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13. ABSTRACT (Maximum 200 words)

Under this research program, we pioneered the development of a new breed of high-resolution micromechanical continuum models of granular materials – with experimentally proven predictive capabilities for emergent structures spanning the length scales from only a few particles through to the macroscopic scale of engineering systems and processes. This breakthrough is underpinned by four disciplines of Mechanics, woven together for the first time into one complete methodology for constitutive model development: *Micromechanics* (the multiscale analysis of behaviour of heterogeneous media from the microscale to observable macroscopic level); *Contact Mechanics* (the study of interaction between deformable solids in contact); *Thermomechanics* (the branch of Mechanics devoted to Thermodynamics); and *Micropolar or Cosserat Theory* (the study of continuum bodies whose kinematics and kinetics have been enriched by the addition of rotational degrees of freedom to each material point). Unique aspects of this approach are: "high-resolution" predictive capability; clear link between macro and micro behaviour; input parameters being identical to those used in particle-based simulations thereby permitting direct comparison of model predictions with simulation and experiments; guaranteed compliance with the laws of thermodynamics. Comparison with experiments show the model can capture emergent internal structures whose characteristic length scales are only a few particles wide, e.g. shear bands. The model can also capture the evolution of novel anisotropies inside the shear band, (e.g. force chains).

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Toward generalized continuum models of granular soil and soil-tire interaction
Proposal Number 42855-EV

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1. Statement of the problem

Granular materials (or particulates) are ubiquitous in everyday life and range from cosmetic powders to pharmaceutical pills, from gravel to M&Ms, from beach sand to the rings of Saturn, and from breakfast cereals to interstellar dust. Considered as the ultimate paradigm of a complex system, granular materials exhibit behaviour that has eluded scientists for centuries. *Today, this class of materials is still lacking a constitutive model of the pedigree of the Navier–Stokes equation of fluid dynamics to predict how it will behave under load.* Consequently, systems and processes involving granulates rarely reach 60% of their design capacity – a far cry from fluids processing which operates on average at 96% design capacity. Thus, even a fractional advance in our understanding of how granular media behave can have a profound economic and social impact.

The great majority of existing models of granular media are developed using classical continuum theory. These models are readily accessible and enjoy widespread use. However, their Achilles heel is that they possess no length scale with which to accommodate microstructural properties governing bulk behaviour of granular media. Thus, the reliability of these models remains questionable. An alternate approach, which is gaining popularity, is the discrete element method (DEM). DEM deals explicitly with the microstructure and, as such, has delivered reliable predictions on granular behaviour. However, the number of particles in current DEM simulations is limited to a few million particles – *roughly the number of particles in a handful of sand!* Thus, many engineering scale processes are beyond the reach of DEM, while prototype scale problems require the use of oversized particles, which leads to scaling errors. Recently, effort has been directed toward formulating a third class of models with the combined strengths of classical continua and DEM models. It is this hybrid that we have been developing using Micromechanics theory. The key objective of a micromechanical analysis is to relate the microstructural/*discrete* properties (*e.g.* contact forces, contact moments, displacements and rotations), to macrostructural/*continuum* properties (*e.g.* stresses, couple stresses, strains and curvature) using a "homogenisation" or averaging procedure. In recent years, interest in Micromechanics has spread and intensified among the different branches of rheology and complex matter physics: in addition to granular materials, examples of other complex matter include polymers, colloids, foams, biological tissue, just to name a few. In fact, research trends relating to these materials show a strong shift towards 'bottom-up' modelling techniques with increasing emphasis on mathematical models that can capture the effects of material structure at multiple length scales, while still retaining efficiency in their computational implementation. Thus, in the context of granular asssemblies, material behaviour is viewed in hierarchical terms, where the relevant length scale may move from particle scale (microscale), to particle clusters (mesoscale), to bulk engineering scale (macroscale).

