Establishing Appropriate Setback Widths for Active Faults

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ABSTRACT

Tectonically undisturbed materials adjacent to active fault traces are defined herein as "freeboard" soils. Such materials have surface fault rupture potentials that are an inverse function of soil age and the activity of the adjacent fault. Surface rupture probability is low for old soils adjacent to extremely active shear zones but relatively high for young soils adjacent to moderately active shear zones. For a soil surface to be ruptured where it has never ruptured before (the "freeboard soil"), the width of the shear zone must increase. As shown in this paper, this becomes increasing unlikely as a shear zone matures (>30 events), at which time a setback should not be required. Young freeboard soils require setbacks, which only can be determined from shear zone widths measured through older soils along a strike. A minor instance in which setbacks would be required involves the grading of flower structures, which may give a false impression of the expected width of the shear zone. Once primary faults are identified, any secondary faults can be avoided only after the mature width of the shear zone has been determined. No setback is then necessary. When this is not possible, structural mitigation to withstand minor offsets is preferable to an arbitrary setback, which gives little more than a false sense of security.

INTRODUCTION

For 35 years, consultants and reviewers for development projects within California's Alquist-Priolo Earthquake Fault Zones have usually required setbacks from Holocene active faults. These setbacks are designed to minimize the potential for surface fault rupture (SFR) to damage structures for human occupancy. Setbacks generally were measured from the nearest active trace, with some jurisdictions routinely requiring a setback of 50 ft (15 m) even when there was no readily apparent geomorphic or subsurface evidence for faulting. Unfortunately, the traditional 50-ft (15-m) setback from active faults was never adequately justified. It was only a suggestion that "Unless proven otherwise, the area within 50 feet of an active fault is presumed to be underlain by active branches of the fault" (Bryant and Hart, 2007, p. 2). Some federal and state jurisdictions even have mandated setbacks of 200 ft (61 m) in an equally unsubstantiated belief that an increase in setback would provide an increase in safety (e.g., California Integrated Waste Management Board, 2002, pp. 13, 59). Utah has minimum setbacks ranging from 15 to 50 ft (5–15 m) geared to "criticality" of the proposed structure (Batatian, 2002) based on the calculation methodology of Batatian and Nelson (1999). This paper attempts to provide a preliminary framework for determining what a reasonable setback should be.

PREDICTING FUTURE OFFSET OF "FREEBOARD" SOILS

I first define the term "freeboard" soil as the ground surface adjacent to an active fault that has no evidence of SFR (defined here as shearing, folding, or warping associated with the current tectonic regime). Because age information is critical for establishing the potential for SFR, I use the term "soil" here in a broad sense, encompassing all near-surface materials. For example, in the absence of pedogenesis, the age of tectonically undeformed bedrock is used as the age of the "freeboard soil." The challenge is to determine whether or not a freeboard soil is suitable for construction, consistent with health and safety involving the potential for SFR. The principal factors are 1) the age of the freeboard soil and 2) the number of ground-rupturing earthquakes undergone by the adjacent shear zone since soil formation began.

Age of the Soil

In general, we expect the probability of SFR through a freeboard soil to be an inverse function of its age. Thus, in general, a 100,000-year-old freeboard soil might be deemed a hundred times less likely to rupture than a 1,000-year-old freeboard soil.

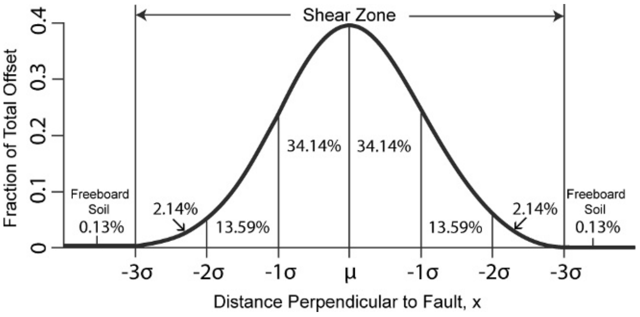

Figure 1. Normal distribution showing the fraction of total offset and the locations of fault traces within an ideal shear zone. Freeboard soils have <0.26 percent of the shearing and are expected to remain so at the 99.7 percent confidence level.

