Southern California Earthquake Center

University of Southern California, 3651 Trousdale Parkway, Suite 169, Los Angeles, CA 90089-0742
Phone: 213-740-5843 Fax: 213-740-0011 E-Mail: scec@usc.edu Web: www.scec.org

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Submitted to

United States Geological Survey
Attn: Dr. Michael Blanpied
12201 Sunrise Valley Drive
Reston, VA 20192

from the

University of Southern California
Southern California Earthquake Center
Department of Earth Sciences
University Park
Los Angeles, CA 90089-0742

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Workshop on Physical Limits to Extreme Ground Motion in Rock

Principal Investigator: Thomas H. Jordan
W. M. Keck Professor of Earth Sciences
Department of Earth Sciences
University of Southern California
Los Angeles, CA 90089-0742
tjordan@usc.edu
213-821-1237; 213-740-0011 (fax)

Report Author: Paul Somerville
URS Corporation
566 El Dorado Street
Pasadena, CA 91101-2560
Paul_Somerville@URSCorp.com
626-449-7650

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WORKSHOP ON PHYSICAL LIMITS TO EARTHQUAKE GROUND MOTION IN ROCK
Palm Springs, September 8 -10, 2005

Workshop Report

1. INTRODUCTION

This report describes the outcome of the SCEC/USGS workshop on physical limits to earthquake ground motion in rock held in Palm Springs during September 8 -10, 2005.

A draft Work Plan was provided before the Workshop. This draft work plan was slightly modified in the course of the workshop, and is presented in modified form in Table 1, with changes shown in Italics.

The Workshop focused its attention on discussing and resolving issues that need to be addressed in accomplishing the work plan, and on prioritizing these issues. These recommendations are presented in the third section of the report.

Appendix I of the report provides the Agenda of the Workshop as it actually transpired. It lists the introductory presentations that were made to frame the issues for discussion, and the open presentations that were made in the course of the ensuing discussion. The presentations that were made at the workshop can be found on the SCEC website.

Appendix II of the report lists the participants and their affiliations.

2. DRAFT WORK PLAN

A draft Work Plan was provided by Norm Abrahamson and circulated among the Workshop participants. The Workshop concluded that the Work Plan is a suitable means of achieving the objectives of the Extreme Ground Motion Project. The Wave Propagation Working Group inserted some details into the Work Plan for Task A1.1. The Work Plan, including these modifications shown in italics, is reproduced below.

Table 1. List of Subtasks for Task A

Task #	Task Description	Schedule	Deliverable
A1.1*a*	Develop a set of representative structural models (applicable to YM) for testing alternative non-linear wave propagation models Characterization down to at least 1 km. These should include small-scale variations that affect scattering properties of the structure.	Oct 05 – Sep 06	Input to Task A1.2
A1.1b	*Identify critical horizons (such as Calico Hills Fm.) and properties under dynamic loading; characterize in situ properties on length and load scales of interest.*	*Oct05 – Sep 07*	
A1.2	Conduct sensitivity study on non-linear wave propagation *in 1D*. Run existing numerical models using structural models from Task A1.1 to obtain initial estimates of the physical limits at Point A and Point B. Prepare report on range of physical limits. *Focus studies on fully nonlinear models, including both continuum and discontinuum models. Investigate sensitivity to scattering properties and assess importance.*	Sep 06 - Mar 07	Report on initial model evaluations and implications for physical limits due to non-linear wave-propagation.
A1.3*a*	Resolve the differences in predicted physical limits identified in Task A1.2.	Apr 07 – Mar 09	*Select recommended wave propagation models*
A1.3b	*Run revised models to develop revised estimates of physical limits at Point A and Point B. Also compile the computed seismograms at Point B.*	*Apr 07 – Mar 09*	*Provide revised estimates of physical limits, including ground motion and strain.*
A1.4	*Develop 3D characterization of seismic P and S wave velocity structure down to level of bottom of relevant faults.*	*Apr 07 – Mar 09*	*Use in selecting wave propagation models in Task A1.3a and doing calculations in Task A1.3b*
A2.0	Conduct sensitivity study using non-linear source models (inputs from Task B3.1)	Jul 05 - Jun 06	Sensitivity Study showing range of physical limits. Also used for focusing WG-A2 activities.
A2.05	Evaluate / validate dynamic source models that are applicable to the realistic earthquake problem (e.g. simpler physical models that work for faults at YM)	Jul 05 - Sep 07	Selection of 2 best dynamic source models ready for application in Task A2.2

