Abstracts

of Posters

Symposium on

The Application of Mechanics to Geophysics

Stability Analysis of Liquefaction Considering Soil-Water Coupling

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Liquefaction refers to a sudden change in ground behavior from solid-like to fluid-like due to ground shaking. Despite the progresses made in previous experimental and numerical studies on liquefaction, the mathematical stability of the solutions for the governing equations of soil and water remains unclear. Applying perturbation analysis, we seek to study the stability theoretically and numerically. Through the theoretical analysis of small perturbations in the form of plane waves, we showed that the stability is lost when the degree of dilatancy exceeds a critical value. The numerical simulation of perturbations in the form of spherical waves confirmed further the existence of unstable solution. Instability of the solutions of the governing equations calls for more cautious numerical treatment in simulations of liquefaction in future studies.

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The friction evolution of siliceous rocks during high-velocity slip by thermal activated transition from powder lubrication to gouge melting

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Experimental analyses of the frictional strength of siliceous rocks (granite, diorite, and tonalite) sheared in a rotary apparatus in the velocity range of 0.002-1 m/s (0.3-7.1 MPa, 0.002 – 1 m/s, total slip up to 60 m) revealed that: (1) During long slip-distances (tens of m) at low to moderate velocity (< 5 cm/s) the friction coefficient evolves with a weakening-strengthening-weakening path (Fig. 1a); and (2) The dependence of the friction coefficient on the slip-velocity is non-monotonous with weakening-strengthening-weakening sections (Reches & Lockner, 2010).

In a typical run with granite, the friction coefficient dropped from a static value of 0.86 to a steady value of 0.35 after 2.5 m of slip, followed by a sharp increase to 0.5±0.1 after ~7 m that was maintained for the next 10 m. Then, the friction started to increase again at 17 m to 0.78 at ~20 m, and finally dropped rapidly to 0.4. The first weakening stage (< 2.5m) is associated with formation of cohesive gouge flakes made of partially hydrated fine-grained gouge (20-50 nm). The top of these flakes displayed cylindrical rolls, 1 micron in diameter, oriented normal to slip, and the macroscopic weakening correlates with the presence of abundant rolls. SEM analysis of fault surfaces at the second weakening stage (> 17m) revealed abundant melt features such as stretched melt drops, melt coating of solid grains and abundant voids in the melt matrix, contrasting with the total melt in high velocity experiments. These friction-distance curves in our granite experiments bears a similar path of gabbro friction curve at high velocity (Hirose and Shimamoto 2005).

We propose that this non-monotonous friction evolution can be explained as a phase transition from initial pulverization of the brittle stage (low velocity, low normal stress, small slip distance), that leads to powder lubrication by powder rolling, to partial-to-full melting of the thermally activated stage (high velocity, high normal stress, long slip-distance) that leads to weakening by viscous flow. Further, the energy dissipation associated with partial-melting explains the unexpected strengthening for granite faults slipping at velocities of 0.05-0.2 m/s.

*Poster Presenter

Powder rolling as a mechanism of dynamic fault weakening

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For millennia, human-made machinery incorporated rolls and wheels to reduce frictional resistance, yet similar elements are practically absent in natural systems. We found in our shear experiments that tiny, cylindrical rolls spontaneously develop along experimental faults, and lead to drastic dynamic weakening. The experiments were conducted on granite samples with a rotary apparatus at slip velocity range of 0.001-1 m/s and normal stress up to 14.35 MPa. At moderate slip velocities of < 0.1 m/s, the fault slip localized along flakes of highly smooth surfaces that frequently displayed a multitude of cylindrical rolls.

Two central observations were made from these experiments: First, the fault-slip was localized within a layer of gouge-powder. Second, cylindrical, elongated rolls developed from the cohesive gouge-powder. The rolls were formed by closely-packed three-dimensional dense structure of 20-50 nm powders. The roll diameters were 0.75-1.4 mm, and lengths vary from 1.7 to 30 mm. The appearance of both intact and fractured rolls suggested that the rolls underwent a life cycle. The rolls were exclusively found on smooth slip surfaces referred to as Principal Slip Zones (PSZs). The PSZs were composed of an outer crust that overlaid a substrate, and together they formed shiny, cohesive flakes in the fault-zone. The crust was 0.1-0.5 mm thick, cohesive, and was built of a dense mosaic of well-compacted powder grains of 20-50 nm diameter.

