Japan Geoscience Union Meeting 2012
(May 20-25 2012 at Makuhari, Chiba, Japan)

SSS28-01 Room:201A Time:May 24 14:00-14:15

Simultaneous estimation of frictional parameters on earthquake and afterslip rapture areas using an adjoint method(II)

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How we assimilate observational information into earthquake generation cycle simulation is one of the key issues for properly predicting spatio-temporal evolution of megathrust earthquakes and the associated afterslips along subduction zones.

We have recently targeted reducing uncertainty of frictional properties on the earthquake and the accompanied afterslip surfaces in the earthquake cycle simulation, introducing empirical information on crustal deformation data into the theoretical time series of the slip velocities.

Kano (2011) developed an adjoint method to specify the frictional properties on the afterslip surfaces of the 2003 Tokachi-oki earthquake. His identical twin experiments demonstrated that the adjoint method was a good candidate of efficiently estimating the frictional properties on the afterslip surfaces in the earthquake cycle simulation. Moreover, Kano (2011) found that the estimation of all the frictional parameters on the afterslip surfaces required the early phase of the slip velocity evolution.

For further improving the earthquake cycle simulation, it would be necessary to extend the adjoint method to identify all the frictional parameters on earthquake slip surfaces, covering the early phase of the slip velocity evolution. In addition, it would be better to perform the data assimilation of the earthquakes and afterslips in one time frame, because earthquakes and afterslips along subductions could not be a simple cause-effect sequence, but could interact in time and space.

We develop an adjoint backward method with reusing the adaptive time steps which the forward calculation of the slip velocity on the rupturing surfaces (the fifth order Runge-Kutta method; Press et al., 1993) employs.

The new adjoint method adaptively changee the time steps, so that the method enables to estimate the frictional properties on the slip surfaces even in their slip velocities changing in different time scales.

We design two identical twin experiments for obtaining frictional parameters on the slip surfaces, having quite differnt slip velocities.

(1) Continuous data assimilation of the early phase ($dV/dt>0$; V is the slip velocity) and the decaying phase ($dV/dt<0$) of the slip velocity data:

The identical twin experiment reveals that the empirical data should be assimilated into the acceleration part of the slip velocity ($dV/dt>0$) as well as the decaying part ($dV/dt<0$) in the time series for adequately estimating all the frictional parameters (a, b, and L). In addition, our sensitivity analyses illustrates that the sensitivities (dV/da, dV/db, dV/dL) intensify along the accelaration part.

(2) Simultaneous data assimilation of the earthquake and afterslip rupturing velocity data:

The data assimilation window spans one earthquake cycle including one earthquake and the associated afterslips. The identical twin experiment begins with the initial model having its frictional parameters purterbed by 5 to 10 percents from the assumed true model. In consequence, we can fix all the frictional parameters within one percent error range of the assumed parameter values. This means that the solution in this adjoint method can iteratively converge close to the true values when the initial (background) frictional parameters adequately set within 5 to 10 percent range of the true model.

Keywords: earthquake cycle simulation, frictional coefficient, adjoint method, data assimilation

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SSS28-02 Room:201A Time:May 24 14:15-14:30

Mathematical analysis of the non-singular solution for steady state dynamic slip pulse problem on a bimaterial interface

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Some major faults as represented by inter-plate faults and tectonic lines are known to be located on material interfaces whose origins are different each other. As an elasticity problem, earthquake occurring on such faults can be modelled by dynamic rupture propagation along an interface of welded two different elastic materials, which is referred to as ”bimaterial”. In fact, up to 30% difference in seismic wave velocities have been reported across the San Andreas and some major faults, and many researchers have investigated behaviour of such faults in many ways. Weertman (1980, JGR) analytically showed that in-plane rupture propagation along a material interface with a constant velocity changes normal stress on its slip plane in proportion to slip velocity unlike in homogeneous medium. Then, rupture propagating towards slip direction of more compliant material, which is referred to as ”preferred direction”, reduces normal stress and rupture towards another direction increases normal stress. This result suggests a possibility that some different phenomena may be observed depending on the propagation direction of rupture along material interface. After his work, many numerical simulations have been done. Such simulations have revealed that rupture towards preferred direction significantly increases slip velocity (Rubin & Ampuero 2007, JGR), or tends to propagate not as crack-like but as pulse-like rupture (Ampuero & Ben-Zion 2008, GJI).