The project objectives are to:

- Develop micromechanical constitutive models of dry granular materials. These models have the potential to offer a computationally efficient alternative to DEM simulations, and fill an

important niche in applications beyond the reach of current DEM simulations (*e.g.* soil-structure/machine interaction systems).
- Experimentally validate these constitutive models to selected soil-structure interaction problems.
- Interact continuously with staff from the Geotechnical and Structures Lab of the US Army Corps of Engineers, Engineer Research and Development Center to ensure that findings from this research are brought to bear on the US Army's soil mechanics and mobility programs. Transfer technology and simulation tools to USACE-ERDC

2. Summary of the most important results for this project

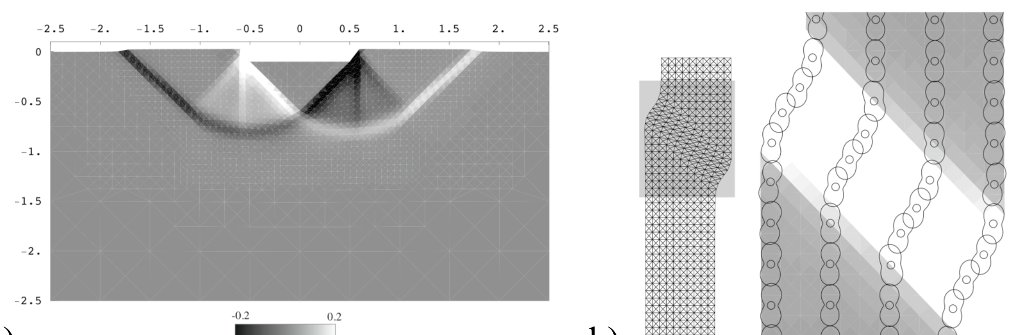
Under this project, our research group pioneered the development of a new breed of high-resolution micromechanical continuum models of granular materials – with experimentally proven predictive capabilities for emergent structures spanning the length scales from only a few particles through to the macroscopic scale of engineering systems and processes. This key breakthrough is underpinned by four disciplines of Mechanics, woven together for the first time into one complete methodology for constitutive model development: *Micromechanics* (the multiscale analysis of behaviour of heterogeneous media from the microscale to the observable macroscopic level); *Contact Mechanics* (the study of interaction between deformable solids in contact); *Thermomechanics* (the branch of Mechanics devoted to Thermodynamics); and *Micropolar or Cosserat Theory* (the study of continuum bodies whose kinematics and kinetics have been enriched by the addition of rotational degrees of freedom to each material point). The most advanced model developed by my research group has undergone a rigorous validation with benchmark experiments, and has delivered unprecedented predictive capabilities for any continuum model developed to date. More importantly, simulations encompassing half a million particles can be completed on a desktop PC within a few hours and can resolve critical failure mechanisms measuring 8-20 particles across in thickness. In dramatic contrast, discrete element simulations (where individual grains are modelled) currently take several months to complete a mere 10% of this number of particles on a supercomputer! *Thus, this new approach to constitutive model development could one day deliver predictive capabilities for material behaviour to within a length scale of a few particles at a fraction of the cost of discrete element simulations.* Reviews of papers containing this body of work have described this as a highly innovative approach at the cutting edge of international geomechanics research, and "*one of the very few which is making a serious attempt to bridge the gap between micromechanical studies of granular media and the application of continuum mechanics on the macro-scale*".

Specific advantages of these continuum micromechanical models and its novel aspects are:

- A correct level of resolution for capturing *emergent* fine-scale microstructures whose characteristic length scales are only a few particles wide, *e.g.* shear bands and force chains. In standard micromechanics theory, such microstructures are "smeared out" in the modelling process, as the averaging domain (representative volume element or 'RVE') in traditional homogenisation methods consists of many thousands of particles.
- A clear link between macro and micro behaviour is established. These new models have predictive capability of bulk behaviour, based on physical properties of the particles and their interactions (e.g. particle stiffness coefficients, coefficients of inter-particle rolling and sliding friction). This is in contrast with the great majority of continuum phenomenological models whose material parameters, which are obtained from "curve-fitting" analysis, have no direct physical meaning.
- Since these models have the same input material parameters as DEM models, direct comparisons could be made not just with experiments, but also with DEM simulations. This is

vital, given that DEM remains the surrogate for experimentation on internal microstructural mechanisms, while non-invasive experimental methods remain severely limited.