Significant friction reduction was revealed in most experiments with rolls, and no (or minor) friction reduction in the three experiments without rolls. The calculated friction reduction ratio had a general linear relationship with the experimental slip distance. The roll-flat deformation geometry suggested a plastic rolling mechanism, as described by Eldredge and Tabor (1955). The calculated rolling friction coefficient from the geometric parameters extracted from AFM topography gave a 0.4 value, slightly lower than the experimental value of 0.47.

We propose that the development of these powder rolls leads to a transition from sliding-dominated slip to rolling-dominated slip. Powder rolling requires two conditions: ultrafine powder and slip localization, and as these conditions are common along natural faults, it is expected that powder rolling would be an effective mechanism of fault weakening.

*Poster Presenter

Röthlisberger Channel Model with Anti-Plane Shear Loading Superposed on In-Plane Compression

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The Röthlisberger channel (R-Channel) is a commonly adopted model that balances creep closure by Nye 2D in-plane straining, driven by the ice overburden pressure, against the melt rate from viscous energy dissipation in turbulent flow within the channel. Perol and Rice (AGU abstr. C11B-0677, 2011) and Suckale et al. (JGR F003008, 2014) have conjectured that these R-Channels may exist at the beds of rapidly straining West Antarctic Ice Stream shear margins. That is expected as a result of melt generation and drainage from forming temperate ice, and the channels may interact through the bed hydrology to partially stabilize the shear margin against lateral expansion. However, at those locations the overburden stresses, driving in-plane flow, are supplemented by substantial anti-plain shear stresses. Similarly, R-Channels in mountain glaciers are also subject to both in-plane and anti-plane stresses. These channels usually form in the downstream direction, where anti-plane shear effects arise horizontally from drag at lateral moraines and vertically from the downslope gravity component. Here we examine how superposed anti-plane loading can alter results of the Nye solution for a 2D R-Channel. We use a combination of perturbation analyses and finite element methods, varying the amount of applied anti-plane stress. A closed-form solution is derived for imposing a small anti-plane perturbation, which has no effect at linear order on the Nye closure rate. Such effects become strong at more substantial perturbations, and the in-plane stress and strain fields are then significantly altered from the Nye solution. We further extend our model to compute channel size in terms of the external stressing and flow rate. Understanding the effect of the ice flow on channel size and formation is important to subglacial hydrology, as well as a potentially vital component for our understanding of the formation and motion of ice-streams found in West Antarctica.

*Poster Presenter

Contact of Viscoelastic Rough Surfaces, Implications for Static and Kinetic Friction

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In the last few decades, the rate and state formulation for static and kinetic friction has been studied with great interest and has been used widely in studies of earthquake phenomena. An understanding of these empirical laws from a micromechanical perspective is important. With this goal, we study the macroscopic frictional response as an emergent behavior resulting from the collective response of evolving microscopic contacts. We have developed a model that includes the interplay between the topography of the contacting surfaces, material properties, and interaction between contacts. The contact of two rough surfaces is approximated by the contact of a rough surface with an ensemble of one-dimensional viscoelastic elements. The heights of the elements is used to simulate the geometry of rough surfaces. The constitutive equation of the system incorporates the long-range viscoelastic interactions between contacts. We perform static contact and velocity jump simulations. During static contact, viscoelastic creep at the contacts leads to increase in the contact area with time, which results in increase in friction coefficient, as observed in experiments. During velocity jumps, the distribution of forces evolves which leads to an evolution of the contact area and hence of the friction coefficient. We study how the friction coefficient is affected by various factors, such as the rms-roughness, the type of correlation, and the viscoelastic properties of the material.

*Poster Presenter

Long-Term Fault Slip in Models with Coseismic Weakening: Depth Extent and Spatio-Temporal Complexity of Earthquake Ruptures

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What determines the depth extent of slip in large earthquakes? Faults feature depth-dependent frictional, hydraulic, and structural properties. Observationally, faults are separated into seismogenic layers (SL) and deeper creeping extensions based on either microseismicity or inferred locking depth. Slip in large earthquakes is often assumed to be limited to the SL. Physically, this separation can be explained by transition, at slow slip rates, from rate-weakening (RW) to rate-strengthening (RS) behavior. However, as revealed in experimental and theoretical studies, enhanced weakening during rapid earthquake slip – e.g., due to thermal pressurization (TP) of pore fluids - may be critical to rupture propagation. The extent of such weakening need not coincide with the traditionally defined SL.