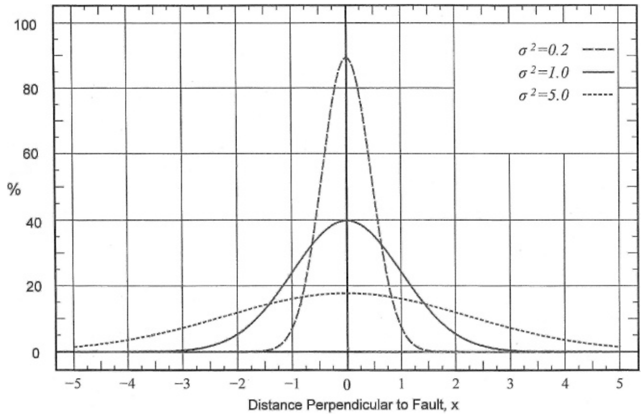

Figure 2. Hypothetical distributions for establishing habitable-structure setbacks near active strike-slip faults. The classic normal distribution (solid line) is bounded by the distribution for linear portions (dashed line) and stepovers or terminations (dotted line). The vertical axis could be either amount of offset, number of shears, or some combination of both.

The Age of the Adjacent Shear Zone

Each ground rupture within the adjacent shear zone serves as a test of the hypothesis that the freeboard soil will never rupture. The freeboard soil, as defined, has survived each test, but will it survive the next one? That depends on how many ground-rupturing events ("tests") have occurred within the adjacent shear zone. Shear zones evolve over time, becoming better defined and eventually reaching either their minimum (Riedel, 1929; Tchalenko, 1970; and Hirschfeld, 1982) or maximum (Weaver, 1982) widths as they equilibrate to associated geologic and tectonic conditions. Here I assume that the probability that a new trace will form outside a known shear zone can be calculated from the distribution of shears within the zone. In the simplest case, a primary fault is bordered by secondary or subsidiary faults. The primary fault usually is the easiest to identify and avoid because it usually displays the most offset within the shear zone. It also is unlikely to rupture outside a mature shear zone.

Secondary traces that widen the shear zone generally carry only a small fraction of the total displacement. Hoexter (1992) found that in 15 of 15 studied shear zones, secondary or subsidiary faulting was 23 percent or less of the primary fault offset. A detailed review of the 1906 surface rupture reiterated Lawson's (1908) contention that 75 percent of the slip occurred on the main trace (Bray and Kelson, 2006). The width of the 1906 zone of rupturing along the San Andreas fault generally was 1–15 m, with a few cracks, probably due to settlement or slope failures branching from the main trace by as much as 100 m. As a rule, the width of fracturing along the main trace was similar to the amount of slip (e.g., 3 m of horizontal slip tended to produce a 3-m–wide zone, while 30 cm of horizontal slip tended to produce a 30-cm–wide zone). Similarly, strike-slip faults in Turkey had 5–20-m–wide shear zones, with 85 percent of the offset being on the primary trace (Rockwell et al., 2001).

In this analysis I assume that, as with many other natural phenomena, well-established shear patterns tend to have normal distributions in the amount of slip and the number of shears (Figure 1). In the ideal case we expect two thirds of the offset to occur in the central one third of the shear zone regardless of its full width. It also predicts that offsets occurring more than one standard deviation (σ) from the primary trace (μ) will be small and fewer in number. Less than 0.26 percent of the total offset will occur outside of a shear zone defined by 6σ width. The upshot is that for a "mature shear zone" with 10-m offsets, only an undetectable amount (1.5 cm) of slip likely would occur within the "freeboard" soil.

As shown in Figure 2, strike-slip faults generally have most offset on the primary trace. Distributions of fault offset tend to be highly leptokurtic (i.e., more concentrated about the mean than normal distributions), with the shear zone being narrow and the sympathetic, triggered, or secondary fault offset measuring 23 percent or less of the total slip (Hoexter, 1992). Stepovers, bends, fault terminations, and weak materials tend to have distributed slip that is platykurtic (i.e., less concentrated about the mean), with a wide shear zone having several "primary" traces (Figure 2). Bifurcations tend to produce two semi-independent shear zones. The pattern for dip-slip faults would be heavily skewed toward the hanging wall, with shears commonly found on the footwall as well (Bonilla and Lienkaemper, 1990, 1991). The idealizations presented in Figure 2 indicate 1) that it is important to locate primary faults and 2) that the width of secondary faulting varies greatly, depending on the character of the local fault.