A2.1	Develop and apply "more physical" models to constrain the simpler parameterization of the source that is used in the dynamic source models being developed in Task A2.05	Jul 05 - Sep 07 – *initial results* *Sep 07 – Jan 09 Updated results*	Numerical models for application in Task A2.2 and A2.3
A2.2	Apply source models selected in Task A2.05 to develop suites of potential seismic sources for use in evaluating (calibrating) source models (see Task C3.1)	Sep 07 - Mar 08	Empirical check of numerical models from Task A2.1
A2.25	Apply source models to generate equivalent source models for kinematic simulations (for high freq),	Mar 08 - Sep 08	Equivalent kinematic source models for input to Task A2.3
A2.3	Apply dynamic source models for long periods and kinematic models for high freq to compute the physical limits of ground motions that are input into the rock at Yucca Mountain. Prepare report on physical limits for input rock motions from non-linear source effects only.	Mar 08 - Mar 09	Input to Task A2.4
A2.4	Use the ground motions from Task A2.3 as input for the non-linear wave propagation using the methods developed in Task A1.3. *Consider both 1D and higher-dimensional models, as necessary to account for shallow energy release and/or complex wave propagation effects.* This will give new physical limits due to both non-linear source and non-linear wave propagation effects. Prepare final report on physical limits at Yucca Mountain.	Jan 09 - Sep 09	Final Report on physical limits.
A3.1*a*	Person knowledgeable of NTS data to provide ongoing review of results from WG-A1 and WG-A2 to check for consistency with NTS data.	Oct 05 – Sep 09	Feedback to project on consistency of project results with NTS data.
A3.1b	*Compare nonlinear wave propagation models used in the study with relevant experimental and field data.*	*Oct 05 – Sep 09*	
A3.2	Compile physical limits on ground motions and constraints on wave propagation model parameters using available NTS data identified in (Task A3.1). Prepare final report on physical limits and data available for non-linear wave propagation calibration from NTS explosion data.		Calibration of models from task A2.1. Physical limits from NTS data.

3. DISCUSSION AND RESOLUTION OF MAJOR ISSUES AND THEIR PRIORITIES

Adopting the draft Work Plan in slightly modified form as a suitable framework within which to accomplish the objectives of the project, the Workshop focused its attention on discussing and resolving issues that need to be addressed in accomplishing the work plan, and on prioritizing these issues. These are described under a series of broad topic areas. The following recommendations were prepared on the afternoon of September 10 by the discussion leaders, working group leaders and a Hanks Committee member (Jim Brune), with the participation of Ruth Harris, Nadia Lapusta and David Buesch.

Geologic Context: Is the YM earthquake system other than generic?

- *Is normal faulting in the Yucca Mt region different from faulting in general (other than in geometry); i.e., in the dynamics of faulting?* There is nothing in particular to distinguish faulting near YM from other normal faults; however, current attenuation relationships are based on data from strike-slip and reverse faulting earthquakes and there is relatively little data on ground motion for normal faulting earthquakes. (Task A2.0 – A2.25) Low Priority.
- *Is the Solitario Canyon fault the main player in dynamic SHA (as indicated by kinematic SHA), or should other sources (e.g., Paintbrush fault) be included?* Unlike the Solitario Canyon fault, the radiation from the Paintbrush would be in the tensional quadrant, it is important to consider ground motion from that fault as well. Other faults are not likely to control extreme ground motion for YM. (Task A2.25 or A2.3) Medium Priority.
- *Is (are) the main fault(s) smooth (like the San Andreas or Punchbowl Faults) or rough (like South African mine faults)?* There is some geological evidence on fault roughness at YM. It is unlikely that we will be able to gather data on fault roughness at depth; however, by compiling data on other large normal faults in Nevada, the geometry of the footwall could be used to constrain likely fault roughness at depth. The Busted Butte fault is a nearby fault that may provide useful information. Based on the collective memory of the group, our expectation is that this will show that faults at depth are relatively smooth. (Task A2.1) Low Priority.
- *Are there insights we can gain from field studies of faults to test model predictions, either at Yucca Mountain or elsewhere (South African Mines, exhumed normal faults, San Andreas Fault)? How do we characterize complex fault geometry and off-fault inelastic response as it relates to strong ground motion?* Yes, field studies of fragmentation, gouge, damage patterns, etc., in the vicinity of exposed faults could help test faulting and/or micromechanical models. Geologic mapping would contribute here, particularly in constraining the partitioning of energy. (Task A2.1) High Priority.

