faults, the 1868 "Haywards" earthquake (Lawson, 1908) and the 1861 Calaveras earthquake (Toppozada *et al.*, 1981), are incomplete and too vague to be of much value in defining potential surface faulting zones. Characterizing the expected deformation along both faults required the review of a wide variety of geologic, geotechnical, and paleoseismic data in order to locate the active fault traces and determine the width of the zones of potential surface rupture. Potentially-active fault traces of the Hayward and Calaveras faults were identified from a number of sources, including: Alquist-Priolo (A-P) Earthquake Fault Zone Maps published by California Geological Survey (CGS); fault zone geomorphic maps (*e.g.*, Herd, 1978); maps of the creeping traces of the Hayward fault (Lienkaemper, 1992); and paleoseismic and site-specific A-P fault zone investigations. Analysis of black and white stereoscopic aerial photographs confirmed fault locations. These data were then compiled to produce detailed active fault trace maps for both faults.

Paleoseismic trench logs and creep measurement profiles provided a detailed picture of the width of the surface faulting zone at specific localities along each fault. The width of the creeping zone along the Hayward fault varies between 2 m to 35 m (Galehouse & Lienkaemper, 2003; Lienkaemper, 1992). Fault trenching indicates a similar fault width, with the majority of deformation occurring in a zone 1 to 3 m wide. Paleoseismic investigations along the Calaveras fault indicate that the majority of faulting has occurred in a zone 1 to 3 m wide, flanked by a broader zone of warping and minor fracturing (Simpson *et al.*, 1999).

In the absence of sufficiently detailed displacement data for the Hayward and Calaveras faults, data for historical surface-rupturing earthquakes in California, including the 1906 **M** 7.9 earthquake on the San Andreas fault (Lawson, 1908), were reviewed in order to characterize the expected surface faulting deformation during a large strike-slip earthquake. These historic surface ruptures show that the majority of displacement occurs in a zone several meters to several tens of meters wide with minor faulting, fracturing, and warping occurring in flanking zones that may be up to several hundreds of meters wide. The cumulative displacement profiles across many surface ruptures are often sigmoidal when deformation is distributed or show distinct steps when the majority of slip is accommodated on a few major fault strands (Figure 6).

The empirical data for each fault provides, at a site-specific level, an accurate location of the most recent fault trace, as well as an understanding of the distribution of the deformation across the fault zone. Professional judgement, based on knowledge of historic fault ruptures and an understanding of the fault trace geometry, is used to extrapolate these fault data along the fault trace in areas where there have been no recent or reliable investigations.

The data on location of active fault traces, width of the fault zones and distribution of deformation within the fault zones are used to produce maps of potential surface faulting along both the Hayward and Calaveras faults (Figure 8). These maps show the most recently active fault traces, as identified by geologic and geomorphic mapping, trenching investigations, creep measurements, and aerial photographic interpretation. The 'A' zones are determined from the width of the fault rupture zones exposed in trench exposures, the width of the geomorphic fault trace, as interpreted from aerial photographs, and on the width of the zones over which contemporary creep has been measured. The outer 'B' zone is the area expected to accommodate the secondary and distributed deformation. These maps depict a better-defined fault zone than that shown on the State of California Alquist-Priolo Earthquake Fault Zone Maps (shown by green line on Figure 8).