Regardless of the fault type, it is imperative to determine the full, mature width of the shear zone for establishing a useful setback. Unfortunately, the mature width of a shear zone seldom will be established in less than 30 events or shears (N). This has to do with how the standard deviation is calculated:

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i-\mu)^2}$$

where σ = standard deviation (m), N = number of events or shears, i = event or shear number, x = distance of shear from the mean or primary trace (m), and μ = mean (0 for the primary trace).

For large N, the factor $1/(N-1)$ approaches $1/N$, and there will be very little improvement in the estimate of the standard deviation by including more events or shears. For $N < 30$, an improvement in the estimate of the shear zone width is obtained by multiplying the calculated σ by a factor of $>\sqrt{\frac{N}{N-1}}$ (Spiegel, 1961, p. 70). Thus, if only two events or shears are known, the measured width of the zone must be multiplied by $\sqrt{2}$, a 40 percent increase. In this idealized case, the setback for one side of the shear zone would be 20 percent of the width of the zone. Of course, only faults having had many surface-fault rupturing earthquakes provide high assurance that the freeboard will not rupture in a future event. For instance, a fault with a 140-year recurrence interval for major events could provide the necessary reassurance within 4,200 years, while a fault with a 1,400-year recurrence interval would require 42,000 years to provide such reassurance. Incidentally, for normal faulting along the Wasatch Front in Utah, the Salt Lake County ordinance requires that freeboard soils be old enough to have experienced several recurrence intervals (Batatian, 2002). In that case, a 1,400-year recurrence interval would require only 4,200 years to provide reassurance.

The statistical technique above represents but one approach to determine the mature width of a shear zone, but it illustrates the type of data necessary for justifying setbacks. Tavchandjian et al. (1997) used a more sophisticated approach to map drift walls in a mine in Canada. Kelson et al. (2004) used a statistical analysis to design a setback width for the Calaveras fault where it was to be crossed by high-pressure natural gas pipelines. They calculated that during a M7.0 event, most of the expected 1.1-m (3.6-ft) slip would occur within 5 m (15 ft) of the primary trace

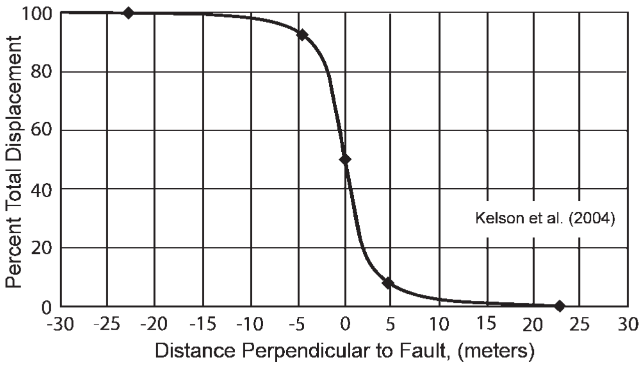

Figure 3. Displacement curve showing 85 percent of slip occurring within 5 m of the primary trace of the Calaveras fault during a hypothetical M7.0 earthquake (from Kelson et al., 2004).

(Figure 3). From the trench log, they concluded that 85 percent of the expected offset would be confined to the 9.1-m–wide (30-ft–wide) "A Zone," whereas only 10 cm (4 in.) of slip would be expected in each "B Zone" having an apparently arbitrary width of 18.3 m (60 ft) (Figure 4).

PRACTICAL USE OF SETBACKS

Characterizing fault zone setbacks is impossible unless the soils along the fault are of sufficient age. Traditional "setbacks" are an inadequate substitute for lack of information. Very young soils will not exhibit the full width of a shear zone. In such cases, a setback of 50 ft (15 m) is clearly insufficient for avoiding all ruptures adjacent to a stepover, bend, termination, or other shear zone having extensively distributed slip. This was clearly shown by the 1992 M7.3 Landers earthquake, wherein distributed shear occurred in zones that were hundreds of meters wide (Lazarte et al., 1994).

