

Performance analysis of TBM excavation parameters related to small-diameter horizontal and inclined tunnels

Original

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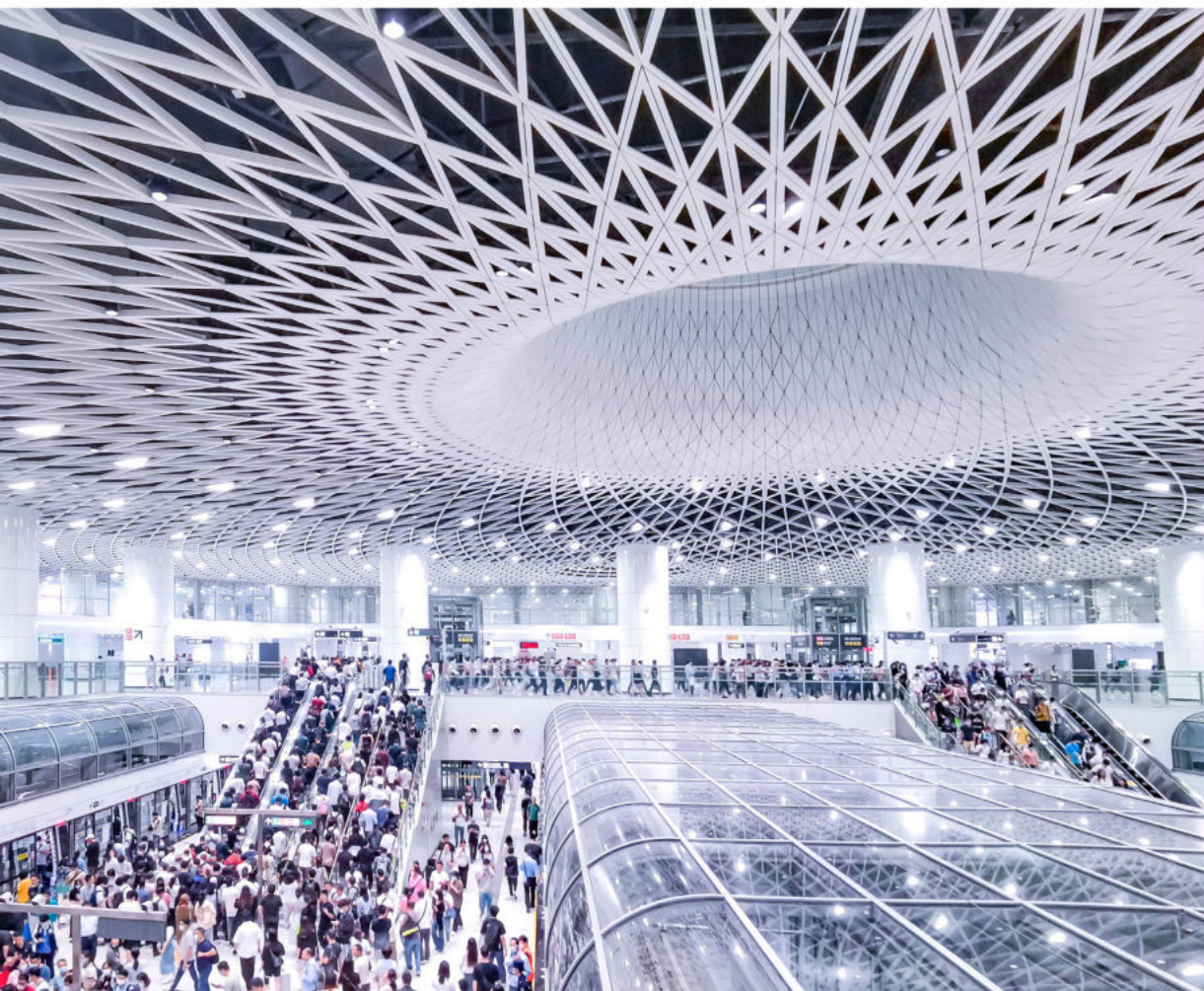
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Tunnelling for a Better Life



EDITED BY

Jinxiu Yan
Tarcisio Celestino
Markus Thewes
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TUNNELLING FOR A BETTER LIFE

Tunnelling for a Better Life contains the contributions presented at the ITA-AITES World Tunnel Congress 2024, which was held from 19-25 April 2024 in Shenzhen, China. As urbanization accelerates, the pivotal role of tunnels and underground spaces in fostering environmental sustainability and improving quality of life becomes ever more pronounced. These underground structures serve as sustainable solutions to the challenges posed by rapid urban growth. By seamlessly integrating into urban landscapes, they alleviate congestion, reduce pollution, and enhance overall mobility, thus contributing to a greener and more sustainable urban environment. Moreover, tunnels and underground works provide vital support for various urban functions, such as accommodating economic activities, providing safe shelters during emergencies or disasters, and facilitating efficient utility management. They address immediate urban needs and lay the foundation for a better and more resilient future.