- The models developed within this framework are guaranteed to be thermodynamically viable. This eliminates the need for checking *a posteriori* that the models are objective and obey the laws of thermodynamics. Furthermore, because no additional constraints need to be introduced, the generalised constitutive relations describe the broadest possible range of thermodynamically admissible models.
- Experiments have shown that local fluctuations in both particle displacements and rotations bear a significant influence on the bulk behaviour of granular media – *even at low to moderate strains.* By appealing to the notion of "internal state variables", our thermomechanics based approach offers a rigorous method for the treatment of such local scale kinematic fluctuations, as well as other state variables, in a thermodynamically consistent manner.
- Conventional micromechanical models require, *a priori,* the evolution of anisotropies for input. The drawback of this approach is that it constrains the model to a predefined mode of deformation – effectively eliminating the emergence of novel anisotropies. In contrast, the proposed approach obviates the need for assumed evolution laws to be introduced into the model. Instead, more sophisticated contact laws are adopted, which enable the model to correctly predict the evolution of anisotropies. Thus, in our approach, the evolution of anisotropies becomes an output of, instead of an input to, the model.
- Enriched continuum models are more computationally efficient than DEM models. DEM simulations are limited by computer hardware. Currently, simulations are limited to a few million particles (roughly the equivalent of a handful of sand). Therefore, many engineering processes (e.g. soil-structure interaction problems) are beyond the reach of DEM analysis, while use of oversized particles to solve prototype scale problems leads to scaling errors in the solution. In fact, Peters has suggested that: *"Unless computing power reaches a point where there is a one-to-one correspondence between simulated particle size and actual particle size, some understanding of the DEM medium as a continuum will be needed."*.



a) b)

Figure 1: Predictive capabilities of micromechanical continuum models from macroscale to particle-scale behavior at the onset of failure: a) particle rotations under a punch indicating extent of plastic flow region and shear zones approximately 15 particles wide in an assembly of over half a million particles; b) region of strain localization or "shear band" approximately 8 particles wide in a specimen under biaxial compression (left), and angular contact force distributions inside the band (right).

3. Accomplishments

The theoretical innovation described above, and results stemming from it, have been reviewed and accepted for publication in world-leading journals in granular media mechanics, multi-scale modelling, and experimental and theoretical geomechanics research. There are now a total of 20 publications reporting on this body of work. In particular, the work in [15]-[17], [19] constitutes seminal contributions that has generated significant interest and is at the forefront of discussions in the field. Specifically, paper [19] presented the first high-resolution, micromechanical continuum model with predictive capabilities for critical internal structures of the order of a few particles in length scale, for example, the shear band, which is the precursor of failure. Paper [17] presented the first micromechanical continuum model that correctly captured the emergent evolution of particle contacts and force propagation inside the shear band – without need for any pre-defined "evolution laws". Previous continuum models assumed a priori evolution laws that constrained behaviour to a pre-defined mode of deformation, thus preventing the emergence of novel structures within the material. Papers [15]-[16] presented the first thermodynamics based formulation for micropolar materials, and comprising the micromechanical approach in [17],[19]. Since 2004, more and more complicating aspects of *real* particulates have been rigorously addressed using this new methodology, resulting in 15 other publications. The journals in which these publications appeared were carefully selected to ensure all aspects of the model development – from the mathematical analysis to the interpretation and use of experimental findings for model refinement and validation – were assessed by world leading specialists in these areas.

Reviews of papers indicate that this theoretical innovation is:

- *"one of the very few which is making a serious attempt to bridge the gap between micromechanical studies of granular media and the application of continuum mechanics on the macro-scale",*
- *"certainly at the cutting edge of international geomechanics research"*
- *"an innovative direction for modelling particulate systems"*
- *"should be very useful, enriching the knowledge of granular materials considerably"*

It has also been said to parallel recent developments on porous media, thereby proving the general applicability of these techniques in the Science of Complex Media and composites.

4. Technology Transfer

Our group has collaborated with Dr. John Peters of the Geotechnical Laboratory at ERDC on a number of projects relating to this grant. In addition to a number of joint publications with Dr Peters, technology transfer was achieved through various research visits and activities:

Some recent collaborative research visits and meetings attended with Peters

- Peters participated in the International Summer School and Workshop: GRANULAR MATTER. This school was co-organized by Tordesillas. Tordesillas and her students gave 4 presentations. Dr Peters presented a talk. Further details on this event, including the list of speakers, can be found in http://wwwrsphysse.anu.edu.au/granularmatter/
  Dec 3-8, 2006; Australian National University, Canberra, Australia
- Peters visited the Department of Mathematics and Statistics, University of Melbourne. November 26-December 3, 2006.
- Tordesillas and Peters participated and gave talks at the US National Congress of Theoretical and Applied Mechanics, June 2006, Colorado, USA
- Tordesillas gave a talk at the US Army Engineering Research and Development Centre Discrete Element Method Workshop organized by Peters, May 2006, Mississippi, USA.
- Tordesillas and Peters attended the *5th World Congress on Particle Technology*. Tordesillas gave a talk. April 2006, Florida, USA,