If the freeboard soils are old enough, we presume that excavations across such areas would have shown the distributed shear that was to come. In the most dramatic case to date, we excavated a 2,040-ft (622-m) trench through Pleistocene soil across a strike-slip fault that had 204 traces, one fault every 10 ft (3 m) (Borchardt, 2007). Had the soil been only a few thousand years old, the shear zone would not have been as well developed and most traces would have been missed. A "setback" of 50 ft (15 m) or 200 ft (61 m) from any one of the first traces to appear during the evolution of the zone would make no sense. It still would have placed habitable structures in an area with a rupture potential every 10 ft (3 m) (Figure 5). In this case, the correct setback would be 1,000 ft (305 m)!

Highly active structures, such as the Hayward fault, could establish a mature shear pattern in as little as

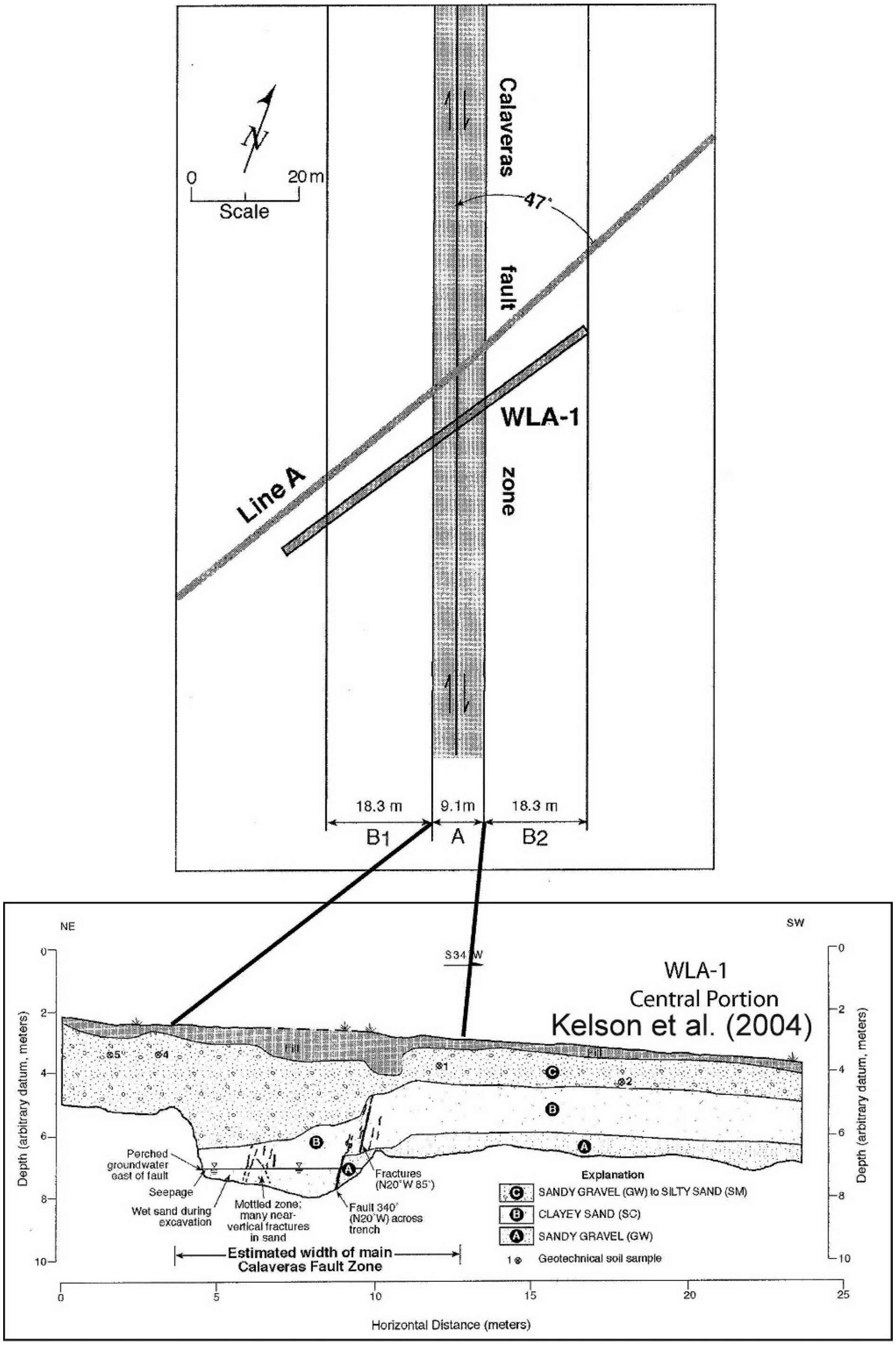

Figure 4. Application of the displacement curve showing A and B Zones along the Calaveras fault. Kelson et al. (2004) estimated that 15 percent of the fault slip could occur within the B Zone, even though there were no fault traces there.