By focusing on the latest trends in tunnelling and underground engineering, and looking ahead to the era of low-carbon and intelligent technology, the papers in this book illustrate the transformative potential of tunnels and underground works in shaping a better life for present and future generations. The contributions cover a comprehensive range of topics on tunnel engineering, showcasing the latest advancements, insights, and innovations across the following areas:

1. Planning and General Aspects
2. Design and Methodology
3. Geotechnics, Geology and Geophysical Prospecting
4. Ground Stability and Consolidation
5. Support and Lining
6. Conventional Tunnelling
7. Mechanized Tunnelling (TBM, shield)
8. Immersed Tunnels
9. Waterproofing and Drainage
10. Instrumentation and Monitoring/Testing and Inspection
11. Digital and Information Technology
12. Machine Learning
13. Underground Caverns/Underground Space Use
14. Operational Safety, Maintenance and Repair
15. Contractual Practices and Risk Management

Tunnelling for a Better Life is a must-read for professionals, engineers, owners, and other stakeholders worldwide in tunnelling and underground engineering.



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Tunnelling for a Better Life

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Table of contents

Preface	xxxvii
Acknowledgements	xxxix
WTC 2024 Organization	xli
<i>Planning and general aspects</i>	
Multilateral institutions and governance of urban underground space <i>N. Bobylev, Y.-K. Qiao & F.-L. Peng</i>	3
Forecast and trends related to key personnel for mechanised excavation with TBMs <i>F. Bove</i>	8
The common duct in New Taipei City <i>H.C. Chao, C. Song, T. Ko, I.K. Chiu & Y.C. Lin</i>	13
Progress and prospect of urban tunnel engineering in China <i>X. Chen</i>	20
New chemicals with reduced carbon footprint <i>F. Couturier, D. Matioszek & T. Boursier</i>	28
City Rail Link – City Rail Link: Managing challenges on the pioneer underground metro project in New Zealand <i>F. Dudouit</i>	33
Nuclear decommissioning in the UK: Cross-sector collaboration and learning with the tunnelling and underground space sector investigating alternative approaches to reactor dismantling and graphite retrievals <i>D. Garbutt & M. Knights</i>	41
Planning of alignment & proposed actions for tunnel collapse in diverse ground conditions on the steepest railway curves in the Eastern Ghats, India <i>R. Gupta, L. Kumar & A. Kumar</i>	47
Comparison of carbon footprint emissions in tunneling projects using innovative methods <i>P. Jarast & V. Nasri</i>	57
Collaboration in Moscow Metro development: Analysis of joint construction efforts by Russian and Chinese builders <i>V.P. Kivlyuk, A.I. Paschenko, D.S. Konyukhov, L. Xue, J. Zhou, S.N. Vinogradov, K.V. Orlov, Y. Song, J. Huo, Y. Lyu, Z. Gu & T. Wang</i>	65

The application of technology for resource utilization, reduction, and harmless treatment of subway shield tunneling waste soil	72
<i>J. Lei, H. Long, K. Jia, T. Song & H. Pan</i>	
Development and prospects of railway tunnels in China	78
<i>X. Li, S. Tian, W. Wang, J. Gong & H. Wang</i>	
Differentiated driving effects of China's green transportation facilities assessment policy	87
<i>Y. Liu & W. Qiu</i>	
Planning and execution of horizontal directional coring method for future tunnelling works	96
<i>F. Mahony, K. Goh & C. Veeresh</i>	
Theory meets practice: Evaluating discrepancies between theoretical settlement projections and actual measurements in tunnelling projects with tunnel boring machines	101
<i>E. Navarro, E. Salvador & F. Diez</i>	
Geotechnical and tunnel engineer's role on the success of major tunnel projects delivery	109
<i>J. Pan, D. Och, A. Kuras & G. Bateman</i>	
TBM traffic tunnels for sustainable infrastructure	116
<i>S. Pompeu-Santos</i>	
Underground space use layout planning using multi-source spatial data	125
<i>Y.K. Qiao, Z. Y. Li, N. Bobylev & F.L. Peng</i>	
Tunnelling in a green country – Brenner Base Tunnel study case: Decision and solutions in construction lot H41 Sill Gorge-Pfons	132
<i>I. Zamberlan & C. Schwarz</i>	
Technical challenges and countermeasures of plateau railway tunnels	139
<i>Y. Zhao, T. Zhu & G. Yan</i>	
<i>Design and methodology</i>	
Observational method and calibration of design safety factors to optimize technical-economical solutions in tunnelling projects	149
<i>A. Antiga, M. Lorenzi & A. Lucia</i>	
Design of Ontario Line South Tunnel	158
<i>M. Bakhshi, V. Nasri, T. Maalouf</i>	
Design challenges in conventional tunnelling on the Sotra Link Project in Norway	164
<i>G. Barbieri, G. Bella, E. Trivellato, S. Agrillo & M. Giani</i>	
(I)-TM: I-System's tunnelling method – four years of application in most challenging ground in India	173
<i>H. Bineshian</i>	
Segment design for Australia's largest diameter TBM tunnel	182
<i>S.F. Chau, H. Asche, D. Oliveira, J. Shepherd & C. D'Hondt</i>	
Review of key technologies for design of Dalian Bay Undersea Tunnel	193
<i>Z. Chen, H. Chen & M. Lu</i>	
Design of tunnel brace and retaining structure on East Artificial Island of Shenzhen-Zhongshan Link	200
<i>H. Chen, C.N. He, X.D. Lai & L. Yu</i>	

