

NG21C-0948 0830h POSTER

Requirements for Verifying Wave-Wave Coupling at Texcoco, Valley of Mexico

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A late-arriving monochromatic wave has been identified at the Texcoco accelerometer array in the Valley of Mexico, for the 2001 October 8 Coyuca, Guerrero (M 6.1) earthquake. Because this wave propagates nearly towards the epicentre, it must be locally-generated, and its combination of low velocity (160m/s phase, 60m/s group) long delay (85sec after s-wave arrival), distance from the basin margin (about 8km), and relatively high amplitude, are not consistent with current beliefs about wave attenuation in the lacustrine mud in which the wave travels. Three possibilities must be considered; that the mud does not attenuate motion as much as believed; that most of the wave energy does not travel in the mud; or that the observed wave is coupled to a less-attenuated wave so that energy lost in the mud is continually being replaced by wave-wave coupling. Wave-wave coupling is a likely mechanism because the monochromatic motion is at a frequency that differs from the readily-evaluated layer frequency, ruling out the layer as the main determinant of frequency. Instead it is possible that the observed frequency is that at which a Rayleigh wave travels at the speed of a wave in a material below the surface (28m thick) layer. In order for wave-wave coupling to be unambiguously confirmed it is necessary to identify a layer of material which will support a wave at the observed velocity of 160m/s. Such a wave is unlikely to be a p-wave because p-waves in the profile are likely to have velocities in excess of 1500m/s. SCPT testing will readily determine whether an s-wave velocity of 160m/s is present in the profile. In the case of coupling of a Rayleigh wave to an acoustic wave it is relatively easy to identify the two waves and to ascertain that they travel at the same speed, on account of the widely differing nature of the two waves. A pressure detector will not respond to the Rayleigh wave, even though a seismometer will respond to the pressure wave. The situation is more complex for a Rayleigh wave coupled to a shear wave at depth. One way of differentiating between a Rayleigh wave in a layer, and the same wave coupled to a shear wave, is that the latter case demands the monochromatic signal be present below the layer. Such a signal has been seen at a depth of 40m at Texcoco, at the frequency observed for the late arriving phase, whereas it is not seen for other frequencies. An essential ingredient of wave-wave coupling is the passing of energy from one wave to another. In the Texcoco case this can only be done indirectly, by showing that the attenuation of the observed wave is less than for some similar wave, perhaps for a vertically-propagating s-wave such as has already been recorded for an earthquake originating directly below the Texcoco site. Most of the requirements for verifying wave-wave coupling at Texcoco exist now. All that is missing is an SCPT profile, and an earthquake of sufficient amplitude to be recorded by the existing surface and vertical accelerometer arrays.

NG21C-0949 0830h POSTER

Wave-Wave Coupling and Disasters: The 1985 Mexico Earthquake and the 2001 WTC Collapse

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Wave-wave coupling occurs in the presence of weak nonlinearity. It can generate quite dramatic, unexpected effects. In the 1985 earthquake disaster in Mexico City more than 400 high-rise buildings collapsed on soft ground with a loss of life of around 10,000. The emergence of a large, monochromatic, coherent ground wave was an unforeseen factor. Linear modeling failed to reproduce the main features of this signal including the prominent spectral peak close to the resonant frequency of the high-rise buildings, and an extremely long time duration (more than five minutes). The signal was apparently due to coupling of a fundamental Rayleigh mode to the quarter-wavelength shear resonance in the surface mud layer through their common frequency at 0.4 Hz. An additional unexpected feature was the low attenuation of these modes in the mud layer, and the presence of prograde particle motion. Prograde rotation, though not necessarily caused by nonlinear effects, will couple with structural modes of vibration that tend to destabilize a tall building, much like a tall ship in ocean waves. Such unanticipated features may play a critical role in earthquake disasters on soft ground. A related case is the World Trade Center disaster of 11 September 2001, which was presumed to be due to gradual heat softening of steel girders. If so, the Twin Towers should have leaned over sideways but actually the collapse occurred vertically and quite suddenly. A likely alternative is coupling between a fireball caused by a phase transition between low- and high-oxygen consumption modes in burning jet fuel:

