

**ADVANCES
IN THE MECHANICS
AND THE FLOW OF
GRANULAR MATERIALS**

VOLUME II



*Mohsen Shahinpoor, Editor
Granular Materials Research Laboratory
Clarkson College of Technology
Potsdam, New York 13676, USA*

FIRST EDITION 1983



TRANS TECH PUBLICATIONS

CONTENTS

PREFACE	XXV
LIST OF CONTRIBUTORS	XXVII
RANDOM PACKING OF GRANULAR MATERIALS	
I – DEFINITION OF DENSE RANDOM PACKING	
J. G. Berryman	
1. Abstract	1
1. Introduction	1
2. Nearest-Neighbor Definition	3
3. Rigid Spheres	6
4. Rigid Disks	10
5. Discussion and Conclusions	14
6. Acknowledgments	15
7. References	15
II – STRUCTURE AND PROPERTIES OF GRANULAR MATERIALS: GUIDELINES FROM MODELLING STUDIES OF LIQUIDS AND AMORPHOUS SOLIDS	
J. L. Finney	
1. Introduction	19
2. Laboratory Models: Dense and Loose Packings	21
3. Sequential Computer Construction Methods	25
4. Collective Rearrangements	26
4.1 – Gas Compression Methods	28
4.2 – Molecular Dynamics	28
5. Methods of Structural Characterization	29
6. Modeling Multicomponent Systems	33
7. References	37
III – RANDOM STRUCTURE OF PARTICLE ASSEMBLIES AND PHYSICOCHEMICAL PROPERTIES OF LIQUIDS	
K. Gotoh	
1. Abstract	41

1. Introduction	41
2. Simplified Approach to Physicochemical	41
3. Spatial Structure of Equal Spheres in Random Assembly	46
3.1 – Average Nearest-Neighbor Spacing	46
3.2 – First-Layer Neighbors	47
3.3 – Coordination Number	50
4. Concluding Remarks	51
5. References	51

**IV – A NEW STATISTICAL STANDPOINT OF THE
PARTICLE PACKING STRUCTURE OF POWDER
RANDOM PARTICLE SYSTEM**

K. Makino and J. Hidaka

I. Abstract	53
II. Introduction	54
1. Modeling of Powder Random Particle System	55
1.1 – Case Where Component Powder Particles Make a Steady Random Movement	56
1.2 – Case Where Component Particles are in Stationary State	56
2. Particle Density Original Wave of Powder Random Particle System	57
2.1 – Relation Between Particle Density Around Specified Particle and That on Z-Plane	58
2.2 – Representation on Z-Plane of Radial Periodicity of Particle Density Around Specified Particle	60
2.3 – Relation Between Particle Density Original Wave Function and Particle Density Around Specified Particle	62
3. Estimation and Validity of Radial Distribution Function by This Model	65
3.1 – Case of One-Component Powder Random Spherical Particle System	65
3.2 – Case of One-Component Powder Random Spherical Particle System (Dispersion System)	67
4. Conclusion	71
5. References	72

V – COMMENTS ON SOME TYPES OF RANDOM PACKING

E. M. Tory and W. S. Jodrey

I. Abstract	75
1. Introduction	76
2. Random Placement of Points in R^n	76
2.1 – Distribution of k th Nearest Neighbors	77

3.	Random Packing of Hard Rods	79
3.1	– Equilibrium Distribution of Hard Rods	79
3.2	– Random Sequential Packing of Hard Rods	80
4.	Random Sequential Packing in R^n	82
4.1	– Packing of Squares, Cubes, and Hypercubes	82
4.2	– Random Placement of Disks	87
4.3	– Random Placement of Spheres	89
5.	Gravitational Packing	91
5.1	– Pure Gravitational Packing of Equal Disks	92
5.2	– A Markov Chain Approach to Sequential Gravitational Packing	92
6.	Cooperative Models for Dense Random Packing	101
7.	Acknowledgment	101
8.	References	102

GRANULAR MATERIALS MORPHOLOGICAL CHARACTERIZATION AND MEASUREMENTS

VI – THEORY AND APPLICATIONS OF MORPHOLOGICAL ANALYSIS **J. K. Beddow**

1.	Table of Contents	107
I.	Purpose of Morphological Analysis	108
II.	Theory of Morphic Descriptors	109
III.	Experimental	110
IV.	Applications	113
A.	General	113
B.	Relating the Mode of Origin of Particles to the Morphology ..	114
C.	On Relating Particle Behavior to Morphology	116
D.	Materials Processing and Morphology	119
E.	Textural Analysis	119
V.	Future Developments	121
VI.	References	125

