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THE JOHN A. Blume EARTHQUAKE ENGINEERING CENTER

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QUAKE '06 CENTENNIAL LECTURE SERIES

Part I of the Quake '06 Centennial Lecture Series, co-sponsored by Stanford University and University of California-Berkeley, was a great success with lectures on the history of the 1906 San Francisco Earthquake. **Professor Kevin Starr's** lecture on *The Great Earthquake and Fire of 1906 -- Lessons Learned*, gave a timeline and history of the events and touched on the failures of the government and the military to appropriately deal with the disaster, drawing parallels to the recent problems with Hurricane Katrina. **Malcolm Barker** (shown in photo) spoke of the human side of the tragedy. His lecture, *Through the Eyes of the Survivors*, gave a glimpse into what it was like to have survived the earthquake, and the aftermath. **Professor Stephen Tobriner** (UC-Berkeley) gave a spirited lecture on the buildings of the period and how engineers and architects learned from the previous earthquakes and attempted, quite successfully, to build "earthquake resistant" buildings.

Part II of the series, which will focus on Earth Science, Earthquake Engineering, Preparedness and Disaster Response, begins on January 17 with **Chris Poland**, who will speak on *Restrain, Respect and Rehabilitate: A Tale of Three Seismic Projects at Stanford*. **Mary Lou Zoback** of the USGS will speak on *The 1906 Earthquake: Lessons Learned, Lessons Forgotten, and Future Directions* on January 31. On February 16, **Eric Elsesser** will discuss *Improving Seismic Safety and Performance through Innovative Structural Engineering*. And finally, **Kathleen Tierney** will talk about *Social Dimensions of Catastrophic Disasters: From the 1906 Earthquake to Hurricane Katrina*.

For more information on the lectures and other events please see the Quake '06 website at http://quake06.stanford.edu.

PUBLISHED PAPERS

Sarabandi P., Adams B., Kiremidjian A. and Eguchi R., " Infrastructure Inventory Compilation Using Single High Resolution Satellite Images," *3rd International Workshop on Remote Sensing Technologies and Disaster Response*, September 12-13, 2005, Chiba University, Japan

Baker J.W., Cornell C.A., "A Vector-Valued Ground Motion Intensity Measure Consisting of Spectral Acceleration and Epsilon". *Earthquake Engineering & Structural Dynamics* 2005; 34:1193-1217

APPRECIATION TO AFFILIATES, FRIENDS AND DONORS

As we reflect on the past year, the faculty of the John. A. Blume Earthquake Engineering Center gratefully acknowledge the generous support of **Mrs. Jene Blume**, the **John A. Blume Foundation**, our professional affiliates, and other donors. Their encouragement, participation and financial support are critical for promoting an exciting research and educational program that promotes the engineering of safer and more sustainable buildings and civil infrastructure.

BLUME CENTER NEWS

Professors Anne Kiremidjian, Jack Baker, and **Allin Cornell** attended and presented papers at the International Conference on Structural Safety and Reliability in Rome, Italy held June 19-23, 2005.

Professor Greg Deierlein presented a paper entitled, "Developing Consensus on Provisions to Evaluate Collapse of Reinforced Concrete Buildings" (co-authored with **PhD Candidate Curt Haselton**) at a US-Japan Workshop held in Berkeley on July 7-8, 2005.

Professor Ronnie Borja delivered plenary lectures at the International Workshop on Modern Trends in Geomechanics on June 27-29 in Vienna; the 8th US National Congress on Computational Mechanics on July 24-28 in Austin, Texas, and the 8th Computational Plasticity Conference (COMPLAS 8) on September 5-8 held in Barcelona, Spain. In addition, he co-authored several papers presented by doctoral students **Craig Foster**, **Jose Andrade**, and **Pablo Sanz** at the Third MIT Conference on Computational Fluid and Solid Mechanics on June 14-17 in Boston, and at the 8th USNCCM in Austin.

Professor Greg Deierlein presented a one-day workshop on the new Direct Analysis and Stability Design Provisions for Steel Buildings at the annual meeting of the Metal Buildings Manufacturer's Association in Cleveland on July 20, 2005.

