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Characterisation of Surface Fault Rupture for Civil Engineering Design

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ABSTRACT

Lifelines crossing active faults are vulnerable to damage during surface faulting earthquakes. The design of mitigation measures requires detailed knowledge of fault location, rupture zone width, and the distribution of strain within the fault zone. Although the general magnitude of surface ruptures can be characterised by empirical relationships, behaviour at a specific location is harder to forecast. To understand displacement distribution within the damage zone we need to examine historical surface ruptures. Recent earthquakes (e.g., Wenchuan, 2008; Darfield 2010) provide the opportunity to study the effects of fault geometry, near surface materials and along-strike location on the damage zone width and strain distribution, allowing the development of preliminary empirical models for surface rupture characterisation. As well as presenting these models this paper evaluates current fault investigation practice and describes an alternative approach to defining potential surface rupture zones using existing geologic data, providing a cost-effective, reasonable and rational basis for characterising site-specific rupture hazard.

Introduction

Invariably mitigation for measures for surface fault rupture involve avoidance (e.g. Tepel, 2010; Weiland *et al.*, 2008). This is not always possible for all projects, especially transport corridors and other lifelines. Mitigation measures for pipelines 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. Although there is a good understanding of the geometry of faults and their displacement profiles, this is based on predominantly subsurface ruptures through essentially isotropic ground conditions. Surface rupturing earthquakes often have complex traces, sometimes involving multiple fault strands, and variable displacement, sometimes involving several faults that had previously been considered independent structures (*e.g.* Johnson *et al.*, 1994).

Recent surface rupturing earthquakes have provided the opportunity to study in detail the effects of fault geometry, near surface materials and along-strike location on the damage zone width and the strain distribution within the damage zone, allowing the development of preliminary empirical models for surface rupture (Fenton, 2006).

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Surface Fault Rupture Behaviour

