

REPORT DOCUMENTATION PAGE			Form Approved OMB NO. 0704-0188				
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1. REPORT DATE (DD-MM-YYYY) 08-04-2014		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 15-Apr-2011 - 14-Sep-2011			
4. TITLE AND SUBTITLE Topology, Structure and Functionality: Analysis, Modelling and Experimentation of Dense Granular Deformation in 2D and 3D			5a. CONTRACT NUMBER W911NF-11-1-0175				
			5b. GRANT NUMBER				
			5c. PROGRAM ELEMENT NUMBER 611102				
6. AUTHORS Antoinette Tordesillas			5d. PROJECT NUMBER				
			5e. TASK NUMBER				
			5f. WORK UNIT NUMBER				
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES University of Melbourne Melbourne Research Swanston Street			8. PERFORMING ORGANIZATION REPORT NUMBER				
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSOR/MONITOR'S ACRONYM(S) ARO				
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16. SECURITY CLASSIFICATION OF:		17. LIMITATION OF ABSTRACT		15. NUMBER OF PAGES		19a. NAME OF RESPONSIBLE PERSON	
a. REPORT	b. ABSTRACT					c. THIS PAGE	Antoinette Tordesillas
UU	UU	UU	UU			19b. TELEPHONE NUMBER 038-344-9685	

## Report Title

Topology, Structure and Functionality: Analysis, Modelling and Experimentation of Dense Granular Deformation in 2D and 3D

### ABSTRACT

A three-pronged approach is employed to study mesoscale phenomena in dense granular materials. This approach interrelates the key elements of topology, structure and function to uncover principles of self-organization in dense granular materials. For the first time, we fuse Structural Mechanics techniques, Graph Theory, and nascent mathematical and statistical techniques from Complex Networks and Dynamical Systems to characterize the stability and dynamics of deforming granular materials. We summarise here five distinct projects undertaken by our group in fulfillment of the objectives of this program. Each project focuses on a particular class of data, distinguished by one or several of the following factors: (i) the type of material studied (photoelastic, and natural geomaterials including Hostun sand, Masonry-concrete and silica-concrete sand, partially molten metal-silicate rock (Kernouve)) (ii) the loading condition, and (iii) source of data, i.e. simulation versus experiment.

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<u>Received</u>	<u>Paper</u>
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**TOTAL:**

**Number of Papers published in peer-reviewed journals:**

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**(b) Papers published in non-peer-reviewed journals (N/A for none)**

<u>Received</u>	<u>Paper</u>
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**TOTAL:**

**Number of Papers published in non peer-reviewed journals:**

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**(c) Presentations**

Number of Presentations: 9.00

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**Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**

Received      Paper

**TOTAL:**

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

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**Peer-Reviewed Conference Proceeding publications (other than abstracts):**

Received      Paper

- 06/06/2012 8.00 David M. Walker , Antoinette Tordesillas. Deciphering D'Alemberts Dream: New Tools for Uncovering Rules for Self-Organized Pattern Formation in Geomaterials, International Workshop on Bifurcation and Degradation in Geomaterials. 22-MAY-11, . . . ,
- 06/06/2012 9.00 Sara Abedi , Antoinette Tordesillas, David M. Walker, Amy Rechenmacher. Discovering Community Structures and Dynamical Networks from Grain-Scale Kinematics of Shear Bands in Sand , International Workshop on Bifurcation and Degradation in Geomaterials. 22-MAY-11, . . . ,
- 06/06/2012 11.00 David M. Walker, Antoinette Tordesillas. Network analysis of force chains in granular materials using a data compression technique , International Symposium on Nonlinear Theory and its Applications (NOLTA). 08-APR-11, . . . ,

**TOTAL:      3**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

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**(d) Manuscripts**

Received      Paper

**TOTAL:**

**Number of Manuscripts:**

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**Books**

Received      Book

**TOTAL:**

Received      Book Chapter

**TOTAL:**

**Patents Submitted**

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**Patents Awarded**

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(5) Research group highlighted in THE VOICE Volume 7 Number 5 May 9 - June 5 2011 "Hundreds and thousands of theories"

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**Graduate Students**

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

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**Names of Post Doctorates**

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
David M Walker	1.00
<b>FTE Equivalent:</b>	<b>1.00</b>
<b>Total Number:</b>	<b>1</b>

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**Names of Faculty Supported**

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**Student Metrics**

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Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

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Andrew Cramer (0)	
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### Names of personnel receiving PhDs

<u>NAME</u>
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### Names of other research staff

<u>NAME</u>
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### Sub Contractors (DD882)

### Inventions (DD882)

### Scientific Progress

For the first time, Structural Mechanics techniques, Graph Theory, and nascent mathematical and statistical techniques from Complex Networks and Dynamical Systems have been fused together to characterize the stability and dynamics of deforming granular materials. Robustness of these has been tested against discrete element simulations from US Army ERDC Geotechnical Laboratory as well as in experiments on a range of synthetic and natural materials including: photoelastic disk assemblies, and various types of sand (i.e. Hostun, Caicos Ooid, masonry-concrete & silica-concrete) and a partially molten metal-silicate system. Results show the techniques are robust and capable of delivering unprecedented details on granular rheology. Key findings include the prediction of the shear band at the initial stages of loading well before peak shear stress through the network measure of closeness centrality -- a measure of how fast information spreads from a given network node (here, representing a grain) to all other nodes in the global network (here, representing the entire granular material).