$$\begin{aligned} & \text{(low-oxygen)} \quad 2C_nH_{2n+2} + (n+1)O_2 = nC_2 + (2n+2)H_2O, \quad (1) \\ & \text{(high-oxygen)} \quad 2C_nH_{2n+2} + (3n+1)O_2 = 2nCO_2 + (2n+2)H_2O, \quad (2) \end{aligned}$$

and a pressure pulse propagating vertically inside the tubular structure. The pulse would have taken out the concrete floors, thus initiating collapse by implosion of the structural shell. Linear thinking may fail to anticipate coupling, and thus appropriate preventive measures may not be provided.

NG21C-0950 0830h POSTER

Measurement and simulation of ground-coupled air waves and diffracted infrasound from the Kokoxili Earthquake, 14th Nov. 2001

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On November 14, 2001, a strong earthquake measuring Mm 7.8 occurred in the Qinghai Province (China). Coherent infrasonic waves were detected during more than one hour by the IS34 infrasound station in Mongolia (1500 km from the epicenter). Using an appropriate acoustic propagation model, the inversion of the infrasonic measurements allows a precise localization of the secondary sources distribution along the Qinghai mountains. The predominant source of infrasound is likely ground-coupled air waves generated by the strong variations of topography due to energy carried out by surface seismic waves that travel from the epicenter region through the Qinghai mountains. To confirm the locations of these distant source regions, the pressure field has been reconstructed at IS34. For each element of the topography, a synthetic seismogram used as an input of the integral relation of Huygens-Rayleigh permits to estimate the pressure variation. The synthetic pressure field fit the recorded data in azimuth and in relative amplitude. These results confirm the hypothesis of a strong coupling between the Rayleigh waves and the atmosphere, as it has already been observed during the Arequipa earthquake of June 23rd 2001. The simulations also permit to validate the infrasonic propagation model. This favorable setting within a region of high mountains makes easier the evaluation of the relative contribution of the different source mechanisms involved in large earthquake.

NG22A MCC: 130 Tuesday 1330h

Recent Advances in Nonlinear Geophysics III: Damage Rheology (joint with S, T, MR)

Presiding: Y Ben-Zion, University of Southern California; D L Turcotte, Cornell University

NG22A-01 1330h INVITED

The shear transformation zone approach to the deformation of dense materials: an overview

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Shear transformation zone (STZ) theory proposes mean-field constitutive equations for dense materials on the basis of a heuristic picture of microstructural rearrangement. Originally introduced to account for elasto-plastic transition in amorphous solids, it has been adapted to granular materials and accounts for the emergence of a Coulomb angle. The dynamics of shear transformation zones thus appears as a general mechanism for jamming resulting from the anisotropy of local structures. A general overview of STZ theory will be given, from its premises, and various recent applications will be discussed.

NG22A-02 1345h INVITED

Statistical Theory of Shear Localization in Brittle Rock

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Shear localization as observed in triaxial experiments on brittle rocks is generally understood to be the consequence of a phenomenological elasto-plastic constitutive relation. However such a description gives no insight into the underlying physics actually responsible for the localization and makes no predictions as to how shear bands grow in the immediate approach to localization. Why do the elasto-plastic phenomenological stress-strain relations have their observed form? The underlying physics at work in localization is the generation and interaction of microcracks. We have developed a statistical mechanics that allows the probability of the various possible crack states in a rock to be determined as a function of the applied deformation. This probability is determined using an entropy maximization principle despite the fact that thermal fluctuations play no role in the problem; all statistics in our theory is due to the initial quenched disorder that is present in a rock before deformation is applied. The probability law takes the form of a Boltzmannian and we develop a model Hamiltonian for interacting crack states. The notion of temperature is unambiguously quantified. Using this theory, we make several analytical predictions about disordered rocks. First, at a well-defined strain point ϵ_c that corresponds to the localization transition, thin bands of coherently oriented (en echelon) cracks can be added to a system at no energetic cost. The free energy and entropy of the system remain continuous and finite at this strain point so localization is formally a continuous (critical point) phase transition. The only divergence at localization is in the correlation function with a correlation length of emergent crack clusters diverging as $(\epsilon_c - \epsilon)^{-2}$. The universal exponent in this law is perhaps the principle prediction of the theory and requires experimental verification (no experimental measures of this exponent have ever been published). For ranges of elastic moduli corresponding to typical rock minerals, localization is predicted to occur after peak stress as is most often seen in lab experiments. However, for materials with a sufficiently small bulk modulus and at sufficiently small radial confining stress, we also predict that localization can occur prior to peak stress.