How should we characterize the medium for wave propagation calculations?

- *At what depth range(s) is nonlinear deformation important in modifying ground motion? The site of interest is known to produce strong scattering at low ground motion amplitudes. Does this scattering and the resulting reduction of ground motion coherence couple significantly to the nonlinear response?* Need characterization down to at least 1 km. This should include small-scale variations that affect scattering properties of the structure. (Task A1.1a) High Priority.
- *What are the critical units in terms of their influence on site response, and what are their elastic and inelastic properties on the length and loading scales of interest? How can we extrapolate laboratory test results to estimate in situ properties?* Identify critical horizons (such as Calico Hills Fm.) and properties under dynamic loading; characterize in situ properties on length and load scales of interest. (Task A1.1b) High Priority.

What is the spatial and temporal variation in stress during dynamic rupture?

- *Can we place useful bounds on pre-stress, static stress drop, dynamic stress drop, dynamic stress variation? How does strength change with slip and slip rate?* It may be possible to place useful bounds on stress based on the strength of materials. Absolute stress measurements provide important constraints on stress levels at Yucca Mountain. Extrapolation of stress to greater depth based on similar measurements at greater depth in other environments can be used to place constraints on absolute stress. Topographically induced stresses could also provide useful constraints. Laboratory experiments suggest that there are multiple mechanisms that can lead to dramatic weakening during seismic slip. (Task 2.1) High Priority, but as a part of other activities.
- *What are the appropriate stochastic descriptions of earthquake parameters?* There is very little information for seismic slip distributions on normal faults; however, for the few normal faulting earthquakes for which there is data, slip appears to be heterogeneous – as it is for other earthquakes. There is considerable data on normal faulting from structural mapping that may provide useful constraints on the geometry of such fault systems. There is also geologic mapping of fault slip that could bear on slip variability in earthquakes. Systematic modeling of variable slip may allow us to explore those situations that would lead to the extreme ground motion. (Task A2.25) High Priority, but as a part of other activities.

Available Modeling Tools: How can we generate wavefields now?

- *Can the end-to-end simulation problem be separated into source, path, and site?* Although this is the traditional approach to ground motion simulation, the situation at Yucca Mountain suggests that this dichotomy might not be viable, due to the fact that shallow slip on the Solitario Canyon fault may dominate ground motion and that ground motion and deformation is likely to be nonlinear. It has been suggested that limiting values on slip rate on the fault may characterize near fault nonlinearities, but the validity of this conjecture, and the separation of the problem into separate parts that it enables, remains to be demonstrated. If such a separation is to be successful, it is essential that the different parts of the problem be treated in a mutually consistent manner. The near field passage of rupture effect might dominate strong ground motion from the Solitario Canyon fault and hence understanding the factors that control the slip velocity of the shallow part of the fault may be critical. (Task A1.2, A2.25) High Priority.
- *Are 3D dynamic source models required?* Yes they will be required because of the importance of geometric effects in the problem. However, 2D models need to be used to model aspects of the physics that may be too difficult to model in 3D, and may represent a worst-case scenario. (Task A1.2, A1.3a) High Priority.
- *What is (are) the most appropriate dynamic rupture model(s) for end-to-end simulation; i.e., codes validated against other codes and verified against data?* High-resolution modeling will be required for some aspects of the project; however, it can't model all of the important aspects of a true earthquake (e.g., geometry, off-fault inelasticity, branching, layering, topography) so that robust, if lower resolution, methods are needed too. (Tasks 2.05, 2.1, 2.2) High Priority.
- *To what extent can nonlinear wave propagation effects be understood from vertical-incidence modeling? Is it important to consider surface waves generated at non-horizontal structural boundaries (e.g., basin edges)? What is the effect of surface topography?* Consider both 1D and higher-dimensional models, as necessary to account for shallow energy release and/or complex wave propagation effects. (Task A1.4) High Priority
- *How can we couple separate source calculations to 1, 2, and 3D nonlinear wave propagation simulation?* Develop 3D characterization of seismic P and S wave velocity structure down to level of bottom of relevant faults. (Task A1.4) High Priority.