Using 3D rate-and-state fault models with temperature and pore pressure evolution, we study the effect of depth-dependent permeability and shear-zone width on long-term fault slip. Competition between the two properties determines the depth dependence of co-seismic weakening due to TP, since permeability decreases with depth (due to higher compression), promoting TP, while the shear-zone width likely increases below certain depth (due to increasingly inelastic bulk properties), lowering the co-seismic temperature increase and suppressing TP.

We find that, indeed, large ruptures can penetrate below the traditionally defined SL, into the "stable" fault regions, due to TP. When they do, microseismicity patterns at the bottom of the SL change, potentially allowing for identification of such penetration in recent events. The behavior of large ruptures, including their depth extent, varies along strike, even though the fault properties are uniform along strike. This is because co-seismic weakening is strongly dependent on the local rupture properties (slip rate and slip), setting up a strong feedback loop between the weakening and rupture response. The non-uniform slip during one event leads to spatio-temporal complexity in subsequent events, including large variations of depth extent with time. Our current efforts are directed towards quantifying these effects, including the relation between rupture slip, depth, and length as well as their variability.

*Poster Presenter

Numerical models of fault friction constrained by geodetic observations of creep on the Imperial Fault, Southern California

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We present a suite of geodetic observations showing the pattern of fault creep and interseismic deformation in the Imperial Valley, California and northern Baja California, Mexico using a combination of multiple InSAR viewing geometries and survey-mode GPS. The dataset is composed of more than 100 survey-mode GPS velocities (Crowell et al., 2013), continuous GPS velocities from the Plate Boundary Observatory, and Envisat InSAR observations from descending tracks 84 and 356 and ascending tracks 77 and 306 (149 total acquisitions), processed using the Stanford Method for Persistent Scatterers (StaMPS) package (Hooper et al., 2007). The data reveal previously unknown variations in the rate of creep along the Imperial fault, and suggest that an extension of the Superstition Hills fault through the town of El Centro may accommodate a significant portion of the slip typically attributed to the Imperial Fault. We investigate a suite of possible models for the transfer of slip from the San Jacinto fault system to the north to the Imperial and Cerro Prieto faults to the south, yielding a range of plausible hazard scenarios. We also compare the geodetic data to models of earthquake cycles with rate- and state-dependent friction to assess the implications for creep depth, moment accumulation rate, and recurrence interval of large events on these faults. We show that in addition to interseismic observations, a record of co- and postseismic slip is required to obtain a unique constraint on the frictional properties of the fault.

*Poster presenter

Formation of ice eddies in mountain valleys of East Antarctica

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Observations show complex structures deep in ice sheets. Folds and accretion ice have been reported for both Greenland and Antarctica. Mismatched stratigraphy in the nearby GRIP and GISP2 cores in Greenland as well as overturning in the NEEM ice core suggest variable behavior within the ice sheet. Furthermore, ice penetrating radar data taken across both ice sheets shows folding at scales up to half the ice thickness. Because individual strata can be traced through the folds, it is clear that ice flow dynamics play an important role. Here we consider the possible formation of recirculation eddies in subglacial mountain valleys. Modeling the ice as a creeping homogeneous power-law shear-thinning viscous fluid, recirculation eddies are shown to form in valleys when the angle of the wall is steep enough that fluid inside the valley cannot return to the main flow. This is analogous to Moatt eddies for a Newtonian viscous fluid. Using a no-slip boundary condition at the valley wall, ice can recirculate in these valleys indefinitely. We examine eddies in the basal ice using theory and simulations based on topography of the Gamburtsev Subglacial Mountains in central East Antarctica. The Gamburtsevs are a large mountain range (750km250km) with steep relief typical of an alpine glacier system. Analytic results point to a necessary critical angle, and for a power-law shear-thinning fluid such as ice, these eddies occur at lower angles than in a Newtonian viscous fluid. We further develop metrics for determining valleys that are likely to contain eddies based on flow velocity and the total relief of the valley. Our simulations show that in some valleys eddies of order one hundred meters form. We then compare our simulations to radar observations to show potential for near-bed stratigraphic disturbances.