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 1). If fault

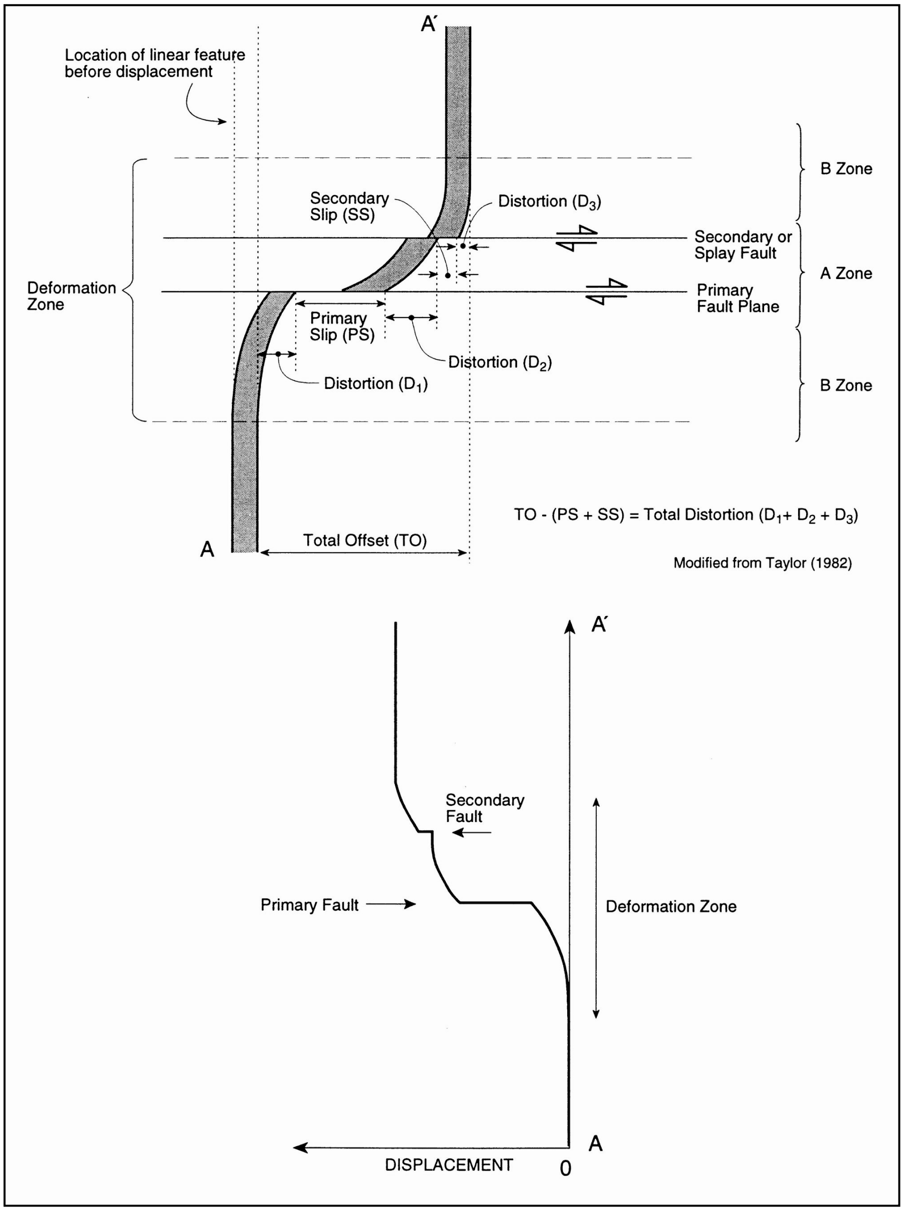

Figure 1. Map view of a schematic strike-slip fault zone showing variation in displacement of a marker horizon (A-A’) across the width of the fault zone. This schematic also represents a section view of a dip-slip fault (Modified from Taylor, 1982).

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 is the geometry of the fault. Fault bends, step overs, and relay ramps are generally associated with a widening of the fault zone. The dip of the fault plane, and changes in the fault plane dip, also control the complexity of surface rupture, in particular the asymmetry of the damage zone.

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 uncemented 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 discontinuities. The amount of offset during repeated earthquakes is also important. Small fault offsets result in subdued, discontinuous, often ‘chaotic’ surface fault features, while larger offsets generally result in more continuous, linear fault zones.

Faults that have had multiple surface ruptures in historic time generally rupture in a similar fashion, along the same fault trace (Hecker *et al*., 2013). 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.

Fault Rupture Hazard Quantification

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. 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.

