

Rock Mechanics in Underground Construction

This page is intentionally left blank

ISRM International Symposium 2006
4th Asian Rock Mechanics Symposium

Rock Mechanics in Underground Construction

8 – 10 November 2006

Singapore



Editors

C. F. Leung

National University of Singapore, Singapore

Y. X. Zhou

Defense Science & Technology Agency, Singapore

 **World Scientific**

NEW JERSEY • LONDON • SINGAPORE • BEIJING • SHANGHAI • HONG KONG • TAIPEI • CHENNAI

Published by

World Scientific Publishing Co. Pte. Ltd.

5 Toh Tuck Link, Singapore 596224

USA office: 27 Warren Street, Suite 401-402, Hackensack, NJ 07601

UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

ROCK MECHANICS IN UNDERGROUND CONSTRUCTION

ISRM International Symposium 2006

4th Asian Rock Mechanics Symposium

Copyright © 2006 by World Scientific Publishing Co. Pte. Ltd.

All rights reserved. This book, or parts thereof, may not be reproduced in any form or by any means, electronic or mechanical, including photocopying, recording or any information storage and retrieval system now known or to be invented, without written permission from the Publisher.

For photocopying of material in this volume, please pay a copying fee through the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, USA. In this case permission to photocopy is not required from the publisher.

ISBN 981-270-437-X

Printed in Singapore by B & JO Enterprise

PREFACE

The 4th Asian Rock Mechanics Symposium (ARMS) received overwhelming response for its call for papers in early 2006 with about 450 abstracts received by the Organising Committee. After a rigorous selection process, just over 300 papers were finally accepted for the proceeding, a record for ARMS. This is also the first time that the ARMS proceedings volume consists of printed copies of full papers of keynote lectures and extended abstracts of all the technical papers while the full technical papers are provided in a CD-ROM. This has enabled the Organising Committee to accept as many high quality technical papers as possible.

The theme of the Symposium is “Rock Mechanics in Underground Construction”. Fittingly all the seven keynote lectures from Asia, Australia, Europe and North America deal with underground rock engineering topics. In fact, about half of the technical papers concern with underground construction such as tunnelling, rock caverns and underground mining. In addition, a large number of the remaining technical papers are directly or indirectly involved with rock mechanics in underground construction. Although the majority of the technical papers are contributed by rock engineers and researchers from Asia, the editors are glad to note that there are considerable number of contributions of high quality technical papers from many countries outside Asia.

The contributions of the technical paper reviewers and the ARMS 2006 award selection committee members are gratefully acknowledged. They play important roles to ensure that the papers in this proceedings volume are of high standard. The editors would like thank the able compilation and thorough checking of the scripts by Ms Chelsea Chin and her colleagues from World Scientific Publishing Company, and the diligent assistance of the staff from the symposium Secretariat, Meeting Matters International. With the efforts of all the above persons, the editors hope that this proceedings volume will serve as a useful reference for the engineers and researchers in rock mechanics and rock engineering.

C. F. Leung
Y. X. Zhou

This page is intentionally left blank

ORGANISATION

ORGANISING COMMITTEE

Chairman: Yingxin **ZHOU**

Honorary Secretary: Jungang **CAI**

Honorary Treasurer: Sek Kwan **TANG**

Members: Eng Choon **LEONG**
Chun Fai **LEUNG**
Guowei **MA**
Leslie **PAKIANATHAN**
Jian **ZHAO**
Zhiye **ZHAO**

So-Keul **CHUNG** (corresponding member - Korea)

Yujing **JIANG** (corresponding member - Japan)

Chun'an **TANG** (corresponding member - China)

INTERNATIONAL ADVISORY BOARD

Mojtaba **GHARAVY** (*Iran*)

Yossef **HATZOR** (*Israel*)

François **HEUZÉ** (*USA*)

John A **HUDSON** (*UK*)

Chung-In **LEE** (*Korea*)

Nielen van der **MERWE** (*South Africa*)

Yuzo **OHNISHI** (*Japan*)

Qihu **QIAN** (*China*)

John **ST. GEORGE** (*New Zealand*)

A **VARADARAJAN** (*India*)

Kwet Yew **YONG** (*Singapore*)

Jian **ZHAO** (*Singapore*)

This page is intentionally left blank

ACKNOWLEDGEMENT OF PAPER REVIEWERS

The editors gratefully appreciate the efforts of the following reviewers who have helped to maintain a high standard of the proceedings. The editors would like to apologise if some names have been left out or misspelled.

Maurice B DUSSEAUT	Canada	Seok-Won LEE	Korea
Shougen CHEN	China	Il-Jae SHIN	Korea
R. K. GOEL	India	Hyu-Soung SHIN	Korea
Shinichi AKUTAGAWA	Japan	Jae-Joon SONG	Korea
Yasuaki ICHIKAWA	Japan	Joong-Ho SYNN	Korea
Yujing JIANG	Japan	Yong-Gyun YOON	Korea
Kiyoshi KISHIDA	Japan	Kwang-Ho YOU	Korea
Harushige KUSUMI	Japan	Ming LU	Norway
Yasuhiro MITANI	Japan	Yonggeng YE	Switzerland
Norikazu SHIMIZU	Japan	Jian ZHAO	Switzerland
Koichi SHIN	Japan	Gang CHEN	USA
Soo-Ho CHANG	Korea	Jungang CAI	Singapore
Seokwon JEON	Korea	Eng Choon LEONG	Singapore
Chee-Hwan KIM	Korea	Guowei MA	Singapore
Young-Keun KIM	Korea	Leslie PAKIANATHAN	Singapore
Gyu-Sang LEE	Korea	Sek Kwan TANG	Singapore
Hee-Seok LEE	Korea	Zhiye ZHAO	Singapore

This page is intentionally left blank

CONTENTS

Preface	v
Organisation	vii
Acknowledgement of Paper Reviewers	ix
KEYNOTE LECTURES	1
Forensic Engineering for Underground Construction <i>E. T. Brown</i>	3
Thermo-Mechanical Behavior of Rock Masses around Underground LNG Storage Cavern <i>S.-K. Chung</i>	19
Rock Mechanics and Hazard Control in Deep Mining Engineering in China <i>M. C. He</i>	29
Rock Mechanics Considerations for Construction of Deep Tunnels in Brittle Rock <i>P. K. Kaiser</i>	47
Development and Application of Discontinuous Deformation Analysis <i>Y. Ohnishi, S. Nishiyama and T. Sasaki</i>	59
The Role of On-Site Engineering in Underground Projects <i>W. Schubert</i>	71
Rock Mechanics and Excavation by Tunnel Boring Machine – Issues and Challenges <i>J. Zhao and Q. M. Gong</i>	83
ROCHA MEDAL AWARD PAPER	97
Strategy for In-Situ Rock Stress Measurements <i>D. Ask and F. H. Cornet</i>	99

EXTENDED ABSTRACTS	109
1. TUNNELLING	111
1.1. General	111
Discontinuum Analysis of a Highway Tunnel <i>R. Chitra, M. Gupta and A. K. Dhawan</i>	113
Ground Reaction to Deep Draining Tunnels <i>M. El Tani</i>	114
Behaviour of Tunnels in Jointed Rock Mass <i>M. Gupta, R. Chitra and A. K. Dhawan</i>	115
On the Stability of a Twin-Tube Tunnel Under Complex Geology <i>Y. Y. Jiao, J. Zhao, S. L. Wang, Q. S. Liu and J. B. Zhu</i>	116
New Approach of Tunnel Observation Using Digital Photogrammetry <i>K. Y. Kim, C. Y. Kim, S. H. Baek and S. D. Lee</i>	117
Optimization of the Round Length in Design Stage for Tunnel Excavation in Weak Rock <i>Y.-Z. Lee, W. Schubert and C.-Y. Kim</i>	118
The Impact of Rock Tunnelling on Groundwater in Epi-Fissure-Karst Zone and Ecological Conditions <i>X. Z. Li, X. B. Zhao and J. Sun</i>	119
Study on Prediction of Tunnel Deformation Considering Degradation of Rock Mass <i>T. Matsunaga, T. Asakura, K. Tsukada, H. Kumasaka and Y. Kojima</i>	120
Observational Method for Tunnel Construction Considering Environmental Impact to Groundwater Using the SWING Method <i>Y. Ohnishi, H. Ohtsu, K. Takahashi and T. Yasuda</i>	121
Net Penetration Rate and Cutter Consumption in Jook-Ryung TBM Tunnel <i>C. W. Park, C. Park, J. H. Synn, J. W. Choi and S. Jeon</i>	122
Stability Analysis of Surrounding Rock of Deep-Lying Long Tunnels <i>X. Ren, J. Zhang, J. Shu and H. Jiao</i>	123
A Tool for Rock Tunnel Design by Convergence-Confinement Method <i>B. Tontavanich, K. H. Park, S. Suwansawat and Y. J. Kim</i>	124