- Ms. Maya Muthuswamy (PhD student of Tordesillas) visited USACE-ERDC Geotechnical and Structures Laboratory, March-April, 2006.
- Tordesillas participated at the NASA-ARO Workshop on Granular Materials in Lunar and Martian Exploration on February 1-3, 2005, Cape Canaveral. Tordesillas gave an invited talk at the workshop and interacted with members of USACE-ERDC Cold Regions Research and Engineering Lab and also the Geotechnical and Structures Lab.
- Tordesillas visited USACE-ERDC Geotechnical and Structures Lab, July 3-6, 2005. The objective of this visit was twofold: (i) to present our research findings to members of staff at the GSL laboratory and (ii) to discuss ongoing projects that our group is conducting in collaboration with Dr John Peters.
- Ms. Maya Muthuswamy visited USACE-ERDC Geotechnical and Structures Lab, November 15, 2004 -January, 28, 2005. The objective of this visit was to continue collaborative research in micromechanics of granular media, in particular in the use of the Discrete Element Method (DEM) to investigate force propagation and failure mechanisms in granular assemblies.

5. Publications

Published papers in peer-reviewed journals

[1] Tordesillas, A#, Walsh, SDC and Muthuswamy, M (2007) "The role of mesoscale kinematics and nonaffine motion in the transition from particle to bulk mechanical properties" *Journal of Engineering Mechanics ASCE* (accepted).

[2] Muthuswamy M, Tordesillas A# (2006) "How do interparticle contact friction, packing density and degree of polydispersity affect force propagation in particulate assemblies?" *Journal of Statistical Mechanics – Theory and Experiment*, **P09003.**

[3] Walsh, SDC, Tordesillas, A# and Peters, JF (2007) "Development of micromechanical models for granular media: The projection problem", *Granular Matter* (in press).

[4] Gardiner, B and Tordesillas, A# (2006) "The effects of particle size distribution based on a 3D homogenisation scheme for micropolar media" *Powder Technology*, **161**, pp 110-121.

[5] Muthuswamy, M, Peters, JP, and Tordesillas, A# (2006) "Uncovering the secrets to relieving stress: discrete element analysis of force chains" *ANZIAM Journal*, **47**, pp C355-C372.

[6] Walsh SDC and Tordesillas, A# (2006) "Finite element methods for micropolar models of granular materials" *Applied Mathematical Modelling* , **30**, pp 1043-1055.

[7] Peters, JP, Muthuswamy, M, Wibowo, J, and Tordesillas, A# (2005) "Characterization of force chains in granular material" *Physical Review E*, **72** (4) :041307.

[8] Tordesillas, A# and Arber, D (2005) "Capturing the S in segregation: a simple model of flowing granular mixtures in rotating drums" *International Journal of Mathematical Education in Science and Technology,* **36**, pp 861-877.

[9] Gardiner, B and Tordesillas, A# (2005) "The link between discrete and continuous modelling of liquid foam at the level of a single bubble" *Journal of Rheology,* **49**, pp 808-819.

[10] Tordesillas, A#, Peters, JP and Muthuswamy, M (2005) "Role of particle rotations and rolling resistance in a semi-infinite particulate solid indented by a rigid flat punch" *ANZIAM Journal,* **46** (E) , pp C260-C275.

[11] Gardiner, B and Tordesillas, A# (2005) "Micromechanical constitutive modelling of granular media: evolution and loss of contact in particle clusters." *Journal of Engineering Mathematics*, **52**, pp 93-106.

[12] Walsh, SDC and Tordesillas, A# (2005) "A thermomechanical formulation of finite element schemes for micropolar continua" *ANZIAM Journal,* **46** (E), pp C336-C350.

[13] Tordesillas, A#, Peters, JF and Gardiner, B (2004) "Insights on 1D localisation theory and micromechanical constitutive laws" *Geotechnique*, **54**, pp 1-4.

[14] Gardiner, B and Tordesillas, A# (2004) "Micromechanics of shear bands" *International Journal of Solids and Structures*, **41**, pp 5885-5901.

[15] Walsh, SDC and Tordesillas, A# (2004) "A thermomechanical approach to the development of micropolar constitutive models for granular media" *Acta Mechanica,* **167** (3-4), pp 145-169.

[16] Tordesillas, A#, Walsh, SDC, and Gardiner, B (2004) "Bridging the length scales: micromechanics of granular media" *BIT Numerical Mathematics,* **44**, pp 539-556.

[17] Tordesillas, A#, Peters, JF, and Gardiner, B (2004) "Shear band evolution and accumulated microstructural development in Cosserat media" *International Journal for Numerical and Analytical Methods in Geomechanics,* **28**, pp 981-1010.