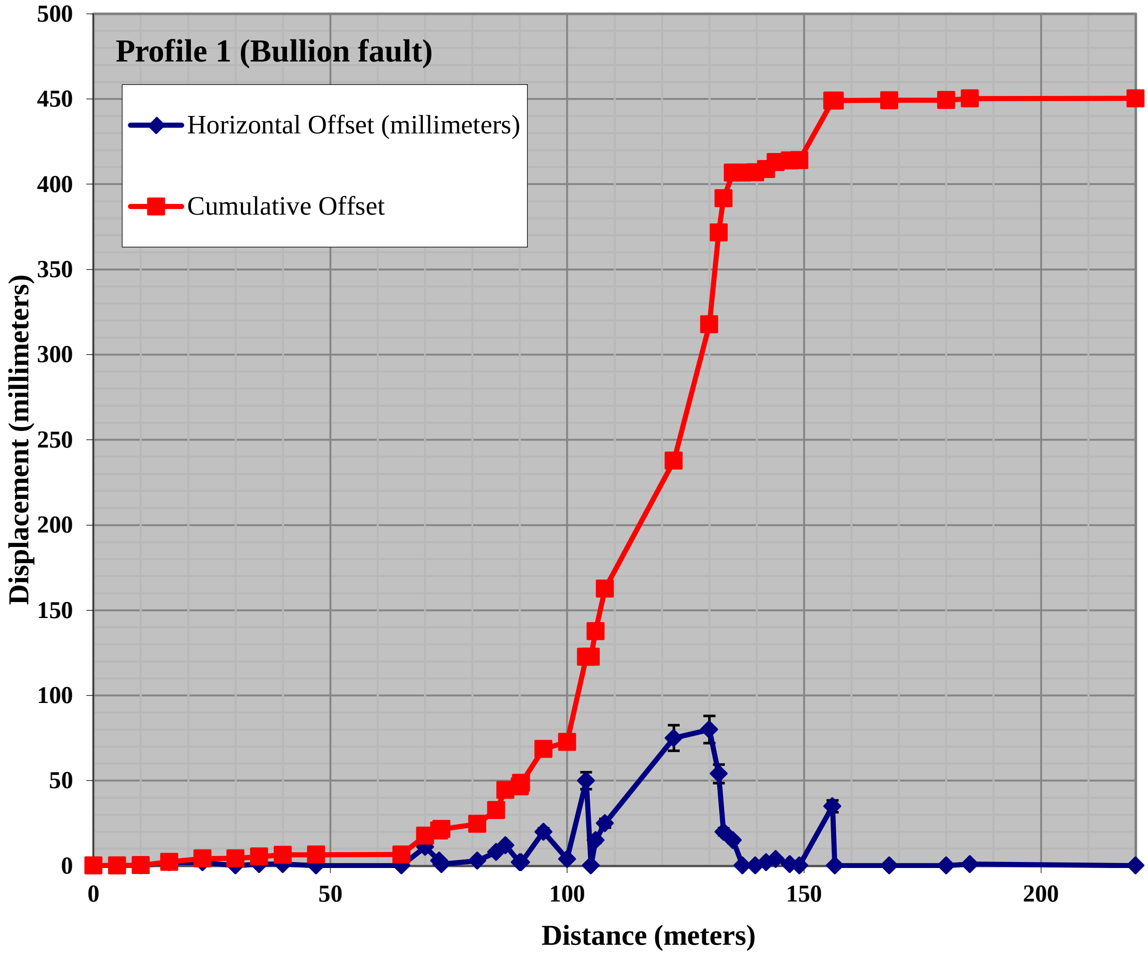

Figure 2. Cumulative displacement plots for traverse across the Bullion fault rupture, 1999 M 7.1 Hector Mine, California, earthquake (Fenton and Dober, 2000).

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. Determining the total width of rupture can be difficult on account of the poor preservation of minor traces with small offsets at the periphery of the surface faulting damage zone. Thus, even detailed, site specific investigation may not be able to accurately quantify the true width of the rupture zone. Recent investigations of surface rupturing earthquakes have allowed an insight into the geometry of the damage zone, and in particular the distribution of slip across the entire zone (*e.g.* Fenton and Dober, 2000). The strain distribution falls between two end members: a smoothed sigmoidal profile, with the slip distributed evenly across the entire damage zone (Figure 2), or a stepped profile where the bulk of the slip is accommodated on one or more dominant fault strands (Figure 3). 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. 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.