Contribution to the Design of Tunnels with Pipe Roof Support <i>G. M. Volkmann and W. Schubert</i>	125
Estimation of Excavation Damaged Zone of Long-Span and Shallow Overburden Tunnel <i>S. Wang, T. Yang, B. Chen, S. Wang and N. Zhang</i>	126
Deformation Monitoring on the Diverging Tunnel at Baziling, P. R. China <i>Z. Wang, S. Li and W. Chen</i>	127
Fundamental Study on Excavating Characteristic of Rock Type Slurry Shield in Soft-Rock <i>D. Yuan and A. Koizumi</i>	128
1.2. Theoretical and Numerical Analyses	129
3-D and Quasi-3-D Analyses of Underground Excavations <i>M. Ahmadi, K. Goshtasbi and R. Ashjari</i>	131
Analysis of Time-Dependent Tunnel Behavior Using a New Rock-Support Interaction Model <i>S.-H. Baek, H.-K. Moon and E.-J. Jo</i>	132
Modeling Coupled Hydro-Mechanical Response of Heterogeneous Fractured Rock During Tunnel Excavation <i>W. Chen and H.-N. Ruan</i>	133
Theoretical Solutions for NATM Excavation in Soft Rock Under Non-Hydrostatic In-Situ Stresses <i>Z. Guan, Y. Jiang and Y. Tanabashi</i>	134
3D Numerical Modeling of Gate Shafts and Surrounding Tunnels in Gotvand Dam Project <i>A. Jafari and J. Hedayatjo</i>	135
Elastic-Plastic Analysis of Circular Openings in Broken Surrounding Rocks <i>B. Jiang, Q. Zhang and Y. He</i>	136
Continuum Methods for Stress and Stability Analysis of Boreholes and Tunnels <i>P. A. Nawrocki</i>	137
Elasto-Plastic Numerical Simulation of Deep Circular Tunnel Subjected to Non-Hydrostatic Loading <i>T. Nishimura, T. Fukuda and H. Kiyama</i>	138

Numerical Analysis of the Change in Groundwater System with Tunnel Excavation in Jointed Rock Mass <i>J.-W. Park, B.-K. Son and C.-I. Lee</i>	139
A Parameter Study of the Damaged Rock Zone Around Shallow Tunnels in Brittle Rock Mass <i>D. Saiang and E. Nordlund</i>	140
Study on Tunnel Stability in Soft Rock Considering Volumetric Strain Using Coupled Analyses <i>T. Sakata, K. Kishida, T. Hosoda, A. Tomita and T. Adachi</i>	141
Boundary Element Analysis of Tunneling through a Weak Zone <i>K.-J. Shou</i>	142
Physical and Numerical Modelling of Underground Opening in Jointed Rock Mass <i>M. Singh, J. Choudhari and T. Kaleshwara Rao</i>	143
Three Dimensional Modelling of a Tunnel Cave-In and Spiling Bolt Support <i>Q. N. Trinh, E. Broch and M. Lu</i>	144
Circular Tunnel Elastic-Plastic Analysis <i>L. Wang, J. Zhao and X. Li</i>	145
Numerical Study of Cavity Unloading in Brittle-Plastic Rock <i>S. Y. Wang, K. C. Lam, I. W. H. Fung, C. A. Tang and T. Xu</i>	146
Numerical Simulation for Shallow Tunnel Under Unsymmetrical Pressure <i>S. Wang, S. Li and G. Wang</i>	147
Technique for Determination of Boundary Stress Conditions in Deep Tunneling <i>C. X. Yang, Y. H. Wu, T. Hon and D. M. Chen</i>	148
1.3. Field and Laboratory Studies	149
Study on Minimal Rock Cover and Route Optimal Scheme of Subsea Road Tunnel <i>W. Ding, Shuca Li, Shuchen Li and W. Zhu</i>	151
TBM Breakdown Causes and Effects on Tunneling Performance in Tarabya Sewerage Tunnel <i>C. Feridunoglu, D. Tumac and N. Bilgin</i>	152
Experience on the World's Longest Railway Tunnel St. Gotthard <i>M. Herrenknecht and K. Bappler</i>	153

A Microseismic Monitoring Trial for the Stability Assessment of a Super Tunnel at Jinping Dam, China	154
<i>X. Luo, H. Su, C. Sha and C. Luo</i>	
Stress-Strain Analysis of “HS Kozjak” Tunnel Due to Movements in Tectonic Fault	155
<i>B. Macuh and B. Žlender</i>	
Instrumentation and Monitoring Technology for Underground Construction in China – Review and Forecast	156
<i>Z. R. Mei, S. W. Ma and X. N. Wang</i>	
Comparison of Identification and Quantification of Squeezing Condition by Different Approaches	157
<i>N. Shafieezadeh</i>	
Instrumentation at Head Race Tunnel Under Adverse Geological Conditions	158
<i>Sripad, R. Singh, K. Sudhakar, R. N. Gupta and R. N. Khazanchi</i>	
Modification of the Proposed System of Rating for Rock Tunnelling Machine Selection Using the AHP Method	159
<i>A. Taheri and H. A. M. Borujeni</i>	
Influence on Groundwater Level Change Due to Water Seepage in Chikushi Shinkansen Tunnel, Japan	160
<i>C. Wang, T. Esaki, Y. Mitani, B. Xu, A. Murakami and C. Qiu</i>	
2. ROCK CAVERNS	161
2.1. General	161
A Thermo-Mechanical Analysis Around Lined LNG Storage Cavern	163
<i>Y.-H. Cho, H.-S. Lee, S.-C. Lee, T.-G. Kim, J.-M. Lee, H.-Y. Kim, E.-S. Park and S.-K. Chung</i>	
Evaluation of the Stability for Underground Tourist Cavern in an Abandoned Coal Mine	164
<i>K. C. Han and Y. S. Jeon</i>	
Hydrogeologic Analysis of Groundwater Drainage System for Underground LNG Storage Cavern	165
<i>W.-C. Jeong, S.-W. Woo, H.-S. Lee, D.-H. Lee, J.-M. Lee, H.-Y. Kim, E.-S. Park and S.-K. Chung</i>	
Design of Rock Caverns in High In-Situ Stress Rock Mass	166
<i>M. Lu, H. Dahle, E. Grøvn, H. Y. Qiao, Q. L. Zhao and B. H. Wen</i>	

Development of the Groundwater Resources in Bedrock Using Rock Caverns <i>T. Nishi, H. Momota, M. Suzuki and M. Honda</i>	167
Cavern Design Consideration with Modern Drilling Equipment <i>G. Nord, H. Stille and M. Bagheri</i>	168
Application of Composite Element Method to PuBugou Underground Engineering <i>S. Qiang, Y. Zhang, S. H. Chen, Z. G. He and L. L. Xue</i>	169
Geotechnical, Environmental and Structural Aspects of Underground Storage of Hazardous Substances <i>G. Reik and W. Rahn</i>	170
Influence of Concealed Karst Caverns on Tunnel Stability <i>Z.-P. Song, N. Li, L.-S. Deng and J.-L. Cheng</i>	171
Fundamental Study on Long-Term Stability of the Underground Cavern <i>Y. Suzuki and K. Sugawara</i>	172
Design Methodology for Hydrocarbon Caverns, Influence of In-Situ Stresses on Large Sections <i>T. You, N. Gatelier and S. Laurent</i>	173
2.2. Theoretical and Numerical Analyses	175
Finite Element Analysis of Underground Nuclear Repositories with Temperature Dependent Rock Properties <i>T. Chakraborty and K. G. Sharma</i>	177
Behaviour Study of Large-Scale Underground Opening in Discontinuous Rock Masses by Using Distinct Element Method <i>Y. J. Jiang, B. Li, Y. Yamashita, Y. Etou, Y. Tanabashi and X. D. Zhao</i>	178
Hydro-Thermal Coupled Analysis of Ice Ring Formation in Underground Pilot LNG Cavern <i>Y. B. Jung, S. K. Chung, C. Park, W. C. Jeong and H. Y. Kim</i>	179
Heat Transfer and Boil-Off Gas Analysis Around Underground LNG Storage Cavern <i>H.-S. Lee, D.-H. Lee, W.-C. Jeong, Y.-W. Song, H.-Y. Kim, E.-S. Park and S.-K. Chung</i>	180
Numerical Simulation and Displacement Field Measurement of Powerhouse Cavern Excavation <i>S. Li, Y. Liu and F. Wu</i>	181

One System Analysis Method in Underground Chambers Excavation and Application <i>X. J. Li, W. S. Zhu, W. M. Yang, S. C. Li and Y. S. H. Guo</i>	182
Numerical Modelling for Feasibility Analysis of PowerHouse Chambers in Weak Formation <i>J. P. Loui, A. Sinha, D. G. Rao, C. H. Ryu and S. O. Choi</i>	183
3D Analysis of Power Cavern in Rock Mass using Joint Factor and Nonlinear Hyperbolic Model <i>V. B. Maji and T. G. Sitharam</i>	184
Comparison of 2D&3D Analyses Results of Masjed Soliman Powerhouse Caverns by ANSYS Software <i>A. A. Safikhani</i>	185
Numerical Simulation of Gas Storage Caverns in Qom Region <i>M. Sharifzadeh and A. M. Ghasr</i>	186
Stability Analysis of a Large Underground Powerhouse Cavern by 3D Discrete Element Method <i>T. Wang and L. Chen</i>	187
2.3. Field and Laboratory Studies	189
Stability Analysis of Lavarak Underground Powerhouse Cavern Using Back Analysis Results <i>M. Assari, M. Moosavi and A. Taherian</i>	191
Microseismic Monitoring Around Large Underground Storage Caverns During Construction <i>J. S. Hong, H. S. Lee, D. H. Lee, H. Y. Kim and Y. T. Choi</i>	192
KAERI Underground Research Facility for the Validation of a High-Level Radioactive Waste Disposal Concept in Korea <i>S. Kwon, J. H. Park, W. J. Cho and P. S. Hahn</i>	193
Monitoring and Analysis about Stabilization on the Tai'an Pumped-Storage Station Underground House <i>J. Li, Shuca Li, Shuchen Li and G. Wang</i>	194
Design Analysis of Experimental Lined Rock Cavern for Natural Gas Storage in Japan <i>K. Niimi, T. Ibata, J. Ono, M. Aiba and Y. Tsutsumi</i>	195
Experimental Lined Rock Cavern for Natural Gas Storage in Japan <i>T. Okuno, N. Wakabayashi, K. Takeuchi, M. Iwano and Y. Tsutsumi</i>	196