Professor Sarah Billington attended and presented an invited paper at the 3rd International Conference on Construction Materials: Performance, Innovations and Structural Implications (ConMat05) held in Vancouver, BC, from August 22-24, 2005.

During her visit to Finland in September **Dr. Renate Fruchter** was keynote speaker at EVTEK's 20th anniversary symposium in Espoo, guest speaker at Nokia Research Center "Insight and Foresight" event, guest speaker at Helsinki University of Technology, and guest of honor of the Mayor of Espoo where she gave a series of presentations on high-performance global teamwork.

Professor Sarah Billington conducted two hands-on sessions for the Stanford Summer Engineering Academy introducing incoming freshman to civil engineering. Students participated in a design competition to build and test the most efficient (height*strength/weight) paper column. The winning column was 6" tall, weighed 0.6 oz. and carried 146 lbs.

Professors Helmut Krawinkler and **Greg Deierlein** participated in the NEES E-Defense Workshop on Steel Structures at the E-Defense Shake Table Facility in Miki, Japan on Aug. 2-3. Krawinkler and Deierlein reported on three NEES projects dealing with (a) evaluation of sidesway building collapse, (b) simulation of earthquake-induced fractures in braced frames, and (c) a new project looking at innovative rocking systems with energy dissipating replaceable fuses.

On August 5, the Blume Center hosted a poster reception and dinner for the Board of Directors of the **Applied Technology Council**, who held their quarterly meeting in Palo Alto. The reception provided a great networking opportunity for students to share information on their research with leading professionals involved in risk mitigation for earthquakes and other hazards.

Marc Ramirez (PhD Candidate), **Professor Greg Deierlein**, and a

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RESEARCH SPOTLIGHT

Capturing Strain Localization in Dense Sands with Random Density

José E. Andrade and Ronaldo I. Borja

Introduction

Development of accurate mathematical models of discrete granular material behavior requires a fundamental understanding of the localization phenomena, such as the formation of shear bands in dense sands. It is important to recognize that the material response observed in the laboratory is a result of many different micro-mechanical processes, such as mineral particle rolling and sliding in granular soils, micro-cracking in brittle rocks, and mineral particle rotation and translation in the cement matrix of soft rocks. Ideally, any localization model for geomaterials must represent all of these processes. However, current limitations of experimental and mathematical modeling techniques in capturing the evolution in the micro-scale throughout testing have inhibited the use of a micro-mechanical description of the localized deformation behavior.

In this article, we adopt a more refined approach to investigating strain localization phenomena based on a meso-scale description of the granular material behavior. As a matter of terminology, the term "meso-scale" is used here to refer to a scale larger than the grain scale (micro-scale) but smaller than the element, or specimen, scale (macro-scale). This approach is motivated primarily by the current advances in laboratory testing capabilities that allow accurate measurements of material imperfection in the specimens, such as X-ray Computed Tomography (CT) and Digital Image Processing (DIP) in granular soils. For example, Figure 1 shows the result of a CT scan on a biaxial specimen of pure silica sand having a mean grain diameter of 0.5 mm and prepared via air pluviation. The gray level variations in the image indicate differences in the meso-scale local density, with lighter colors indicating regions of higher density (the large white spot in the lower level of the specimen is a piece of gravel). This advanced technology in laboratory testing, combined with DIP to quantitatively transfer the CT results as input into a numerical model, enhances an accurate meso-scale description of granular material behavior and motivates the development of robust meso-scale modeling approaches for replicating the shear banding processes in discrete granular materials.

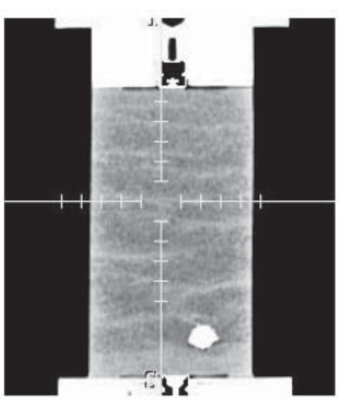

Figure 1: Cross-section through a biaxial test specimen of silica sand; white spot is a piece of gravel

Methodology

In order to simulate strain localization phenomena in dense sands, we have developed a mathematical model utilizing nonlinear continuum mechanics, theoretical and computational plasticity and the finite element method. Continuum mechanics furnishes a mathematical framework to describe the kinematics of bodies and develop balance laws governing the deformation of solids and fluids. We also obtain suitable stress and strain measures from this framework.