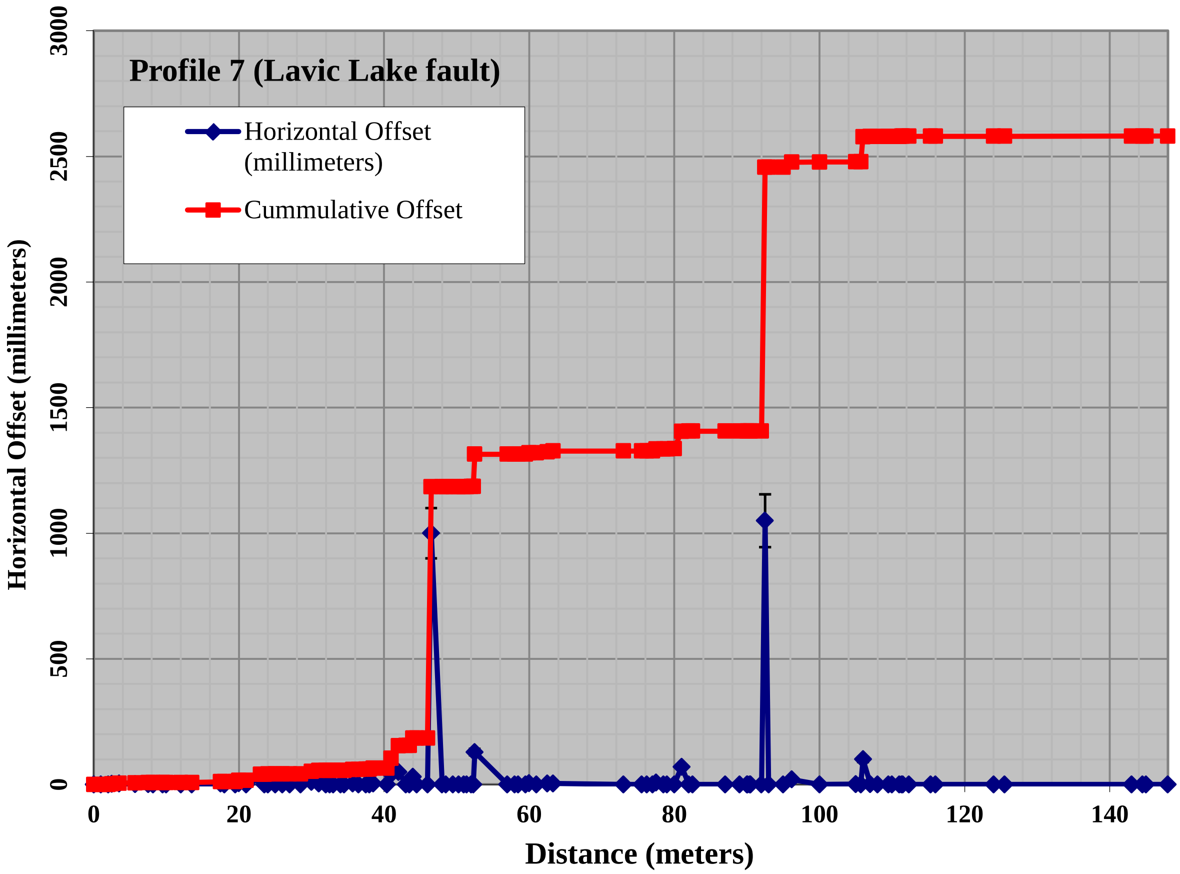

Figure 3. Cumulative displacement plots for traverse across the Lavik Lake fault rupture, 1999 M 7.1 Hector Mine, California, earthquake (Fenton and Dober, 2000).

The determination of fault rupture length can be estimated with a reasonable degree of accuracy from empirical relationships (e.g. Wells and Coppersmith, 1994), however the rate of displacement decay towards the ends of surface fault ruptures are poorly known. This introduces a significant uncertainty in determining the extent of surface rupture from any given point along what may be a poorly preserved historical or palaeoseismic rupture. In order to understand this aspect of fault geometry a number of normal faulting earthquakes with well-documented surface rupture have been examined to investigate the rates of displacement decay towards the ends of faults (Figure 4). These data, along with the models for strain distribution across the width of the damage zone are providing a preliminary insight into the geometry of surface fault ruptures. Although the data are sparse, for well-documented surface rupturing events we can analyse the rate of decay towards the fault tips (Figure 4), thus allowing the beginnings of an understanding of surface fault rupture and its quantification for engineering design of lifelines and other fault-crossing structures.