NG22A-03 1400h INVITED

A Damage Rheology Model Based on Continuum Mechanics and Irreversible Thermodynamics

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We present a damage rheology model that provides a generalization of Hookean elasticity to a nonlinear continuum mechanics framework incorporating large strain and irreversible deformation. The model accounts for fracture nucleation, development of process zone at rupture tip, branching from the main rupture plane, and various observed space-time failure patterns. Our approach is based on the assumption that the density of micro cracks is uniform over a length scale much larger than the length of a typical crack, yet much smaller than the size of the entire deforming domain. For a system with a sufficiently large number of cracks, one can define a representative volume in which the crack density is uniform and introduce an intensive damage variable for this volume.

The model treats the following two aspects of the physics of damage: (1) A mechanical aspect associated with sensitivity of the macroscopic elastic moduli to distributed cracks and to the sense of loading. (2) A kinetic aspect associated with the evolution of damage (degradation and recovery of elasticity) in response to loading. Distributed cracks modify the elastic behavior by breaking the symmetry to loading-unloading and reducing the apparent moduli. Sliding takes place on microcracks having stresses that exceed a criterion equivalent to the static friction limit. Under Coulomb friction, the critical stress for sliding is proportional to the normal stress. We replace the Coulomb stress criterion constrained by experiments on undamaged media with an equivalent critical applied strain, which does not depend on the effective modulus. For a general 3-D loading, the critical strain is defined in terms of the invariants of the strain tensor. Motivated by recent stress-strain and acoustic emission experiments,

we augment the model with damage-related viscosity to account for inelastic deformation that precedes brittle failure.

Analytical and numerical results based on the model formulation reproduce key features of rock behavior under large strain, including damage self-organization and localization into a narrow zones, crack extension path under mixed mode loading and more. The damage model includes post-failure behavior (healing) that allows a stick-slip motion along a narrow zone with localized damage. Averaging such stick-slip motion in space and time fits the experimentally observed relations of rate- and state-dependent friction between slip velocity, normal, and shear stress components. Three dimensional numerical simulations reproduce the main features of a quasi-static fault nucleation observed in a triaxial laboratory test. Additional model features compatible with seismicity patterns are discussed in a companion presentation by Ben-Zion and Lyakhovskiy.

NG22A-04 1415h

The void Limit of Two-phase Damage; Applications to Shear Localization and Shear-Enhanced Compaction

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Using a classical averaging approach, we derive the limit of a two-phase viscous theory, when both the viscosity and the density of the less viscous phase become zero. The resulting model describes the behavior of a porous matrix containing voids. The presence of surface tension at the surface of the matrix grains is taken into account. In addition to the equations of matrix mass and momentum conservations, non-equilibrium thermodynamic considerations allow us to propose an energy balance where both mechanical heat dissipation and storage of surface energy are taken into account. This model gives therefore a simple description of an isotropic damage theory that we use to interpret the failure envelopes of rock samples. For a sample under triaxial compression, the theory predicts in a mean stress/differential stress plane, the positions of the dilations or compressions and the rates of porosity changes. Comparisons with various sandstone experiments show that the experimental failure envelopes corresponds exactly to a critical rate of porosity change according to our equations, either negative (shear enhanced compression) or positive (fracture). One of the parameters of our equations that characterizes the percentage of work that is not dissipated but is stored as surface energy appears surprisingly constant for all sandstone experiments of the data base that we compiled. The dependencies of the failure envelope as a function of porosity (cohesion strength, onset of grain crushing, onset of dilation, and maximum sustainable differential stress) are very satisfactorily predicted by our approach.