On the other hand, a novel constitutive model for sands capable of capturing the more salient features of this particulate material was developed based on plasticity theory. The model utilizes a three-invariant yield surface, which delimits the elastic behavior of the material while accounting for the difference in strength between compressive and tensile behavior. Models based on plasticity theory can capture permanent deformations typical of geomaterials (e.g. concrete, soils, rocks, etc).

Inhomogeneities at the meso-scale are incorporated into the plasticity model via a state parameter ψ, which contains information on the relative density at a point in the specimen. If $\psi < 0$, the point is said to be denser than critical, whereas $\psi > 0$ implies a point looser than critical. In this fashion, the macroscopic model is able to incorporate information on relative densities that could be present in the sample at the meso-scale and that, as we will show in the next section, could trigger unstable behavior at the specimen level. Further, it is well known that the behavior of dense sands is very different to that of loose sands. For example, dense sands tend to behave in a more 'brittle' fashion; reaching a distinct peak strength, whether loose sands do not show such a clear peak. Hence, any realistic model for sands should be able to capture this difference in behavior at different relative densities.

Finally, the aforementioned model is cast into a nonlinear finite element program to simulate the behavior of sand specimens numerically. At the same time, we prescribe the (inhomogenous) density field using a probabilistic approach where the void ratio of the sample is represented by a suitable probability density function. Hence, the behavior of imperfect sand specimens is simulated by combining deterministic and probabilistic techniques to capture the behavior of sands more realistically and to account for inherent uncertainties in the density field. In what follows, we present a numerical simulation demonstrating the effectiveness of our approach.

Numerical simulations with rectangular specimens

Randomization of the density field in a specimen is achieved through the void ratio e, defined as the ratio between the volume occupied by empty voids and the intrinsic volume of the solid phase, i.e., $e = V_v / V_s$. Here, we adopted a truncated exponential density function for e of the form

$$f(e) = \frac{\gamma \exp(-\gamma e)}{\exp(-\gamma e_d) - \exp(-\gamma e_l)} \tag{1}$$

where e_d is the lower bound of the distribution corresponding to the densest state, e_l is the upper bound of the distribution corresponding to the loosest state, and γ plays the role of a fitting parameter. We used these bounds to restrict the amount of dispersion in the density of the sample, thus controlling the amount of inhomogeneities. The expected value of the distribution is given by

$$\bar{e} = \frac{1}{\gamma} + \frac{e_d \exp(-\gamma e_d) - e_l \exp(-\gamma e_l)}{\exp(-\gamma e_d) - \exp(-\gamma e_l)} \tag{2}$$

Hence, we can *prescribe* the expected value or mean void ratio $\bar{e}$ subject to the upper and lower bounds e_l and e_d, respectively, provided we solve for the fitting coefficient γ. This is easily accomplished by a Newton-Raphson scheme. The random density field was then generated based on the assumption that the values of void ratio in space are mutually independent.

We then sheared in compression two rectangular specimens with dimensions 1x1x2m and assumed to behave according to the constitutive framework presented above, up to the onset of localization. At the structural level the density field was generated using the exponential distribution described above with a mean void ratio $\bar{e} = 0.63$ and lower and upper bounds $e_d = 0.54$ and $e_l = 0.64$, respectively. Hence, the two specimens, which we will call 'INHOMOGENEOUS 1' and 'INHOMOGENEOUS 2' for identification purposes, represent two different realizations of the same distribution function for the void ratio field, with otherwise identical mechanical properties. Figure 2 shows the discretized specimens with their respective initial specific volume field $v := 1 + e$. The rectangular domains were discretized using 2000 trilinear hexahedral finite elements.