On the other hand, analytical study in this field have not shown many major progresses after Weertman (1980) mainly because the analysis is highly complicated if we assume friction law dependent on normal stress change: note that the normal stress change depends on slip velocity if bimaterial is assumed. Significant results have been provided only by a few researches including Adams (2001, J. App. Mech.), and Adda-Bedia & Ben Amar (2003, J. Mech. Phys. Solids). They concluded that, as long as constant dynamic friction coefficient is assumed, only a singular solution is obtained, which represents divergence of normal stress. In general, however, analytical study plays a complementary role to numerical studies, so that progress in analytical study may be required in order to interpret results obtained by numerical studies.

In this study, we treat steady state slip pulse propagating on a bimaterial interface, construct an singular integral equation for this problem, and analyse its solution. First, we show that the singular solution obtained by previous studies yields finite energy release rate even though its singularity is, if rupture propagates towards the preferred direction, larger than the square root singularity appearing in the solution for homogeneous problem. Next, we analytically derive the condition to remove the singularity, namely the condition that the shear stress drops continuously from the peak value tau_p to the residual value tau_r at the pulse tip as illustrated in fig.(a); tau_0 is the background stress level. This condition is found to be a function of the stress ratio (tau_0 - tau_r) / (tau_p - tau_r), ratio R/L, propagation velocity of pulse c and propagation direction of pulse as shown in fig.(b), where L is a length of the pulse and R is a characteristic length of process zone. For a homogeneous medium, this condition have been derived by Rice et al. (2005, BSSA), which, however, does not depend on rupture velocity (solid line in fig. (b)). This result suggests that rupture towards the preferred direction requires small stress drop relative to rupture towards opposite direction if the same size of process zone is considered. That is to say, in a different point of view, rupture towards the preferred direction may generate larger process zone if the same value is assumes for the stress drop. We mention some physical implications and applicabilities of this result.

Keywords: fault, dynamic rupture, bimaterial interface, slip pulse, analytical solution

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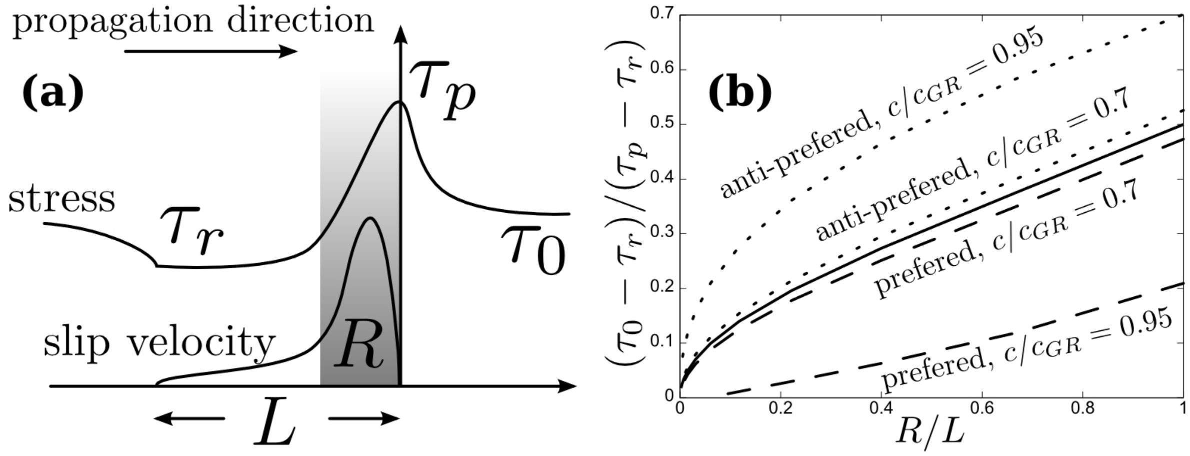

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SSS28-03 Room:201A Time:May 24 14:30-14:45