Sustainability of Shihmen reservoir by desilting tunnel in Taiwan <i>C.E. Chiang, P.S. Kuo, H.T. Chiang & Y.J. Lin</i>	209
Advanced countermeasure for encountering heavy gas influx in new Wu-shan-ling divert water tunnel <i>K.H. Chou, S.H. Wang, C.H. Chen & T.H. Chen</i>	214
The “hybrid” tunnel. An innovative solution for urban tunnel in soils. The case of Américo Vespucio Oriente AVO1, in Santiago de Chile <i>J.M. Galera, M. de Cabo & G. Ibarra</i>	220
The effect of the movement joint on the seismic response of the cross-passage intersection in segmental tunnel lining <i>G. Giordano, D. L’Amante & G. Fantauzzi</i>	228
Development of sustainable criteria for the Italian railway tunnel design <i>F. Iacobini & A. Pranno</i>	235
Analysis on applicability of seismic calculation methods for shield tunnel in Shanghai area <i>X.X. Li & H. Chen</i>	240
Validation of joint non-linear numerical analysis with large-scale physical testing for arched cut and cover tunnels at HS2 project (UK) <i>M. Li, S. Psomas & N. Al Haddid</i>	247
Innovative application of low-carbon and energy-saving technology in underground space: A case study of erlangshan tunnel on Sichuan-Tibet expressway <i>G. Lin, J. Zheng, J. Wang & F. Yang</i>	256
Low carbon emission design concept and method for tunnels and underground engineering <i>G. Lu, J. Liu, Y. Zhao, S. Shi & Z. Zhang</i>	261
Design of the REM Aéroport de Montreal’s P5 ventilation shaft <i>M. Mains, J. Lee & V. Nasri</i>	270
Tunnels and stations design of Montreal Blue Line <i>V. Nasri</i>	277
Influence of calculation method on the design of the secondary lining <i>J. Ortuta & M. Bakoš</i>	285
Research on smart design and innovation of Jiaozhou bay second tunnel <i>L. Qu, X. Li, M. Tan, H. Jiang, M. Xiao & W. Sun</i>	292
Application of a confinement-dependent spalling criterion for tunnels in highly stressed brittle rock <i>M. Rahjoo & E. Eberhardt</i>	300
Practical considerations of shale swelling impact on underground structures liner design for Ontario Line transit project in Toronto, Canada <i>M. Rahjoo & V. Nasri</i>	308
How to consider the effects of longitudinal joint imperfections on internal forces in segmental tunnel linings <i>F. Rauch & O. Fischer</i>	315
Athens metro “Piraeus” station: Numerical analysis versus observational method <i>K. Sampsakis-Bakopoulos & N. Gerolymos</i>	323

Karanga-a-Hape Station MC21 Junction – Collaborative solutions for complex geology and geometrical constraints - Tackling the challenges at Karanga-a-Hape Station caverns <i>A. Sarathchandran, G. Charlesworth & R. Graafhuis</i>	329
Design of temporary cofferdam and deep excavation for cofferdam tunnel of Shenzhen-Zhongshan Link <i>Z. Shi, C.N. He, L. Yu & Q.W. Xia</i>	337
Comparative effects of twin-stacked tunnel excavation on adjacent structure using different simulation models <i>N. Sittiamornporn, P. Jongpradist, C. Phutthananon, A. Chayaroon & P. Malaisree</i>	345
Key technology of Submarine railway tunnel in complex environment and high-water pressure <i>C. Song, W. He, S. Lv & Y. Yu</i>	352
Development and innovation of design method for railway tunnel support system in China <i>S. Tian, D. Liu, Y. Zhang & X. Li</i>	360
Maungawhau mined tunnels - Collaborative design – Management of design amendments for Maungawhau mined tunnels for improved construction schedule outcomes <i>H. Toi, R. Gong, D. Wang & G. Charlesworth</i>	368
“SINTEF-TriPOD” in underground design – A demonstration for two projects in Norway <i>N. Trinh & E. Grov</i>	377
Automatic computation for design of tunnel shafts <i>C.K. Tsang, A. Koay & T. Sia</i>	385
Case study about adjacent three-arch tunnel <i>H. Tseng, K. Kuo & T. Chu</i>	390
Optimizing the tunnel ventilation design related to respirable dust in tunnelling by using CFD <i>R. Wei, R. Galler & C. Weiß</i>	396
Study on the mechanism of tunnel structure damage under the combined effects of fault creep and earthquakes <i>Z. Xia, S. Jia, J. Wang & Q. Wang</i>	402
Theory and practice of total safety factor method for tunnel support structure design <i>M. Xiao, B. Xie, C. Xu, K. Wang & Z. Deng</i>	406
Considerations of the coefficient of subgrade reaction forces on seismic response displacement method of a double-circular shield tunnel <i>M. Xu & T. Manabe</i>	416
Analysis of key technologies in structural design of prefabricated station of Shenzhen Metro <i>Z. Xu, D. Meng, R. Liu & M. Li</i>	424
Addressing design challenges in large diameter tunnels with big openings in deep soft ground: Innovative solutions and analysis techniques <i>J. Yuan, V.C.S. Goh & C. Maxcia</i>	432
Aseismic mechanism of laminated shear energy dissipation structure in tunnels during an earthquake <i>X. Zhang, A. Cao, Y. Jiang & X. Wang</i>	441