VII – ON CERTAIN GEOMETRIC CHARACTERISTICS OF A SINGLE CONVEX GRAIN **Jakub Bodziony and Wladyslaw Kraj**

I.	Abstract	129
1.	Introduction	129
2.	Equivalence of Feret's Diameter and the Total Mean Curvature of a Grain	131
3.	Natural Characteristics of the Size and Shape of a Grain	132

4. The Projection Method	134
4.1 – Surface Area of a Grain	134
4.2 – The Total Mean Curvature of a Grain	141
5. The Section Method of Determining the Numerical Characteristics of The Geometric Structure of a Granular Material	142
6. Final Remarks	145
7. References	146

VIII – UNDERSTANDING OF THE MICROSTRUCTURE

OF SINTERED MATERIALS

J. L. Chermant, M. Coster, and J. P. Jernot

I. Abstract	157
1. Introduction	157
2. Development of the Model	157
2.1 – Change in the Specific Surface Area Per Unit Volume of Material	157
2.2 – Change in the Specific Surface Area Per Unit Weight of Material	161
2.3 – Establishment of the Relationship Between the Mean Free Path in the Porous Phase and the Normalized Density	163
3. Semi-Theoretical Evaluation of the Model	164
4. Experimental Results	167
5. Discussion	170
6. Conclusion	176
7. References	176

IX – CHARACTERIZATION OF POROUS MATERIALS USING

MERCURY POROSIMETRY

J. Kloubek

1. Introduction	170
2. Parameters of Washburn Equation	181
3. Methods of θ_A Determination	182
4. Hysteresis Phenomena	183
5. Characteristics of Pores Based on Contact Angles	186
6. Conclusions	189
7. References	190

X – RECENT DEVELOPMENTS IN MERCURY POROSIMETRY

S. Lowell and J. E. Shields

I. Abstract	193
1. Introduction	193

2. Intrusion-Extrusion Hysteresis	194
3. Pore Potential	196
4. Equivalency of Mercury Porosimetry and Gas Adsorption	199
5. Contact Angle	202
6. Instrumental Methods	202
7. References	205

XI - RECENT ADVANCES IN PARTICLE SIZE MEASUREMENT**Clyde Orr**

I. Abstract	207
1. Introduction	207
2. Photon Correlation Spectroscopy	207
3. Light Scattering	209
3.1 - Single Particles	210
3.2 - Multiple Particles	210
4. Hydrodynamic Chromatography (HDC)	212
4.1 - Column	214
4.2 - Capillary	215
5. Field-Flow Fractionation	215
6. Ferrographic Analysis	216
7. Centrifugal Sedimentation	216
8. Coulter Counter (LPS)	217
9. References	218

**XII - TOPOGRAPHY OF COMPRESSED
AND NON-COMPRESSED PARTICULATE SOLIDS****N. G. Stanley-Wood**

1. Introduction	221
1.1 - Fluid Bonds in a Porous Media	221
1.2 - Flow of Fluids Through Porous Media	221
1.3 - Stereological Measurements	222
1.4 - Topography of Granules or Particulate Solids	222
2. Mesopore Space Distribution	223
2.1 - Porous Matrix Models	223
2.2 - Pore Space Characterization	229
2.3 - Adsorption and Desorption Capillary Condensation Equations	227
2.4 - Non-Porous t-Curves	232
2.5 - Adsorption on Porous Surfaces	235
3. Micropore Space Distributions	239
4. Mercury Porosimetry	241
5. References	244

XIII - POROSITY AND PORE SIZE DURING CERAMIC PROCESSING
O. J. Whittemore

I. Abstract	249
1. Introduction	249
2. Particle Size, Distribution and Shape	250
3. Compaction	251
4. Other Forming Methods	252
5. Firing	253
6. Sintering	254
7. Summary	255
8. Acknowledgments	255
9. References	256

