Asperity slip based fault surface rupture occurrence criteria

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1. Introduction

Few building codes contain provisions for fault surface ruptures and accompanying soil deformations. The lack of appropriate building codes poses a great risk to humans, buildings and infrastructure. A successful design example is the Alaskan pipeline [1] which performed very well during the 2002 Denali earthquake, in contrast to a bullet-train tunnel which failed during the 2004 earthquake in Mid Niigata prefecture, Japan [2, 3]. Earthquakes causing surface ruptures occur on the average every 6-7 years since 1890 in Japan.

There is a need for simple design formulas for estimating "bedrock" fault offset required for a surface rupture to occur. Many researchers have performed model experiments, but our ability to estimate surface rupture displacements is still fairly low and differentiating between earthquakes that may or may not cause surface rupture is difficult.

There is also some evidence that surface rupturing earthquakes may lead to lower peak ground accelerations than earthquakes with buried faults[4], and thus a criterion for estimating the possibility of surface rupture would be useful for judging which attenuation relations to use.

Several researchers' experiments and simulations have resulted in parameters and graphs potentially useful for engineering design [5, 6, 7, 8, 9, 2, 10]. On the other hand, several researchers have proposed empirical relationships between earthquake magnitude and rupture length [11, 12, 13], which have been later incorporated into the concept of probabilistic-fault-displacement-hazard-analysis (PFDHA[14, 15].) A drawback is that these empirical relationships[13] do not explain why equal magnitude earthquakes may or may not cause a surface rupture, and therefore a dichotomous variable has to be used in PFDHA.

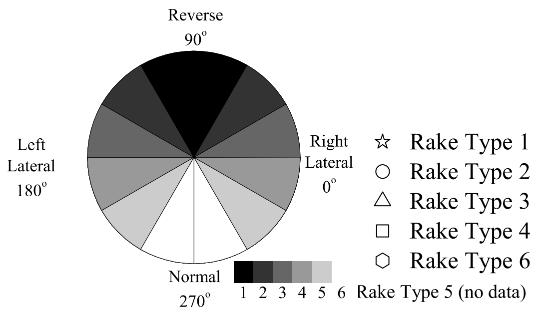
Trying to connect the results of experiments and simulations with observations and analyses of real earthquakes, we have made use of many researchers' field observations of surface ruptures and results from fault rupture process inversion analysis (see [16, 17]), even though there are many uncertainties and assumptions in the inversion process [18, 19]. Even though it is often observed that fault-induced strains and slips are distributed over a wide zone, we have focused on the maximum dislocation of principal faulting along the surface ruptures. The "Research Matrix" shown in figure 1 gives an overview of the current research's relation to previous studies.

2. Overall strain applied to fault inversion analysis and field observations of surface ruptures

"Common" engineering scaled model fault experiments[5, 6, 7, 8, 9, 2, 10] have resulted in a few important parameters. The ones used in here are 1) the "over-all strain" D/H, where D is the base uplift needed for the rupture to reach the surface, and H, the height of the soil deposit; 2) the fault dip-angle; and 3) the slip direction or rake.

We applied the concept of overall strain to the inversion analysis results by taking the maximum slip at an asperity as D and normalizing it with the distance along the fault surface from the asperity to the ground surface (H). Data sources are available from the authors upon request. We have used considerable data collected by Manighetti et. al.[16] and Coppersmith and Wells[13].

Both small scale model experiments [8, 9] and simulations[2] have shown how the type of fault mechanism is very important for the amount of base uplift needed for a surface rupture. To consider in a simple way the above observations about mechanics and geometry, the faults were classified into six types according to their rake angle (see Figure 1a). For field observations we have used the maximum surface displacement along the rupture, even though its location may not always have the shortest distance to the selected asperity.



"Research Matrix"	Earthquake size: Magnitude	Geomechanical parameters: D/H, θ, discontinuous deformation.
Models: experiments & simulations		Engineering design graphs & formulas: Cole & Lade, Bray et. al., Tani & Ueta, Lee & Hamada etc.[5, 6, 7, 8, 9, 2, 10]
Reality: field observation of surface ruptures	Empirical Correlations: Bonilla, Matsuda,Wells & Coppersmith, and others.[11, 12, 13]	This study: overall strain D/H: ratio asperity slip and distance to surface.