- *With what accuracy can the existing nonlinear models predict existing strong ground motion records?* Compare nonlinear wave propagation models used in the study with relevant experimental and field data. (Task A3.1b) High Priority, but suitable data for testing are scarce.
- *How can these existing capabilities be used to explore extreme ground motions?* By creating suites of physically realistic source models and the ground motions they generate. (Task A1.2, A2.0) High Priority.

Emerging Modeling Tools: How can we generate wavefields that are more physics based?

- *What is the applicability of existing fracture-mechanics codes; e.g., discrete-element, non-elastic finite-element methods?* The potential of these methods rests on their ability to model more physics than is presently done in standard practice. (Task A2.1) High Priority.
- *What is the role of micro-mechanical modeling in this project?* A distinction can be made between (1) strict micro-mechanical modeling where the element size is kept small enough to represent rock mechanics results, and scaling to the size of real earthquakes that requires huge (perhaps unrealistic) computing power, and (2) macro-mechanical modeling with the same type of discretization method used in micro-mechanical modeling, but in which the elements are too large to represent rock mechanics results. The issue is then whether the discretization used in micro-mechanical modeling is applicable for macro-mechanical modeling. While micro-mechanical modeling cannot be used to model the entire process, it can be used to model individual processes (such as damage constraints, strain localization) and as a basis for constitutive behavior of larger scale elements. (Task A2.1) Medium Priority.
- *Are there improved rheologies for a 3D fault zone that can be feasibly incorporated into dynamic rupture models? Are there rock mechanics experiments and fault observations that can be carried out to answer this question?* Interface vibrations, flash heating, melting, thermal pressurization, silica gel, are all processes that might strongly influence fault behavior, and which can be incorporated into dynamic rupture modeling. High sliding velocity rock mechanics experiments can be used to explore and understand these processes. Geological observations of exposed faults may help determine which of these processes are relevant. (Task A2.1) High Priority.
- *Which numerical models are appropriate for modeling the response of this structure? Can continuum models deal with the type of tensile fracturing, and opening and closing of fractures, that might be expected from intense ground motion with both P and S wave components?* (Task A2.1) Focus studies on fully nonlinear models, including both continuum and discontinuum models. Investigate sensitivity to scattering properties and assess importance. High Priority.
- *How can these new capabilities be used to explore extreme ground motions?* By creating suites of physically realistic source models and the ground motions they generate. (Task A1.3b) High Priority.

APPENDIX I. WORKSHOP AGENDA

SCEC/USGS Workshop on Physical Limits to Earthquake Ground Motion in Rock
Palm Springs, September 8-10, 2005

September 8, 3pm -6 pm. **Introduction**

3:00 pm. **Extreme Ground Motions Research Plan**
Norm Abrahamson

Physical limits, unexceeded values, and event frequencies.
This workshop will only address physical limits.
Research results must fit into PSHA application.
Described how the structured research environment will work.

3:30 pm**. 2004 Workshop examples**:

Non-linear Wave-propagation
Mark Board

Described the available information on rock properties at Yucca Mtn, described the types of non-linear wave propagation models that have been used

Non-linear Source
Joe Andrews

Updated version of 2004 workshop talk.

4:30 pm**. Summary of Related SCEC Studies / Initiatives**
Ralph Archuleta, Ruth Harris

Described the SCEC working group on dynamic source models, and other SCEC work that addresses non-linear wave propagation, fracture mechanics, lab rock mechanics, fault zone geology studies relevant to physical limits of ground motion

Bill Ellsworth

Described early results from SAFOD and plans for future observations of earthquakes in the near field

5:30 pm**. Discussion**

September 9, 8 am – 6 pm. **Elicitation from Participants**

What is there about wave propagation, fault zone geology, lab rock mechanics, fracture mechanics, and rupture dynamics that could lead to physical limits?