The boundary conditions applied to the specimens were as follows. All four lateral faces were initially subjected to a constant confining pressure of 100 kPa (Newman BCs). The bottom and top faces of the specimens (z=0,2 m) were supported by rollers with a pin at the (0,0,0)m point for stability (Dirichlet BCs). The bottom face was constrained from displacement in the z-direction, whereas the top face was subjected to a vertical displacement responsible for shearing the samples in compression. A homogeneous sample with constant void ratio $v = 1.63$ was subjected to the same BCs described above, and its response compared against its inhomogeneous counterparts.

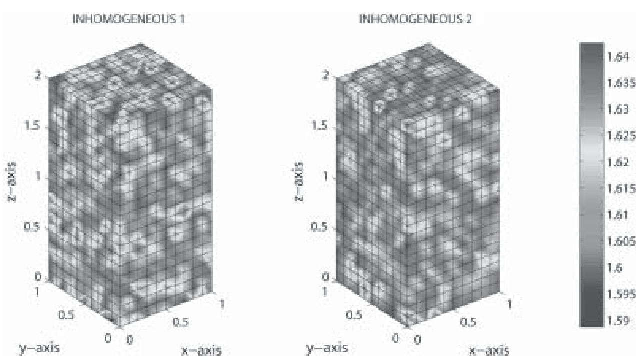

Figure 2: Initial specific volume field and finite element discretization for inhomogenous rectangular specimens

Figure 3 shows the nominal axial stress as a function of the nominal axial strain for both inhomogeneous specimens and their homogeneous counterpart. We see a close agreement in the global responses up to about 4% nominal axial strain, where the inhomogeneous responses softened and eventually localized at 5.8% strain. The homogeneous sample, however, underwent very little softening and in fact continued to harden. Figure 4 shows the contours of the determinant of the so-called acoustic tensor, for both inhomogeneous samples, superimposed on the deformed mesh at the onset of localization. Here, we define localization when one or more points in the sample have detected the first negative incursion of the determinant function. Both inhomogeneous samples localized at a nominal axial strain of around 5.8%, yet, from Figure 4, we observe that the deformation patterns and the inclinations of the impending shear bands are conjugate to each other, almost looking as mirror images.

From these simulations we conclude that perturbations in the density field via inhomogeneities at the meso-scale tend to trigger the onset of localization. The mechanical responses of the heterogeneous samples in the early stages of deformation are very similar to those of their homogeneous counterpart, suggesting that we can calibrate the meso-scale model parameters from global specimen responses during the early stages of loading.

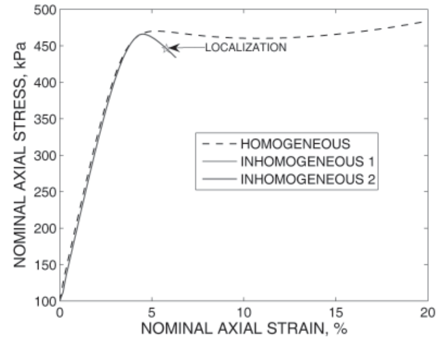

Figure 3: Nominal axial stress response for rectangular specimens

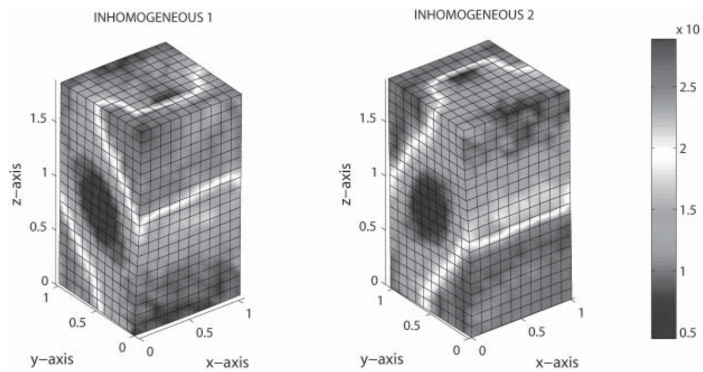

Figure 4: Contour of determinant function at onset of localization for inhomogeneous rectangular specimens

Closure

We have presented a mathematical model for deformation and strain localization analyses of granular materials with random unstructured density at meso-scale. At the macroscopic level, the model was showed to capture some of the most important features of sand behavior such as 'brittle' behavior in relatively dense sands under shear loading. Boundary-value problems mimicking soil samples have been analyzed using a truncated exponential distribution to generate random and unstructured density fields. Results of numerical simulations suggest that inhomogeneities tend to trigger strain localization, with heterogeneous samples localizing when their equivalent homogeneous counterparts would not. Results of the studies also suggest that heterogeneity in the density field tends to enhance and accelerate the onset of strain localization, even if the initial global deformation responses of a homogeneous sample and its heterogeneous counterpart appear to be the same. The framework presented in this article is useful for investigating strain localization phenomena in heterogeneous granular materials at a finer scale.