3. MINING	197
Instability Modes of Abandoned Lignite Mines and the Assessment of Their Stability <i>Ö. Aydan, M. Daido, T. Ito, H. Tano and T. Kawamoto</i>	199
Physical Simulation of Full-Seam Mining for a 20m Thick Seam by Sub-Level Caving Mining Method <i>T. Kang, Y. Li, Z. Chai and S. Zhang</i>	200
Numerical Investigation on Stability of the Rock Pillar in an In-Situ Experiment <i>L. C. Li and C. A. Tang</i>	201
Stability Behaviour of Roadway Intersection in Deep Underground <i>T. Lu, L. Chen, Y. Liu and B. Guo</i>	202
Effect of Backfilling on Stability of Pillars in Highwall Mining Systems <i>K. Matsui, H. Shimada, T. Sasaoka and M. Ichinose</i>	203
New Method of Roof-Fall Hazard Evaluation in Polish Copper Mines <i>S. Orzepowski and J. Butra</i>	204
Dimensioning of Salt-Rock Pillars in “Polkowice-Sieroszowice” Copper Deep Mine Based on FEM <i>W. Pytel and J. Butra</i>	205
Failure Modes and Responses of Abandoned Lignite Mines Induced by Earthquakes <i>A. Sakamoto, N. Yamada, K. Sugiura, Ö. Aydan, H. Tano and M. Hamada</i>	206
A Damage Model of Acoustic Emission in Pillar Failure and Its Numerical Simulation <i>S. Y. Wang, I. W. H. Fung, S. K. Au, C. A. Tang and Z. Z. Liang</i>	207
Measuring Rock Mass Modulus of Deformation in a Stopping-Affected Cross-Cut in Pongkor Underground Gold Mine <i>R. K. Wattimena, B. Sulistianto, K. Matsui, B. Dwinagara and E. Barnas</i>	208
Correlating Apparent Stresses Predicted by Microseismic Monitoring and Tunnel Displacements Measured with Convergencemeter in the DOZ Block Caving Mine <i>R. K. Wattimena, E. Widijanto and R. Ernawan</i>	209
Geotechnical Challenges in the DOZ Block Cave Mine <i>E. Widijanto, N. Arsana and A. Srikant</i>	210
Modeling of Mining Induced Delay Outbursts in Terms of Material Degradation <i>T. Xu, C. A. Tang, L. C. Li and S. Y. Wang</i>	211

Study on Creep Behavior of Coal Rock and Stability of Tunnel Through Coal-Rock Layer <i>C. Zhang, C. Yang, C. J. Liu and F. Chen</i>	212
3-D Numerical Simulation and Calculation Models Discussion of Mining Subsidence <i>Q.-S. Zhang, Shuca Li, Shuchen Li and Y.-F. Gao</i>	213
Development of GIS-Based System for Predicting Coal Mining Subsidence and Assessment of Environment Impacts in North China <i>X. Zhao, Y. Jiang, Z. Song and T. Esaki</i>	214
Massive Collapse of Pillars in Mines <i>Z. Zhou, X. Li, G. Zhao and Xiling Liu</i>	215
Dynamic Simulation and Optimum Analysis on Construction Process for Joint Arch Tunnel in Partial Pressure <i>H. Zhu, N. Zhuang, Xuezheng Liu and Y. Cai</i>	216
4. BLASTING AND DYNAMICS	217
Effect of Stress Level and Excitation Size on Compression Waves in Jointed Rocks <i>M. S. Cha and G. C. Cho</i>	219
Wave Propagation and Attenuation in Discontinuous Rock Media <i>J. Chen, J. Li, G. Ma and Y. Zhou</i>	220
Test and Theory Study on Middle-Deep Cut-Hole Blasting in Hard Rock Tunnel <i>S. Chen</i>	221
Calculation of the Burden of Periphery Blast-Holes in Smooth Blasting for Deep Tunnel Driving <i>J. Dai</i>	222
Validation of UDEC Modeling 2-Dimensional Wave Propagation in Rock <i>W. D. Lei, J. Zhao, A. M. Hefny and J. Teng</i>	223
Penetration Depth of Long-Rod Into Geomaterials <i>J. C. Li, M. H. Yu and G. W. Ma</i>	224
Study on the Stability Safety of Dangerous Rock No.2 in Suofengying Hydropower Station <i>Xiaoqing Liu, L. Li and T. Li</i>	225

In-Situ Experimental Study on Blasting Vibration Wave Propagation Rules in Complicated Underground Tunnel Group <i>X.-P. Li, C.-L. Zhang, T. Wang, Y.-H. Li and Y. F. Dai</i>	226
Blasting Vibration Analysis in Shallow Buried Tunnel Excavation <i>C. Lin, L. Yang and J. Cui</i>	227
Dynamic Response of Surrounding Rockmass Induced by the Transient Unloading of In-Situ Stress <i>W. B. Lu, P. Yan and C. B. Zhou</i>	228
Research on Frozen Weathered Rock Blasting Techniques in Shaft <i>Q.-Y. Ma</i>	229
Assessment of Blast-Induced Vibration in Jointed Rock Mass <i>B. K. Park, S. Jeon and G. J. Park</i>	230
Study on Split-Second Delay Time of Parallel Cut Blasting in Rock Drifting <i>D. Qiao</i>	231
Seismic Analysis of Tunnels — The Quasi-Static Method <i>R. Resende and J. V. Lemos</i>	232
Long Hole Blasting Excavation in Single-Track Railway Tunneling <i>H. Sasao and T. Asakura</i>	233
Ballistic Penetration and Perforation of Granite Target Plates by Hard Projectiles <i>C. C. Seah, T. Børvik, S. Remseth and T. C. Pan</i>	234
Optimized Blasting Design for Large-Scaled Quarrying Based on a 3D Spatial Distribution of Rock Factor <i>H. J. Shim, D. W. Ryu, C. Y. Han and S. M. Ahn</i>	235
Prediction of Fragmentation Zone Induced by Blasting in Rock <i>Y. J. Sim and G. C. Cho</i>	236
Stability Assessment of 290 Level Cave Subjected to Blast-Induced Vibrations <i>H. Sun, Q. Chen, S. Wang, X. Niu and W. Chen</i>	237
Modeling Dynamic Split Failure of Granite using Smoothed Particle Hydrodynamic Method <i>X. J. Wang and G. W. Ma</i>	238
Blasting Vibration Effect in Excavating a Multi-Arch Tunnel <i>C. Wu, X. Chen, Z. Xu and Q. Zhang</i>	239

Study on Blast-Induced Damage in Bedrock Excavation <i>X. Xia, J.-R. Li, H.-B. Li, X.-W. Wang and Q.-C. Zhou</i>	240
Dynamic Uniaxial Compression Tests on a Cement Mortar <i>X. B. Zhao, J. G. Cai, J. Zhao, G. W. Ma and H. B. Li</i>	241
Rock Response Under Blast Load by the Discontinuous Deformation Analysis <i>Z. Zhao and J. Gu</i>	242
Dynamic Shear Properties of Brittle Materials Subjected to Cyclic Loading <i>Q. J. Zhou, B. N. Gong and T. C. Li</i>	243
5. SUPPORT AND REINFORCEMENT	245
Design of Rock Support System for Sub-Sea Dock Excavation <i>J. Bergh-Christensen and T. K. Sandaker</i>	247
Non-Destructive Evaluation System of the Tunnel Concrete Lining Using Wavelet Transform Analysis and New Acoustic Tapping Measurement <i>H. Enomoto, K. Tsukada and T. Asakura</i>	248
Benefits and Comparisons of Pre-Reinforcement Applications in Tunnelling <i>R. Fuchs</i>	249
Numerical Analysis for Better Understanding Mechanism of Support Effect on Ground Stability by Using Distinct Element Method <i>T. Funatsu, T. Hoshino, M. Ishikawa and N. Shimizu</i>	250
Full-Column Grouted Rock Bolts and Support Pressure <i>R. K. Goel</i>	251
Concrete Segmental Liner Instrumentation to Quantify Stresses Induced by Ground Freezing <i>J. F. Hatley, M. E. Fowler and R. Beddoes</i>	252
Testing Equipment for Rock Under Coupling Loads <i>X. Li, Z. Zhou, Q. Li and L. Hong</i>	253
FEM Analysis and Detection for Structural Damage of Tunnel Lining <i>D. Liu, Y. Deng, G. Xu and D. Gu</i>	254
Ground Reaction Curve for a Phenomenological Damage Model <i>F. Martin, R. Desmorat and A. Saïta</i>	255

