CORRELATIONS OF STRESS DISTRIBUTIONS ALONG THE FAULT: FROM LABORATORY FRACTURE ROUGHNESS TO FAULT ASPERITY SQUEEZE

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ABSTRACT

We analyze the spatial correlations of the absolute stress field along the Nojima fault, Japan in terms of scaling invariance (self-affine scaling). Despite the small range of resolution, we obtain a signature of correlations consistent with an elastic compression of the fault roughness. Indeed, we compare the wavelet spectrum of the measured stress field to that obtained from a numerical model that fully squeezes two thick elastic media bounded by interfaces which include spatially correlated asperities (i.e. non diluted asperities). Friction is assumed to follow a Coulomb law locally and interface roughness is described using the self-affine topography that is observed over a very wide range of scales from fractures to faults, with a Hurst exponent H. We find that the stress field is also self-affine, but with a Hurst exponent $H-1$. Fluctuations of the normal stress are shown to be important, especially at local scales with anti-persistent correlations.

1 INTRODUCTION

Numerous recent studies have been proposed to reconstruct the slip and stress histories along the fault during large earthquakes (*e.g. Bouchon* [1], *Olsen et al* [2], *Ide and Takeo* [3]). Even if inversions for the same fault show discrepancies, co-seismic slip and stress drop distributions exhibit very heterogeneous patterns. Such observations suggest that either dynamical processes roughen the stress fields or strong heterogeneities of the initial stress field exist along the fault.

Absolute stress field however is more difficult to obtain. It has been obtained in the case of the Kobe, 1995 earthquake (*Bouchon* [4]). It relies on the rotation of the slip vector during the earthquake (*Spudich et al* [5]). The absolute initial stress field shows significant spatial fluctuations (see Fig. 1). The characteristic size of asperities is of the order of 10 km with an isotropic distribution. Fig. 1 also shows the final stress field. It is of interest to note that although magnitude of the peaks are smaller, their positions are persistent. Accordingly, heterogeneities of the stress field are quenched along the fault and weakly sensitive to dynamical stress fluctuations due to earthquake propagation.

In this study, we analyze the possible spatial correlations of the absolute stress field using wavelet transform. We show that a power law behavior is compatible with the data and characterize the stress field fluctuations as a self-affine distribution. As a second step, we attempt to link the stress distribution along the fault to that resulting from the squeeze of fault surface asperities. For that purpose, we analyze the elastic transformation of the fault plane roughness on the basis of a boundary element model.

2 CORRELATIONS OF THE STRESS FIELD ALONG THE FAULT

We search in the initial stress field $\tau(x,z)$ presented in Fig. 1 for spatial correlations. The grid of estimated value is 61×22 with a spatial resolution of 1km×1km. Actually, stress estimates are

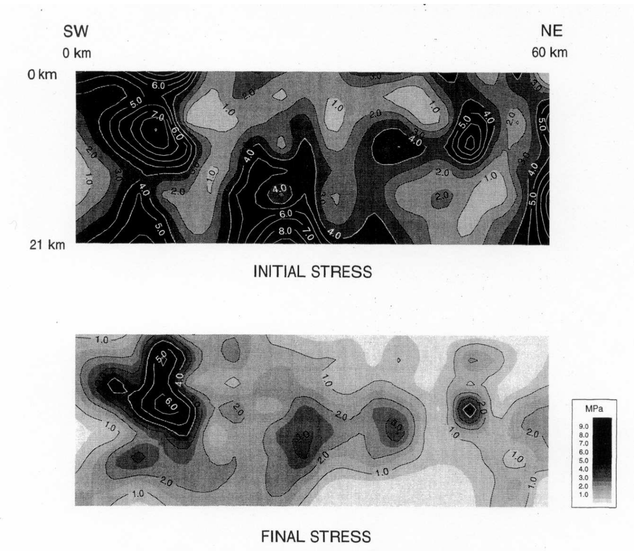

Figure 1: Absolute shear stress distributions along the Nojima Fault, Japan: before (initial stress) and after (final stress) the Kobe, 1995 Earthquake (from Bouchon et al [4])

obtained from the inverted slip distribution along the fault (*Bouchon et al* [4]) and an interpolation is performed at the lowest scales ($<$ 5km). Along horizontal profiles, we search for the auto-correlation function of the local stress estimate, using wavelet transform. Because of the limited statistics, we used a sensitive tool: the Average Wavelet Coefficient technique (*Simonsen et al* [6]). It consists of an average of the wavelet transform:

$$W_{a,b} = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} dx \; \psi \left(\frac{x-b}{a} \right) |\tau(x, z = const)| \tag{1}$$

where ψ is the wavelet: Daubechies wavelet of order 12. Then the wavelet coefficients are averaged over the translation factor b for each length scale a:

$$W_a = \langle W_{a,b} \rangle_b \; . \tag{2}$$

If the auto-correlation function of a stress profile scales as:

$$C(\tau(x), \tau(x+d)) \propto d^{2H_\tau} \tag{3}$$

where H_τ is the Hurst exponent of the shear stress field, then the average wavelet coefficient scales as:

$$W_a \propto a^{H_\tau + 1/2} \; . \tag{4}$$

Figure 2 shows the average wavelet spectra at different depths z and the mean over all accessible depths in a log-log plot. Two regimes emerge: at small scales (2km $< a <$ 10km) a linear behavior is consistent with data interpolation. At large scales (a >10km), a power law with an exponent

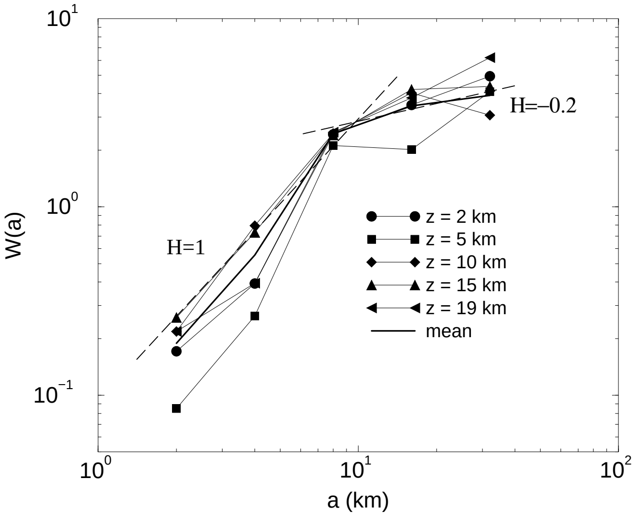

Figure 2: Average wavelet spectrum of the horizontal initial stress profiles at various depths. At small scale the spectrum is controlled by the linear interpolation prodecure. At large scale, data are compatible with a power law with a slope of 0.3 in agreement with a Hurst exponent $H_\sigma = -0.2$.

0.3 ± 0.1 is a possible fit. The latter leads to a negative Hurst exponent of $H_\tau = -0.2 \pm 0.1$.

3 FAULT ROUGHNESS

Roughness of fault plane has been largely studied both at lab scales (*Scholz* [7]; *Power and Durham* [8]) and at field scale (*Power et al* [9]; *Schmittbuhl et al* [10]). We report on a measurement of the topography of a fault surface extracted from the Bastille Hill fault near the city of Grenoble, France. A optical profiler has been used with a resolution of $3\mu m$ for positions along the mean fracture plane and of $1\mu m$ for height estimates (*Renard et al* [11]). The grid was 4100×873 with a mesh of $24\mu m \times 24\mu m$. Analysis of the roughness has been performed using the same wavelet technique as described above, *i.e.* the AWC technique. Figure 3 shows the wavelet spectrum averaged along the 873 profiles.

A power law behavior with a slope of 1.31, *i.e.* corresponding to a Husrt exponent of $H = 0.81$, is very consistent with the data over three decades. This result is also similar to other measurements (*e.g. Scholz* [7]).

4 ASPERITY SQUEEZE MODEL

We attempt to link the roughness of fault surfaces to the stress field distribution owing to the analysis of the transformation of the fault asperities when submitted to a normal load. We limit ourself to an elastic deformation of the topography but include the broad range of asperity scales as observed on natural fault surfaces. The approach is based on the work of *Hansen et al* [12] which consists of a boundary element modeling of the interface deformation using Fourier acceleration. The code provides an estimate of the normal stress distribution when squeezing elastically a rough surface with large range of Hurst exponents as shown in Figure 4 ($H \in [-1; 2]$). We then apply the AWC