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Enhanced velocity-weakening at high temperature inferred from direct shear experiments on Westerly granite

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The deep limit of earthquake nucleation is thought to be caused by a transition in the frictional properties of fault rocks from velocity-weakening to velocity-strengthening with increasing temperature [Tse and Rice, 1986]. In their pioneering study, Blanpied et al., [1991] reported that elevated pore fluid pressure was essential in producing velocity-weakening between 100 and 350 ºC and pronounced velocity-strengthening from 350 to 600 ºC based on their triaxial experiments on Westerly granite under hydrothermal conditions. In this study, we investigate the effects of temperature in the range of 20 - 600 ºC on the frictional properties of room dry Westerly granite at driving velocities of 10^-4 – 10^-2 mm/s using a heated direct shear apparatus. It can be argued that the direct shear apparatus more closely approximates in situ conditions than the triaxial apparatus since the direct shear setup allows for larger total slip and the production of well developed shear fabric within the rock sample. We conducted experiments on solid blocks of granite as well as very thick simulated gouge sandwiched between rough driving plates. We find that (a-b) decreases with temperature up to 600 ºC for both solid and granular Westerly granite based on our velocity-stepping tests and numerical modeling. We do not observe a high temperature transition to velocity-strengthening, which is thought to control the deep limit of earthquake nucleation. We conducted additional tests on the granular samples at 500 ºC in which we pumped steam into the bottom of the sample. At these unconfined conditions, the addition of water made sliding even more unstable. We plan to conduct tests at high temperature in the presence of water at much lower driving velocity (~10^-6 mm/s) to determine if that will allow more time for weakening reactions at asperity contacts to produce stable sliding conditions. Our results highlight the importance of temperature, shear localization, driving speed and water content on the frictional stability of fault rocks.

How subglacial hydrology can control the shear margin location for Western Antarctic ice streams

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Ice streams are large drainage routes that control the discharge of ice from West Antarctica. The fast flowing ice streams are separated from the nearly stagnant ice in the adjacent ridge by zones of highly localized deformation known as shear margins. It is still unclear what mechanisms select the location of shear margins, or how this relates to observations of margin migration.

In this paper we study the structure of a shear margin using a two-dimensional thermo-mechanical model in a cross-section perpendicular to the direction of downstream flow. We show that intense straining at the margins can partially melt the ice, and introduce a drainage channel at the base of the shear margin that collects the melt produced. As shown in Rothlisberger (1972), the channel locally decreases the pore pressure in the subglacial till, leading to an effective normal stress just outside the channel that can be twenty to sixty times higher than that inferred under the majority of the ice stream.

First, we introduce a channel at the slipping-to-locked bed transition and couple the ice flow with a subglacial hydrology model for the ice stream basal shear strength assuming that the till has a Coulomb-plastic rheology. Our calculations show that the additional basal resistance produced by the channel over a kilometer wide zone lowers the stress concentrated on the locked portion of the bed adjacent to the channel. We highlight the importance of the normal stress variations on the bed in the channel vicinity on solutions for which the locked bed does not yield. Next we relax the assumption that the channel coincides with the basal slipping-to-locked transition and determine the transmissivity of the subglacial hydrologic system that allows for a smooth transition from a deforming to an underforming bed at the margin.

*Poster presenter

Towards Reconciling Magnitude-Invariant Stress Drops with Dynamic Weakening

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Stress drops, observed to be magnitude invariant, are a key characteristic used to describe natural earthquakes. Laboratory experiments indicate that dynamic weakening, such as thermal pressurization and flash heating, may be present in the natural earthquake setting. At first glance, these two seem incompatible. How can stress drops remain constant across many orders of magnitude of different sized events if the larger events experience greater weakening and should thus experience lower final stresses? We hypothesize that dynamic weakening can be reconciled with magnitude-invariant stress drops due to larger events having lower average prestresses when compared to smaller events. The additional weakening would allow the final stresses to also be lower, but the stress drops may be roughly the same.

We simulate a one-dimensional (1D) fault in an elastic half space using a fully dynamic earthquake sequence simulation code that uses rate-and-state friction and allows for dynamic weakening due to thermal pressurization and flash heating. Through these simulations we are also able to explore the trend of increasing breakdown energy with increasing event size. Our results show that a single simulation may explain both the stress drop magnitude invariance and breakdown energy increase. Dynamic weakening is able to explain the increases in breakdown energy, as Rice (2006) has suggested. Importantly, smaller events have larger initial stresses than medium-sized events, and the simulations produce near-constant stress drops for a range of magnitudes. However, our largest, model-spanning events do not fit the trend, exhibiting larger stress drops. Our current and future work includes simulations with more heterogeneous fault models that may allow the largest events to nucleate under lower levers of stress and also have magnitude invariant stress drops. We will also move to a 2D fault model for more natural comparisons with observed earthquake data.