3D dynamic rupture process on a shallow-dipping reverse fault

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The Mw 9.0 Tohoku-Oki earthquake hit the northeast Japan on March 11, 2011 generating huge strong motion and tsunami and the area with the largest slip amount was located near the Japan Trench. Exploring the dynamics of the Tohoku-Oki earthquake is important for understanding physics of mega-thrust earthquakes and estimating the probability of rupture extensions or tsunami geneses to prevent future disasters. We model a shallow dipping mega-thrust earthquake on a bi-material interface with a free surface by using a 3D finite element method to solve elastodynamic equations and a slip-weakening friction law on the fault plane. As a preliminary study, we simulate in the relatively simple situations with a planar fault and a homogeneous prestress. Reflected body waves from the free surface strongly affect the normal and shear stress on the fault, and both the normal and the shear stress decrease just after the rupture reaches the trench. The slip on the fault reflects at the trench and rapidly propagates downward at the P-wave velocity. This downward reflected slip is consistent with the west-northwest directivity of the Tohoku-Oki earthquake. Final slip distribution with largest slip at the trench is also consistent with some kinematic slip models. Deformation style of the free surface changes depending on the dip angle and material contrast. The amount of vertical motion of the hanging wall is larger for the case of more compliant hanging wall and much larger than that of the footwall. Our simulations suggest that the huge tsunami is generated due to large amount of the surface deformation which is enhanced in the wedge part of the compliant hanging wall.

Keywords: dynamic rupture propagation, break of the trench, shallow-dipping reverse fault, 3D FEM

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SSS28-04 Room:201A Time:May 24 14:45-15:00

Dynamic ruptures with thermal pressurization: Effect of changes in physical properties due to phase transition of water

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Phase transitions of pore water have never been considered in dynamic rupture simulations to investigate effect of thermal pressurization (TP), although they can control TP. From our 3-D numerical simulations of dynamic rupture propagation including TP in the absence of any phase transition processes of water, we predict, for a strike-slip fault under depth-dependent stress in the semi-infinite medium, that frictional heating and TP are likely to change liquid pore water into supercritical pore water. The transition from liquid to supercritical phase causes changes in viscosity, compressibility, and thermal expansion of water by a few orders of magnitude, which can affect diffusion of pore pressure. Accordingly, we performed numerical simulations of dynamic ruptures with TP, taking into account the physical properties varying with pressure and temperature of pore water. The characteristics of the rupture were examined under uniform stress in the infinite medium. The results suggest that the varying physical properties suppress the total slip amount when stresses are high at depth and shear zone thickness is small. When spatial variations of the fluid density and viscosity are allowed in the diffusion equation of pore water, the total slip amount decreases further. The results also suggest that TP reduces temperature rise in a fault zone less effectively, compared to that estimated with constant physical properties. It has been considered that TP works more effectively in thinner shear zone. Our simulations, however, show that the transition from liquid to supercritical phase can produce situations violating the relationship.

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Imaging rupture transfer to another fault plane: the 2000 Western Tottori and the 2009 Sagami-bay earthquakes

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In this study, we analyze the P-wave portion before the S-wave arrival of the waveform records at local strong-motion stations relatively near the source area to investigate the initial stage of the rupture in the 2000 Western Tottori earthquake (Mjma 7.3) and the 2009 Suruga-bay earthquake (Mjma 6.5). Both earthquakes have multi fault planes of different geometry. Here we focus on the rupture transfer process from the first fault plane to the second fault plane. We scanned the source area during this initial rupture stage by using a source imaging technique (Takenaka et al., 2009) for mapping the radiated wave energy (called radiation strength) into a volume or onto planes at sequential time intervals. From the mapped radiation strength, it is found that for both earthquakes most of the strong radiation spots during the imaged rupture periods could be included in the connection area between the first and the second fault planes. It could be interpreted that the connection area worked as barriers at the initial rupture process, and was then ruptured at the beginning of the main rupture.

Acknowledgments: We used the strong-motion records of K-NET, KiK-net, F-net, JMA, and SK-net.

References:

Takenaka, H., Y. Yamamoto and H. Yamasaki, Rupture process at the beginning of the 2007 Chuetsu-oki, Niigata, Japan, earthquake, Earth, Planets and Space, 61(2), 279-283, 2009.

Keywords: 2000 Western Tottori earthquake, initial rupture, main rupture, source process, strong motion, 2009 Suruga-bay earthquake

SSS28-06 Room:201A Time:May 24 15:30-15:45

Relationship between corner frequency and seismic moment for AE from continuous and broadband records (2)

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The seismic moment (Mo) and the corner frequency (fc) are fundamental parameters which characterize the source properties of the earthquake rupture. The scaling relationship that Mo is proportional to cube of fc is satisfied for natural earthquakes larger than about Mw -2. In a fracturing rock sample, a series of elastic waves radiated from micro cracking (Acoustic Emission; AE) enables us to estimate whether this relationship can be extended down to the AE size events.