### Technology Transfer

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**Sub Contractors (DD882)**

## **Inventions (DD882)**

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### **Technology Transfer**

**2011 US ARO - TERRESTRIAL SCIENCES PROGRAM****Proposal Number 58763-EV  
Project Report I****Dates covered: June 1-September 14, 2011****Topology, Structure and Functionality:  
Analysis, Modelling and Experimentation of Dense Granular Deformation in 2D and 3D****Antoinette Tordesillas (Principal Investigator) & David M. Walker  
Department of Mathematics and Statistics  
University of Melbourne**

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**A. Objectives**

The proposed program investigates the rheological behavior of the upper soil surface in soil-structure and soil vehicle interaction systems. The overarching objective is to identify novel measures which can be used to: (i) characterize the rheological behaviour of soil at an unprecedented level of detail in two and three dimensions, and (ii) predict the mechanical response of granular materials in a wide range of loading conditions, particularly, *soil-solid interactions both on-surface and near surface of soils*. An important aspect of this work is the technology transfer to the US Army and other US Department of Defense Research Laboratories. This is made possible by Tordesillas' ongoing collaborations with researchers from ERDC and continuing interactions with researchers from various other US DoD laboratories in the area of Soil Mechanics, Soil-Structure Interaction and Multiscale Material Modelling.

The deformation regime of interest in this study is the solid-like to liquid-like transition of granular materials. In soil mechanics, this is more commonly known as the three consecutive regimes of: I: Strain-hardening, II: Strain-softening, and III. Critical state. We are interested in the mechanisms which govern each of these states especially in the transition from the

stable states in regime I to the ultimate failure states in regime III. All three regimes are highly relevant to at least two key aspects of the Army's land operations: off-road vehicle mobility and soil stability. Key aspects of this transition involve force transmission, energy dissipation, and kinematics in granular assemblies. The project objectives are to:

- Identify and apply completely new structural measures to characterize granular deformation and failure in experiments and simulations in fully 3D as well as 2D systems
- Develop structural mechanics models of the evolving stabilities of emergent mesoscopic structures arising from self-organization inside the deforming granular medium (e.g. force chains, shear bands); develop new continuum descriptions, as well as fast discrete cellular automata and lattice models, that incorporate the findings from these studies
- Extend all facets of the investigations to non-spherical particles, starting with ellipses, and then more complex particle shapes
- Probe the effects of grain polydispersity

## B. Approach

The analytical, computational and experimental approaches in this program present a strategic combination of pioneering capabilities in high-resolution measurements, material characterization and modeling in 2D and 3D systems. This three-part micromechanics program (see Figure 1) is the first-of-its-kind in scope, focus and the level of detail to be defined on granular material behavior and, in particular, on soil. Its direct use of a wide variety of experimental data (i.e. synthetic and natural materials under a broad range of loading conditions) and advanced discrete element simulations to guide and test model development is unprecedented.

The experimental data sets being analysed by the Tordesillas group are unique in their ability to provide key information, unavailable elsewhere in both 2D and 3D systems. The blend of mathematical techniques is both unique and highly novel, with many aspects seeing their first application in the field of granular media mechanics and physics. ***Specifically, a three-pronged approach is employed to study mesoscale phenomena. This approach interrelates the key elements of topology, structure and function to uncover principles of self-organization in dense granular materials. For the first time, we will fuse Structural Mechanics techniques, Graph Theory, and nascent mathematical and statistical techniques from Complex Networks and Dynamical Systems to characterize the stability and dynamics of deforming granular materials.***