Geotechnics, geology and geophysical prospecting

An improved simplified solution for the characteristic line of tunnels in strain-softening rocks <i>M. Anthi, Th. Pferdekämper & G. Anagnostou</i>	451
Estimation of tunnel support loads due to large deformation in squeezing ground conditions <i>K. Arora & M. Gutierrez</i>	457
Tunnelling in weak sandstone: A case study of Subansiri Lower Hydroelectric Project (2000 MW) <i>M.S. Chouhan & S. Potnis</i>	467
Correlation of empirical classification systems in squeezing anisotropic environment and optimisation of underground supports in a headrace tunnel; a case study from Tanahu Hydropower, Nepal <i>E. Christakis, B. Parajuli, P. Yao & R.K. Adhikari</i>	476
Hydro-geo-mechanical properties for water flow prediction in tunnelling <i>M. Coli & R.E. Rizzo</i>	485
3D Geological reconstruction and application of tunnel face <i>D. Duan, H. Bai, W. Li & W. Qiu</i>	493
Study of microgravity survey to predict the Bukit Timah rock head for tunnelling in Singapore <i>T.E.S. Ernest, C. Veeresh, J. Kumarasamy & K.H. Goh</i>	501
Rock drilling aerosol deslagging technology and CFD-DEM two-way coupling numerical simulation of weak surrounding rock geology <i>S. Guo</i>	509
Uninterrupted continuous forecasting in mechanized tunnelling in rock <i>J. Hecht-Méndez, T. Dickmann & D. Krueger</i>	517
Limits on the estimation of the EPB face pressure. A concrete example based on Kalman filter approach <i>C. Iasiello, A. Flor & P. Fantini</i>	523
Experimental study of rheological characteristics of bentonite-based drilling fluids <i>S. Javarone, M. Palombini, M. Cinelli, I. Bavasso & D. Sebastiani</i>	529
Optimized electrical exploration for predicting geological transitions ahead of a tunnel based on harmony search algorithm <i>M. Kang, K. Kwon, S. Park, Y. Choe & H. Choi</i>	536
High resolution resistivity imaging for assessment of geological conditions ahead of tunnel face in a complex geology <i>S.L. Kapil</i>	542
Tunnel engineering application of assessment technology of karst development degree based on hydrochemical kinetics and fractal theory <i>C. Li, J. Wu, Q. Li, W. Yu & S. Lu</i>	548
Model test and analysis of failure mechanism of deep high sidewall tunnel from splitting failure to zonal disintegration <i>F. Li, Q. Zhang, G. Xin & G. Long</i>	556
Development and test of directional coring drilling system for advanced geological exploration <i>J. Liu</i>	565

Geological risks in TBM tunneling and its prediction by HSP method <i>S. Lu, Y. Xiao & X. Wang</i>	572
Rock abrasiveness in the studies of são paulo metro: Tests, classification systems, parameters obtained from various lithotypes and their relationship with weathering degree <i>M.D. Monteiro, H.C. Rocha, G.B. Robbe & A.M. de Almeida</i>	579
Phased prediction method for construction period of secondary lining construction time of tunnel in squeezed rocks <i>L. Ning</i>	584
Ground characterisation of the Sydney Basin for tunnelling works <i>D.J. Och, J. Pan, I.T. Graham, N. Walker, A. Kuras & G. Alvarado</i>	591
Chengdu-Guiyang High-speed railway—Yujingshan Mountain Tunnel crossing giant karst cave and underground river <i>W. Qing, Y. Yu, J. Zheng, Y. Zhu & Y. Wang</i>	598
Tunnel behavior in soft soils subjected to pore water pressure drawdown <i>A. Santos, R. Pérez-Léon, J. Rodríguez-Rebolledo & B. Caicedo</i>	608
The deformation characteristics of soft soil layers with different sand content and the time and space effects of foundation pit excavation on the tunnels below <i>C. Shen, M. Miao, C. Huang, Y. Dong & J. Fan</i>	616
Non-invasive tunnelling investigations using muon tomography <i>C. Steer & L.F. Thompson</i>	625
Empirical correlations between ground's mechanical properties and I-system <i>C. Upadhye, S. Potnis & B. Hoss</i>	629
Research on key technology of design of long tunnel in water-rich karst platform of compound syncline basin <i>H. Wang, M. Wang, H. Fu, P. Li & Z. Li</i>	638
Numerical simulation of the mechanism of strain rockburst under true triaxial loading and unloading conditions <i>Y. Xue & H. Tian</i>	647
Sequential 3D geological information system using re-grid of voxel model based on exploration data ahead of the tunnel face <i>S. Yoshikawa, Y. Aono, K. Saito & T. Nishi</i>	655
HSP Method-based advanced geological prediction and tunneling parameter pre-control technology for super-large diameter pipe-jacking project <i>Z. Zhao, F. Lan, B. Wang, L. Meng, X. Wang & S. Lu</i>	660
<i>Ground stability and consolidation</i>	
Excavation induced settlement in Sydney area <i>G. Alvarado, S. Sadeghian & Y. Dong</i>	671
A modified approach to assess tunnel excavation stability <i>S. Anwar & G. Charlesworth</i>	678
Study on crosslink-induced Xanthan Gum biopolymer treated soil as a subsea tunnel backfill grout for saline condition permeability control <i>J. Bang, D.-Y. Park, J. Kim, S. Im & G.-C. Cho</i>	685