**GENERAL STATISTICAL/MECHANICAL CONSIDERATION
IN GRANULAR MATERIALS****XIV - STATISTICAL MECHANICS OF GRANULAR MATERIALS**
B. F. Backman, C. B. Brown, P. W. Jowitt, and J. Munro

I. Abstract	259
1. Objective	259
2. Maximum Entropy Principle	260
3. Theoretical Model	261
4. Kinematic and Packing	262
4.1 - Volume and Relative Approach	262
4.2 - Porosity	263
4.3 - Packing	265
5. Dynamics	265
5.1 - Relative Approach and Contact Force	265
5.2 - Internal and External Forces	266
5.3 - Incremental Bulk Modulus	266
6. Application: Speed of Sound	267
7. Evidence and Discussion	268
7.1 - Random Heap Evidence	268
7.2 - Natural Granular Material Evidence	270
8. Future Studies	270
9. References	271

**XV – MACROSCOPIC AND MICROSCOPIC DESCRIPTIONS
OF THE MECHANICS OF GRANULAR MATERIALS**
Ken-Ichi Kanatani

1. Abstract	273
1. Introduction	273
2. Macroscopic Plasticity Approach	273
2.1 – The Associated Flow Rule for Granular Materials	273
2.2 – Plastic Deformation of Dilatant Materials	275
3. Microscopic Statistical Approach	276
3.1 – The Stress, Strain and the Particle Contacts	276
3.2 – The Flow of Particles	278
4. The Use of Entropy in the Description of a Packing State	281
5. References	281

**XVI – APPLICATION OF MARKOV PROCESS TO MECHANICS
OF SOIL AND GRANULAR MATERIAL**
R. Kitamura

1. Abstract	285
1. Introduction	285
2. Markov Process and Its Application to Mechanical Behaviours of Granular Material	286
2.1 – Markov Process	286
2.2 – Application to Shearing and Compression Behaviours of Granular Material	287
2.3 – Application to Permeability for Granular Material	293
2.4 – Application to Consolidation Behaviour of Granular Materials	295
3. Conclusions	295
4. References	296

**XVII – SOME RECENT RESULTS ON THE BEHAVIOR
OF GRANULAR MATERIALS**
M. Shahinpoor

I. Abstract	297
1. Introduction	297
2. Entropy Maximization	305
3. Granular Phase Equilibria and Transitions	308
4. Rapid Granular Flow With Friction and Inelasticity	313
5. Dynamics of Planetary Granular Rings	317
6. Acknowledgments	320
7. References	321

ELECTROMAGNETIC, THERMAL, AND GENERAL TRANSPORT PROPERTIES OF GRANULAR MATERIALS
XVIII – MECHANICS OF SEPARATING PARTICULATE SOLIDS IN LIQUID DIELECTRICS AND MAGNETICS
U. Ts. Andres

I. Abstract	331
1. Separation of Particulate Solids in Stressed Liquid Media	331
2. Dielectric Separation	334
2.1 – Behaviour of Solid Particles in Electric Field	334
2.2 – Dielectric Precipitation Processes of Mineral Separation	338
2.3 – Dielectrophoretic Process of Mineral Separation	340
3. Magnetohydrostatic Separation	344
3.1 – Behaviour of Solid Particles in Liquid Magetics Permeated by Magnetic Field	344
3.2 – Stages of Development of MHS Separation	346
3.3 – Development of Commercial Version of MHS Separation	347
4. References	352

XIX – DYNAMICS OF AN ELECTRIC (PARTICULATE) SUSPENSION
G. M. Colver

I. Abstract	355
1. Introduction	355
2. Single Particle Phenomena	356
2.1 – Comments on Single Particle Phenomena	363
3. Multiparticle Phenomena	365
3.1 – Comments on Multiparticle Phenomena	371
4. Acknowledgments	371
5. References	372

XX – RHEOLOGICAL AND MAGNETIC PROPERTIES IN RECORDING MATERIALS
A. R. Corradi

I. Abstract	375
1. Introduction	375
2. Production Processes for Magnetic Iron Oxides	382
2.1 – Yellow Iron Oxides Preparation: Precursors for $\gamma\text{-Fe}_2\text{O}_3$ Production	382
2.2 – Conversion to Magnetic Materials	383
2.3 – Densification	384
2.4 – Cobalt Adsorbed Materials	384
2.5 – Metallic Particles	385