[18] Walsh, SDC and Tordesillas, A# (2004) "The stress response of a semi-infinite granular material subject to a normal point force at the boundary" *Granular Matter,* **6**, pp 27-37.

[19] Tordesillas, A# and Walsh, SDC (2002) "Incorporating rolling resistance and contact anisotropy in micromechanical models of granular media", *Powder Technology*, **124** (1-2), pp 106-111.

Book chapter

Tordesillas A, "Nonaffine deformations in deforming granular media" to Topical Volume series: "Lecture Notes in Complex Systems", Editors: Aste, T and Tordesillas A, Publisher: World Scientific.

Research Publications in Peer-Reviewed Conference Proceedings

[1] Tordesillas, A#, Walsh, SDC, Peters, JF, Bosko, J and Muthuswamy, M (2006) "Development of micromechanical models for granular media: kinematics and nonaffine motion", *Proceedings of the 5th World Congress on Particle Technology*. American Institute of Chemical Engineers, 18 pages, ISBN 0-8169-1005-7.

[2] Walsh, SDC and Tordesillas, A# (2006) "Injecting particle scale physics into continuum models of granular materials for large-scale applications" *Earth and Space 2006 Proceedings of the 10th ASCE Aerospace Division International Conference on Engineering, Construction and Operations in Challenging Environments.* Editors: RB Malla, WK Binienda, AK Maji. American Society of Civil Engineers, 10 pages, ISBN 0784408300.

[3] Muthuswamy, M and Tordesillas, A# (2006) "Multiscale analysis of the effects of changing gravity on stress propagation in a material subject to an indenting rigid flat punch" *Earth and Space 2006 Proceedings of the 10th ASCE Aerospace Division of International Conference on Engineering, Construction and Operations in Challenging Environments.* Editors: RB Malla, WK Binienda, AK Maji, 8 pages, ISBN 0784408300.

[4] Bosko, J and Tordesillas, A# (2006) " Evolution of Contact Forces, Fabric, and Their Collective Behavior in Granular Media under Deformation: a DEM Study" *Earth and Space 2006 Proceedings of the 10th ASCE Aerospace Division of International Conference on Engineering, Construction and Operations in Challenging Environments*. Editors: RB Malla, WK Binienda, AK Maji. ASCE, 8 pages, ISBN 0784408300.

[5] Tordesillas, A# and Walsh SDC (2005) "Analysis of deformation and localization in thermomicromechanical Cosserat models of granular media" in *Proceedings of the Fifth International Conference on the Micromechanics of Granular Media Powders and Grains 2005* Editors: Garc´ıa-Rojo, H.J., Herrmann & S. McNamara, R., A.A.Balkema, Rotterdam, **1**, Powders and Grains, pp 419-424, ISBN 041538348X.

[6] Gardiner, B#, Tordesillas, A and Peters JP (2003) “Incorporating microstructural evolution into micromechanically based continuum models of dry granular media” *Proceedings of the Workshop on the Quasi-Static Deformations of Particulate Materials* pp. 107-118.
[7] Walsh, SDC and Tordesillas, A# (2002) “Stranger than friction -Micromechanics of granular media”, *Proceedings, 14th International Conference of the ISTVS* **1**, pp 1-10.
[8] Tordesillas, A# and Shi, J (1999) “Stresses, flow and deformation of soils in contact with metallic and/or rubber-like bodies” *Proceedings, 13th International Conference of the ISTVS* **1**, pp 201-208.
[9] Tordesillas, A# and Hill, JM (1989) “Numerical comparison of pressure distributions for non-conforming line contact between circular elastic cylinders”, *Computational Techniques and Applications - 89' Proceedings*, pp 525-532.
[10] Tordesillas, A (1994) “A contact mechanics approach to the soil-tyre interaction problem”, *Proceedings, First North American Workshop on Modeling the Mechanics of Off-Road Mobility. Paper GL-94-30 U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi USA,* 4 pages.