Fixing of unstable water-saturated soils by artificial freezing for construction of inter-tunnel joints during metro construction	689
<i>E.A. Deplagni, V.P. Kivliuk & D.S. Konyukhov</i>	
Factors impacting thawing-refreezing around tunnels in permafrost soils	695
<i>S. Gavhane & S. Potnis</i>	
Deformation characteristics of long and narrow deep foundation pit with partition walls	705
<i>H. Geng, S. Guan, Z. Chen, G. Dai & Z. Li</i>	
Disturbance effect and surrounding rock pressure characteristics of loess shield tunnels	711
<i>X. Han, P. Wang, Z. Chen, H. Feng, H. Cui & F. Ye</i>	
Numerical simulation of polymer grouting for rock fracture: Influence of isocyanate index on grout propagation	718
<i>M. Hao, J. Zhang, L. Zou & X. Li</i>	
Dynamic soil response around a shallow rectangular tunnel and adjacent building	726
<i>Z. He & S.P. Gopal Madabhushi</i>	
Chemical-combined jet grouting for mass treatment of break-in area in Vietnamese urban underground construction	732
<i>H.Q. Le, H. Oyama & P.N. Do</i>	
A systematic deformation control methodology for underground space construction in close proximity to an existing metro station	740
<i>J. Li, R. Wen, W.W. Yang & W.F. Mou</i>	
Study on diffusion mechanism of backfill grouting in sand and clay stratums	747
<i>S. Li, F. Ye, T. Xia, K. Ying & X. Han</i>	
Influences of stress-dilatancy rule on the derivation of ground response curve for deep-buried tunnels	755
<i>J. Liang, J. Chen, J. Ma, H. Yang & L. Huang</i>	
The use of jet grouting technology: An overview of the different applications in tunnelling	760
<i>P. Lunardi, G. Lunardi, G. Cassani, M. Gatti, L. Bellardo & C.L. Zenti</i>	
Stability analysis of surrounding rock in a highway tunnel crossing a Water-Rich fault fracture zone	769
<i>S. Luo, X. Xie & D. Zhu</i>	
Selection of an ontological model for phyllite tunnel based on on-site measured	777
<i>J. Ma & J. Zhang</i>	
Analysis of stability of rock column between cut & cover metro station and NATM tunnels	783
<i>S. Maiti, M. Khare & S. Potnis</i>	
The freezing technique for the world's longest railway tunnel	789
<i>A. Marottoli, M. Ianeselli, R. Marrazzo, A. Gallotto, G. Vecchione, M. Cavolo & F. Gallo</i>	
Stability of portal slopes of a diversion tunnel after the Kahramanmaraş, Turkey (Türkiye) February 6, 2023 Earthquakes	798
<i>A.A. Mert & F. Caliskan</i>	
Numerical analysis of the deformation of undersea tunnel crossing fault zone	806
<i>J. Ni, J. Zhang, H. Huang, D. Zhang, & L. Zhang</i>	

Research on surrounding rock by shallow tunnelling in Boulder-Cobble Mixed formation: Instability characteristics and control strategies	813
<i>Y. Qin</i>	
Practical approach for the control of surface settlements due to TBM tunnelling during excavation by following up of monitoring	822
<i>V. Rattia, H. Rocha, A. Dantas, T. Mendes & A. Assis</i>	
Jet grouting soil improvement to excavate a tunnel under passing the A4 Milano-Venezia motorway for the extension of the line 1 of the Milan metro	828
<i>M. Silvestri, D. Chirulli, A. Antiga & P. Coppola</i>	
Study on the mechanical behavior of the vertical pre-reinforcement	836
<i>Y. Tatebayashi, N. Tamura, T. Amemiya, K. Kawata & N. Isago</i>	
Marble sludge in two-component grout applications	842
<i>C. Todaro, A. Carigi, M. Cardu & D. Peila</i>	
Study of support design and construction results of unconsolidated in Aso Caldera	848
<i>T. Tomita, T. Ano, H. Nagamatsu, H. Hirano & H. Tabata</i>	
State of the art of soil conditioning technology for earth pressure balance shield tunnelling	857
<i>Z. Wan, S. Li, S. Zhao, K. Qiu & S. Hao</i>	
Numerical prediction of tunnelling-induced displacement field in large and very shallow tunnels	865
<i>W. Yang, D. Zhang & D. Boldini</i>	
Stability numerical investigation of laminated and randomly discontinuous flat roof	871
<i>P. Yiouta-Mitra & E. Vougioukas</i>	
Responses of a shallow tunnel in liquefiable ground subject to multiple shakings	877
<i>J. Zhang, E. Bilotta, Y. Yang & Y. Yuan</i>	
Failure mechanism of reinforced faces and design method of advanced supports for tunnels excavated by the full-face mechanized method	882
<i>X. Zhang, M. Wang & L. Yu</i>	
Key technologies and safety analysis of deep foundation pit construction in a sea area	890
<i>Z. Zhao & S. Gao</i>	
Data-driven stability analysis and uncertainty quantification of surrounding rock mass for tunnel	897
<i>H. Zhao & L. Zhang</i>	
Study on settlement deformation of existing structures under ultra-large diameter shield tunnel	906
<i>M. Zou, C.L. Zhen & X. Xie</i>	
<i>Support and lining</i>	
Rock bolt design, A numerical parametric study	917
<i>S. Anwar, A. Mann & S. Sadeghian</i>	
The effect of a frictional interface in a preliminary yielding support for a deep tunnel	926
<i>L. Batocchioni, V. González & S. Miliziano</i>	
Numerical calculation approach for the design of segmental tunnel lining equipped with inflatable O-ring sealing	932
<i>M. Bazzani, F.D. Santis, P. Fantini, M. Daniele & S. Pesa</i>	