The Evaluation of the Effect of Long Face Bolting by 3D Distinct Element Method <i>Y. Mitarashi, H. Tezuka, T. Okabe, S. Morimoto and Y. Jiang</i>	256
Mechanism and Measures of Coarse Aggregate Spalling in Aged Tunnel Concrete Linings <i>S. Nishio, T. Sasaki and Y. Kojima</i>	257
Effect of Contact Roof Zone on the Performance of Longwall Powered Supports <i>V. R. Sastry, R. Nair and M. S. V. Ramaiah</i>	258
Comparison Between Numerical Analyses and Actual Test in Field for Prestress Anchors (Monobars) <i>M. R. Shahverdiloo and B. Ahadi Manafi</i>	259
Shear Reinforcing Effect of Rust Proofing Expansive Rock Bolts <i>M. Shinji, H. Mukaiyama, N. Kanda and H. Tanase</i>	260
Deterioration Mechanisms of Tunnel Lining Concrete <i>H. Ueda, S. Nishio, T. Sasaki and Y. Matsuda</i>	261
Floor Heave Roadway Prestressed Anchor and Inverted-Arch Combined Support Design and Its Numerical Analysis <i>H.-P. Wang, S.-C. Li, Y.-F. Gao, W.-S. Zhu and Q.-S. Zhang</i>	262
Experimental Study on the Influence Factors of Cable Bolt Reinforcement <i>Y. D. Xue and H. W. Huang</i>	263
Auxiliary Method to Stabilize Cutting Face of Mountain Tunnel <i>H. Yamada, M. Baba and Y. Jiang</i>	264
Reinforcing Analysis of New Prestressed Anchored Rope Based on Interface Element Method <i>Q. Zhang, Z. Li, J. Zhuo and X. Sun</i>	265
6. ROCK MASS	267
6.1. General	267
A Proposal for the Modification of RQD (MRQD) <i>M. S. Araghi, F. B. Samani and M. T. Goudarzi</i>	269
Rock Mass Characterization and Rock Mass Property Variability Considerations for Tunnel and Cavern Design <i>M. Cai and P. K. Kaiser</i>	270

Strain-Dependent Permeability Tensor for Coupled M-H Analysis of Underground Opening <i>Y. Chen, Y. Sheng and C. Zhou</i>	271
Application and Research of Seismic Investigation Methods to Predict Rock Mass Conditions Ahead of the Face <i>T. Dickmann and S. K. Tang</i>	272
Analyzing of the Representative Length of Rock Mass Subjected to Load by In Situ Loading Tests to Evaluation of Rock Mass Deformation Modulus <i>L. Faramarzi and K. Sugawara</i>	273
Rock Mass Quality Evaluation by Fractal Dimension of Rock Mass Discontinuity Distribution <i>Y.-Z. Liu, J.-L. Sheng, X.-R. Ge and S.-L. Wang</i>	274
Risk Evaluation of Water Inrush During Shaft Excavation in Fractured Rock Masses <i>H. Ohtsu, Y. Sakai, H. Saegusa, H. Onoe, Y. Ijiri and T. Motoshima</i>	275
Simulation of Fracture Mechanics for Rock Masses Under Very Low Temperature Conditions <i>E.-S. Park, S.-K. Chung, H.-Y. Kim and D.-H. Lee</i>	276
New Approach for Prediction of Bearing Capacity in Rock and Rock Mass <i>K. S. Rao, R. P. Tiwari and C. Kumar</i>	277
Prediction of Ground Condition and Evaluation of Its Uncertainty by Simulated Annealing <i>D.-W. Ryu, S. Choon, W.-K. Song and T.-H. Kim</i>	278
Considerations on Long-Term Strength of Jointed Rock Upon the Homogenized Crack Propagation <i>K. Sugawara, Y. Suzuki and T. Tokuoka</i>	279
Modified Rock Mass Classification System for Preliminary Design of Rock Slopes <i>Abbas Taheri, Ali Taheri and K. Tani</i>	280
Engineering Behaviour of Simulated Block Mass Models <i>R. P. Tiwari and K. S. Rao</i>	281
Evaluation of Rock Mass Quality and Its Application <i>L. Wang, J. Li, H. Deng and J. Liu</i>	282
Complete Stress-Strain Curve for Jointed Rock Masses <i>T. T. Wang and T. H. Huang</i>	283

A Parametric Study on Flow of Groundwater in Fractured-Porous Media: 3D Simulation <i>J. Yudan, P. G. Ranjith, A. K. Verma, S. K. Choi and A. Haque</i>	284
6.2. Theoretical and Numerical Analyses	285
Simulation of Stratified Rocks Using COSSERAT Model <i>S. G. Chen</i>	287
Application of Meshless Method for Behavior Analysis of Jointed Rock Mass <i>M. Hajiazizi, N. Hataf, F. Daneshmand and A. Ghahramani</i>	288
Elastic-Plastic Analysis of Jointed Rock Mass Using Meshless Method <i>M. Hajiazizi, N. Hataf, F. Daneshmand and A. Ghahramani</i>	289
Stochastic Simulation of Rock Mass Properties Using a Modified Genetic Algorithm <i>C. Hong and S. Jeon</i>	290
Numerical Analysis on Rock Failure Mechanics Under Loading and Unloading Conditions <i>P. Jia, C. A. Tang and Z. Z. Liang</i>	291
Application of a Fuzzy Model to Estimate the Engineering Rock Mass Properties <i>H.-K. Lee, S.-W. Jeon, Y.-I. Yu and D.-H. Lee</i>	292
An Analytical Study on Electrical Resistivity-Based Rock Mass Classification <i>H.-H. Ryu, G.-C. Cho and I.-M. Lee</i>	293
Applying the Theory of Seismic Interferometry to Geological Survey Using Artificial Sources in Tunnels <i>K. Shiraishi, K. Onishi, S. Ito, T. Aizawa and T. Matsuoka</i>	294
Geotechnical Concerns During the Development of the AB Tunnels in PT Freeport Indonesia <i>F. Sinaga, I. Qudraturrahman and A. Srikant</i>	295
Numerical Modeling of Jointed Rock Mass: A Practical Equivalent Continuum Model <i>T. G. Sitharam and V. B. Maji</i>	296
Application of Extended Finite Element Method to Cracking Analysis of Rock Masses <i>T. Yu and L. Li</i>	297
A 2-D Natural Element Model for Jointed Rock Masses <i>T. Yu and M. Y. Otache</i>	298

6.3. Field and Laboratory Studies	299
Physical Properties of Fractured Rock Mass Determined by Geophysical Methods <i>A. F. Idziak and I. Stan-Kleczek</i>	301
Rock Mass Mechanics at the Mining of Large Ore Bodies in the Uranium Deposit of Rožná <i>B. Michálek, P. Kříž and A. Grmela</i>	302
Prediction of Modulus of Elasticity and Deformability of Rock Masses from Laboratory and Geotechnical Parameter <i>M. R. Shahverdilo</i>	303
Scale Effect of Shear Strength of Conglomerate Evaluated by Field and Laboratory Triaxial Tests <i>K. Tani</i>	304
Effect of Rock Strength Properties on Breakage of Rock Mass: An Experimental Analysis of Indian Mines <i>N. R. Thote and D. P. Singh</i>	305
Study on Design Scheme for Control of Seepage of Pingtuo Underground Hydropower Plant <i>Y.-M. Zhu, W.-J. Cen, B.-Y. Lin and X.-L. Fan</i>	306
7. ROCK PROPERTIES	307
7.1. General	307
Estimation of Geomechanical Parameters of Reservoir Rocks, Using Conventional Porosity Log <i>V. Azizi and H. Memarian</i>	309
Prediction of Mechanical Parameters of Rock, Using Shear Wave Travel Time <i>V. Azizi and H. Memarian</i>	310
Rock Strain-Strength Criterion and Its Application <i>Y. Chang</i>	311
The Effect of Calcium Carbonate Content of Marlstones on the Strength Response <i>A. H. Ghazvinian, A. Fathi, Z. A. Moradian and M. R. Nikudel</i>	312

Analysis of Structure Properties and Load Carrying of Destructive Rock Under Different Constraints <i>L. Han, Y. He and H. Zhang</i>	313
Characteristics of Roughness Mobilization <i>E. S. Hong, J. S. Lee, H. S. Shin, S. O. Choi and I. M. Lee</i>	314
Brief Rock Evaluation by Shock Response Value and MRCI <i>Y. Ito, S. Nakagawa, K. Kikuchi, T. Kobayashi and T. Saito</i>	315
Three Dimensional Thermo-Hydromechanical Modeling of a Heating Test in Mudstone <i>Y. Jia, Y. Wileveau, K. Su, G. Duveau and J. F. Shao</i>	316
Element Free Analysis for a Material Heterogeneity: 2D Example <i>H. M. Kim, J. Inoue and K. Ando</i>	317
Impact of Pyrite Oxidation on Mechanical Properties of Rock and Environment <i>J. G. Kim, G. H. Lee, I. Woo, T. H. Kim, C.-M. Chon and J.-S. Lee</i>	318
Characterisation of Marble and Effect of High Confining Pressure <i>R. Kumar, K. G. Sharma and A. Varadarajan</i>	319
Behavior of a Sandstone Under AXI- and Asymmetric Compressive Stress Conditions <i>M. Kwaśniewski and M. Takahashi</i>	320
An Investigation of Hydromechanical Behaviour and Transportability of Rock Joints <i>B. Li, Y. J. Jiang, R. Saho, Y. Tasaku and Y. Tanabashi</i>	321
Evaluation of the State of Stress in the Vicinity of a Mine Drift Through Core Logging <i>C. C. Li</i>	322
Theoretical and Experimental Analysis on the Mechanism of Kaiser Effect of Acoustic Emission in Brittle Rocks <i>Y. H. Li, R. F. Yuan and X. D. Zhao</i>	323
Numerical Modelling of Size Effect of Single-Edge-Notched Brittle Specimens Subjected to Uniaxial Tension <i>Z. Z. Liang, L. G. Tham, C. A. Tang, S. K. Au, S. Y. Wang and Y. B. Zhang</i>	324
Site Investigation for Underground Oil and Gas Storage Rock Caverns at Jurong Island of Singapore <i>M. Lu, J. G. Cai and A. Beitnes</i>	325
Lithophysal Porosity Effect on Mechanical Properties of Welded Topopah Spring Tuff <i>L. Ma and J. J. K. Daemen</i>	326