Series Editor

Topical Volume series: “Lecture Notes in Complex Systems”, Editors: Aste, T and Tordesillas, A, Publisher: World Scientific

Papers in Review

[1] Tordesillas, A “Unjamming transitions in dense granular assemblies under biaxial compression” *Philosophical Magazine*, Date received by PM: April 7, 2007
[2] Muthuswamy, M and Tordesillas, A “Modelling the confined buckling of force chains” *Proceedings of the Royal Society of London Series A*, Date received by PRSL: April 29, 2007
[3] Liu, N and Tordesillas, A “Modelling of a Steady Fully-Developed granular flow down an inclined plane” *International Journal of Mathematical Education in Science and Technology,* Date received by IjMEST: March 15, 2007
[4] Walsh, SDC, Muthuswamy, M and Tordesillas, A “A definition of micropolar strain for non-affine deformation of granular media”, *Mechanics of Materials* Date received by MM: April 7, 2006

6. Invited Conference Presentations, Including Keynote Lectures

[1] Tordesillas, A “Unjamming transitions in densely packed granular systems” *DEM 07*, Aug 27-29, 2007, Brisbane, Queensland.
[2] Tordesillas, A and Muthuswamy, M “High resolution continuum models of large scale processes” *International Fine Particle Research Institute Annual General Meeting* Jul 8-12, 2007 Perth, Western Australia.
[3] Tordesillas, A “Mechanisms for energy dissipation in dense cohesionless granular assemblies: implications for shear banding interpreted as a bifurcation phenomenon.” *6th International Congress in Industrial and Applied Mathematics,* Jul 16-20, 2007; Zürich, Switzerland.
[4] Tordesillas, A “Challenges in modelling and simulation of soil-vehicle interaction systems” University of Alaska Fairbanks *ISTVS 2007 Conference (International Society for Terrain-Vehicle Systems)*, Jun 23-26, 2007, Fairbanks, Alaska, U.S.A.
[5] Tordesillas, A “Instabilities in Granular Systems” *International Workshop on Complex Mechanics*, May 1-3, 2007, Perth, Western Australia.
[6] Tordesillas, A "Across micro, to meso, to macro domains: forces, kinematics and energy" *Granular Matter: International Summer School and Workshop*, ANU (2006).

[7] Tordesillas, A and Liu N “On the Importance of Granular Materials Research for Martian and Other Planetary Exploration.” *6th Australian Mars Exploration Conference*. Oct 13-15, 2006; Melbourne, Australia

[8] Tordesillas, A “Role of mesoscale mechanics in the transition from particle to bulk mechanical properties of particulate media” *The Gordon Research Conference on Granular Flow*, Oxford UK (2006).

[9] Walsh, SDC, Tordesillas, A and Peters, JF “Implications of shear band micromechanics on the mathematical structure of constitutive relationships” *US National Congress of Theoretical and Applied Mechanics*, Colorado, USA (2006).

[10] Tordesillas, A and Peters, JF “Mathematical analysis of the micromechanics of shear bands” *US National Congress of Theoretical and Applied Mechanics*, Colorado, USA (2006).

[11] Tordesillas, A "Micromechanics: How is DEM used to answer fundamental questions about material behavior?" *US Army Engineering Research and Development Centre Discrete Element Method Workshop,* Mississippi, USA (2006).

[12] Tordesillas, A, Walsh, SDC and Peters, JF “Mesoscale mechanics” *5th World Congress on Particle Technology*, Florida, USA (2006).

[13] Muthuswamy, M and Tordesillas, A “Multiscale analysis of the effects of changing gravity on stress propagation in a material subject to an indenting rigid flat” *Earth and Space 2006; ASCE Aerospace Division International Conference on Engineering, Construction and Operations in Challenging Environments,* Texas, USA (2006).

[14] Tordesillas, A and Walsh, SDC “Injecting particle scale physics into continuum models of granular materials for large-scale applications” *Earth and Space 2006; ASCE Aerospace Division International Conference on Engineering, Construction and Operations in Challenging Environments,* Texas, USA (2006).

[15] Tordesillas, A and Walsh, SDC “Deformation and localisation in thermomicromechanical Cosserat models of granular materials”, *Powders and Grains 05,* Stuttgart, Germany (2005).

[16] Tordesillas, A “Towards modelling granular-machine/vehicle/structure interaction systems” *Inaugural Workshop on Granular Materials in Lunar and Martian Explorations*, NASA JF Kennedy Space Centre, USA (2005).

[17] Tordesillas, A “Micromechanics of shear bands” *International Workshop on Bifurcation, Instabilities and Degradation in Geomechanics*, Crete, Greece (2005). (unable to attend)

[18] Tordesillas, A “Understanding a granular material as a continuum” *The Mathematics and Mechanics of Granular Media symposia, 5th International Congress on Industrial and Applied Mathematics*, Sydney, Australia (2003).