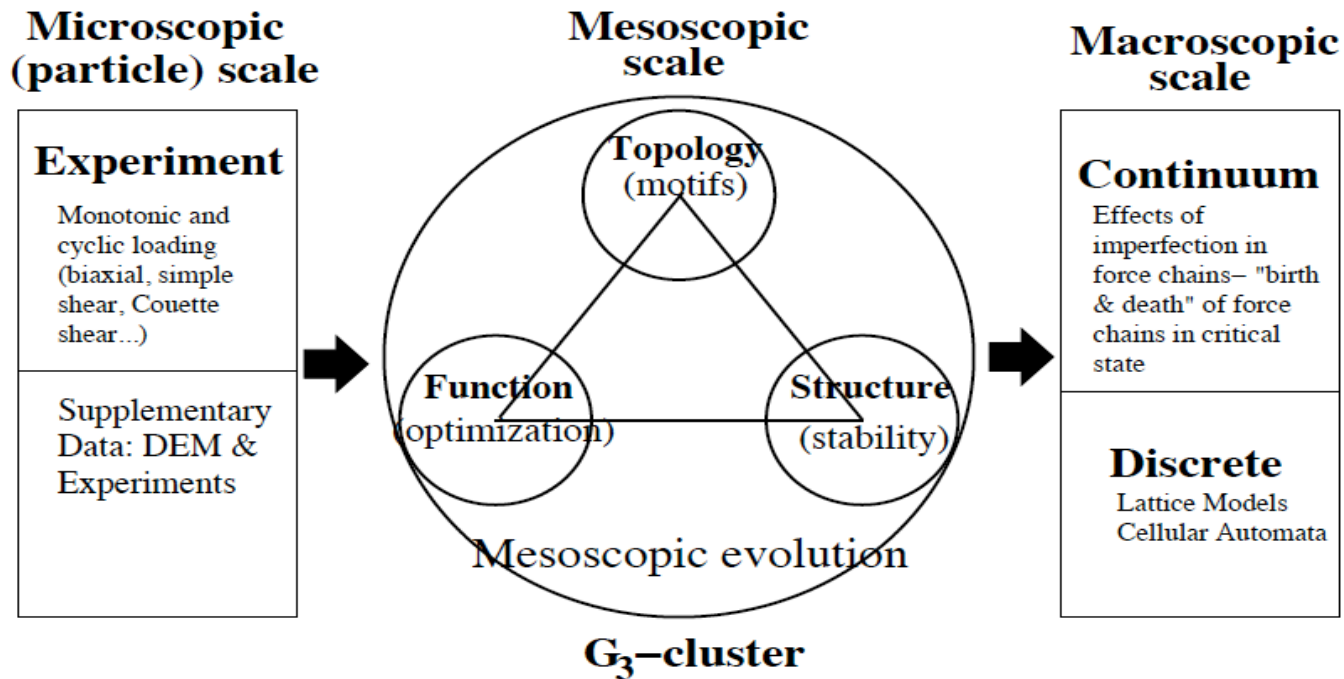


Figure 1: The three phases of the proposed research program. Experimental and theoretical efforts are closely integrated so that the development of analytical techniques for material characterization as well as predictive models are frequently informed by and validated against experimental data. A core element is the  $G_3$ -cluster program which embodies algorithms that characterize and model the three interrelated aspects of material behavior: topology, functionality and structure.

We summarise below five distinct projects undertaken by our group in fulfillment of the objectives of this program. Each project focuses on a particular class of data, distinguished by one or several of the following factors: (i) the type of material studied, (ii) the loading condition, and (iii) source of data, i.e. simulation versus experiment.

**Project [1]:** Currently experiments (e.g. cyclic shear and granular slider) are carried out at Duke University which exploit the special properties of photoelastic materials. These photoelastic materials, plus the expertise developed by Behringer and his group, allow for the detailed particle-scale determination of all physically relevant properties of a model of photoelastic disk assemblies at the individual particle scale.

To ensure fidelity of models with real soil and soil-interaction systems, we supplemented our studies of photoelastic materials by analyses of data from actual soil as well as advanced discrete element simulations incorporating complicating aspects of real soil (e.g. particle shape). **Our group at Melbourne is currently working with leading experimental teams worldwide in the area of geostructural engineering, geology, physics and geomechanics to ensure that the techniques are robust for as wide a range of synthetic and natural materials. Existing collaborative efforts in soil and rock mechanics have made possible the analysis of novel data sets in support of this research program, *but at no cost to US ARO.*** These include:

**Project [2]:** The highest resolution kinematical and contact data sets achieved to date on soil samples under combined shear and compression from Cino Viggiani's group (Laboratoire Sols, Solides, Structures-Risques, Université Joseph Fourier) using X-ray microtomography. Triaxial compression of two types of sand undergoing localized failure have been characterized: Hostun and Caicos Oid.

**Project [3]:** Grain scale kinematical measurements for various types of soil using Digital Image Correlation have also been achieved with data from Amy Rechenmacher's group's (Sonny Astani Department of Civil and Environmental Engineering University of Southern California) using Digital Image Correlation. Examined to date are plane strain compression of masonry-concrete & silica-concrete sand.

**Project [4]:** Phase and composition data on a deforming Kernouve rock sample have been studied. Data were acquired using electron micrograph by Tracy Rushmer from GEMOC/Department of Earth and Planetary Sciences Key Centre Geochemical Evolution, Macquarie University.

