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We use a catalog of 57 repeating earthquake sequences to study the damage to near-surface materials, manifest as changes in seismic wave velocity, caused by strong ground motion. We believe that near surface damage (cracking) is the most likely cause for velocity reductions that we observe immediately following both the M6.9 Loma Prieta and M5.4 Chittenden earthquakes. The strong ground motion during both of these events was strong enough to open cracks near the Earth's surface, the presence of which reduces seismic velocities. The velocity reductions heal with time, following Loma Prieta and Chittenden in a manner similar to the "slow dynamic" healing behavior observed in laboratory studies [TenCate, et al., 2000]. Since the damage left by Loma Prieta had not completely healed by the time Chittenden occurred, it is probable that the local rocks were more susceptible to further damage, allowing the much weaker motions of the Chittenden Earthquake to cause damage comparable in magnitude as that of the Loma Prieta Earthquake.

We have identified the above conditions by studying repeating earthquakes (multiplets) on the San Andreas Fault. Using a moving window cross correlation technique to identify changes in the nearly identical waveforms of a repeating earthquake sequence, we can observe late-arriving phases, after both the Loma Prieta and Chittenden earthquakes. We attribute these delays to near surface velocity reductions localized to a damage zone close to the Loma Prieta rupture zone.

We observe a similar phenomenon in the cross correlation coefficient (CCC) data. Immediately following the Loma Prieta and Chittenden Earthquakes, the CCC drops sharply and heals in time in a manner similar to the healing of the velocity reductions. This is not surprising because the changes in CCC reductions should scale linearly with the magnitude of the velocity perturbation. The drops in CCC don't always parallel velocity changes; however, they can also measure more general changes in waveform character. A combination of the two measurements not only allows us to identify parts of the seismogram where an arrival disappears or a new one appears, but it also allows us to further constrain the nature of the variation.

TenCate, J.N., D.E. Smith, and R. Guyer, Universal Slow Dynamics in Granular Solids, Physical Review Letters, 85, 1020-1023, 2000.

NG21B-0943 0830h POSTER

Dynamic parameters estimation of the 1999 Chi-Chi, Taiwan, Earthquake

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We estimated the dynamic parameters of the 1999 Chi-Chi earthquake from a dynamic finite-difference code that calculate a north-south dipping fault in a heterogeneous medium with a free surface and use the kinematic inverted slip solutions as constraints. The stress time history over the thrust fault plane show stress continuous to drop through the entire duration of slip at the region with slip greater than 12 m. The regions surround large slips show significant strengthening of the fault during the rupture. Large strength of up to 10-15 MPa is found at the bottom of hinge-axis, the axis where the fault bending to the northeast. The derived slip-weakening curves for the subfaults with large slips yield a large Dc of up to 10m. Considering the trade-off between Dc and strength, the Dc could be reduced to the value of 3 m, which is still much larger than the value from laboratory experiment. The determination of Dc value might be limited by the resolution on the numerical calculation. This large Dc is suspicious, but might be also physically implicit. The maximum fracture energy over the fault plane is up to 108 J/m². The estimated dynamic parameters will be further discussed with laboratory experiments to understand the stability and instability of fault slip.

NG21B-0944 0830h POSTER

Generic Quasi-static Nucleation With Slip Dependent Friction

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The stable quasi-static nucleation of slip has been the focus of various experimental studies in the past. In the framework of non linear slip dependent friction laws, mechanical models were proposed to explain this phase of nucleation and its transition to the dynamic unstable regime. To account for details of experimental observations and seismological scalings between the size of the nucleation zone and the size of the whole earthquake, those models relied on the presence of specific heterogeneities of constitutive properties and ad hoc assumptions about their geometry. We raise the question of the need of such assumptions and an underlying question about the interaction between structural heterogeneities and the non-linear behavior of faults.

We show that most of the physics of the quasi-static nucleation and stability in a heterogeneous fault described by non-linear slip dependent friction, with strengthening and weakening phases, can be understood, qualitatively and quantitatively, by studying a special aspect of an ideal case: the bifurcations to localized slip in a homogeneous, perfect, fault. In fact, a range of loading conditions lead a homogeneous fault to continuously evolve from uniform sliding to a stable a non uniform slipping state. We analytically characterize those conditions as well as the behavior and stability in a vicinity of the bifurcation point by a perturbative analysis.

Depending on the load coupling of the fault, the nucleation can be characterized by a localization process preceding the instability. The localization phase is followed by a crack-like growth with classical fracture mechanics scalings. This post-bifurcation regime is solved by numerical means, showing the progressive localisation of slip inside a shrinking nucleation zone, as seen in rate-and-state models.