[19] Tordesillas, A “Bridging the length scales: Micromechanics of granular media”, *Keynote Lecture International Conf. on Scientific Computation and Differential Equations SciCADE’ 03*, Trondheim, Norway (2003).

[20] Tordesillas, A “The anatomy of failure in particulate media” *Advanced Problems in Mechanics 2003: Institute for Problems in Mechanical Engineering of the Russian Academy of Sciences*, St. Petersburg Russia (2003). (unable to attend)

7. Conference Presentations on Research

[21] Walsh, SDC and Tordesillas, A “A patchwork continuum for granular media” *ANZIAM 06,* Victoria, Australia (2006).

[22] Olshina, N and Tordesillas, A “Squashing sand: high-resolution comparison between experiment and simulation” *ANZIAM 06,* Victoria, Australia (2006).

[23] Muthuswamy, M and Tordesillas, A “Getting unstuck in microgravity: analysis of granular materials for lunar and Martian exploration” *ANZIAM 06,* Victoria, Australia (2006).

[24] Cole, S and Tordesillas, A "Body piercing by Cosserat" *ANZIAM 06,* Vic, Australia (2006).

[25] Bosko, J and Tordesillas, A "Statistical analysis and correlations of microstructure in jammed granular materials" *ANZIAM 06,* Victoria, Australia (2006).

[26] Liu, N and Tordesillas, A "Surviving a Martian Avalanche: Granular Flows Down a Bumpy Incline" *ANZIAM 06,* Victoria, Australia (2006).

[27] Muthuswamy, M and Tordesillas, A "Uncovering the secrets to relieving stress: discrete element analysis of force chains" *Engineering Mathematics and Applications Conference EMAC 05,* Victoria, Australia (2005).

[28] Walsh, SDC and Tordesillas, A "Large deformation modelling of granular materials" *ANZIAM 05,* Napier, New Zealand (2005).

[29] Walsh, SDC and Tordesillas, A "Mesoscopic simulations of contact problems involving Cosserat continua" *Computational Techniques and Applications Conference CTAC05,* Victoria Australia (2005).

[30] Gardiner, B and Tordesillas, A "Role of particle rotations revealed through discrete and continuum simulations of particulate solids" *Computational Techniques and Applications Conference CTAC05,* Victoria Australia (2005).

[31] Walsh, SDC and Tordesillas, A "Sandy Feet: Coming in contact with granular media." *ANZIAM 04,* Hobart, Australia (2004).

[32] Walsh, SDC and Tordesillas, A "A thermomechanical approach to the modelling of micropolar media" *International Congress on Industrial and Applied Mathematics ICIAM03,* Sydney, Australia (2003).

[33] Arber, D and Tordesillas, A "Separating salt and pepper: axial segregation of granular media" *International Congress on Industrial and Applied Mathematics ICIAM03,* Sydney, Australia (2003).

[34] Gardiner, B and Tordesillas, A "Granular disorder and localisation" *International Congress on Industrial and Applied Mathematics ICIAM 03,* Sydney, Australia (2003).

[35] Muthuswamy M, Arber D and Tordesillas A "Adventures with the shear band" *International Congress on Industrial and Applied Mathematics ICIAM03,* Sydney, Australia (2003).

[36] Gardiner, B and Tordesillas, A "Incorporating microstructural evolution into micromechanically-based continuum models of dry granular media" *Workshop on the Quasi-Static Deformations of Particulate Materials QuadMP03 ,* Budapest, Hungary (2003).

[37] Gardiner, B and Tordesillas, A "Gross slippery sand" *ANZIAM 02,* Canberra, Australia (2002).

8. Selected Invited Lectures and Seminars on Research

[38] Tordesillas, A "*Can you see the continuum in the discrete? An analysis of granular behaviour across micro, meso and macro domains*" A series of five lectures delivered at the School of Civil Engineering, Purdue University, USA (2006).

[39] Tordesillas, A "*Micromechanics: the driving force in materials science*" School of Mathematics and Statistics, University of Sydney (2005).

[40] Muthuswamy, M and Tordesillas, A "*Powder fingers rock lunar and Martian exploration!*" Department of Mathematics and Statistics, University of Melbourne, Special Lecture (2005).

[41] Walsh, SDC and Tordesillas, A "*Micromechanics of granular media*" Particulate Fluids Processing Centre Seminar Series, University of Melbourne (2005).

[42] Tordesillas, A and Muthuswamy, M "*Granular complexities: from everyday materials to the extraterrestrial kind*" The ARC Centre of Excellence for Mathematics and Statistics of Complex Systems (MASCOS) colloquium, University of Melbourne (2005).