3. The Influence of Some Production Parameters Related to the Rheological Properties	386
3.1 – Thixotropy and Viscosity During Yellow Oxide Preparation	386
3.2 – The Effect of Reduction Temperature	387
3.3 – Effect of Antisintering Agents	389
3.4 – Effect of Powder Density	391
4. Effect of the Granular Nature of the Powders	395
5. Conclusions	396
6. Acknowledgments	397
7. References	397

**XXI – CHARACTERIZATION OF SOME RETENTION
AND TRANSFER PROPERTIES OF GRANULAR MATERIALS
IN RELATION WITH GEOMETRICAL AND LIQUID PROPERTIES**

L. W. de Backer

I. Abstract	399
1. Introduction	399
2. Geometrical Characteristics of the Porous Media	400
2.1 – Determination of the Grain and Pore Size	401
2.2 – Coefficients of Similitude	402
3. Water Retention and Geometrical Properties	403
4. Liquid Transfer and Geometrical Properties	405
4.1 – Penetration Coefficient	406
4.2 – Diffusivity Coefficient	407
4.3 – Conductivity Coefficient	409
5. Conclusion	410
6. References	411

**XXII – TRANSPORT PROPERTIES OF TWO-PHASE
COMPOSITE MATERIALS**

R. C. McPhedran, D. R. McKenzie, and N. Phan-Thien

I. Abstract	415
1. Introduction	415
2. The Scalar Transport Coefficient	417
2.1 – Two-Dimensional Composites	419
2.2 – Three-Dimensional Composites	438
2.3 – Some Applications	451
3. The Vector Transport Problem	458
3.1 – General Results	460
3.2 – Third-Order Microstructural Parameters	464
3.3 – Nearly-Touching Arrays	466
3.4 – Bounds on Effective Moduli	467

4. Conclusions	476
5. Acknowledgments	476
6. References	477

**GRANULAR MATERIALS RAPID FLOWS, GENERAL DYNAMICS,
AND FLUIDIZATION**

**XXIII – GENERALIZED CONTINUUM THEORY FOR FLOW
OF GRANULAR MATERIALS**
G. Ahmadi

I. Abstract	497
1. Introduction	497
2. Basic Equations	498
3. Constitutive Equations for Rapid Flows	504
4. Equations of Motion	507
5. Plane Shear Flows	509
6. Conclusions	522
7. References	523

**XXIV – FLUID MECHANIC CHARACTERISTICS
OF BUBBLING FLUIDIZED BEDS**

A. Bar-Cohen

I. Abstract	529
1. Introduction	529
2. Theory of Bubbling Beds	530
3. Theoretical Bounds for Bubble Fraction	533
3.1 – Slow Bubble Regime	533
3.2 – Fast Bubble Regime	535
4. Prediction of Bubble Diameter	539
4.1 – Analysis	539
4.2 – Comparison With Data	539
4.3 – Modified Darfon Formulation	540
5. Tube/Bubble Interactions	546
5.1 – Qualitative Description	546
5.2 – Quantitative Description	548
6. Closure	548
7. Acknowledgment	549
8. References	549

XXV – ADVANCES IN THE FLUIDIZATION OF COARSE PARTICLES
D. Geldart

I. Abstract	553
1. Introduction	553

2. What Are Coarse Particles	553
3. General Fluidization Characteristics of Coarse Particles	555
4. Recent Studies with Coarse Particles	555
4.1 - Segregation by Size	555
4.2 - Entrainment and Elutriation	559
4.3 - Fluidized Discharge of Coarse Solids	561
5. Conclusions	562
6. References	563

XXVI - THE FLOW OF SOLID PARTICLES IN AN AERATED INCLINED CHANNEL

M. Ishida and H. Hatano

1. Abstract	565
1. Introduction	565
2. Experimental	565
2.1 - Effects of Gas Velocity and Slope of the Channel	566
2.2 - Effect of Layer Height	567
2.3 - Classification of Flow Types	567
2.4 - Bulk Density of Particles in the Flow	569
2.5 - Variational Analysis	569
3. Conclusions	572
4. Appendix: Velocity Distribution to Make the Integral J-Minimum	
A.1 - Newtonian Fluid	573
A.2 - Bingham Fluid	574
A.3 - Particles	574
5. Nomenclature	575
6. References	575