A Study on Estimating Hydraulic Characteristics of Rock Specimens Using Elastic Wave	327
<i>A. Miyata, Y. Ohnishi, S. Nishiyama, T. Yano and M. Takahashi</i>	
Using Artificial Neural Networks to Predict Pressure-Deformation of Solids with Flat Jacks	328
<i>M. Moosavi and R. Doostmohammadi</i>	
Influence of Water Vapor Pressure of Surrounding Environment on Fracture Toughness of Rock	329
<i>Y. Obara, K. Sasaki, T. Matsuyama and T. Yoshinaga</i>	
Recent Experiences in Singapore Limestone Rocks	330
<i>L. J. Pakianathan, K. Jeyatharan, C. F. Leung and V. Chepurthy</i>	
Subsurface Assessment in the Karst Area Using 3-D Resistivity Technique	331
<i>S. M. Park, M. J. Yi, J. H. Kim, C. Kim, J. S. Son and S. J. Cho</i>	
Considerations in Developing an Empirical Strength Criterion for Bimrocks	332
<i>H. Sonmez, H. Altinsoy, C. Gokceoglu and E. W. Medley</i>	
Ground Stability at Limestone Region with Ubiquitous Cavities by Fluctuation of Groundwater	333
<i>J. H. Synn, C. Park and W. K. Song</i>	
Strength Degradation of Granite Under Constant Loading	334
<i>L. G. Tham, Q. X. Lin, Y. M. Liu, P. K. K. Lee and J. Wang</i>	
Application of Design of Experiments to Process Improvement of PFC Model Calibration in Uniaxial Compression Simulation	335
<i>J. Yoon, O. Stephansson and G. Dresen</i>	
Acoustic Emission Behavior in the Progressive Failure of Rock Sample Containing Weak Zones	336
<i>H. Zhang, Y. He, L. Han, W. Kang and C. Tang</i>	
Study on the Damage Evolution Equation of the Fractured Rocks Based on the Triaxial Compression Tests	337
<i>J. M. Zhu and Q. Nie</i>	
Growth and Coalescence of Internal Flaws in Brittle Materials	338
<i>W. S. Zhu, Y. S. H. Guo, S. C. Li, R. H. C. Wong and X. J. Li</i>	

7.2. In-Situ and Laboratory Tests	339
Modeling Brittle Failure of Rock Using Damage-Controlled Test <i>D. S. Cheon, C. Park, Y. B. Jung and S. Jeon</i>	341
Determination of Elastic Constants for Transversely Isotropic Rock Specimens by a Single Uniaxial Compression Test <i>J.-W. Cho, H.-Y. Kim and S. Jeon</i>	342
Mechanical Response of Vindhyan Sandstones Under Drained and Confined Conditions <i>R. K. Dubey</i>	343
Roof Geostructure Logging System Using Portable Pneumatic Drilling Machine <i>K.-I. Itakura, S. Tomita, S. Iguchi, Y. Ichihara, P. Mastalir, T. Bergner and C. Coyte</i>	344
Effect of Porosity Between Spiral Bar and Crushed Rock in Borehole <i>S. S. Kang, S. Kokaji and A. Hirata</i>	345
Determination of Mode II Stress Intensity Factor Using Short Beam Compression Test <i>T. Y. Ko and J. Kemeny</i>	346
Experimental Study on Strength and Deformation Characteristics of Phyllite <i>A. Kumar, N. K. Samadhiya and M. Singh</i>	347
Study of Anisotropy of Rock Elastic Properties of Fairbanks Schist Utilizing Ultrasonic Waves <i>H. Li and G. Chen</i>	348
Experimental Investigation of Creep in a Salty Mudstone <i>W. Liang, C. Yang, Y. Zhao and M. B. Dusseault</i>	349
Comparison of Direct Shear Test Results Using a Portable Developed and Conventional Direct Shear Test Apparatus <i>M. Gharouni-Nik and S. Hashemi</i>	350
Measuring Electric Resistivity of Rock Cores for the Underground Sequestration of Carbon Dioxide <i>K. Onishi, Y. Ishikawa, K. Okamoto, Z. Xue, Y. Yamada and T. Matsuoka</i>	351
Research of Mechanical Energy and Temperature Distribution During Dynamic Loading of Rocks <i>V. Petroš, J. Šancer and P. Michalčík</i>	352
Experimental Study on Deformation Behavior of Rock under Uniaxial Compression and Direct Tension <i>Q. Xie, X. Yu, C. D. Da Gama, Y. Na and Y. Zhang</i>	353

Field Test and Analysis of Rocks of the South-To-North Water Diversion Project <i>H. F. Xing, Q. B. Li, Z. H. Liu, G. B. Ye and C. Xu</i>	354
Experimental Study on Mechanical Properties and Longitudinal Wave Characteristics of Tuff, Granite and Breccia After High Temperature <i>Z. G. Yan and H. H. Zhu</i>	355
Experimental Study on the Permeability of Soft Rock <i>L. D. Yang, X. B. Yan, Y. Li and X. X. Zhang</i>	356
Requirements for Rock Stress Measurements in Pressure Tunnels of Seymareh Dam Project <i>M. Yazdani</i>	357
8. DISCONTINUITIES	359
8.1. General	359
Effect of Excavation Sequence and Fault Orientation on Stresses and Deformation Around a Cavern <i>H. C. Chua and E. C. Leong</i>	361
Importance of Infilled Joints in Shear Strength Assessment of Rock Mass <i>M. Jayanathan, B. Indraratna and H. S. Welideniya</i>	362
Unstable Phenomena at the Face Based on the Quantification of Discontinuity in Rock Masses for TBM Excavation <i>M. Kawakita, I. Ohtsuka, M. Iwano, S. Shimaya and M. Matsubara</i>	363
Influence of the Elasticity of Rock Walls at Large Scale on the Mechanical Behavior of Rock Joints <i>F. Vallier, M. Boulon, Y. Mitani and T. Esaki</i>	364
Surrounding Rock Reinforcement of Underground Powerhouse by Joint Mapping <i>F. M. Zhang, Z. Y. Chen, X. G. Wang, Z. X. Jia and Y. F. Dong</i>	365
Three Dimensional Joint Mapping and Its Application on Rock Mass Simulation <i>F. M. Zhang, J. Li, L. Wu, X. G. Wang and Z. Y. Chen</i>	366
8.2. Theoretical and Numerical Analyses	367
Improvement on Spacing Simulation in 3-D Network Modeling of Discontinuities in Rockmass <i>H. B. Jia, S. Z. Ma and H. M. Tang</i>	369

Numerical Modeling of Shear Behaviour of Inclined Saw-Tooth Mudstone-Concrete Joint using FLAC <i>K. H. Kong, A. Haque, J. Kodikara and P. G. Ranjith</i>	370
Unified Shear Model for Rock Joints <i>J. Muralha</i>	371
New Considerations on Rock Loads for Mined Tunnels <i>B. F. Townsend, C. R. Sperrs and H. Lager</i>	372
Research on Coupled Penetrating-Dissolving Model and Experiment for Rock Salt Crack <i>H. Zhou, Y. C. Tang, D. W. Hu, X. T. Feng and J. F. Shao</i>	373
8.3. Field and Laboratory Studies	375
Hydromechanical Behavior of Rock Joints by Rotary Shear-Flow Test <i>Y.-Y. Jeong, E. Kim and C.-I. Lee</i>	377
Study of the Interaction Between Hydraulic Fractures and Geological Discontinuities <i>E. M. Llanos, R. G. Jeffrey, R. R. Hillis and X. Zhang</i>	378
Experimental Study and Numerical Modeling of Direct Shear Tests of Rock Joints Under Constant Normal Stiffness <i>B. K. Son, C. I. Lee and J. J. Song</i>	379
Crossing of Fault Zones in the MFS Faido by Using the Observational Method <i>R. Stadelmann, M. Rehbock-Sander and M. Rausch</i>	380
Estimation of Permeability Structure of the Median Tectonic Line Fault Zone in Ohshika-Mura, Nagano, Japan, by using Laboratory Tests Under High Pressure <i>S. Uehara and T. Shimamoto</i>	381
Effect of Dilation Angle on Failure Mode and Entire Deformational Characteristics of Rock Specimen <i>X. B. Wang</i>	382
9. BLOCK THEORY AND DDA	383
Vibration Analysis of Laminated Blocks by Discontinuous Deformation Analysis <i>S. Akao, Y. Ohnishi, S. Nishiyama, T. Yano, T. Fukawa, T. Nishimura and K. Urano</i>	385
Block Removability Analysis of A Rock Slope Using Statistical Joint Modeling <i>S. W. Cho and J.-J. Song</i>	386