Figure 1: Rake type pie chart shown in gray scale. In subsequent plots rake types will be indicated by the marker types as shown in the middle figure.

3. Upper and lower bound for surface rupture to occur

Figure 2 shows maximum surface slips normalized with maximum asperity slips versus overall strain. For earthquakes with no surface rupture, the ratios of maximum surface slip to maximum asperity slip were set to 10^{-3} to be able to show the results in a log-log plot. The overall strain ranges from less than 0.001% to 1%, and, for earthquakes with surface ruptures, the ordinate ranges from 0.01 to 3. Seemingly, earthquakes do not produce any surface ruptures, for overall strains less than 0.03 and for overall strains above 0.63, earthquakes will always cause surface ruptures. However, between these lower and upper bounds, there is still a range of overall strains for which earthquakes may or may not cause surface ruptures. Interestingly, the earthquakes with an y-axis value larger than one are mainly dip-slip earthquakes with dip-angles lower than 60°, i.e. faults that induce considerable horizontal compression or extension.

Keywords: Surface rupture, field observation, inversion analysis, over-all strain.
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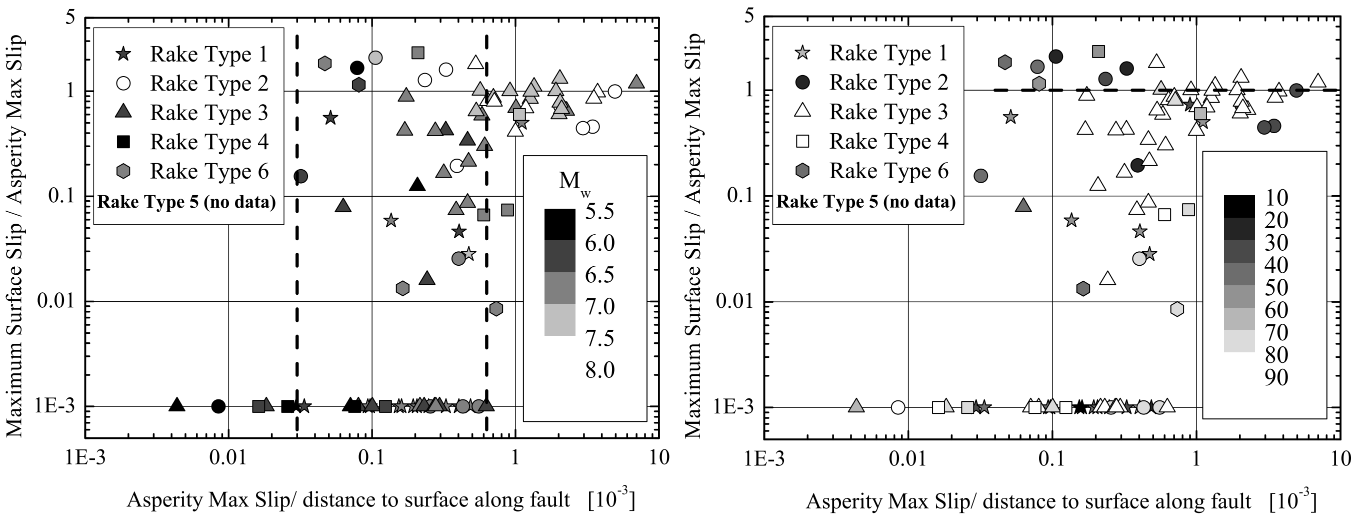

Figure 2: Ratio of maximum surface slip and maximum asperity slip versus overall strain for different rake types. Overall strain is defined as the ratio between maximum asperity slip and distance to ground surface along the fault plane. The gray scale corresponds to the earthquakes' moment magnitude (left), and fault dip-angle (right).

4. Final Remarks

We have presented empirical upper and lower bounds of "over-all strain", D/H, for which earthquakes may or may not cause surface ruptures, which could potentially be useful for reducing the dichotomousness of fault surface ruptures. The overall strain necessary to cause a surface rupture in model experiment are on the order of 0.4% to 3%, but the overall strain estimated from inversion analysis of earthquakes ranges from less than 0.001% to 1%. Assuming the asperity slips are correct, at least to an order of magnitude, there are still considerable differences in overall strains between the inversion analyses and model experiments. Further investigation is necessary to explain this difference.