XXVII - SOME MATHEMATICAL MODELS OF SNOW AVALANCHES

E. Margarita Egli

1. Introduction	577
2. Governing Equations	577
3. Numerical Results	581
3.1 - The Influence of Slope Curvature	581
3.2 - Changing of Friction Law at Stopping	582
3.3 - Replacement of Turbulent Friction by Laminar Friction	582
3.4 - Effect of Involving Additional Parts of Snow from the Slope	583
4. Equations for the Two-Layer Models	583
5. References	588

**XXVIII – SIMULATION OF SOLID PARTICLE MOTION
IN TURBULENT GAS-SOLID PIPE FLOW
AND RELATED TOPICS**
H. Masuda, H. Yoshida, and K. Iinoya

I. Abstract	589
1. Simulation of Coarse-Particle Motion	589
2. Simulation of Fine-Particle Motion	591
3. Further Comments on the Calculations of Particle Trajectories ..	595
4. Nomenclature	597
5. References	599

**XXIX – ON THE STATISTICAL APPROACHES TO THE DYNAMICS
OF FULLY FLUIDIZED GRANULAR MATERIALS**
S. Ogawa

I. Abstract	601
1. Introduction	601
2. Inelastic Binary Collision of Spherical Granular Particles	602
3. Boltzmann Equation for Granular Particles	605
4. Monte Carlo Method	606
5. Results and Discussions	608
6. Conclusions	611
7. Acknowledgment	612
8. References	612

XXX – ON SHEAR FLOW OF COHESIONLESS GRANULAR MATERIALS
T. Scheiwiller and K. Hutter

I. Abstract	613
1. Introduction	613
2. The Boundary Value Problem	615
3. Numerical Solution Procedure	618
4. Numerical Values	619
5. Discussion of Results	620
5.1 – Variation of the Coefficient of Restitution	620
5.2 – Variation of the Inclination Angle	624
5.3 – Variation of the Sliding Conditions	625
5.4 – Variation of the Particle Size and the Parameter P	633
6. Conclusions	636
7. Acknowledgment	638
8. References	638

**XXXI – A KINETIC THEORY FOR THE RAPID FLOW
OF ROUGH IDENTICAL SPHERICAL PARTICLES
AND THE EVOLUTION OF FLUCTUATIONS**
M. Shahinpoor and G. Ahmadi

I. Abstract	641
1. Introduction	641
2. Governing Kinetic Equations	644
3. Detail of a Binary Collision of Rough Inelastic Particles	647
4. An Iterative Solution for the Distribution Function	653
5. Shear and Gravity Flows of Granular Materials	657
5.1 – Simple Gravity Flow Down an Inclined Plane	659
5.2 – Simple Shear Flows: Plane Couette Flows	662
6. Acknowledgment	664
7. References	665

**XXXII – GEOMETRICAL FOUNDATION OF THE ANALYSIS
OF GRANULAR MATERIALS FLOWS**
M. Shimbo

I. Abstract	669
1. Introduction	669
2. Material Space-Time	669
3. Asymmetric Fields in Flow	670
4. Concluding Remarks	672
5. References	672

XXXIII – DYNAMIC INTERACTIONS OF GRANULAR MATERIALS
S. L. Soo

I. Abstract	675
1. Introduction	676
2. Fraction Impacted	677
3. Collision of Elastic Spheres	678
4. Transfer of Momentum	681
5. Heat Transfer	684
6. Erosion and Attrition	687
6.1 – Ductile Mode	688
6.2 – Brittle Mode	689
7. Charge Transfer	693
8. Concluding Remarks	696
9. References	697

XXXIV - DEBRIS FLOW AND DEBRIS FLOW DEPOSITION**T. Takahashi**

1. Introduction	699
2. Criteria for Occurrence of Various Types of Sediment Transport ..	699
3. Mechanics of Quasi-Steady Debris Flow	702
3.1 - Process of Formation	702
3.2 - Velocity Distribution and the Front Translation	703
3.3 - Mechanics of Accumulation of Boulders at Front of Debris Flow	703
3.4 - Mechanics of Transportation of Huge Stones	706
3.5 - Roll Waves	707
4. Deposition of Debris Flow	708
4.1 - Stoppage Mechanism	708
4.2 - The Debris Cone Formation Process	711
5. Sediment Gravity Flow on Flatter Slope and the Erosion of Debris Cone	713
5.1 - Mechanics of Sediment Gravity Flow	713
5.2 - Erosion of Debris Cone by a Flood Flow	714
6. Concluding Remarks	717
7. References	717