Seismic Risk Determination Using Numerical Analysis of Block Displacements in Historical Monuments with DDA <i>R. Kamai and Y. H. Hatzor</i>	387
Determination of Block Sizes Considering Joint Persistence <i>B. H. Kim, M. Cai and P. K. Kaiser</i>	388
Numerical Manifold Method for the Potential Problem for the Groundwater Flow <i>S. C. Li, S. C. Li, Q. S. Zhang and W. Zhu</i>	389
Coupling of Certain and Stochastic Discontinuities in 3-D Discontinuity Network Modeling <i>S. Z. Ma, H. B. Jia, H. M. Tang and Y. Y. Xia</i>	390
Engineering Geology Characteristic and the Low-Loose Method of Caving Mining System in Xiadian Gold Mine <i>F. Ren, S. Wang, P. Wang and T. Mu</i>	391
Cutting Joint Blocks and Finding Key Blocks for General Free Surfaces <i>G.-H. Shi</i>	392
An Experimental-Computational Approach to the Investigation of Damage Evolution of EDZ in Anisotropic Rock Mass <i>S. Wang, S. Jeon, C.-I. Lee, H. Lee, J. Kim and C.-A. Tang</i>	393
10. FAILURE, FRACTURE AND BURST	395
Numerical Study of Fracture Control Technique for Smooth Blasting <i>X. M. An and G. W. Ma</i>	397
Numerical Analysis of Rock Fracturing Process by DEM using Bonded Particles Model <i>K. Aoki, Y. Mito, C. S. Chang and T. Maejima</i>	398
Development of Fluid Flow Analysis Program in 3-D Discrete Fracture Network Including Consideration of Its Input Parameters and Hydraulic Behaviour <i>S. H. Bang and S. Jeon</i>	399
The Conductivity Variations of Single Rock Fracture During Normal Loading <i>C. Y. Chao, T. H. Huang and L. S. Chang</i>	400
Influence of Celestial Body Activity on the Rock Burst Occurrence in Coal Mine <i>X. H. Chen and M. L. Huang</i>	401

Experimental Assessment of Healing of Fractures in Rock Salt <i>K. Fuenkajorn</i>	402
Elastic-Plastic Fracture Damage Analyses on the Rock Cover of Ningbo Xiangshan Harbor Subsea Tunnel <i>G. Wang, S. Li and S. Wang</i>	403
A Coupled Approach for Gas Outburst Simulation <i>S. G. Chen</i>	404
Numerical Study of the Shearing of Large Fractures Having Propagating Boundaries <i>H. Hakami</i>	405
Study of Occurrence Conditions and Criteria of Rock Burst in Coal Mine <i>M.-L. Huang, X.-H. Chen and W. Lu</i>	406
Analyzing Scale and Pressure Dependent Properties of Fracture Using CT Scanner <i>T. H. Kim and D. S. Schechter</i>	407
Effects of Shearing Processes on Fluid Flow and Particle Transport in a Single Rock Fracture <i>T. Koyama and L. Jing</i>	408
Study on Interactive Mechanisms of Two Cracks Under Compressive Conditions <i>M. T. Li, S. C. Li, H. Zhou and W. T. Ding</i>	409
Geological Setting of the Rockburst of Qinling Tunnels in Central China <i>J. Ma, B. S. Berggren and H. Stille</i>	410
Localization of Water Flow in a Sheared Fracture as Estimated by Large Fractal Fractures <i>K. Matsuki and K. Sakaguchi</i>	411
Rock Burst Characterization for Underground Constructions <i>C. A. Öztürk, A. Fisne and E. Nasuf</i>	412
Rock Bursts, Experience Gained in Deep Tunnels and Mines <i>M. Rehbock-Sander, R. Stadelmann and A. Gerdes</i>	413
Research on the Coupling Support Mechanism of Soft Rock Tunnel at Great Depth <i>X.-M. Sun, M.-C. He and J. Yang</i>	414
Damage Assessment of EDZ in Rock Around Circular Opening by Acoustic Emission <i>S. Wang, C.-I. Lee, S. Jeon, H. Lee and C.-A. Tang</i>	415

Visualization and Quantitative Evaluation of Aperture Distribution, Fluid Flow and Tracer Transport in a Variable Aperture Fracture <i>J. Xiao, H. Satou, A. Sawada and A. Takebe</i>	416
Seismic Source Theory of Rock Burst and Analysis of Burst Process <i>Y. Yan, L. Kang, X. Zhang and X. Wang</i>	417
Induced Fracturing in the Opalinus Clay: An Intergrated Field Experiment <i>S. Yong, S. Loew, C. Fidelibus, E. Frank, F. Lemy and K. Schuster</i>	418
11. DAMS AND SLOPES	419
11.1. General	419
Stability Analysis of a Potentially Toppling Over-Tilted Slope in Granite <i>L. R. Alejano, I. Gómez Márquez, B. Pons, F. G. Bastante and E. Alonso</i>	421
Prediction of Post-Failure Motions of Rock Slopes Induced by Earthquakes <i>Ö. Aydan, N. Tokashiki, T. Akagi and R. Ulusay</i>	422
Calculation of Deterioration Depth of Rock Slope Caused by Freezing-Thawing in Korea <i>Y. Baek, O.-I. Kwon, S.-B. Yim, Y.-S. Seo and S.-H. Shim</i>	423
Slope Stability Analysis and Determination of Stable Slopes in Chador-Malu Iron Mine <i>S. Bodaghabadi and M. Ataei</i>	424
Fire Dam Construction for Underground Openings <i>A. Fisne, C. A. Öztürk and G. Ökten</i>	425
Analyses on the Rock Slopes Using Hazard Area Estimation System for Rock Mass Failure Debris <i>T. Kuwano, Y. Ohnishi, S. Nishiyama, M. Kawakita and Y. Sasaki</i>	426
Study on the Dynamic Response and Progressive Failure of a Rock Slope Subjected to Explosions <i>Y. Q. Liu, H. B. Li, J. R. Li, Q. C. Zhou, C. W. Luo and X. Xia</i>	427
Application of ANNs to Permeability Analysis at the Shivashan Dam, Iran <i>H. Owladeghaffari, Y. Pourrahimian and A. Majdi</i>	428
New Implementation Approach of Three-Dimensional Slope Stability Analysis Using Geographical Information System <i>C. Qiu, T. Esaki, M. Xie, Y. Mitani and C. Wang</i>	429

Investigation on Dam Foundation Grouting Process <i>H. Satoh, Y. Yamaguchi and T. Abe</i>	430
Slope Deformation Characteristics and Instability Analysis <i>B. Yuan, L. Ren and X. Zhu</i>	431
11.2. Theoretical and Numerical Analyses	433
Numerical Seismic Stability Safety Evaluation for Rock Slopes <i>M. Dai and T. Li</i>	435
Study on the Prediction of the Hazard Area Due to Rock Slope Failure by Using Neural Network System <i>T. Kanamoto, Y. Ohnishi, S. Nishiyama, T. Kuwano, M. Kawakita and Y. Sasaki</i>	436
Simulation Analysis of Toppling Failure of Rock Slope by Distinct Element Method Using Bonding Theory <i>H. Kusumi, S. Ohtsuki, T. Matsuoka and Y. Ashida</i>	437
Seismic Response Analysis and Earthquake-Induced Slope Failure — A Case Study of LAS Colinas Landslide, El Salvador <i>H. Y. Luo, W. Zhou, S. L. Huang and G. Chen</i>	438
A New Ground Water Analysis Method with Rainfall for Slope Stability Evaluation <i>S. Tachibana, Y. Ohnishi, S. Nishiyama and M. Ramli</i>	439
Three-Dimensional Stability of Slopes with Building Loads <i>F.-C. Zhu, P. Cao and K.-S. Zhang</i>	440
On Refined FEM Solution to Seepage in Arch Dam Foundation <i>Y.-M. Zhu, D.-M. Sun, E. Bauer and S. Semprich</i>	441
11.3. Field and Laboratory Studies	443
Comprehensive Back Analysis Techniques for Assessing Factors Affecting Open Stope Performance <i>P. M. Cepuritis and E. Villaescusa</i>	445
Presenting a Technical-Economical Solution for “Rockfall” Control in Section I of Rock Slope Facing Tehran-Fasham Road <i>M. A. Chermahini, A. A. Chermahini, F. Bahrami Samani and M. Züger</i>	446
A Case Study of Deformation Measurements of Slates at Javeh Dam Site in Iran <i>S. Hashemi and M. Gharouni-Nik</i>	447

Safety Factor Assessment Method for Rock Slope using Centrifuge Model Test <i>Y. Kusakabe, K. Miura, H. Ishikawa and Y. Ito</i>	448
Case Study on the Causes for the Failure of Large-Scale Rock Slope Composed of Metasedimentary Rocks in Korea <i>B. S. Park, H. Jo, C. S. Kim and J. H. Lee</i>	449
Probability of Rock Slope Failures at Part of a Mountain Road, Saudi Arabia <i>B. H. Sadagah</i>	450
Water Pressure Tests for Dam Foundations <i>Y. Yamaguchi, H. Satoh and T. Araie</i>	451
Measurement of the Dynamic Behavior of Unstable Rock Blocks Existing in the Rock Cliff <i>Y. Yamauchi, Y. Jiang and Y. Tanabashi</i>	452
The Deformation Mechanism and Dynamic Stability on Creeping Slope of Fushun West Open Cast Side-Slopes <i>T. H. Yang, S. H. Wang, C. A. Tang, S. Y. Wang, Q. L. Yu and Y. Q. Rui</i>	453
12. OTHER APPLICATIONS	455
Evaluation of the Excavation Damage Zone (EDZ) by using 3D Laser Scanning Technique <i>A. Bäckström, Q. Feng, F. Lanaro and R. Christiansson</i>	457
Numerical Simulation of Ice-Rock Interface Under Shear Loading <i>A. Bashir, Y. Zhang and H. Zhang</i>	458
Improvement of Rock Strata for Foundation of Reactor Buildings <i>A. Boominathan and S. R. Gandhi</i>	459
Feasibility Analysis of Physical and Chemical Soft Rock Modifications <i>Z. Y. Chai, T. H. Kang and Y. B. Li</i>	460
GIS System Development for Surface Subsidence Prediction Due to Complex Tabular Extractions <i>I. Djamaluddin, T. Esaki and Y. Mitani</i>	461
Application of the Design Parameters from Statistical Analysis <i>J. G. Kim, T. W. Ha and H. S. Yang</i>	462