8:00 am. **Approach** to Develop Results for Application to PSHA
Norm Abrahamson

(1) Separation of non-linear wave propagation and non-linear source parts of the problem. (2) For source use different levels of abstraction of physics: (A) kinematic models for broadband calculation (highest level of abstraction), (B) dynamic rupture models used to constrain kinematic models (intermediate level of abstraction), (C) Fracture mechanics used to constrain dynamic rupture models (lowest level of abstraction), (D) fault zone geology and lab rock mechanics provide input data for fracture mechanics.

8:15 am. **Fault Zone Geology**: what do we know about fault geology that could lead to physical limits?

Judi Chester and Zev Reches

Described observations of rock damage in fault zones that can be used as input to the fracture mechanics.

Open presentations: Ben Zion, Brune, Lockner, Reches, Sammis, Tullis

9:15 am. **Lab Rock Mechanics**: what do we know from rock mechanics experiments that could lead to physical constraints or data for fracture mechanics or non-linear wave propagation?

Terry Tullis and Dave Lockner

Described what we learn from lab rock mechanics that provides constraints or data for the fracture mechanics (source) or for the non-linear wave propagation?

Open presentations: Lockner - testing of Topopah Spring tuff

10:45 am. **Break** (15 minutes)

11:00 am. **Fracture mechanics** / energy dissipation for source (not wave propagation): what do we know from fracture mechanics models that could lead to physical constraints on the parameters in rupture dynamics models?

Jim Rice and Peter Cundall

Described what we can learn from fracture mechanics that would provide constraints for the key parameters in the dynamic rupture models.

Open presentations: Lapusta, Purvance

12:30 **Lunch**

1:30 pm. **Rupture dynamics and kinematics**– what do we know about rupture dynamics and kinematics that could lead to physical limits on ground motion amplitudes?

Day and Heaton

Identified the key parameters in the dynamic source models that control the physical limits of the ground motion generated by the source. (1) Presented a summary list of model parameters used in kinematic and dynamic rupture models and (2) Identified parameters that are well constrained and those that are not well constrained.

Open presentations: Paul Somerville

3:00 **Break**

3:15 **Integration –** how do we best integrate fracture mechanics information into dynamic and kinematic rupture models that can be used to constrain upper bound ground motions?

Jim Rice and Steve Day – discussion leaders

4:15 pm. **Wave-propagation** – what are the wave propagation limits on ground motion levels?

Branko Damjanac and Tarabay Antoun - Discussion leaders

Branko Damjanac - Wave Propagation Codes

Described the key features of wave propagation models that lead to physical limits of ground motion. (2) Give list of examples of codes that have the required capabilities (does not have to be exhaustive).

Tarabay Antoun – NTS data

Described modeling of NTS data and key features that would limit ground motions

Peterssen – LLNL regional wave propagation code (15 minutes)

Describe LLNL project and chance to modify it to address non-linear wave propagation

Discussion

6:00 pm **Adjourn**

September 10, 8 am – 4 pm. **Develop Recommendations**

8:00 am **Working Groups** for Task A1 and Task A2
Develop recommendations for research plans
What is feasible in a four year time frame?
Identify metrics of success / progress

10:15 am **Break**

10: 30 am **Summaries** from two groups on recommendations

11:00 am **Discussion**

12:00 noon **End of Plenary Part of Workshop**

12:00 noon **Lunch**

1:00 pm **Report Writing Session** for discussion leaders, working group leaders and Hanks Committee members

4:15 pm **Adjourn** writing session.