The mechanism, functioning and installation of reinforced ribs of shotcrete in Norwegian Method of Tunnelling (NMT)	941
<i>R. Bhasin & M. Shabanimashcool</i>	
Shotcrete structural behaviours as tunnel support in hard jointed rocks – Swedish state of the art	946
<i>Y. Chang & C. Höök</i>	
Study on the influence of cracks on mechanical behaviors of tunnel lining of high speed railway with a speed of 400 km/h	953
<i>P. Chen, K. Liu & C. Yan</i>	
Design and verification of shear key support system for segmental lining openings at cross passages using non-linear finite element model	962
<i>J.T. Chong</i>	
Environmental and economic advantages in using HPFRSCC in tunnelling	969
<i>M. Coli, M. Francini, L. Martelli & M. Tanzini</i>	
Structural and sustainability requirement with high performance fibre reinforced precast segment carbon counting example	977
<i>B. de Rivaz</i>	
Research on reinforcement measures for soft plastic loess tunnel base	983
<i>Q. Deng</i>	
Analytical solution to failure history of segment joint with inclined steel bolt	991
<i>X. Dong, B. Du & X. Chen</i>	
Numerical analysis of two deep circular shafts at a former gas works site on the London Power Tunnels Phase 2 scheme	1000
<i>J. Ellis, O. Brown, A. Simic, R. Kundan & J. Coupland</i>	
Comparative analysis of simplified solutions for the radial joint behaviour of segmental tunnel linings with finite element numerical modelling	1008
<i>A. Emadi & A.R. Gomes</i>	
Steel lining support in headrace tunnel of Uma Oya Project, Sri Lanka	1015
<i>A.R. Farshbar, A. Noorzad, P.V. Yuvaraju & B. Rejith Kumar</i>	
Durability of two-component backfill grout: An experimental study	1021
<i>M.D. Felice, A.D. Giulio & N. Valiante</i>	
Tangential resistance between primary and secondary lining with PVC waterproofing sheet membrane	1027
<i>L. Forlingieri, C. Hu, M. Morosi & A. Zanichelli</i>	
Carbon reduction in conventional tunnelling by advanced design	1036
<i>A. Gakis, P. Salak & F. Wilhelmstoetter</i>	
Advanced joint non-linear design analysis and verification of the arched cut and cover tunnels at high speed 2 project (UK)	1044
<i>N.A. Haddid, S. Psomas & M. Li</i>	
The stiffness of circular joints and its effect on the deformation of the tunnel segmental lining along the longitudinal direction	1053
<i>X. Han, F. Ye & P. Oreste</i>	

Comparison of structural load-bearing performance between precast and cast-in-place permanent linings <i>K. Kikuchi, A. Kusaka, Y. Koizumi, T. Watanabe & Y. Tatsumi</i>	1062
Development and application of highly adaptable lining equipment for complex tunnels with variable sections <i>J. Liu</i>	1071
Mechanism of anchor cable in super-span tunnel and its design method <i>J. Liu, G. Lu, Y. Zhao & S. Shi</i>	1078
Using orthogonal flexible support structure to deal with large deformation of soft surrounding rock tunnel: A case study <i>Y. Liu & W. Qiu</i>	1086
Study on railway tunnel lining anti-crack surface reinforcement strengthening and design method <i>Z. Liu, X. Xing & L. Gong</i>	1092
An innovative primary support system of steel shotcrete composite structure in the tunnel <i>J. Lu & M. Li</i>	1098
Stress analysis of high geothermal tunnel lining structures considering different cooling measures <i>M. Luo, Z. Yuan, L. Fan, L. Tao & Y. Zeng</i>	1105
Thrust jack loading of large diameter precast segmental tunnel lining <i>M.A. Mooney, H. Zheng, C. Naito, S. Quiel & Z. Ouyang</i>	1112
Computational approaches towards segmental linings with a reduced environmental impact <i>G.E. Neu, V. Gudžulić & G. Meschke</i>	1118
Snowy 2.0 - Support design for intersections between access tunnel and caverns <i>X.-P. Nguyen, P.-L. Tonioni, A.-N. Blaise, R. Taherzadeh, D. Galli & G. Cardone</i>	1126
Research on high-quality and high-durability of tunnel lining by mixing volcanic glass powder <i>M. Nomura, S. Tomoto, T. Shiina, N. Mitsui, S. Yoshida & D. Hanaoka</i>	1135
Achieving high load-bearing capacity linings in sprayed concrete and segmental linings with high-performance steel fibres <i>D. Oliveira</i>	1144
EN 14488-3 notched panel versus EN 14651 notched beam testing for pre-construction trial conformance testing of Sprayed Concrete Linings (SCL) <i>C. Peaston & B.D. Rivaz</i>	1151
Tunnel lining design in hard rock conditions. application of observation method. A case study of a large-scale tunnel cavern for underground train station <i>M. Petkov, P. Hansson & J. Pilbacka</i>	1159
Risk assessment and large diameter segmental lining design in swelling ground <i>S. Sánchez, M. Mains, C. Álvarez, E. Barrouillet, C. Garrido & M. Ferreres</i>	1167
The numerical analysis for the segments floating mechanism of the large-diameter shield tunnel in the Rich Water Strata <i>Z. Shi, J.-F. Xu & X.-Y. Xie</i>	1174