Stability Analysis of Spread-Footing Foundations on Weak Rock Using Non-Linear FEM Modelling <i>D. Kumar and S. K. Das</i>	463
Rock Damage Zone Analysis using Back-Calculated Critical Strain <i>J.-G. Lee, E.-S. Hong and K.-H. Cho</i>	464
Parameter Identification and Prediction of Subsidence Using Artificial Neural Networks and FEM Database <i>J. H. Lee, Y. Yokota and S. Akutagawa</i>	465
Experimental Research on Pendulum Impact Properties of Frozen Clay <i>Q. Y. Ma and Q. H. Yu</i>	466
Experimental Study on the Mechanical Behavior of the Rib Arch Structure <i>S. M. Na, S. J. Lee, S. H. Cho and S. D. Lee</i>	467
Effects of Composition and Microstructures on Elastic Strain Energy in Clastic Rock <i>J. N. Pan, Z. P. Meng and J. C. Zhang</i>	468
Stress Variability Around Large Structural Features and Its Impact on Permeability for Coupled Modelling Simulations <i>Q. Ta and S. Hunt</i>	469
Application of Roadheader in High Strength Rock Formations <i>D. Tümac, C. Feridunoglu and N. Bilgin</i>	470
The Measurement of Present Crustal Stress in Lijin Oil Field and Its Application <i>H. Wang, D. Sun, G. Zhu, X. Chen, Y. Yang and H. Li</i>	471
Study on the Back Analysis of Multi-Parameters <i>S. L. Wang, Y. Y. Jiao, C. G. Li and X. R. Ge</i>	472
Crustal Stresses in Ryukyu Islands of Japan <i>H. Watanabe, H. Tano, N. Tokashiki, T. Akagi and Ö. Aydan</i>	473
Research of the Seepage Law of Adsorptive Gas in Single Coal Fracture <i>D. Yang, Y. Hu and Y. Zhao</i>	474
Method of Susceptivity Analysis of Parameters and Engineering Application <i>W. Yang, S. Li, X. Li and S. Li</i>	475
Stress and Pressure Changes Analyzed with a Fully Coupled Reservoir Model <i>S. Yin, M. B. Dusseault and L. Rothenburg</i>	476

Numerical Method for Mixed Failure of Rocklike Materials Based on Virtual Multi-Dimensional Internal Bonds <i>Z. Zhang, X. Ge and M. Zhang</i>	477
--	-----

Author Index	479
---------------------	-----

MEASURING ROCK MASS MODULUS OF DEFORMATION IN A STOPING-AFFECTED CROSS-CUT IN PONGKOR UNDERGROUND GOLD MINE

R.K. WATTIMENA¹, B. SULISTIANTO¹, K. MATSUI², B. DWINAGARA¹, and E. BARNAS¹

¹*Mining Engineering Study Program, Institut Teknologi Bandung, Indonesia
(e-mail of corresponding author: rkw@mining.itb.ac.id)*

²*Department of Earth Resources and Mining Engineering, Kyushu University, Japan*

This paper explains a rock mass deformation modulus measurement conducted in a cross cut at Pongkor underground gold mine, where there was an active stope underneath the cross-cut. It is revealed that the resulted rock mass deformation modulus was controlled by the stoping progress. The larger the dimension of the underneath stope, the higher the rock mass deformation modulus obtained, which was due to the higher induced stress in the test location. There was a 20-30% increase of rock mass modulus of deformation when the stope was advanced vertically from one mining slice to two mining slices, where the height of the slice was four metre.

Keywords: Rock mass; modulus of deformation; underground mine.

1. Introduction

Deformability is capacity of rock to strain under load or without load caused by an excavation that can be expressed quantitatively as modulus of elasticity or modulus of deformation (Goodman, 1989). Modulus of deformation of rock mass is one of the important factors required for design work within the rock mass, especially the design of an underground structure. It can be determined indirectly by applying a reduction factor to the rock elasticity modulus measured in laboratory or by using a number of formulas relating it with the rock mass quality or directly from *in situ* measurement.

In Pongkor underground gold mine, the first *in situ* measurement of rock mass modulus of deformation was carried out just recently. As the development and mining in Pongkor underground gold mine progress continuously, the measurement was conducted in an area that was affected by the stoping activities. The work reported in this paper is aimed at the investigation of the influence of stoping on the rock mass modulus of deformation measured in a cross-cut located above the stope.

2. Determination of Rock Mass Modulus of Deformation

2.1. Determination from intact rock modulus of elasticity

After reviewing a number of papers where laboratory and modelling properties were given, Mohammad, *et al.* (1997) found that if the Young's modulus results from laboratory tests (E) were plotted with those used in the model (E_m), the equation of the fitted straight line was:

$$E_m = 0.469 E \quad (1)$$

If the data were plotted as reduction factors, they also found a trend of increased reduction factors for low stiffness rock types and observed a number of very high reduction factors for very low stiffness rocks.

2.2. Determination based on rock mass quality

In the last 30 years, a number of authors have proposed formulas that can be used to estimate the rock mass modulus of deformation (E_m) from the Rock Mass Rating (RMR) and some of the formulas are given in the followings.

Bieniawski (1978) proposed that for fair to very good qualities rock masses with RMR greater than 50, the following formula could be applied:

$$E_m = 2 \text{ RMR} - 100 \text{ [GPa]} \quad (2)$$

whereas Serafim and Pereira (1983) suggested that the relation is not linear but follows the following formula:

$$E_m = 10^{\frac{\text{RMR} - 10}{40}} \text{ [GPa]} \quad (3)$$

For covering all qualities of rock mass, from very poor to very good qualities, the values in Table 1 were suggested by Chappel (1984).

Table 1. Modulus of Deformation Based on RMR (Chappel, 1984)

Rock mass quality	Description	RMR	E_m (GPa)
V	Very poor	0 – 20	0.05 – 0.5
IV	Poor	20 – 40	0.5 – 4
III	Fair	40 – 60	4 – 5
II	Good	60 – 80	5 – 25
I	Very good	80 – 100	25 – 50

As a result from his work with very poor to fair qualities rock masses with RMR less than 52, Stille (1986) introduced the following formula:

$$E_m = 0.05 \text{ RMR} \text{ [GPa]} \quad (4)$$

Other non-linear relations between RMR and E were put forward by Mehrotra, *et al.* (1991), Iasarevic and Kovacevic (1996), and Berardi and Bellingeri (1998) as given respectively in Equations (5), (6), and (7) below.

$$E_m = 10^{\frac{\text{RMR} - 30}{50}} \text{ [GPa]} \quad (5)$$

$$E_m = e^{(4.407 + 0.08\text{RMR})} \text{ [GPa]} \quad (6)$$

$$E_m = 0.87 e^{0.0455\text{RMR}} \text{ [GPa]} \quad (7)$$

Following the introduction of the Geological Strength Index (GSI) by Hoek (1994) and Hoek, *et al.* (1995) as a replacement of RMR in their failure criterion, Hoek and Brown (1997) modified the Serafim and Pereira (1983) equation for rock mass with intact rock uniaxial compressive strength σ_{ci} less than 100 MPa, as follows:

$$E_m = \sqrt{\frac{\sigma_{ci}}{100}} 10^{\frac{GSI-10}{40}} \text{ [GPa]} \quad (8)$$

Furthermore, taking into account the blast damage and stress relaxation, Hoek and Brown (2002) introduced the disturbance factor D and modified Equation (8) as follows:

$$E_m = \left(1 - \frac{D}{2}\right) \sqrt{\frac{\sigma_{ci}}{100}} 10^{\frac{GSI-10}{40}} \text{ [GPa]} \quad (9)$$

and for σ_{ci} greater than 100 MPa, the following equation was suggested:

$$E_m = \left(1 - \frac{D}{2}\right) 10^{\frac{RMR-10}{40}} \text{ [GPa]} \quad (10)$$

2.3. In situ measurement

In the last few years, there are three types of *in situ* tests are mostly used to determine the rock mass modulus of deformation (Palmström & Singh, 2001): Plate jacking test, plate loading test, and Goodman's jack test. In this work, rock mass modulus of deformation was determined by the Goodman's jack test. The Goodman's jack (see Figure 1) consists of a curved rigid bearing plate which can be forced inside an NX size borehole by a number of pistons. The displacement is measured with LVDT.