NG22A-05 1430h

Correlations in the damage zone and fracture roughness

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We suggest that the observed large-scale universal roughness of brittle fracture surfaces is due to the fracture process being a correlated percolation process in a self-generated damage gradient. We show that the roughness exponent ζ of an in-plane crack front slowly propagating along a heterogeneous interface embedded in an elastic body, is in full agreement with a correlated percolation problem in a linear gradient. We obtain $\zeta = \nu/(1 + \nu)$ where ν is the correlation length critical exponent. We develop an elastic brittle model based on both the 3D Green function in an elastic half-space and a discrete interface of brittle fibers and find numerically that $\nu = 1.5$, which therefore yields $\zeta = 0.6$. We also obtain by direct numerical simulations $\zeta = 0.6$ in excellent agreement with our prediction. This modelling is for the first time in close agreement with experimental observations. Moreover, for three-dimensional brittle fractures, the gradient is quadratic and the roughness exponent is shown to be: $\zeta = 2\nu/(1+2\nu)$. A mean-field theory gives $\nu = 2$, leading to $\zeta = 4/5$ in full accordance with the universally observed value $\zeta = 0.80$.

NG22A-06 1445h

Physical Interpretation of Laboratory Friction Laws in the Context of Damage Physics

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Frictional on sliding surfaces is ultimately related to processes of surface damage, and can be understood in the context of the physics of dynamical threshold systems. Threshold systems are known to be some of the most important nonlinear, self-organizing systems in nature, including networks of earthquake faults, neural networks, superconductors and semiconductors, and the World Wide Web, as well as political, social, and ecological systems. All of these systems have dynamics that are strongly correlated in space and time, and all typically display a multiplicity of spatial and temporal scales. Here we discuss the physics of self-organization and damage in earthquake threshold systems at the microscopic laboratory scale, in which consideration of results from simulations leads to dynamical equations that can be used to derive results obtained from sliding friction experiments, specifically, the empirical rate-and-state friction equations of Ruina. Paradoxically, in all of these dissipative systems, long-range interactions induce the existence of locally ergodic dynamics, even though the dissipation of energy is involved. The existence of dissipative effects leads to the appearance of a leaky threshold dynamics, equivalent to a new scaling field that controls the size of nucleation events relative to the size of the background fluctuations. The corresponding appearance of a mean field spinodal leads to a general coarse-grained equation, which expresses the balance between rate of stress supplied, and rate of stress dissipated in the processes leading to surface damage. We can use ideas from thermodynamics and kinetics of phase transitions to develop the exact form of the rate-and-state equations, giving clear physical meaning to all terms and variables. Ultimately, the self-organizing dynamics arise from the appearance of an energy landscape in these systems, which in turn arises from the strong correlations and mean field nature of the physics.

NG22B MCC: 130 Tuesday 1515h

Recent Advances in Nonlinear Geophysics IV: Hydrology/Nonlinear Waves (joint with H, S, T)

Presiding: C Lomnitz, National

University of Mexico /UNAM; D

Benson, Desert Research Institute; M

Meerschaert, University of Nevada

NG22B-01 1515h INVITED

Wave-Wave Coupling: A Nonlinear Phenomenon of Classical Physics

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Linear physics does not admit the possibility of wave coupling. With the advent of nonlinear research, wave-wave coupling has been observed and described theoretically in many media. For example, in hydrodynamics the Euler equations can lead to the Nonlinear Schroedinger Equation (NLS), which in turn admits three-wave coupling. Simple theory yields surprisingly good results [1, 2]. In plasma physics, the wave coupling phenomenon can be derived directly from the Vlasov equation [3]. Recent interest has been renewed when four-wave coupling was observed in experiments on Bose-Einstein condensates. Here, a successful theory has recently been developed based on the Gross-Pitayevski equation, a NLS for this condensate. Although now four waves may couple instead of three, the ideas and even the formalisms are almost identical [4]. Other fields in which the phenomenon is observed include optics and even population studies. When looking for this effect in new fields, one should ask whether similar coupling mechanisms are in place.