PZT elements which have often been used as AE sensors in laboratories have narrow frequency ranges, and the waveform records with them can not be used to estimate Mo and fc. To solve this problem, Sellers et al. (2003) recorded AE waveforms with broadband transducers during a uniaxial rock fracture experiment. They indicated that the source parameters of AE satisfied the extrapolated scaling relationship of natural earthquakes. However, they carried out triggered recording which hid some events behind the mask times and/or below the trigger level. Yoshimitsu et al. (2011) estimated Mo and fc of AE in a fracturing rock sample under uniaxial conditions with broadband, continuous recording, and indicated the scaling for natural earthquakes can be extended down to AE size. Both Sellers et al. (2003) and Yoshimitsu et al. (2011) did not make clear that the source parameters of AE satisfy their own cube law. In this study, we carried out the experiment under the same conditions as Yoshimitsu et al. (2011) with advanced measurement, to confirm that their result is independent of the sample. Further, we are interested in whether AE source parameters satisfy their own cube law.

We prepared eight broadband transducers (sensitive range; 100 kHz - 1,000 kHz), two PZT elements, and a cylindrical Westerly granite sample (100 mm in height and 50 mm in diameter). Six strips with 60 degree intervals parallel to the loading axis of the sample were grounded to mount the transducers on. Six broadband transducers and two PZT elements were attached on the side surfaces and the other two were attached inside of metallic pressure tight housings placed at the upper and lower ends of the sample. High sampling recording as 20 MS/s per channel was continued, during uniaxial loading which was continued to be controlled even after the peak strength. We estimated the frequency response of the transducer and removed it from the recorded waveform spectra, and we obtained displacement waveform spectra for S waves to estimate fc. Mo is estimated for the events which have S/N high enough, using path lengths, and low-frequency displacement spectral levels of S wave spectra. The new data of this study is satisfied the same scaling relationship as Yoshimitsu et al. (2011) indicated, and it verified the independency of the result on individual samples.

Keywords: corner frequency, seismic moment, scaling, AE, rock fracture experiment

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AE measurements at 1 km depth in a deep South African gold mine and their activities related to two M0 earthquakes

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We have developed a new AE (Acoustic Emission) monitoring array at 1 km depth in the Ezulwini mine in South Africa, which consists of 28 AE sensors (covering 1 - 40 kHz) and 6 tri-axial accelerometers (three of them have a flat frequency response up to 25 kHz, others have up to 10 kHz). Network was almost completed in July 2011, and more than 6,400,000 waveforms at 500 kHz sampling were stored from December 2010 to October 2011. Although many working noise (e.g, vibration with drilling) are contained in these records, more than 1,000,000 waveforms related to AEs are stored.

In this study, we applied the automatic arrival time picking program (Horiuchi et al. 2011, JPGU) to waveforms from August 17 to September 23, 2011, and selected 220,000 hypocenters for which at least 10 P-arrivals were picked and the root mean square residual of arrival time was $<$ 0.2 ms. More than 90% of them were located in front of cavity being made by mining of gold reef, whereas several planar AE distributions were found away from the mining face. Most AEs belonged to either the mining front cluster or such planar clusters, i.e, few AEs occurred away from these clusters. The planar clusters were composed of a few hundred ˜ a few thousand AEs, and their spatial extent were 20 ˜ 100 m. Positions and attitudes of three clusters of them were consistent with geological faults which were identified by our/mine's survey, therefore these AEs must be related to pre-existing weak planes. Other planar clusters may also delineate unknown pre-existing weak planes.

In one of clusters whose strike is consistent with a fault identified by the mine, sudden increasing of AE rate on September 21 and subsequent decay followed Omori's law was found. We estimated Mw for 4645 AEs belonging to this planar cluster by fitting omega-square model to the observed spectrums, and found two relatively-large events (Mw 0.0 event at 6:50 a.m and Mw -0.2 at 7:01 a.m on September 21). Concentration of AEs around rupture initiation point of the first M0 event or accelerated AE rate were not found. Rather, Mw 0.0 seemed to occur in relatively low activity area. While spatial extent of AE activity before Mw 0.0 (2955 events) was 90 m along strike and 60 m along dip, extent of aftershock areas in five minutes after Mw 0.0 and Mw -0.2 were only 10˜15m in diameter, which is consistent with typical M0 rupture size. These two events seem to have ruptured only parts of the region illuminated by AE activity. Initial rupture point of the second M0 event was located at the edge of the aftershock area of the first event. It can be interpreted as the Mw -0.2 was induced by stress concentration at rupture edge of the Mw 0.0. Rubin and Gillard [2000] studied M 0.5 ˜ M 3.5 microearthquakes on San Andreas fault, and suggested the same triggering process from the observation that lower limit of separation between consecutive events were consistent with rupture radius of the first event. We could directly observe this process from the aftershock area indicated by activities of very small AEs.