5. References

[1] William J. Hall, Douglas J. Nyman, Elden R. Johnson, and J. David Norton. Performance of the trans-alaska pipeline in the november 3, 2002 denali fault earthquake. In *Proceedings of the Sixth U.S. Conference and Workshop on Lifeline Earthquake Engineering*. ASCE Technical Council on Lifeline Earthquake Engineering, 2003.

[2] Jörgen Johansson and Kazuo Konagai. Fault induced permanent ground deformations: experimental verification of wet and dry soil, numerical findings' relation to field observations of tunnel damage and implications for design. *Soil dynamics and earthquake engineering*, 2007. (revised version accepted).

[3] East Japan Railway Company. Niigata chuetsu earthquake railway tunnel damage causes investigation committee report. Technical report, East Japan Railway Company, March 2006. in Japanese.

[4] P. G. Somerville. Magnitude scaling of the near fault rupture directivity pulse. *Physics of the Earth and Planetary Interiors*, 137:201–212, May 2003.

[5] Jonathan Donald Bray, Raymond B. Seed, Lloyd S. Cluff, and H. Bolton Seed. Earthquake fault rupture propagation through soil. *Journal of Geotechnical Engineering*, 120(3):543–561, 1990.

[6] David A. Jr. Cole and Poul V. Lade. Influence zones in alluvium over dip-slip faults. *Journal of Geotechnical Engineering*, 110(5):597–615, 1984.

[7] Jea Woo Lee, Masanori Hamada, Go Tabuchi, and Kazuhito Suzuki. Prediction of fault rupture propagation based on physical model tests in sandy soil deposit. In *Proceedings of the 13th World Conference on Earthquake Engineering, Paper No. 119*. International Association of Earthquake Engineering, 2004. Published on CD-rom.

[8] Kazuo Tani, Keiichi Ueta, and Nobuhiro Onizuka. Discussion on "Earthquake fault rupture propagation through soil" by J.D. Bray, R.B. Seed, L.S. Cluff and H.B.Seed. *Journal of Geotechnical Engineering, ASCE*, 122(1):80–82, 1996.

[9] Keiichi Ueta and Kazuo Tani. Bedrock fault movements considering the accompanying deformation of quaternary deposits and ground surface, part 2 - normal and reverse fault model experiments. Technical Report U98048, Central research institute of the electic power industry, CRIEPI, Denryokuchuo-kenkyuujou, 1999. (in japanese).

[10] Jörgen Johansson and Kazuo Konagai. Shear band development length and implications for rupture propagation through soil. *JSCE Journal of Earthquake Engineering*, 28, 2005. Published on CD-rom.

[11] M. G. Bonilla and J. M. Buchanan. Interim report on worldwide historic surface faulting. Open-file report, United States Geological Survey, 1970.

[12] Tokihiko Matsuda. Magnitude and recurrence interval of earthquake from a fault. *Zishin*, 2(28):269–283, 1975. in Japanese with English abstract.

[13] D.W. Wells and K.J. Coppersmith. New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bulletin of the Seismological Society of America*, 84:974–1002, 1994.

[14] R.R. et. al. Youngs. A methodology for probabilistic fault displacement hazard analysis (pfdha). *Earthquake Spectra*, 19(1):191–219, 2003.

[15] K. J. Coppersmith and R.R. Youngs. Data needs for probalistic fault displacment hazard. *Journal of Geodynamics*, 29:329–343, 2000.

[16] I. Manighetti, M. Campillo, C. Sammis, P. M. Mai, and G. King. Evidence for self-similar, triangular slip distributions on earthquakes: Implications for earthquake and fault mechanics. *Journal of Geophysical Research*, 110:B05302, 2005.

[17] Martin Mai. Database of finite-source rupture models. Internet, Downloaded December 2005. www.seismo.ethz.ch/srcmod.

[18] Igor A. Beresnev. Uncertainties in Finite-Fault Slip Inversions: To What Extent to Believe? (A Critical Review). *Bulletin of the Seismological Society of America*, 93(6):2445–2458, 2003.

[19] Mariagiovanna Guatteri and Paul Spudich. What Can Strong-Motion Data Tell Us about Slip-Weakening Fault-Friction Laws? *Bulletin of the Seismological Society of America*, 90(1):98–116, 2000.