**Project [5]:** Advanced discrete element simulations of assemblies of complex-shaped, i.e. polyellipsoidal, particles from Mark Hopkins and John Peters (US Army Engineering Research and Development Center, Cold Regions Research and Engineering Laboratory and Geotechnical Laboratory, respectively). Additional data on triaxial tests on binary sand-silt mixtures and steel- plastic particles are also being explored to better understand contact and contact force network percolation in granular mixtures. The direct interaction with ERDC researchers ensures that technology transfer to Army laboratories is immediate.

### C. Significance to Army Off-Road Vehicle Mobility and Construction Operations

The Army has extensive on-land and near surface ground operations. The Army deploys a wide range of off-road vehicles which must move over or rest on the soil—i.e. a granular material – without getting bogged down or immobilized. Similarly, machines which excavate, drill, penetrate, move and carry the soil are common in many military construction operations. Most of these off-road processes imposes forces on the soil that then induce regimes of behaviour covering the broad gamut from stable to unstable states of deformation, to complete failure where the material loses load-carrying capacity and

undergoes full plastic flow. A further challenge in these operations is that all these regimes can co-exist, leading to highly unpredictable conditions with destructive and at times fatal consequences.

This project will provide key insights into the nature of stability and failure of geomaterials (soil and rock) and, more broadly, granular as well other complex materials. A key goal will be to develop models of geomaterials that can robustly predict soil behaviour (i.e. deformation and stability) – and which can ultimately be used in the design and operation of off-road vehicles and geotechnical machines.

#### **D. Accomplishments, Activities, and Publications**

We present here a summary of the accomplishments to date on each of the five projects highlighted in Section B. Additional project deliverables and technology transfer relating to this program are also included after the summary.

**1 Photoelastic disk experiments by RP Behringer and co-workers.** The Tordesillas group has been provided two experimental data sets by the Behringer group: (a) cyclic shear and (b) granular slider. Outlined below are outcomes and deliverables achieved to date on the analysis of these data sets.

**1.1 Cyclic shear** We examine emergent, self-organized particle cluster conformations in quasistatically deforming dense granular materials from the perspective of structural stability. A structural mechanics approach is employed, first, to devise a new stability measure for such conformations in equilibrium and, second, to use this measure to explore the evolving stability of jammed states of specific cluster conformations, i.e. particles forming force chains and minimal contact cycles. Knowledge gained on (a) the spatial and temporal evolution of stability of individual jammed conformations and (b) their relative stability levels, offer valuable clues on the rheology and, in particular, self-assembly of granular materials. This study is undertaken using data from assemblies of nonuniformly sized circular particles undergoing 2D deformation in two biaxial compression tests: a discrete element simulation of monotonic loading under constant confining pressure, and cyclic loading of a photoelastic disk assembly under constant volume. Our results suggest that the process of self-assembly in these systems is realized at multiple length scales, and that jammed force chains and minimal cycles form the basic building blocks of this process. In particular, 3-cycles are stabilizing agents that act as granular trusses to the load-bearing force chain columns. This co-evolutionary synergy between force chains and 3-cycles proved common to the different materials under different loading conditions. Indeed, the remarkable similarities in the evolution of stability, prevalence and persistence of minimal cycles and force chains in these systems suggest that these structures and their co-evolution together form a generic feature of dense granular systems under quasistatic loading. This work has just been published:



A Tordesillas, Q Lin, J Zhang, R. P. Behringer and J Shi, Structural stability and jamming of self-organized cluster conformations in dense granular materials, *Journal of the Mechanics and Physics of Solids* 59, 265--296 (2011).

- 1.1.1 We have characterized the contact and contact force networks and have identified which aspects of these networks govern: stability (here, established in terms of the degree of redundancy or static indeterminacy of the system), and their contribution to the material's ability to support deviatoric (shear) stress. This work has just been published:

D.M. Walker, A. Tordesillas, C. Thornton, R. P. Behringer, J. Zhang, and J. F. Peters, Percolating contact subnetworks on the edge of isostaticity, *Granular Matter* 13 233-240 (2011).

- 1.1.2 We present the first comprehensive study of deformation of a granular material, by considering the process of self-organization of an assembly of frictional particles (birefringent photoelastic disks). Transition dynamics of granular cluster conformations and their conformational stability states are completely mapped-out -- explicitly linking topology, dynamics, structure and function. In the process, we discover "magic number behaviour" reminiscent of those seen for molecular clusters. Such behaviour is unambiguously tied to the cooperative evolution of key functional groups: truss-like 3-cycles provide lateral support to major load-bearing columnar force chains -- a striking resemblance to architectural structures. This study is an example of the results achievable through an inter-disciplinary approach to science linking data from cutting edge experimental physics, mathematical methods from pure and applied dynamical and complex systems analysis, to investigate self-organization and emergent structures in granular systems. This paper has been submitted for publication:

A. Tordesillas, D. M. Walker, G. Froyland, J. Zhang, and R. P. Behringer, Transition Dynamics of Frictional Granular Clusters, 2011

## 1.2 Granular slider

This data set is currently being analysed. We will discuss this project in the next progress report.