Keywords: South African gold mines, Acoustic Emission, aftershocks, triggering

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Rupture processes of the tsunami earthquakes and seismic activity of the normal-faulting earthquake

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A 'tsunami earthquake' excites considerably larger tsunamis than expected from its magnitude estimated by seismic wave (Kanamori, 1972). Tsunami earthquakes seem to occur in shallow part of subduction zones. It had been difficult to find clear characteristics of tsunami earthquakes, since observed waveforms are contaminated by multi-reflected waves due to heterogeneity of sea floor structure. The 2011 off the Pacific coast of Tohoku earthquake broke an area such as near trench where the 1896 Meiji-Sanriku tsunami earthquake occurred. The characteristics of tsunami earthquakes are also important to understand nature of mega-thrust earthquakes.

We applied new waveform inversion, introducing uncertainty of Green's function (Yagi and Fukahata, 2011), to tele-seismic body-waves of tsunami earthquakes detected by other studies (e.g., Bilek and Engdahl, 2007) so as to estimate stable and detailed rupture process. We collected tele-seismic body waveforms (P-wave) recorded at Federation of Digital Broad-Band Seismograph Network (FDSN) and Global Seismograph Network (GSN) from IRIS-DMC.

We found that slow slip (about 0.1 m/s) continued over 50 sec near trench and trapezoidal moment-rate function is in 3 earthquakes : the 1992 Nicaragua earthquake, the 2006 Java earthquake and the 2010 Mentawai earthquake. From final slip distribution of the three earthquakes, large slip area located along trench excites large tsunamis.

We also investigated seismic activities of the normal-faulting earthquakes in and around seismic source area of the great thrust earthquakes. Normal-faulting earthquakes in and around seismic source area of the three tsunami earthquakes become active after the tsunami earthquakes, which is also observed in aftershock activity of the 2011 off the Pacific coast of Tohoku earthquake. The long slip duration near trench and normal-faulting earthquake in and around seismic source area implied that the earthquake released roughly all of the accumulated elastic strain on the plate interface owing to exceptional weakening of the fault.

Keywords: tsunami earthquake, source process, uncertainty of Green's function, normal-faulting earthquake

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Tsunami Earthquakes and Their Unusual Source Character

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Updip limit of seismicity observed worldwide suggests that there is an upper transition from seismic to aseismic faulting for subduction zones, which prohibits large slip near the trench during earthquakes. Here we show, however, large amount of slip during two tsunami earthquakes are located near trench.

We use a back project method to analyze the July 17, 2006 Java (Mw 7.7) and October 25, 2010 Sumatra (Mw 7.8) earthquakes, using low- (0.03 to 0.05 Hz) and high frequency (1.0 to 10 Hz) Hi-net data. The results show that {under}(1) the ruptures extended all the way to the trench with a relative slow rupture velocity (1.0 to 1.5 km/s), and (2) released large slips at shallow portion of the source regions (Figure 1).{/under} The source durations of 100˜150 s are much longer than usual earthquakes. The large near-trench slips are coincident with the tsunami generation areas, as identified by tsunami waveform inversion and field investigation.

The correlation between seamounts and tsunami earthquakes locations indicates that seamounts, which represent seafloor roughness, could be capable of increasing the locking of the subducting interface for the shallow portion of the thrust zone.

Understanding the updip locking for the shallow region of subduction zones is important for understanding tsunami earthquake mechanisms and their occurrence intervals. It is difficult to infer the updip locking from onshore observations as it may overlook the potential hazard from tsunami earthquakes. We suggest the importance of seafloor roughness and offshore observation for understanding tsunami earthquakes.

Figure 1. (a) 2010 Sumatra earthquake. Top show the seismograms recorded at station HMNH, the stacked amplitude curve and rupture velocity. The red, yellow and green lines present a rupture velocity of 1.0, 2.0, and 3.0 km/s, respectively. Bottom shows the locations, timing and amplitudes of the maximum amplitudes for the high frequency band. Red star shows the epicenter. The gray solid circles indicate the low frequency centroids. (b) Same results for the 2006 Java tsunami earthquake.

Keywords: 2006 Java earthquake, 2010 Mentawai earthquake, tsunami, seamounts, rupture process