[*]Poster Presenter

The role of gouge and temperature on flash heating and its hysteresis

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Geophysical observations and high-velocity friction experiments suggest that mature faults weaken significantly during earthquakes. One proposed weakening mechanism is the breakdown of frictional contacts at a critical weakening temperature, a process known as flash heating. For bare surface sliding *Rice* [2006] showed that heat generation at frictional contacts triggers flash heating above a critical weakening velocity V_w of ~0.1 m/s. However, all faults generate a gouge layer at least a few millimeters wide, and the efficiency of flash heating in gouge is still unknown.

Building on *Beeler et al.* [2008], we model flash heating in gouge by assuming that the total slip rate applied across the deforming zone is shared between multiple frictional contacts. Solving for the contact temperature we show that flash heating occurs when the strain rate exceeds a critical weakening strain rate controlled by the gouge properties. For a deforming zone 100 microns wide the equivalent V_w is ~4 m/s, making flash heating much less efficient in gouge than for bare surfaces.

The lower contact slip rate associated with distributed shear leads to longer contact lifetimes, increasing the thickness of the thermal boundary layer at a slipping contact W. We show that W can become comparable to the expected spacing between slipping contacts D. Accounting for this in a new model for contact temperature we show that when $W \gg D$ flash heating begins at much lower slip rates, and friction decreases slowly as the slip rate increases.

Finally we study the hysteresis commonly seen in bare surface experiments, with higher friction observed during acceleration than deceleration. Accounting for the sensitive dependence of V_w on sliding surface temperature T_f allows us to match some experimental data for both acceleration and deceleration over a wide range of slip rates. Building on this we discuss how flash heating may operate near the trailing edge of a rupture where temperatures are high and slip is decelerating.

*Poster presenter

Full source tensors of San Jacinto fault zone earthquakes based on the gCAP inversion method and 3D velocity model

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We analyze full source tensor properties of moderate-sized earthquakes in the complex trifurcation area of the San Jacinto Fault Zone (SJFZ), CA, with a focus on isotropic radiation that may be produced by rock damage in the source volumes. The earthquake mechanisms are derived with generalized 'Cut and Paste' (gCAP) inversions of 3-component waveforms typically recorded by >70 stations at regional distances. The gCAP method includes parameters z and c representing, respectively, the relative strength of the isotropic and CLVD source terms. In a previous analysis using the 1D velocity model of Hadley and Kanamori (1977) we found statistically significant explosive isotropic components for at least six of seven examined events, corresponding to ~0.4-8% of the total potency/moment of the sources. Possible errors due to station variability and inaccurate Green's functions were quantified with bootstrap resampling and velocity model perturbations. Here we expand the gCAP inversions to incorporate a 3D velocity model combining the regional SCEC community model and the detailed tomographic results of Allam and Ben-Zion (2012) and Zigone et al. (2015) for the region around the SJFZ. The 3D Green functions are calculated with the finite difference algorithm of Graves (1996). We tested the accuracy of the computational method by comparing finite difference and FK calculations for the 1D Hadley and Kanamori (1977) model. Next, the employed 3D velocity model was used to calculate the eighteen relevant 3D Green's functions. Work on waveforms inversion based on the 3D Green's functions for moderate SJFZ earthquakes is in progress.

Modeling non-volcanic tremor, slow slip events and large earthquakes in the Guerrero subduction zone (Mexico) with space-variable frictional weakening and creep

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We explore with numerical simulations basic physical conditions leading to key observed features of Non Volcanic Tremor (NVT) in relation to Slow Slip Events (SSE) and earthquakes along the Guerrero segment of the Mexican subduction zone. To study the interactions between different modes of slip, and examine possible variations over timescales larger than the 15 year observational interval, we use a model with a planar interface governed by space-varying static/kinetic friction and dislocation creep in a 3D elastic solid. A fault section with zero weakening during frictional slip fails in a mode corresponding to a "critical depinning transition" that produces many observed features of NVT. A patch with elevated creep coefficients represents a section with SSE. Simulations with small added stress oscillations are used to examine triggering of NVT by large remote earthquakes. The results reproduce well the basic observed properties of NVT and SSE in the Guerrero area, while pointing to complex interactions between large earthquake cycles, quasi-period SSE and fractal-like NVT behavior. The model simulations provide additional information on expected frequency-magnitude statistics, slip distributions and space-time properties of the different event types that may be tested with accumulation of future data. Some earthquake and NVT events near the opposite sides of the SSE patch have significant separation between their hypocenters and centroids. The rates of these events are correlated with the creep evolution in the SSE section. The results also suggest that the aseismic deformation in the area may have transients on time scales larger than the observational period.