References [1] E Infeld, Phys Rev Letters 47 717, 1981 [2] E Infeld and G Rowlands, Nonlinear Waves, Solitons and Chaos, CUP, 1990, second edition, Chapter 5. [3] R C Davidson, Methods in Nonlinear Plasma Theory, Academic, NY, 1972, chapter 6. [4] M. Trippbach et al., Phys. Rev. A 62, 023608, 2000.

NG22B-02 1545h

T Waves at the Seafloor: Coupled Seismoacoustic Modes and Spiciness

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T waves are routinely observed at the Hawaii-2 Observatory (H2O) on the seafloor between Hawaii and California, even though the seafloor (4979 m) is substantially below the conjugate depth of the SOFAR channel. These interface T waves, termed Ti, show specific polarization characteristics in the sediments at H2O and underlying basement (at the OSN-1 borehole site). The sedimentary observations are polarized dominantly on the radial-horizontal direction, whereas the borehole measurements are dominantly vertical. The frequency spectra displays a modal structure of seismoacoustic coupling on the seismometer and hydrophone observations. The polarization of individual modes exhibits elliptical particle motion characteristic of Rayleigh waves. Ti is observed at H2O with frequencies up to 80 Hz at 2200 km from the Blanco Fracture Zone, 2.5-15 Hz at 5500 km from earthquakes near Kamchatka, and 5-15 Hz at a distance of 9400 km from the Pacific-Antarctic Ridge. Energy analyses of Ti indicate that below around 5 Hz, Ti dominantly propagates as seismoacoustic coupled Rayleigh modes in the sediments, whereas above 5 Hz the dominant energy is observed on the hydrophone. Seismoacoustic modal coupling in Ti above 5 Hz may be locally generated in part from energy scattered from the SOFAR channel. It is hypothesized that the higher frequency (>5 Hz) components of Ti include scattering of T waves from the SOFAR channel to the seafloor attributable to "spiciness", the variability of temperature and salinity along a surface of constant density due to air-sea fluxes, turbulent mixing and advection. While dynamically neutral in the ocean by virtue of the density compensation, sound speed correlates positively with both temperature and salinity, so that spicity structures create velocity heterogeneity which scatter T waves. The 5-80 Hz frequency range and corresponding wavelengths observed at H2O suggests spicity length scales of 300 to 20 m in the region of the H2O site.

NG22B-03 1600h INVITED

Anomalous Dispersion, Finite-Size Lyapunov Exponents, the Full Intermediate Scattering Function and 3D-PTV

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Velocity fluctuations over evolving scales of motion, on the scale of observation, often lead to anomalous dispersion of conservative tracers in fluid mechanics studies of turbulence and heterogeneous porous media. Recent theories of anomalous dispersion lead to space-time non-local constitutive models for the flux of concentration, which can adequately model this problem. We review one such model, which has its foundations in non-equilibrium statistical mechanics. The basic premise is that knowledge of the evolution of the self-part of the intermediate scattering function is all that is required to model the phenomena of interest. We derive the basic integro-partial-differential equation this function satisfies and solve the inverse problem to obtain the kernels and use these to describe the wave-vector and frequency dependent dispersion tensor. Subsequently we use this information to study the transition from anomalous to Fickian dispersion. We also make use of the finite size Lyapunov exponent in the description of the dispersive process. Three-camera, three-dimensional, particle-tracking velocimetry experiments are undertaken to study dispersion within a matched-index heterogeneous porous medium. Particle trajectories, mean square displacements, velocity covariance's, intermediate scattering functions, classical dispersion tensors, wave-vector and frequency dependent generalized dispersion tensors and the finite-size Lyapunov exponents are obtained. Comparisons are made in the small frequency and small wave vector limits to obtain the transition from preasymptotic to asymptotic dispersion.