Analysis of composite shell lining based on laminated theory <i>W. Shuyi</i>	1183
Singapore's land transport authority: 25 years of sprayed concrete lining tunnelling <i>A. Sim, K.B. Chang, M. Marotta, C.K. Poh & M. Mohiadeen</i>	1189
Design of precast bolted universal segmental tunnel lining for the London Power Tunnels phase 2 scheme <i>A. Simic, O. Brown & J. Ellis</i>	1199
Value engineering of concrete mix to save 230 tonnes of steel fibre for the west section of the Thames Tideway Tunnel <i>J. Su, S. Sheth, A. Ellison & C. Barret</i>	1207
Dynamic response characteristics of ultra-shallow buried metro station structures under surface vibration load <i>L. Tao, L. Deng, Y. Zhang & Z. Jia</i>	1216
Mechanical response and fault-resistant design of urban shallow subway tunnel under normal fault <i>L. Tao, J. Liu, Z. Wang & M. Shi</i>	1224
Analytical solution for longitudinal response of cross-fault mountain tunnels based on foundation beam model <i>L. Tao, M. Qiu, H. Zhang, Z. Jia, C. Shi</i>	1231
Experimental study on mechanical properties of grouted π -type SCCS arch <i>Z. Wang, W. Li & Y. Cai</i>	1238
Study on deformation joint width of mining tunnel under the operation of a normal fault <i>Q. Wang, D. He, J. Chen, P. Geng & H. Shen</i>	1244
Analysis of issues in the theory and calculation methods of composite lining for hard rock tunnels <i>N. Wang & X. Yang</i>	1250
Analysis of mechanical behavior and engineering suggestions for double-arch tunnel without middle drift <i>C. Wang, D. Zhang & Y. Li</i>	1258
A mechanical analysis model for tunnels crossing active fault zones <i>M. Wang, X. Zhang & L. Yu</i>	1267
Study on mechanical characteristics of a DDCI connection structure for longitudinal joints <i>M. Xiao, J. Chen, G. Xue, Z. Yan & S. Wang</i>	1276
Research on support parameters of the second Jiaozhou Bay Subsea tunnel based on the total safety factor method <i>M. Xiao, W. Sun, L. Chen & L. Jin</i>	1282
Research on the airproof performance of shield tunnel segment sealing gasket based on laser surface microstructure <i>M. Xiao, G. Xue, J. Chen, C. Zhang & S. Wang</i>	1291
Research on the application of marine engineering mass concrete with anti-cracking agent <i>B. Xie, W. Xu, Y.J. Wang, J. Zhang, W. Jin & J. Liu</i>	1297

Development and application of wall-climbing grinding robot for tunnel lining steel formwork <i>K. Yan</i>	1303
Retrospective analysis of the design and manufacture of a case of steel fibre reinforced segmental lining in view of the actual behaviour of some rings on site <i>Z. Yang, Z. Gu & P. García de Haro</i>	1312
Robustness evaluation on non-circular segmental tunnel linings: Case study on quasi-rectangular shield tunnel <i>Y. Ye, Z. Liu & X. Liu</i>	1321
The effect of polypropylene fiber on the strength and crack propagation of foam concrete <i>R. Yin, Q. Li, X. Zeng & W. Qiao</i>	1326
Research on construction technology of drilling and blasting tunnel based on load adjustment control technology <i>G. Ying, R. Zheng, Y. Xing & W. Chen</i>	1333
Construction and applicability of using double supports in a large overburden ground conditions as a countermeasure to suppress displacements <i>S. Zhai, D. Abeyawardena, H. Aoki, S. Ohmori & N. Isago</i>	1340
Mechanical evolution mechanism of primary support under steel arch frame corrosion in subsea tunnel <i>Y. Zhang, S. Tian, M. Wang & L. Yu</i>	1347
Effect of excavation on the pipe roof deformation under the action of the pipe roof-beam support system <i>W. Zhao, Q. Bai & D. Pi</i>	1356
Study on horizontal earth pressure of segment considering the influence of backfill grouting pressure <i>J.-L. Zhong, X.-C. Zhong, Y.-Z. Jian & F.-D. Li</i>	1365
Impact of base rock deterioration on the mechanical characteristics of loess-expansive mudstone tunnel lining structure <i>H. Zhu</i>	1373
 <i>Conventional tunnelling</i>	
Crystalline silica exposure in tunnel construction: Identifying barriers to safe practices <i>F. Anlimah, V. Gopaldasani, C. MacPhail & B. Davies</i>	1383
Design and construction optimisation of the Karanga-a-Hape Station mined tunnels and bored tunnel cross passages on the City Rail Link project <i>V. Balakumarsingham, P. Daudibertières, E. Chatoux & W. Okada</i>	1390
Experiences during tunnelling in extreme ground conditions in the Himalayas - Excavation of Rohtang Tunnel, India <i>R. Bernard</i>	1399
The impact of ramp width on tunnel face stability during ramp excavation <i>Q. Chen & Y. Cui</i>	1405
Deep underground mined cavern excavations in Auckland city centre, New Zealand <i>T. Cheung, W. Okada & S.F. Chau</i>	1412