## 2 Hostun and Caicos Oid sand

- 2.1 Techniques from complex networks and nonlinear dynamical systems are used to construct and analyse kinematical data from X-ray micro-CT measurements of grain displacements and rotations for Hostun sand under triaxial compression. Community structures, and shortest paths within network communities and throughout the sample, uncover several new aspects of granular rheology. We find a spatial length scale from the shortest paths. This remains essentially invariant throughout loading and is consistent with the observed thickness of the shear band. Those nodes with the {at least} mean shortest path length to all the other nodes in the network, or highest relative closeness centrality, reside in the region where the so-called persistent shear band ultimately develops. Thus information in

these networks spreads the fastest to and from those nodes corresponding to the particles in the region of strain localization. This trend, whereby a group of particles distinguishes themselves from the rest in the sample, by their high relative closeness centrality in the network, remarkably manifests from the onset of loading. This raises the tantalizing possibility that the formation and location of the persistent shear band may be decided in the nascent stages of the loading history, well before peak shear stress. Statistical tests confirm the results are robust. Moreover, the trends are unambiguously reproduced in a discrete element simulation of plane strain compression. This study takes the essential steps toward a complete map of the evolution of functional and structural connections in a deforming sand. A paper is now in its final draft stages and will be submitted by mid October:

A. Tordesillas, D. M. Walker, E. Ando and G. Viggiani, Revisiting strain localization in sand with complex systems theory, *Proceedings of the Royal Society of London Series A*, 2011.

### 3 Masonry-concrete & silica-concrete sand

3.1 We have applied novel ideas from network theory to study plastic deformation in a plane strain compression test of a dense sand specimen using data on grain scale displacements. Kinematical information for the deforming material is obtained using digital image correlation (DIC) and summarized by two types of complex network with different connectivity rules establishing links between the network nodes which represent the DIC observation sites. We find different network properties of each network provide useful information about plastic deformation and non-affine processes emerging within the material. In particular, persistent shear bands and mesoscale structures within them (e.g. vortices) appear to be closely related to the values of network properties including closeness centrality, clustering coefficients, *k*-cores and the boundaries of community structures determined using local modularity. A paper has been submitted:

D. M. Walker, A. Tordesillas, S. Pucilowski, Q. Lin, A. Rechenmacher and S Abedi, Analysis of grain-scale measurements of sand using kinematical complex networks. *International Journal of Bifurcation and Chaos* 2011.

### 4 Silicate-Metal (Kernouve) sample

4.1 This study utilizes complex networks and dynamical systems techniques to quantify the growth of metallic liquid blebs in silicate melt bearing experiments. This is used to better understand the first steps of segregation of metal from silicate in a natural partially molten Metal-Silicate system. A paper has been submitted:

Rushmer T, A. Tordesillas, D.M. Walker "A Complex Network Analysis of Growth and Mixing Dynamics in Natural Metal-Silicate Systems" *Physics of the Earth and Planetary Interiors* 2011.

## 5 Triaxial compression of an assembly of polyellipsoidal particles in three dimensions

5.1 This study capitalizes on recent advances from ERDC in the area of discrete element analysis. Here we join forces and combine pioneering developments in simulation with data mining techniques, particularly exploiting methods from complex networks and statistics to quantify the rheological behaviour of a dense granular material. We uncover new insights into the evolution of mesoscopic structural building blocks of force chains and their supporting contact cycles. A paper is now in press and Dr John Peters (ERDC) has made presentations to US Army research laboratories:

- A. Tordesillas, S. Pucilowski, D.M. Walker, J.F. Peters, M. Hopkins (2011) "A complex network analysis of granular fabric evolution in three-dimensions" *Dynamics of Continuous, Discrete and Impulsive Systems-B*. (In press. Accepted Oct 28, 2010)
- A. Tordesillas, J.F. Peters and M. Hopkins "Network analysis of granular failure in three dimensions" *Particulate Mechanics in Extreme Environments 2010, Lawrence, Livermore USA*
- A. Tordesillas, J.F. Peters and M. Hopkins "Network Analysis of Evolving Three Dimensional Granular Media Structure" *Engineering Mechanics Institute of American Society for Civil Engineers EMI 2010, California USA*.