XXXV - RHEOLOGY OF POWDER SYSTEMS**K. Umeya**

I. Abstract	719
1. Packing Character of Powder Liquid Systems	719
2. Construction Equations and Rheological Models Corresponding to the Every Stage of Table 1	722
3. Rheological Properties in Slurry Systems	724
3.1 - Flow Pattern in Steady and Transient States	724
3.2 - Normal Stress Effect of Suspensions	728
4. Some Rheological Problems in the Powder System	729
4.1 - Deformation Pattern (Stress-Strain Diagram)	730
4.2 - Determination of Rheological Properties of a Packed Bed ..	731
5. Some Rheological Problems in the Mud System	738
5.1 - Relation Between an Axial and a Radial Pressure in the Extruding Procedure	739
5.2 - Consideration of Liquid Content Abnormality from the Concept of Rankine's Coefficients	741
6. Conclusions	743
7. References	743

MECHANICS OF GRANULAR MATERIALS AND SOILS**XXXVI - AN ELASTIC-PLASTIC ISOTROPIC CONSTITUTIVE MODEL FOR SAND****G. Y. Baladi**

I. Abstract	745
1. Introduction	745
2. Constitutive Model	746
2.1 - Elastic Behavior	746
2.2 - Plastic Behavior	747
3. Comparisons of Laboratory Test Data with Model Behavior	750
3.1 - Experimental Program	750
3.2 - Material Constants	750
3.3 - Correlation with Test Results	753
4. Model Predictions	753
5. References	759

XXXVII - MECHANICAL BEHAVIOR OF SOILS DESCRIBED BY HYPOELASTICITY EQUATIONS**L. Dragusin**

1. Introduction	761
2. Some Basic Concepts of Soil Mechanics	761
3. Motion Equations	764
4. Constitutive Equations	767
5. Comparison Between Theoretical Results and Experimental Data	774
6. References	777

**XXXVIII - A DISCRETE LIMIT ANALYSIS
OF FOUNDATION STRUCTURES****T. Kawai and N. Takeuchi**

I. Abstract	779
1. Nomenclature	779
2. Introduction	780
3. Theoretical Basis of New Discrete Model	781
4. Convergency of the RBSM Solutions	790
5. No-Tension and Tension Crack Analysis of Soil and Rock Foundations	793
6. Conclusion	808
7. Acknowledgments	808
8. References	808

XXXIX – DEFORMATION AND STRENGTH OF GRANULAR MATERIALS BASED ON THE THEORY OF “COMPOUNDED MOBILIZED PLANES” (CMP) AND “SPATIAL MOBILIZED PLANE” (SMP)
H. Matsuoka

I. Abstract	813
1. Microscopic Analysis of Shear Deformation of Granular Materials	813
1.1 – Introduction	813
1.2 – Relationship Between Shear-Normal Stress Ratio (τ/σ_N) Potential Sliding Plane and Average Interparticle Contact Angle ($\bar{\theta}$)	814
1.3 – Relationship Between Shear Strain (γ) and Normal Strain (ε_N) on Potential Sliding Plane, and Average Interparticle Contact Angle ($\bar{\theta}$)	816
1.4 – Basic Stress-Strain Relationship on Potential Sliding Plane ..	820
2. Concept of “Compounded Mobilized Planes” (CMP) and “Spatial Mobilized Plane” (SMP)	823
3. Stress-Strain Relationship Based on the Theory of “Compounded Mobilized Planes” (CMP)	824
4. Stress-Strain Relationship and Failure Criterion Based on the Theory of “Spatial Mobilized Plane” (SMP)	828
5. Analysis of Anisotropy in Granular Materials	832
5.1 – Failure Criterion for Anisotropic Soil	832
5.2 – Analysis of Deformation for Anisotropic Soil	833
6. References	835

XXXX – DEFORMATION AND STRENGTH OF GRANULAR MATERIALS BASED ON THE EXTENDED THEORY OF “SPATIAL MOBILIZED PLANE”, (SMP)
T. Nakai and H. Matsuoka