4,200 years. With the recurrence interval of 140 years that was determined for major ground-rupturing events (Lienkaemper et al., 2002), that is the amount of time needed to produce 30 events. By definition, a 10,000-year-old freeboard soil adjacent to the Hayward fault has not experienced even a centimeter of SFR during 70 events. In other words, the fault has had 70 chances to produce surface rupture through

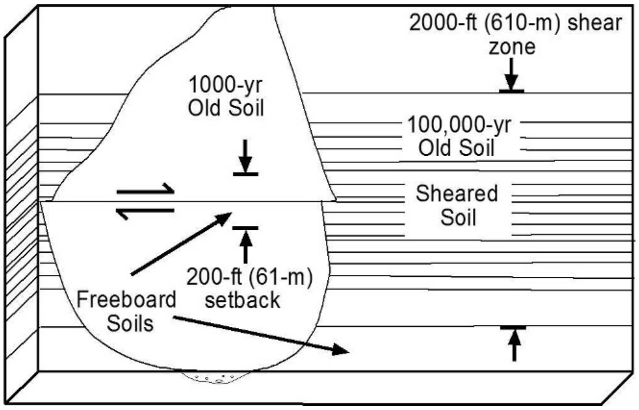

Figure 5. Inappropriate use of setbacks in fault zoning. Even a 200-ft (61-m) setback provides only a false sense of security.

the freeboard soil and has failed to do so. In this case, a setback of any amount also makes no sense for avoiding SFR.

The idealizations presented in Figure 2 show that a particular building site either is within reach of possible SFR or it is not. Given a sufficiently old soil and a sufficiently active fault, we can answer this question confidently, and setbacks are unwarranted, except for the vagaries of surveying and other site-specific conditions. However, young soils fail us and, thus, may require setbacks (Figure 6). The idea is that evidence for more ground-rupturing earthquakes along a particular fault segment might provide enough data to delimit an appropriate shear-zone width. Accordingly, the data derived from an older soil could be extrapolated along a strike to adjacent younger soil, where we expect the fault to behave similarly.

A less important case involves the relative degree of recent aggradation or degradation that might influence confinement pressures within a shear zone

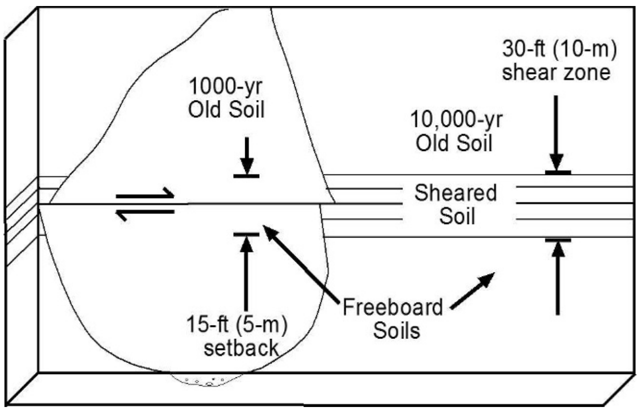

Figure 6. Appropriate use of setbacks in fault zoning. There must be sufficient opportunity for the full extent of the shear zone to manifest itself before a scientifically defendable setback can be established.