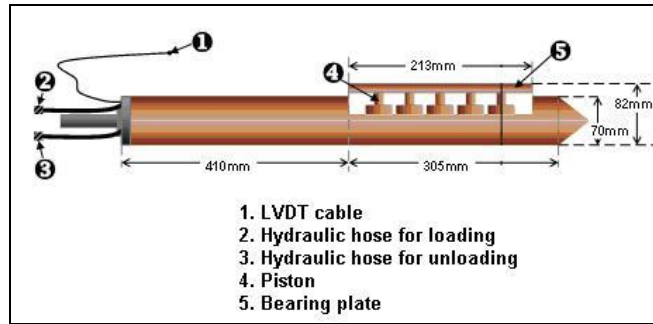


Fig. 1. Goodman's jack

The Goodman's jack test is conducted by applying pressure to the borehole wall in a number of loading-unloading cycles, and the rock mass modulus of deformation (E_m) is calculated using the following formula (Goodman, *et al.*, 1970):

$$E_m = \frac{\Delta Q}{\Delta u_d/d} K(\beta, \nu) \quad (11)$$

ΔQ = Pressure increment

d = Hole diameter

Δu_d = Change in hole diameter

K = Stress factor as a function of the central angle β of the load and of Poisson's ratio ν

3. Data Collecting

3.1. Test location

The Goodman's jack test was conducted in the Cross-Cut 6A Ciurug, Level 570, Pongkor Underground Gold Mine. Underneath the test location there was an active stope which was advancing towards the test location (see Figure 2). Three boreholes were used for the test, namely left, right, and front boreholes. The left and right boreholes penetrate the footwall (Andesitic breccia rock mass) whereas the front borehole was drilled into the Au-Ag orebody. In each borehole, three tests were conducted. In each test, eight measurements were conducted at eight different depths from the collar and at each depth four different loading directions were applied.

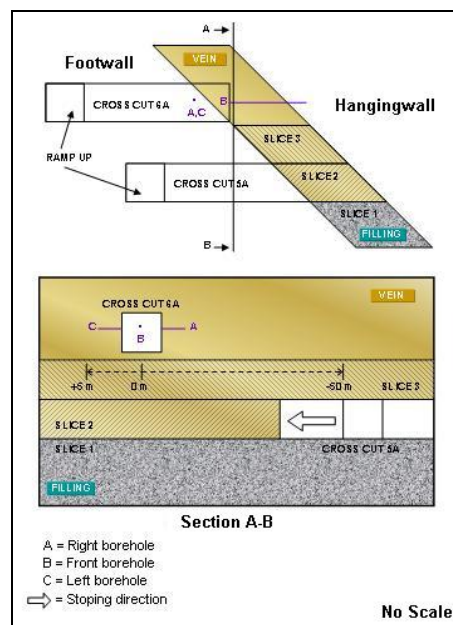


Fig. 2. Test location and boreholes configuration

3.2. Measured rock mass modulus of deformation

Table 1 shows the average values of the modulus of deformation of andesitic breccia rock mass and that of Au-Ag orebody. E_{GJ2} is modulus of deformation measured in a previous work (Hananta, 2005) that was conducted in the same boreholes, when the underneath stope was being mined in Slice 2 in Figure 2. E_{GJ3} is modulus of deformation measured in this work.

Table 1. Measured rock mass modulus of deformation

Rock mass	Measured modulus of deformation (GPa)	
	E_{GJ2}	E_{GJ3}
Andesitic breccia	5.58	6.67
Au-Ag orebody	5.28	6.96

4. Discussions

4.1. Comparison with intact rock modulus of elasticity

The uniaxial compressive strength tests conducted on andesitic breccia and Au-Ag samples revealed that the uniaxial compressive strength (σ_{ci}) of andesitic breccia was 63.35 MPa with Young's modulus (E) of 14.46 GPa. σ_{ci} and E for the Au-Ag ore were 57.83 MPa and 13.72 GPa, respectively. It means that the reduction factors are 0.46 for the andesitic breccia rock and 0.51 for the Au-Ag ore, which is generally in line with the findings of Mohammad, et al. (1997) described earlier in this paper.

4.2. Comparison with values estimated using rock mass quality

The Geotechnical Section of Pongkor Underround Gold Mine reported that the RMR of the andesitic breccia rock mass at the test locations was 52 and that of Au-Ag orebody was 53. Using these values in the equations relating rock mass modulus with RMR given earlier, the rock mass modulus of deformation were estimated and they are given in Table 2.

Table 2. Estimated rock mass modulus of deformation

Formula	Estimated modulus of deformation (GPa)	
	Andesitic breccia	Au-Ag orebody
Bieniawski (1978)	4.50	5.78
Serafim & Pereira (1983)	11.38	11.81
Chappel (1984)	4.61	4.64
Stille (1986)	n.a.	n.a.
Mehrotra, et al. (1991)	2.78	2.86
Iasarevic & Kovacevic (1996)	5.36	5.64
Berardi & Bellingeri (1998)	9.37	9.65
Hoek & Brown (1997)	9.06	8.98
Hoek & Brown (2002) with D = 0.7	5.89	5.84

It can be observed from Table 2 that rock mass modulus of deformation measured in this work are relatively closed to those estimated using the equations proposed by Iasarevic and Kovacevic (1996) and Hoek and Brown (2002). The measured values are lower than those estimated by Serafim and Pereira (1983), Berardi and Bellingeri (1998) and Hoek and Brown (1997) formulas.

4.3. Effect of the underneath stoping

There was a 20-30% increase in rock mass modulus of deformation measured in this work compared to that obtained in the previous work. It is obvious that when the stope was mining in Slice 3 the excavation dimension was larger than the dimension when the stope was mining in Slice 2 which caused higher induced stresses to the rock mass in the test location. Consequently, due to the nature of the Goodman's jack test, to enlarge the borehole diameter by a particular length, higher pressure was required for larger stope dimension. Subsequently, the gradient of pressure-displacement curve used in the determination of the rock mass modulus of deformation was higher which gave a higher rock mass modulus of deformation.

5. Conclusions

Determination of rock mass modulus of deformation in the area that was affected by underneath stoping has been carried out. It was observed that the stoping activity affected the measurement results. Higher rock mass modulus of deformation was obtained for larger underneath stope.

Acknowledgments

The authors wish to thank the management of Pongkor Gold Mining Business Unit of PT Aneka Tambang, Tbk. for giving permission to publish this paper.

References

- Berardi, R. and Bellingeri, P. (1998). "Deformabilità Degli Ammassi Rocciosi da Approcci Empirici e influenza Della Qualità del Materiale Roccioso e Dello Stato di Sforzo In Sito". *Rivista Italiana di Geotecnica Anno XXXII*, **1**: 39-55.
- Bieniawski, Z. T. (1978). "Determining Rock Mass Deformability: Experience from Case Histories". *International Journal of Rock Mechanics and Mining Science and Geomechanics Abstract*, **15**: 237-247.
- Chappel, B. A. (1984). "Determination of Rock Mass Modulus", Proceedings of the 4th Australia New Zealand Conference on Geomechanics, 1984.
- Goodman, R. E. (1989). "Introduction to Rock Mechanics", John Wiley & Sons, New York.
- Goodman, R. E., Van, T. K., and Heuze, F. E. (1970). "Measurement of Rock Deformability in Boreholes", *Proceedings of the 10th US Symposium on Rock Mechanics*, May, 1970.
- Hananta, F. N. (2005). "A Rock Mass Deformation Modulus Comparison Between Goodman's Jack Test and Estimation from Rock Mass Rating in the Cross Cut 6A Ciurug, Level 570, Pongkor Underground Gold Mine" (in Indonesian), Thesis (unpublished), Mining Engineering Study Program, Institut Teknologi Bandung, Bandung.
- Hoek, E. (1994). "Strength of Rock and Rock Masses". *ISRM News Journal*, **2**(2), 4-16.
- Hoek, E., Kaiser, P. K., and Bawden, W. F. (1995). "Support of Underground Excavations in Hard Rock", Balkema, Rotterdam.
- Hoek, E. and Brown, E.T. (1997). "Practical Estimates of Rock Mass Strength". *International Journal of Rock Mechanics and Mining Science*, **34**(8): 1165-1186.
- Hoek, E., Carranza-Torres, C. T., and Corkum, B. (2002). "Hoek-Brown Failure Criterion – 2002 Edition", Proceedings of the 5th NARM Symposium and the 17th Tunneling Association of Canada Symposium, July 7-10, 2002.
- Iasarevic, I. and Kovacevic, M. S. (1996). "Analyzing Applicability of Existing Classification for Hard Carbonate Rock in Mediterranean Area", Proceedings of International Symposium on Prediction and Performance in Rock Engineering, September 2-5, 1996.
- Mehrotra, V. K., Mitra, S., and Agrawal C. K. (1991). "Need of Long-term Evaluation of Rock Parameters in the Himalaya", Proceedings of the 7th International Congress on Rock Mechanics, 1991.
- Mohammad, N., Reddish, D. J., and Stace, L.R. (1997). "The Relation Between In-situ and Laboratory Rock Properties Used in Numerical Modelling". *International Journal of Rock Mechanics and Mining Science*, **34**(2): 289-297.
- Palmström, A. and Singh, R. (2001). "The Deformation Modulus of Rock Masses – Comparisons Between In Situ Tests and Indirect Estimates". *Tunnelling and Underground Space*

Technology, **16**(3): 115-131.

Serafim, J. L and Pereira, J. P. (1983). "Consideration on the Geomechanics Classification of Bieniawski", Proceedings of International Symposium of Engineering Geology and Underground Constructions, 1983.

Stille, H. (1986), "Experiences of Design of Large Caverns in Sweden", Proceedings of International Symposium on Large Rock Caverns, August 25-28, 1986.