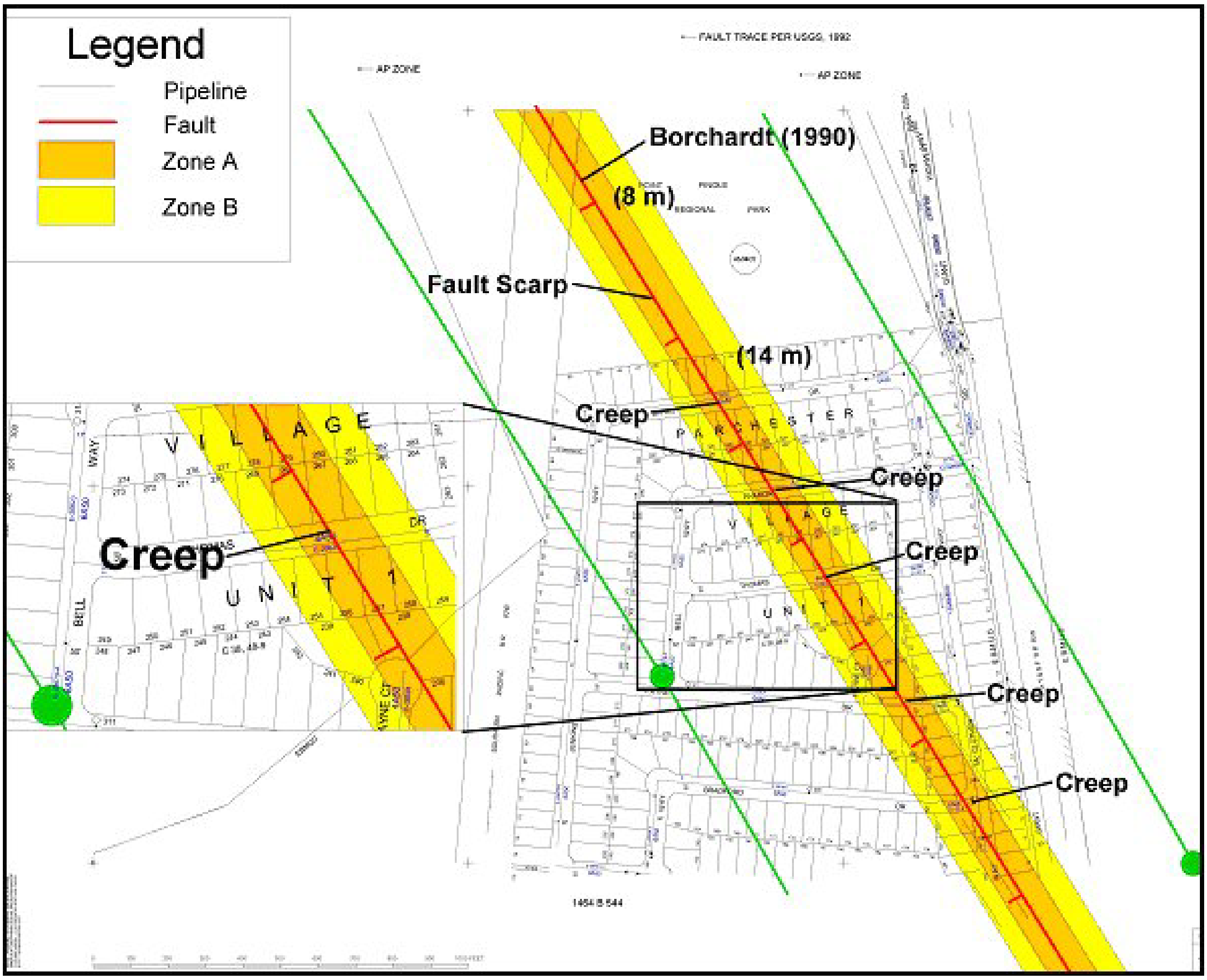

Figure 8. Fault rupture map for the northern Hayward fault, Parchester Village, Contra Costa County (Location is indicated on Figure 7). The green lines denote the extent of the State of California's Alquist-Priolo Earthquake Fault Zone. Development within this zone usually requires site-specific fault investigations. The base map shows individual property lots (black lines) and the distribution network for the East Bay Municipal Utility District's water supply system (blue lines). The figures in parenthesis indicate the width of the primary fault zone as observed from creep measurements or in trench exposures. Figure modified from URS (1999).

In a number of areas, especially at the northern end of the Calaveras fault, there is either insufficient geologic and geomorphic data with which to locate the active fault traces or the fault traces are obscured by landsliding. Based on existing information, it is not possible to accurately locate the fault at these locations. Such areas were annotated on the surface faulting hazard maps as "Insufficient data to locate fault" or "Fault obscured by landslides". Site specific geologic investigations will be required to further refine the location of the active fault traces in these areas.

CONCLUSIONS

This paper outlines an approach to defining potential surface rupture zones using existing geologic data. This approach was developed in order to provide a reasonable and rational basis for estimating the location and width of potential surface faulting accompanying a large earthquake on either the Hayward or Calaveras fault without recourse to extensive site-specific investigations. Based on the review of available geologic data, maps of the most recently active fault traces were developed. In addition, using geologic and paleoseismic trenching data for each fault, in conjunction with fault displacement data from historic surface faulting strike-slip earthquakes in California, zones of potential surface faulting were delineated. Although they are not intended to be a replacement for detailed, site-specific investigations, these maps provide a first order approximation for the location and geometry of surface rupture. These maps will allow utilities to plan system-wide seismic retrofit programs and design post-earthquake repair strategies. The fault rupture zone maps are considered to be 'living documents', with the location of the potential rupture zones based on the current state of geologic knowledge. These maps should be periodically updated with new geologic data and the potential rupture zones should be altered accordingly. Although this approach has been developed for strike-slip faulting, it could equally be used for other styles of faulting in regions where there is already a wealth of existing geologic and paleoseismic data. In areas with less site-specific fault data, this general approach can also be used. However, rather than producing fault rupture hazard maps, we can identify data gaps that will assist in formulating future fault investigations.

Acknowledgements: This paper resulted from numerous studies carried out while the author was at URS Corporation. Discussions with Said Salah-Mars, Lelio Mejia, Ivan Wong, Mark Schmoll, and Carlos Lazarte (URS), Tim Fuette (EBMUD), Tim Hall and Donald Wells (Geomatrix Consultants), and Jim Lienkaemper (US Geological Survey) are greatly appreciated. Doug Wright and Fumiko Goss (URS) drafted the original figures. Beatrice Baudet (UCL) is thanked for translating the abstract into French at short notice.

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