[43] Tordesillas, A "*What is achievable today in multiscale continuum modelling?*" The Australian Research Council Centre for Complex Open Systems Network (COSNet) colloquium, Australian National University (2005).
[44] Tordesillas, A and Muthuswamy, M "*Is a pile of sand simple or complex?*" The University of Melbourne Engineering and Science Seminar Series (2005).
[45] Walsh, SDC and Tordesillas, A "*Granular Matter: Why it matters.*" Possibilities in Mathematics and Statistics Lecture Series, University of Melbourne (2003).
[46] Tordesillas, A, Muthuswamy, M, Arber, D and Walsh, SDC "*The 5th State of Matter*" The University of Melbourne School Mathematics Competition (2002).
[47] Tordesillas, A "*Improving predictive capabilities of computer models of soil compaction*" Faculty of Engineering and Surveying Colloquium, Univ. Southern Queensland (2002).

9. Recent conference organizing committees

[1] Granular Matter: International Summer School and Workshop, ANU, Dec 4-8, 2006
[2] Invited Speakers Committee Member, ANZIAM 2006, annual conference of the Australian and New Zealand Industrial and Applied Mathematics society, Feb 5-9, Mansfield, Australia.
[3] Co-chair, Numerical and Experimental Modeling of Lunar and Martian Soil Simulants, Earth & Space 2006

10. National Committees and Memberships

2005- National Committee for the Mechanical Sciences, Australian Academy of Science
2002-2004 Chair, Executive Committee Victoria Branch, ANZIAM Society

11. International Committees and Memberships

2008 Member of the Gordon Research Conference, Scientific Advisory Committee
2006 Nominated to the Granular Mechanics Committee, American Society of Civil Engineers
2006- Nominated to the Geomechanics Committee, American Society of Mechanical Engineers
2005- Member of NASA Grains Research
1998- Member of the International Society for Terrain-Vehicle Systems

12. Research supervision

(a) Research Supervision - Postdoctoral Research Fellows

2007 Dr Jingyu Shi (Senior Research Associate; PhD in Mathematics)
2006 Dr Stuart Walsh (Senior Research Associate; PhD in Applied Mathematics)
Project Title: *Micromechanical analysis of instabilities due to buckling of force chains*
2005-2008 Dr Jaroslaw Bosko (Senior Research Associate; PhD in Materials Science)
Project Title: *Discrete element analysis and statistical mechanics of jamming transitions*
2005 Dr Con Lozanovski (Research Assistant; PhD in Statistical Mechanics)
Project Title: *Higher order analysis of micropolar media*
2001-2004 Dr Bruce Gardiner (Senior Research Associate; PhD in Physics of Complex Media)
Project Title: *Micropolar/Cosserat theory for complex media*

(b) Research Supervision- Students Graduated

2006 Stuart Walsh (PhD)
Project Title: *A thermomechanical approach for micromechanical continuum models of granular media*
2006 Shaun Cole (Honours)
Project Title: *Higher order thermomicropolar models of granular media*
2004 Rick Webb (Honours)

	Project Title: *Analysis of granular-solid contact systems*
2003	Matthew Wightwick (Honours)
	Project Title: *Modelling of granular segregation in rotating drums*

(c) Research Supervision - Current Postgraduate Students

2005-2008	Maya Muthuswamy (PhD)
	Project Title: *A combined discrete element and continuum approach to the study of densely packed granular assemblies*
2007	Steve McAteer (Honours)

(d) Research Supervision - Undergraduate Students

2007	David Rafferty (3rd year)
	Sudhir Raskutti (3rd year)
	Ray Zhang (3rd year)
2006	Nana Liu (1st year, Science)
2005	Hussein Hafez (4th year, Combined Software Engineering and Science)
	Noam Olshina (4th year, Combined Mechanical Engineering and Science)
	Omar Shum (3rd year Science, 5th year Medicine)
2004	Maya Muthuswamy (4th year, Combined Software Engineering and Science)
2003	Shun Yip (3rd year, Combined Mechanical Engineering and Science)
	Damian Zammit (2nd year, Combined Commerce and Science)
2002	Cecilia Ross (2nd year, Combined Civil Engineering and Science)
	Daniel Arber (2nd year, Combined Mechanical Engineering and Science)

(e) Research Supervision - Vacation Scholar Students

2007	Tessa Dawn Satherley
	Steve McAteer
	Nana Liu