We then assess the robustness of these results to the presence of different kinds of heterogeneities. We show that the essential characteristics are preserved and that the spectrum of sensitivity introduces a characteristic screening length. This length can be related to the bifurcations of the ideal case first studied. Interestingly enough, the quasi-static nucleation appears as a cascade from long to short wavelengths, a feature not present in a recent analysis of the linear slip weakening nucleation length. As a result, at the onset of instability the state of the fault can be heterogeneous but not by structural reasons.

NG21C MCC: Hall C Tuesday 0830h

Wave-Wave Coupling at Interfaces: From Ground Roll to Morning Glory Phenomena Posters (joint with A, S, T)

Presiding: C Lomnitz, National University of Mexico /UNAM; W Stephenson, Institute of Geological and Nuclear Sciences

NG21C-0945 0830h POSTER

The Non-Linear Morning-Glory Wave of Southern California

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A pulse-like disturbance traveling across the Los Angeles basin was observed on Oct 12, 2001 with seismographs of the TriNET network. This wave had a period of about 1000 s, and a propagation speed of about 10 m/s, much slower than seismic waves. The seismograph data was compared with barograph data and a good correlation was found, so the wave was determined to be atmospheric in origin. It had an amplitude of about 1 mbar, but it was not known what process could produce such a wave. Since the initial finding, we inspected all the TriNET barograph and seismograph data for a period of two and a half years (from Jan 2000 to July 2002), and found 5 more events with similar characteristics. Another event occurred in 1988. Each of the events has an amplitude between 0.8 and 1.3 mbar, a period between 700 and 1400 s, and a propagation speed between 5 and 25 m/s. Analysis of these data has led us to the conclusion that the wave is a solitary wave (a non-linear internal gravity wave) similar to the spectacular morning glory wave observed in Australia. We present data here that supports the hypothesis that this morning-glory wave of Southern California is caused by an excitation of the stable inversion

layer by some atmospheric condition or seismic disturbance as it enters the LA basin. In particular, we believe it may be coupled to stormy weather, winds such as the Santa Ana Winds, and large teleseismic events. Furthermore, the morning-glory wave could contribute to the excitation of the background free oscillations of the Earth reported recently. Additionally, because of its large amplitude, it could have important implications for aviation safety, as was suggested earlier for the morning-glory waves in Australia.

NG21C-0946 0830h POSTER

Infrared sounds coupled with the Earth's free oscillations

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Recent observations of Earth's free oscillations show that they are continuously excited at nano gal level. The most probable mechanism of such oscillations is that these oscillations are excited by turbulence motions in the atmosphere. To confirm the mechanism, a survey of atmospheric disturbances is necessary. If atmospheric turbulence can excite the free oscillations, the same mechanism can also excite continuous atmospheric infrared sounds. Detection of the sound waves can be another test for the mechanism that our atmosphere can really excite the global oscillations. Thus, Fukao et al. (2002) recently installed an array of high resolution barometers to search continuously excited atmospheric oscillations. To evaluate the observational feasibility, here we discuss the excitation of sounds by atmospheric turbulence.

The sound waves considered here are trapped between the Earth's surface and the mesopause. For the infrared sounds the mesopause behaves a lid. The frequency of the waves is about 3.7 mHz which is just inverse of propagation time of traveling sounds nearly vertically in the region, and Q of the waves is low (about 100) since the lid is not perfect. The excitation mechanism of sounds by turbulence is well known as Lighthill mechanism, which shows that efficiency (E) of sound generation is 2n + 1-th power of ratio of fluid velocity to sound velocity. The input energy per unit mass per unit time (I) is evaluated from solar radiation energy absorbed in the lower atmosphere. Thus sound energy per unit mass is equated to I x E multiplied by fraction of solid angle for vertical radiation of sounds, the period of sounds and the squared root of Q. From this equation, the pressure intensity of sound waves are about 1 x 10⁻³ Pa for n=2 (quadrupole radiation) as a whole. For each singlet mode, this corresponds to 1 x 10⁻⁷ Pa.

On the other hand, from the amplitudes of the continuously excited Earth's free oscillation mode (0S₂₉) that is coupled with atmospheric sounds, we can evaluate amplitudes of the coupled infrared sounds. The evaluated value is consistent with the above value. Thus we conclude that infrared sounds in the mHz band can be excited by turbulence in the lowest atmosphere as same as the Earth's free oscillations can be.

NG21C-0947 0830h POSTER

Hamiltonian formalism and the Garrett-Munk spectrum of internal waves in the ocean

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Wave turbulence formalism for long internal waves in a stratified fluid is developed, based on a natural Hamiltonian description. A kinetic equation appropriate for the description of spectral energy transfer is derived, and its self-similar stationary solution corresponding to a direct cascade of energy toward the short scales is found. This solution is very close to the high wavenumber limit of the Garrett-Munk spectrum of long internal waves in the ocean. In fact, a small modification of the Garrett-Munk formalism includes a spectrum consistent with the one predicted by wave turbulence.

URL: <http://www.rpi.edu/~lvov>

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,