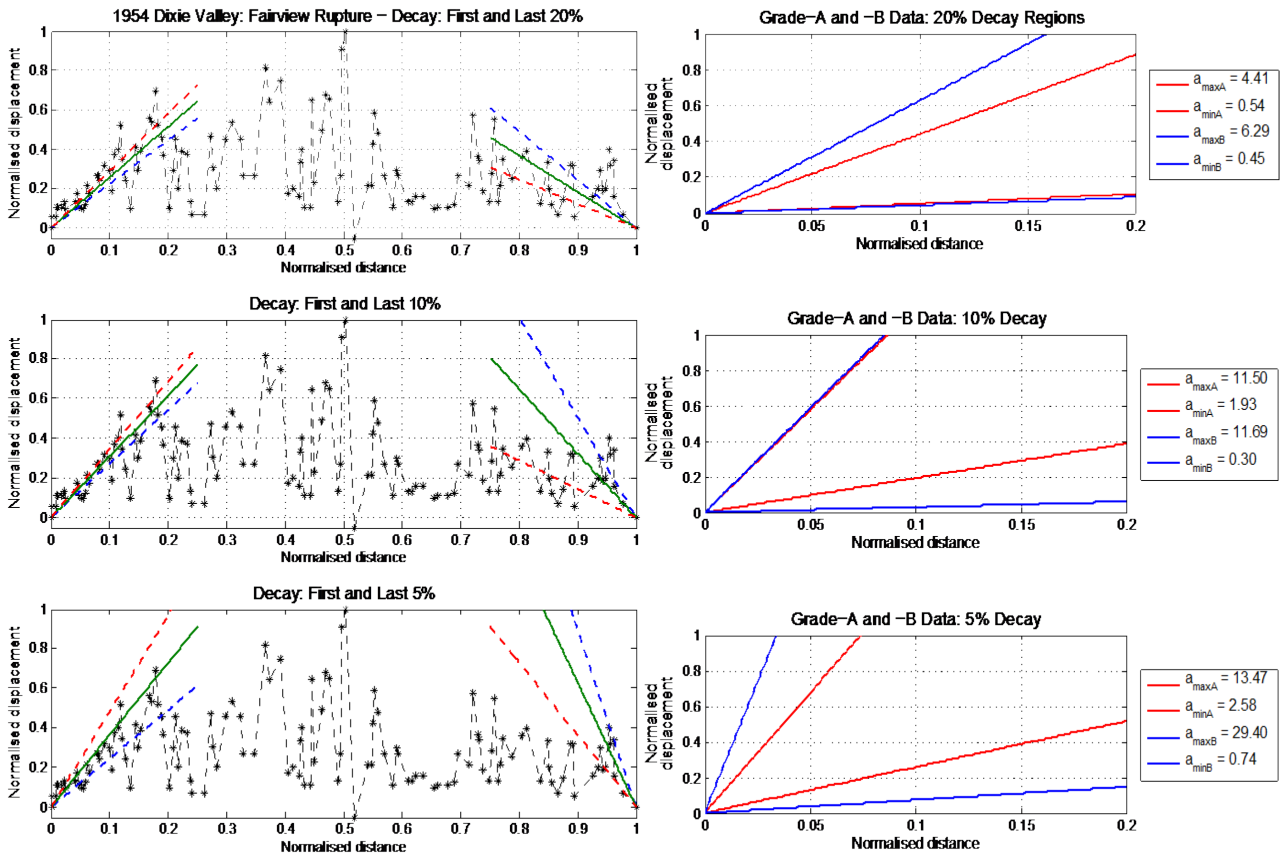

Figure 4. Fairview fault rupture with fitted linear decay models projected over the first and last 25%. Green line represents best-fit line, and the dotted red and blue lines are 95% confidence intervals. Left: Ranges of gradients. In-between the red lines represent the range for grade-A quality data; in-between the blue lines represent the whole range, based on the grade-B quality data.

Conclusions

The evaluation of surface rupture hazard usually involves detailed, expensive and time-consuming invasive investigation. It is hoped that by careful analysis of historical ruptures that empirical relationships describing fault rupture magnitude and strain distribution within fault damage zones can be developed. Future post-earthquake reconnaissance investigations are encouraged to map in detail surface rupture, especially in areas where the rupture becomes distributed. Small individual surface displacements are delicate features that are easily damaged, especially in high-traffic areas therefore, careful, immediate mapping and measurement are a necessity. These studies will allow the development of relationships among surface fault displacement and fault geometries, near surface materials, and other relevant factors, ultimately leading to a better understanding of potential rupture hazard, thereby allowing the development of better mitigation measures, including less conservative setback distances.

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