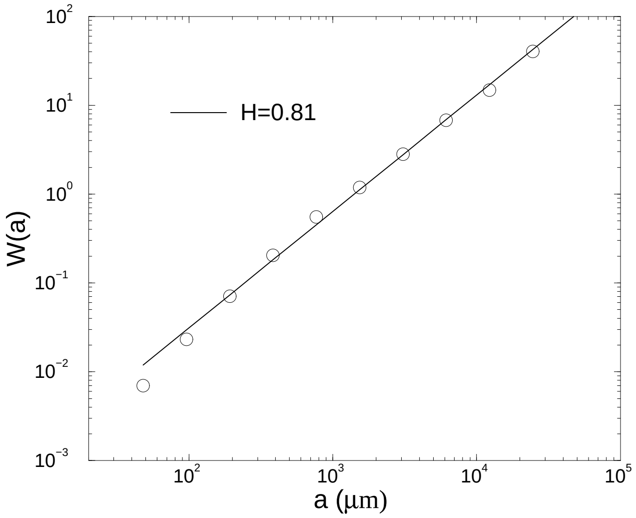

Figure 3: Average wavelet spectrum of fault roughness at laboratory scale. The sampled fault is located on the Bastille hill, Grenoble, France.

technique to the produced stress field and obtained the Hurst exponent of the normal stress field H_σ. If we assume a local Coulomb friction law (prior to the earthquake) at any point along the fault, we obtained a prediction of the Hurst exponent of the shear stress field along the fault H_τ. Therfore, if the Hurst exponent of the fault roughness is $H = 0.8$, we predict that the Hurst exponent of the shear stress field is $H_\tau = -0.2$ which is good agreement with what is obtained at large scale (*i.e.* above the smoothing length scale) as shown in Figure 2.

5 CONCLUSIONS

For the 1995 Kobe earthquake, it has been possible to reconstruct not only the relative stress field during the event (stress drop), but also the absolute stress field (*Bouchon et al* [4]). It appears that distributions of initial and final stresses before and after the earthquake, look very similar. This suggests that stress distribution constitutes an intrinsic property of Nojima fault, and is only slightly affected by earthquakes.

We have examined whether the dominant control of this stress distribution could be the compression of an effective fault roughness. We analyze the spatial correlations of the initial stress field in terms of scaling invariance (self-affine scaling). It can be shown (Hansen et al [12]) that the normal stress field resulting from the full squeeze of elastically-correlated asperites characterized by a roughness exponent H is self-affine with a Hurst exponent $H - 1$. Since roughness exponents of surfaces are systematically below unity (for a wide range of scales from fractures to faults), squeeze-induced normal stresses are expected to display large spatial fluctuations with anti-persistent correlations.

Initial shear stress along Nojima fault is indeed characterized by strong spatial variability. Despite a small range of resolution, its averaged wavelet spectrum is consistent with a slightly negative Hurst exponent ($H_\tau = -0.2$). A similar self-affine behavior is observed for the stress drop during the event. Total slip during the earthquake also seems to display self-affine properties, with a Hurst exponent slightly below unity ($H_u = 0.8$).

Hence, the signature of stress correlations along Nojima fault is consistent with the squeeze of a self-

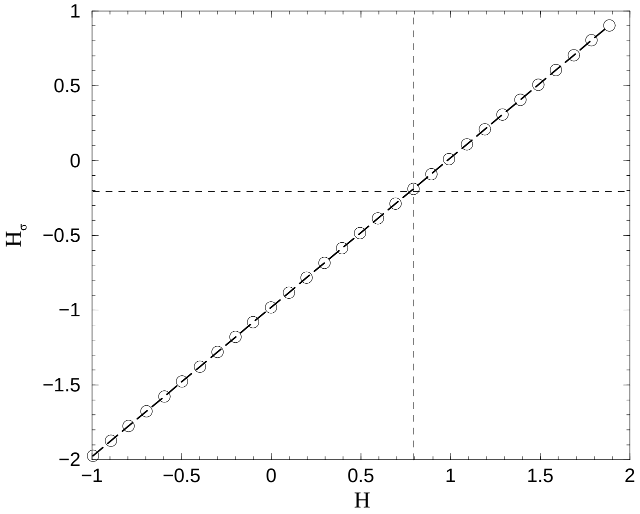

Figure 4: Estimate of the Hurst exponent H_σ of the stress field when a surface of roughness exponent H is fully squeezed in the elastic regime. The relationship: $H_\sigma = H - 1$ is remarquably fulfilled over a large range of surface geometry.

affine roughness. Furthermore, we also show that the initial stress field along the fault constitutes a strong guide for the the development of the earthquake (stress drop and slip). Note that seismological data concern shear stresses, whereas, at the moment, squeeze models only account for normal stresses. Assuming a simple friction law, *i.e.* Coulomb law, we may infer from our results that stress distributions along large faults, and earthquake mechanisms, could be primarily controlled by an effective fault roughness.

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