### Recent Publications

- [1] Tordesillas A, Pucilowski S, Walker DM, Peters J, Hopkins M (2011) "A complex network analysis of granular fabric evolution in three-dimensions" *Dynamics of Continuous, Discrete and Impulsive Systems-B*. (In press. Accepted Oct 28, 2010)
- [2] Walker DM, Tordesillas A, Einav I, Small M (2011) "Complex networks in confined comminution" *Physical Review E* **84**, 021301.
- [3] Tordesillas A, Hunt G, Shi J (2011) "A characteristic length scale for confined elastic buckling of force chains" *Granular Matter*. **13** pp 215-218.
- [4] Walker DM, Tordesillas A, Thornton C, Behringer RP, Zhang J, Peters J (2011) "Percolating contact sub-networks on the edge of isostaticity" *Granular Matter* **13** pp 233-240.
- [5] Tordesillas A, Sibille L, Pucilowski, S, Nicot F, Darve F (2011) "Microstructural evolution in diffuse granular failure: force chains and contact cycles" *Proceedings, 2011 International Symposium on Computational Geomechanics (ComGeo II)* (In press. Accepted Jan 26, 2011)
- [6] Tordesillas A, Walker DM, Rechenmacher, A, Abedi, S (2011) "Discovering community structures and dynamical networks from grain-scale kinematics of shear bands in sand" *Proceedings, 2011 International Workshop on Bifurcations and Degradations in Geomechanics*. (In press. Accepted Nov 16, 2010)
- [7] Tordesillas A, Walker DM (2011) "Deciphering D'Alembert's dream: new tools for uncovering rules for self-organized pattern formation in geomaterials" *Proceedings, 2011 International Workshop on Bifurcations and Degradations in Geomechanics*. (In press. Accepted Apr 1, 2010)

- [8] Tordesillas A, Lin Q, Zhang J, Behringer, RP and Shi, J (2011) "Structural stability and jamming of self-organized cluster conformations in dense granular materials" *Journal of the Mechanics and Physics of Solids* **59** pp 265-296.
- [9] Tordesillas, A., O'Sullivan P, Walker D.M. and Paramitha (2010) "Evolution of functional connectivity in contact and force chain networks: feature vectors, k-cores and minimal cycles," *CRAS, Proceedings of the French Academy of Sciences* **338** pp 556-569.
- [10] Tordesillas, A, Shi, J and Tshaikiwsky, T (2010) "Stress-dilatancy and force chain evolution", *International Journal of Numerical and Analytical Methods in Geomechanics* **35** pp 264-292.
- [11] Ben-Nun O, Einav I and Tordesillas A (2010) "Force Attractor in Confined Comminution of Granular Materials" *Physical Review Letters* **104** 108001.
- [12] Zhang, J, Majmudar, T, Tordesillas, A and Behringer, R (2010) "Statistical Properties of a 2D Granular Materials Subjected to Cyclic Shear" *Granular Matter* **12** pp 159-172.
- [13] Tordesillas, A, Walker D and Lin Q (2010) "Force cycles and force chains" *Physical Review E* **81**, 011302.
- [14] Walker D and Tordesillas A (2010) "Topological evolution in dense granular materials: A complex networks perspective" *International Journal of Solids and Structures* **47** pp 624-639.
- [15] Hunt G, Tordesillas, A, Green, S and Shi, J (2010) "Force chain buckling in granular media: A structural mechanics perspective" *Philosophical Transactions of the Royal Society* **368** pp 249-262.

### Recent Plenary/Keynote/Invited Lectures

- [1] Tordesillas, A "Fabric evolution and dynamical patterns in sand to molten planetesimals: does form follow function or vice versa?" *2011 Alliance of Laboratories in Europe for Research and Technology (ALERT) of Geomaterials - Workshop I on Multiscale geomechanics: from fabric to material properties* Oct 3, 2011, Aussois, France.
- [2] Tordesillas, A "Anatomy of granular failure: the what, how and why of diffuse versus localized modes" *2011 Alliance of Laboratories in Europe for Research and Technology (ALERT) of Geomaterials – Workshop III on Localized versus diffuse failure in geomaterials* Oct 5, 2011, Aussois, France.
- [3] Tordesillas A "From brains to grains: unravelling the physics of sand through structural and functional networks derived from X-ray tomography" *The 8th International Workshop on Complex Systems and Networks* Sep 17-19, 2011 Melbourne Australia.
- [4] Rushmer T, Tordesillas A, Walker DM "A Complex Network Analysis of Growth and Mixing Dynamics in Natural Metal-Silicate Systems" *Goldschmidt2011*, August 14-19, 2011, Prague, Czech Republic. (Tracy Rushmer presented this paper.)
- [5] Walker DM, Tordesillas A, "Network analysis of force chain structures within granular materials using a data compression technique" *2011 International Symposium on Nonlinear Theory and its Applications NOLTA*, September 4–7, 2011, Kobe Japan. (David M Walker presented this paper.)