I. Abstract	837
1. Stress-Strain Relationship Based on the Extended Theory of “Spatial Mobilized Plane” (SMP*)	837
2. Constitutive Equation for Soils Based on the Extended Theory of “Spatial Mobilized Plane” (SMP*)	845
3. Analysis of Stress-Strain Behavior Under Cyclic Loading	849
4. References	853

XXXXI – ON STATIC AND DYNAMIC RESPONSE OF GEOMATERIALS
V. N. Nikolaevski

I. Summary	855
1. Introduction	855

2. Elasto* Plastic Dilatancy Model	856
3. Dilatancy Under Explosion Motions	859
4. Limit Slip Velocity and Dynamic Compressibility	863
5. Nonelastic Strains and Acoustic Emission	867
6. References	868

**XXXXII – ON THE ROTATION OF PRINCIPAL STRESS AXES
IN THE SIMPLE SHEAR TEST AND ITS UTILIZATION**

H. Ochiai, T. Yamanouchi, and Y. Tanahashi

I. Abstract	871
1. Rotation of Principal Stress Areas During Simple Shear Test	871
2. Principal Stresses in Simple Shear Test	873
3. Determination of the Constant K	875
4. On the Plane of Maximum Obliquity in Simple Shear Test	876
5. Relationship Between θ'_{cv} and θ_μ	877
6. Coefficient of Earth Pressure at Rest	878
7. Undrained Strength Ratio of Normally Consolidated Clay Measured in Simple Shear Test	879
8. Concluding Remarks	882
9. References	882

**XXXXIII – EFFECTS OF FABRIC CHANGE ON DEFORMATION
CHARACTERISTICS OF SAND IN CYCLIC SHEARING**

Y. Tobita

I. Abstract	885
1. Introduction	885
2. Experimental Procedures	886
2.1 – Biaxial Compression Test with Photoelastic Techniques	886
2.2 – Experimental Procedure of Simple Shear Test and Triaxial Test	887
3. Experimental Results	887
3.1 – Hardening and Softening Effects of Granular Material in Deformation	887
3.2 – Two Fundamental Mechanisms in Deformation of Granular Materials	888
3.3 – Loading Regime of Granular Material in Shear Loading	892
4. Discussions on the Deformation Characteristics of Sand in Cyclic Shearing	892
4.1 – Loading Regime 1	892
4.2 – Loading Regime 2	893
4.3 – Loading Regime 3	896
4.4 – Summary	896

5. Continuum Mechanical Description of Granular Materials	899
6. Concluding Remarks	900
7. Acknowledgments	900
8. References	900

**XXXXIV - RESPONSE OF SAND IN CYCLIC TORSIONAL LOADING
INFLUENCED BY ROTATION
OF PRINCIPAL STRESS DIRECTIONS**

I. Towhata and K. Ishihara

I. Abstract	903
1. Introduction	903
2. Triaxial Torsion Shear Apparatus	904
3. Test Material and Procedures	905
4. Loading Scheme	905
5. Test Results	909
6. Comparisons Between Two Tests With and Without Rotation of Principal Stress Axes	923
7. Conclusions	926
8. Acknowledgments	928
9. References	928

**XXXXV - THREE-DIMENSIONAL DEFORMATION MODEL
FOR SAND UNDER DRAINED CONDITIONS**

Y. Yamada and K. Ishihara

I. Abstract	929
1. Introduction	929
2. Outline of Model	930
3. True Triaxial Tests	931
4. Stress-Strain Relationship in Two-Dimensional Stress System	933
5. Comparison Between Predicted and Measured Strains	939
6. Conclusion	944
7. Acknowledgment	944
8. References	944

**XXXXVI - INFLUENCE OF VOID RATIO AND STRESS CONDITION ON
THE DYNAMIC SHEAR MODULUS OF GRANULAR MEDIA**

E. Yanagisawa

I. Abstract	947
1. Introduction	947
2. Contact Points in Granular Materials	948

3. Elastic Constants of Uniform Spheres in Contact	949
4. The Shear Modulus of Granular Media	951
5. Influence of Stress Condition on the Shear Modulus	954
6. Effect of Octahedral Shear Stress	956
7. Conclusions	959
8. References	959
INDEX TO REFERENCES	961