APPENDIX II. LIST OF PARTICIPANTS

Last Name	First Name	Organization	Email
Abrahamson	Norm	PG&E	naa3@earthlink.net
Anderson	John	UNR	jga@seismo.unr.edu
Andrews	Joe	USGS	jandrews@usgs.gov
Anooshehpoor	Rasool	UNR	rasool@seismo.unr.edu
Antoun	Tarabay	LLNL	antoun1@llnl.gov
Archuleta	Ralph	UCSB	ralph@crustal.ucsb.edu
Atkinson	Gail	Carleton	gmatkinson@aol.com
Beeler	Nick	USGS	nbeeler@usgs.gov
Benesh	Nathan	Harvard	benesh@fas.harvard.edu
Ben-Zion	Yehuda	USC	benzion@terra.usc.edu
Beroza	Greg	Stanford	beroza@geo.stanford.edu
Bhat	Harsha	Harvard	bhat@esag.harvard.edu
Board	Mark	Itasca Consulting	mpboard@yahoo.com
Boore	Dave	USGS	boore@usgs.gov
Bozorgnia	Yousef	PEER / UC Berkeley	yousef@berkeley.edu
Bradley	Christopher	LANL	cbradley@lanl.gov
Brune	Jim	UNR	brune@seismo.unr.edu
Budnitz	Bob	LLNL	budnitz1 @ LLNL.gov
Buesch	Dave	USGS	dbuesch@usgs.gov
Chester	Judi	Texas A&M	chesterj@geo.tamu.edu
Cundall	Peter	Itasca Consulting	pac@compuserve.com
Dalguer	Luis	SDSU	ldalguer@moho.sdsu.edu
Damjanac	Branko	Itasca Consulting	branko@itascacg.com
Day	Steve	SDSU	day@moho.sdsu.edu
Duncan	Doug	USGS	dduncan@usgs.gov
Ellsworth	Bill	USGS	ellsworth@usgs.gov
Fairhurst	Charles	Minnesota	fairh001@umn.edu
Field	Ned	USGS	field@usgs.gov
Foxall	Bill	LLNL	bfoxall@llnl.gov
Goldsby	David	Brown	David_Goldsby@brown.edu
Gonzalez	Sarah	SWRI	shgonzalez@cnwra.swri.edu
Graves	Rob	URS	robert_graves@urscorp.com
Hanks	Tom	USGS	thanks@usgs.gov
Harris	Ruth	USGS	harris@usgs.gov
Heaton	Tom	Caltech	heatont@institute.caltech.edu
Henyey	Sally	USC	shenyey@usc.edu
Jordan	Tom	USC	tjordan@usc.edu
Kaneko	Yoshihiro	Caltech	ykaneko@gps.caltech.edu

Lapusta	Nadia	Caltech	lapusta@caltech.edu
Liu	Yi	Caltech	yil@caltech.edu
Lockner	David	USGS	dlockner@usgs.gov
Ma	Shuo	UCSB	sma@crustal.ucsb.edu
McCallen	David	LLNL	mccallen2@llnl.gov
McGarr	Art	USGS	mcgarr@usgs.gov
McRaney	John	SCEC / USC	mcraney@usc.edu
Nishenko	Stuart	PG&E	spn3@pge.com
Oglesby	David	UCR	david.oglesby@ucr.edu
Page	Morgan	UCSB	pagem@physics.ucsb.edu
Petersson	Anders	LLNL	andersp@llnl.gov
Pitarka	Arben	URS	arben_pitarka@urscorp.com
Prakash	Vikas	Case Western	prakash@mae.cwru.edu
Purvance	Matt	UNR	mdp@seismo.unr.edu
Quittmeyer	Richard	ISSI / YMP	Richard_Quittmeyer@ymp.gov
Ramirez-Guzman	Leonardo	Carnegie Mellon	lramirez@andrew.cmu.edu
Reches	Ze'ev	Oklahoma	reches@ou.edu
Reiter	Leon	US NWTRB	reiter@nwtrb.gov
Rice	Jim	Harvard	rice@esag.harvard.edu
Sammis	Charlie	USC	sammis@usc.edu
Somerville	Paul	URS	Paul_Somerville@urscorp.com
Stirling	Mark	IGNS	m.stirling@gns.cri.nz
Templeton	Elizabeth	Harvard	templet@fas.harvard.edu
Tsai	Ben	PG&E	yibentsai@gmail.com
Tullis	Terry	Brown	Terry_Tullis@brown.edu