- [6] Tordesillas, A "Pesky particles pacified in pixels" *2011 ALERT O. Zienkiewicz Doctoral School: "Discrete Mechanics of Geomaterials"* June 27-July 1, 2011, Grenoble, France.
- [7] Tordesillas, A "Deciphering D'Alemberts dream: new tools for uncovering rules for self-organized pattern formation" *2011 International International Workshop on Bifurcation and Degradation in Geomechanics*. May 23 - 26, 2011 Porquerolles France.
- [8] Tordesillas, A "Discovering community structures and dynamical networks from grain-scale kinematics of shear bands in sand" *2011 International International Workshop on Bifurcation and Degradation in Geomechanics*. May 23 - 26, 2011 Porquerolles France.
- [9] Tordesillas, A, Sibille, L, Pucilowski, S, Nicot, F, Darve F. "Microstructural evolution in diffuse granular failure: force chains and force cycles" *2011 International Symposium on Computational Geomechanics (ComGeo II)*

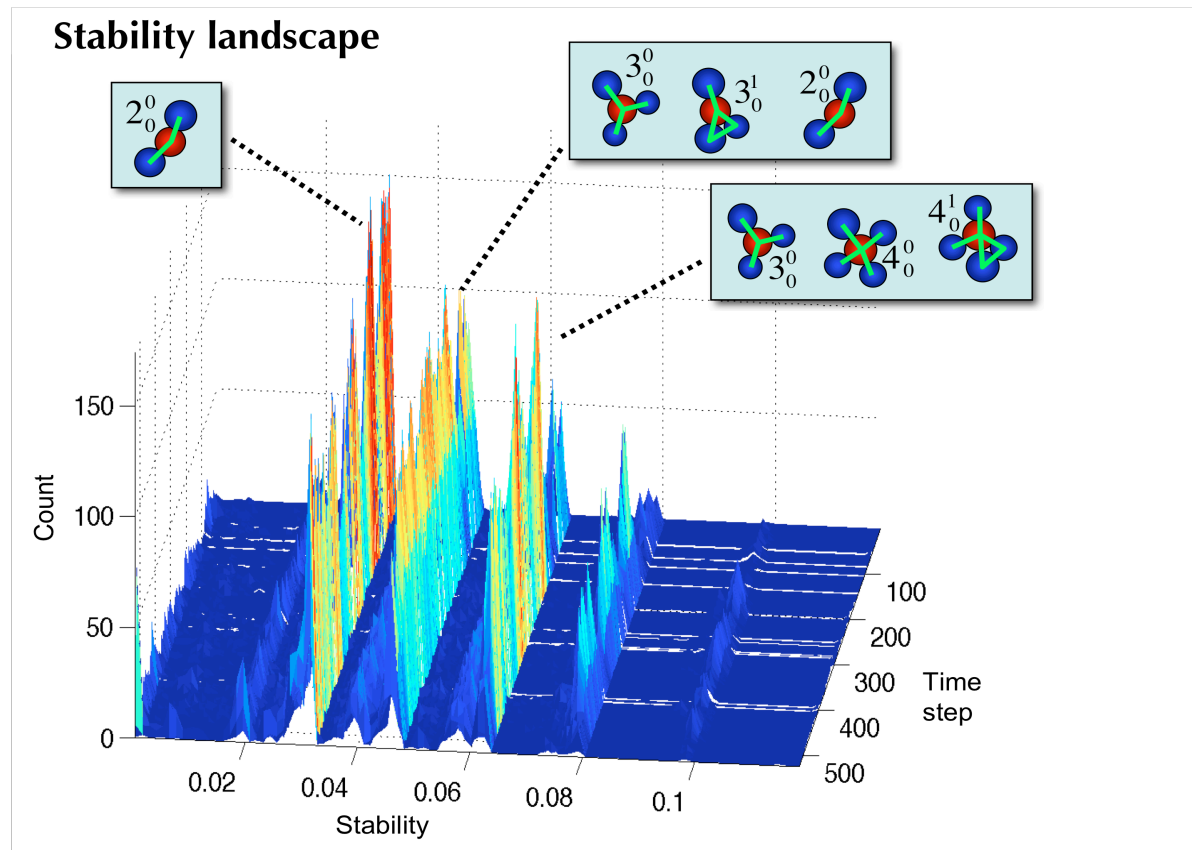


Figure 2: We examined the stability of every particle relative to its first ring of contacting neighbours in the cyclic shear experiment. Shown here is the stability landscape: the frequency distribution of resulting stability states of each particle at the various stages (time steps) in the experiment. We also show here the most prevalent cluster conformations found in the most resolved stability bands: note the peaks in stability which prevail throughout loading history of the cyclic shear experiment. These are reminiscent of magic number behaviour of molecular clusters, i.e. persistent and preferred cluster configurations, which have been associated with favourable energy states. **From A. Tordesillas, D. M. Walker, G. Froyland, J. Zhang, and R. P. Behringer, *Transition Dynamics of Frictional Granular Clusters*, 2011**