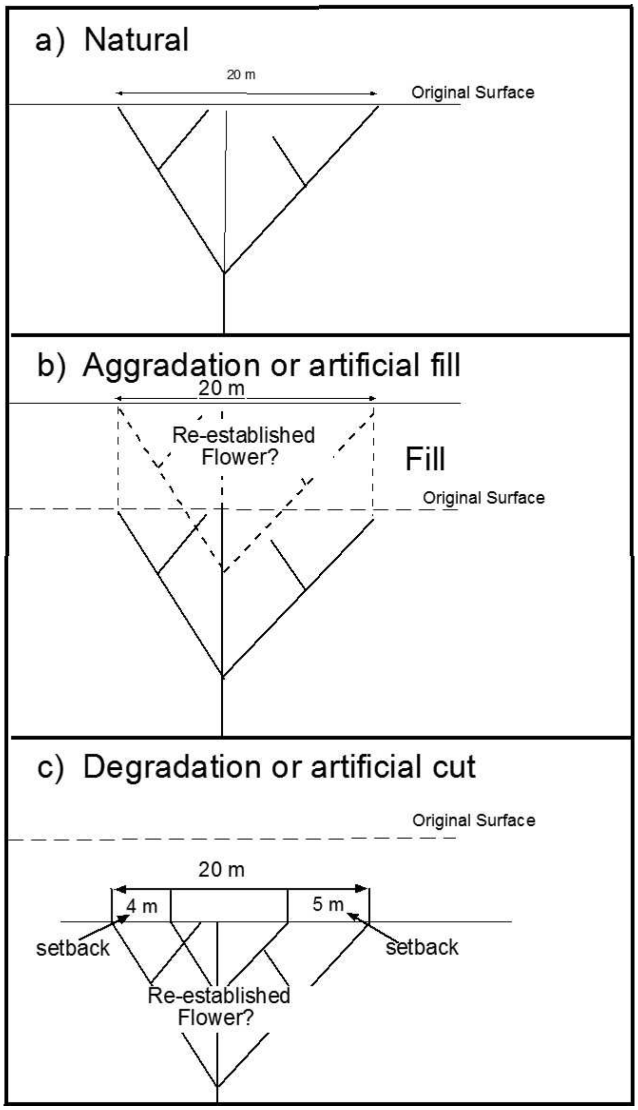

Figure 7. Recommended setback after grading a flower structure.

(Figure 7). Vertical "flower structures" form along fault traces as a result of reduced confinement pressure in weak materials near the surface of the earth. Shears within a flower structure usually dip toward the primary fault trace, joining it at depth. Antithetic shears within a flower structure usually are short, joining with longer secondary shears that dip toward and join the primary fault at depth. A flower structure that has been truncated or filled may respond to the change in confinement pressure by re-establishing its original relationship with the surface. Hence, the original configuration of the flower must be known for determining the appropriate setbacks for a graded shear zone (Figure 7). Relatively recent geologic degradation also may cause narrowing of the flower structure width as a result of corresponding decreases in confinement pressure. The presence of a soil with missing surface horizons within a flower structure implies that the full width of the shear zone is no longer visible. An appropriate setback therefore requires reconstruction of the original flower structure.

MITIGATION: ELIMINATING ARBITRARY SETBACK WIDTHS

If all shear zones were well delineated with as many as 30 events, the associated freeboard soils would have a minimum risk for SFR. Ostensibly, a structure could be placed within inches of an accurately surveyed shear zone or the strike projected from nearby older soils. Because such information often is not available, we therefore need an alternative method of avoiding the false sense of security provided by the traditional use of setbacks (Sexton, 2008). Once primary fault traces have been located, characterized, and avoided, geotechnical/structural engineering mitigation methods can minimize the impact of relatively small displacements that might occur on secondary faults along shear zone margins. As Hoexter (1992) showed for strike-slip faults, most secondary faults display less than 1 ft (30 cm) of horizontal offset during a single event. Most practical, therefore, is the expansion of Hoexter's database, with the inclusion of reverse and normal faults. For secondary faults, mitigative construction to survive 1 ft (30 cm) of SFR is vastly preferable to many currently unjustifiable and perhaps unsafe setbacks. Where deemed necessary, setbacks should be established only by using reasonable site-specific technical data for determining the width. Reviewers and regulators should be discouraged from blindly applying simple deterministic numbers to encompass the uncertainty inherent in SFR.

CONCLUSIONS

1. The age of the freeboard soil is the most important factor for establishing setbacks from active shear zones.
2. The "mature width" of the adjacent shear zone must be known or estimated before a meaningful setback can be established, with this determination requiring about 30 events.
3. Setback widths on relatively young freeboard soils may be calculated from data gathered from relatively old soils and mature shear zones along a strike.
4. Aggraded or degraded flower structures require setbacks that anticipate their possible re-establishment.
5. For secondary faults, construction to survive 1 ft (30 cm) of SFR is more preferable than establishing an unjustifiable, and perhaps unsafe, setback width.
6. The age of a freeboard soil and the mature width of an associated shear zone may be used to determine the probable hazard due to SFR.

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