Acknowledgments

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References

[1] J. E. Andrade and R. I. Borja. Capturing strain localization in dense sands with random density. *International Journal for Numerical Methods in Engineering*. In review, 2006.

[2] R. I. Borja and J. E. Andrade. Critical state plasticity, Part VI: Meso-scale finite element simulation of strain localization in discrete granular materials. *Computer Methods in Applied Mechanics and Engineering*, 2006. In press for the John Argyris Memorial Special Issue.

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team of undergraduate researchers (**Carlos Ortiz** and **Jonathan Huang**) collaborated with engineers from Skidmore Owings and Merrill (Blume Center Affiliate) on the testing and analysis of a new type of pinned-fuse beam column connection. Ortiz and Huang presented the research findings at an Undergraduate Research Forum held in the Stanford Alumni Center on October 20, 2005.

PhD Candidates Jose Andrade and **Jack Baker** organized a series of seminars by the Blume Center graduate students this summer. The series was intended to share information and engage in discussions among the Blume Center students and faculty. The speakers included **Jiro Takagi**, **Dimitrios Lignos**, **Pablo Sanz**, **Krishnan Nair**, **Curt Haselton**, **Farzin Zareian**, **Kyle Douglas** and **Yang Wang**.

Grad Student Aids Tsunami Victims

This past summer, grad student **Molly Morse**, project coordinator with *Engineers for a Sustainable World Stanford (ESW)*, led a team of students to the Andaman & Nicobar Islands (India) to help with rebuilding following the devastating damage from the December 26 earthquake and tsunami. Working with an Indian based NGO, *Sustainable Environment and Ecological Development Society (SEEDS)*, based out of Delhi, Molly worked on a report for the *Social Welfare Advisory Board (SWAB)* about the extent of damage on Mahila Mandals (women's centers) on South Andaman Island. During her six weeks in India, Molly helped with a master drainage design for Nanjapanagar, the temporary shelter site in Hutbay on Little Andaman Island, and aided in the design for a community center, at the same site. Her fellow students in ESW stayed in the Andamans through November.

Newly Published Blume Center Technical Reports

TR149 - **G.L Yeo and C.A. Cornell**, *Stochastic Characterization and Decision Bases under Time -Dependent Aftershock Risk in Performance-Based Earthquake Engineering*

TR150 - **J.W. Baker and C.A. Cornell**, *Vector-Valued Ground Motion Intensity Measures for Probabilistic Seismic Demand Analysis*

TR151 - **D. Vamvatsikos and C.A. Cornell**, *Seismic Performance, Capacity and Reliability of Structures as Seen Through Incremental Dynamic Analysis*

TR152 - **L.F. Ibarra and H. Krawinkler**, *Global Collapse of Frame Structures under Seismic Excitations*

TR153 - **J. Ruiz-Garcia and E. Miranda**, *Performance-Based Assessment of Existing Structures Accounting for Residual Displacements*

Blume Center Technical Reports are available for free as downloads at http://blume.stanford.edu/Blume/TechnicalReports.htm.

Summer 2005 Graduates

Congratulations to our students who received their degrees during the Summer Quarter. Master of Science degrees were awarded to **Ryan Lawrence**, **Jury Shin**, **Subashri Swaminathan** and **Marc Ramirez** (continuing in the PhD program); an Engineer degree was awarded to **Satoshi Matsuki**. Doctorate degrees were awarded to **Paul Cordova** (post-doc at Stanford), **Qiang Fu** and **Jack Baker** (Asst. Professor at Stanford) in the Structural Engineering & Geomechanics Program and **Peng Li** in the Design/Construction Integration Program.

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