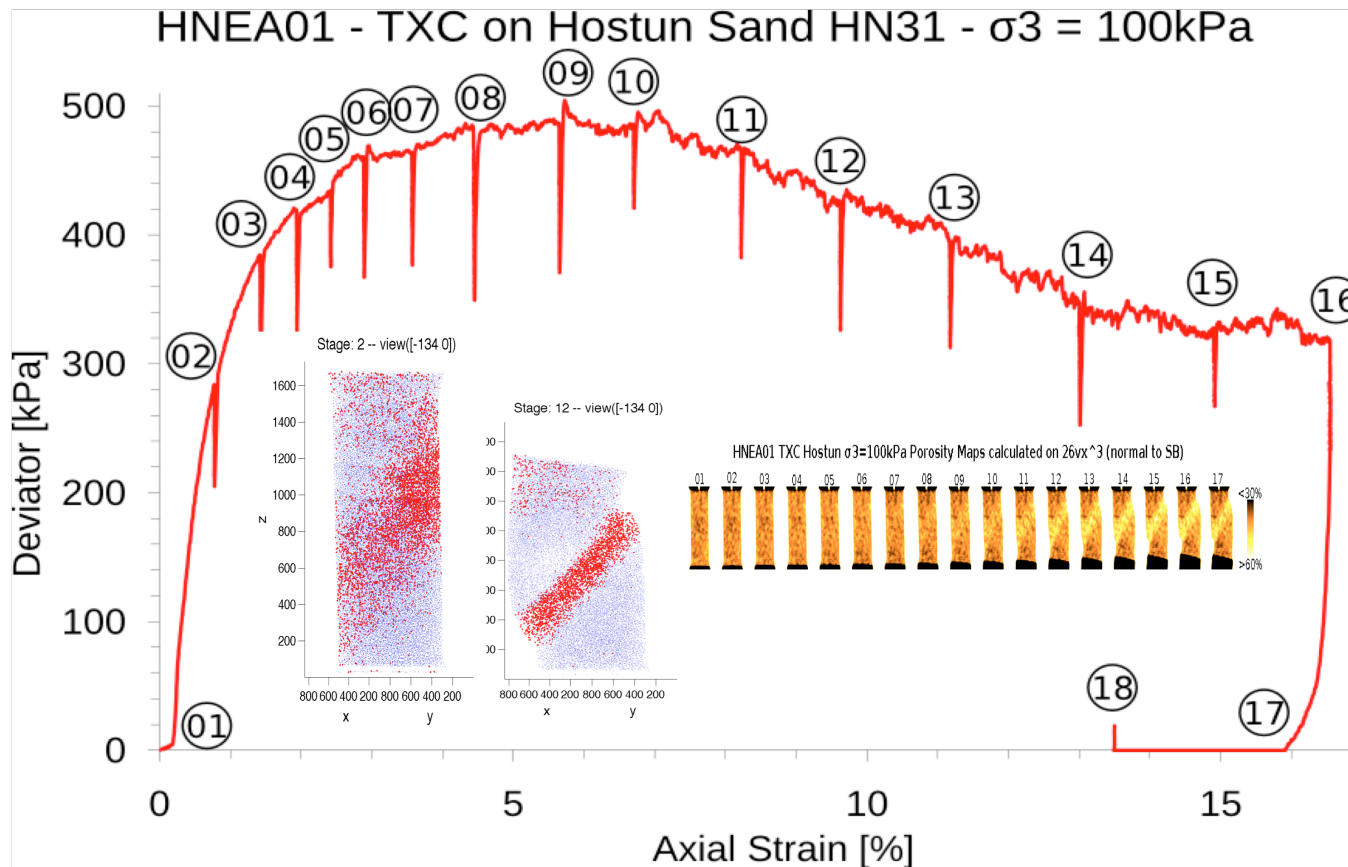


Figure 3: We examined Hostun sand under triaxial compression. Shown here is a plot of the shear stress (deviator) versus axial strain. In the left inset, we show the sample at the initial and final stages (i.e. stages 2 and 12) of loading history with the particles having the highest closeness centrality values coloured red (top 10%). Closeness centrality is a measure of how fast information travels from one node (here, representing a particle) to all the other nodes in the network (whole soil sample). Note that closeness centrality predicts the location of the shear band well before peak shear stress. For comparison, we have shown the porosity maps of the sample at successive stages of loading history (left to right corresponds to stages 1 to 17): these maps show no evidence of localization in stage 2. Our findings suggest that the ultimate failure of the material may be decided in the nascent stages of loading history. **From A. Tordesillas, D. M. Walker, E. Ando and G. Viggiani. Revisiting strain localization in sand with complex systems theory, submitted to Proceedings of the Royal Society of London Series A, 2011**