Construction of Girgaon Station of Mumbai metro line – 3, a combination of cut & cover and conventional tunnelling and mix of social and technical challenges in congested urban environment	1418
<i>S.G. Dalvi, R.R. Kumar, S.K. Gupta & A. Rawat</i>	
Challenges in the conventional tunnel mixed-face execution	1424
<i>T. de Sá Lima, B. Scodeler & E.P. Filho</i>	
Research on key technologies for the construction of extra long tunnels on green roads in karst peak cluster areas	1429
<i>Z. Dong, B. Guo, Y. Zhou, Mengyan & S. Xing</i>	
Challenges and lessons learned from 100 km of major hydropower tunnels in Bhutan	1437
<i>T. Dorji, D. Brox & S. Wangdi</i>	
Design and construction considerations for cross passages in Bangkok subsoil	1446
<i>O. Duangsano, A. Sramoon, A. Asanprakit, A. Chayaroon & N. Phienwej</i>	
Construction of underground rail tunnel above deep tunnel sewerage system	1455
<i>H.M. Fong, Q. Li & C. Veeresh</i>	
A study of merits and demerits of steel decking verses concrete decking for traffic management and construction logistics during construction of underground metro stations for Colaba-bandra-seepz (line 3) in Mumbai, India	1461
<i>S.K. Gupta, R.R. Kumar, D. Binnar & S. Vishwakarma</i>	
Automatic blasting design and construction system optimized for geological conditions	1469
<i>R. Hemmi, Y. Ide, K. Kakimi, T. Shizawa & F. Ito</i>	
Effect of focusing tube geometry and abrasive flow rate on rock drilling width	1475
<i>H.-J. Hwang, Y. Cha, J. Kim, C. Park & G.-C. Cho</i>	
Development of advanced tunnel blasting and shotcrete as automated tunnel construction system	1479
<i>K. Iwano, T. Aoyagi, T. Yamagishi, T. Mega & T. Inuzuka</i>	
Unforeseen excavation of mixed face soil conditions in a hard rock drill and blast road tunnel	1486
<i>P.D. Jakobsen, H. Nilsen & A.K. Lund</i>	
Evaluation of removable time of tunnel lining formworks using surface wave techniques	1492
<i>K. Kato, C. Kuroda, N. Utagawa & K. Ohno</i>	
Construction of desilting chambers and connecting tunnels for Vishnugad Pipalkoti He Project (444mw) in adverse geological conditions and very remote location - A case study	1499
<i>R.K. Khali</i>	
Construction of tunnel T-49A on Dharam – Qazigund section of Udhampur-Srinagar-Baramulla New BG railway line project in highly adverse geological conditions- A case study	1507
<i>R.K. Khali & S. Yalal</i>	
Construction of a new tunnel in proximity to an in-service tunnel by implementing measures to control blasting vibration and ground displacement	1517
<i>Y. Kobayashi, T. Ishii, T. Koma, K. Nakano & Y. Kinomura</i>	
Cross passage tunnel excavation by core cutting machine (Stitching) and hydraulic rock splitters in hard rock at Mumbai Metro Station Line-03 (Aqua Line)	1526
<i>A. Kumar Saw, S. Potnis, M.J.C. & M. Roy</i>	

Test and research on load spectrum of tunnel drill jumbo <i>X. Liu</i>	1532
Experimental study of step method construction in soft and broken surrounding rock section of super-long and large section tunnels <i>Y. Liu, Y. Wang, T. Zhu, M. Tian & Q. Cheng</i>	1540
Innovative practice of mechanized and intelligent construction technology for railway mountain tunnel drilling and blasting method <i>K. Liu, Y. Yu, Y. Li & X. Liu</i>	1549
The Brenner Base Tunnel: An overview of the excavation types used in the project <i>D. Marini, G. Venditti, D. Unteregger, R. Insam & R. Marazzo</i>	1561
Key construction technologies for high-speed railway tunnels that with shallow buried depth and gentle slope in loess platform <i>W. Mi, Y. Wang, H. Zhang, X. Miao, J. Zhang & M. Zhang</i>	1569
Construction procedures of the tunnel for the extension works of Madrid Metro Line 3 from Villaverde Alto to El Casar <i>M. Núñez & J. Zurdo</i>	1579
Deformation failure characteristics and control measures of shallow loess tunnel of water-rich stratum: A case study <i>K. Tang & J. Qiu</i>	1586
Impacts of the February 2023 Kahramanmaraş, Turkey earthquakes on outlet works in rock formations <i>P. Uygur, Ö. Öztürk, E. Dumlu & F. Çalıřkan</i>	1594
Research and development support for the construction of the big circle line on the example of the line's intersection with the existing facilities of the Moscow metro <i>V.V. Viazovoi, R.A. Evtushenko, D.S. Konyukhov & D.S. Petunina</i>	1602
Evaluation of impacts on existing structures induced by deep excavations in Bangkok MWA project <i>P. Vonghirunyika, W. Kroehong, T. Yonjoho, K. Kandavorawong, A. Chayaroon, O. Duangsano & P. Jongpradist</i>	1610
<i>Mechanized tunnelling (TBM, shield)</i>	
Investigation of vibration patterns generated during rock cutting tests <i>U. Ates, H. Copur & A. Shaterpour-Mamaghani</i>	1621
Bio-polymer sodium alginate application as an eco-friendly additive in slurry TBM excavation <i>A. Bae, Y.J. Shin, Y. Choe, S. Kim & H. Choi</i>	1630
More efficient, cost-effective and reliable Slurry Treatment Plants (STPs) for mechanized tunnelling operations in the Asia-Pacific region <i>K. Bai & G. Vogt</i>	1634
An evaluation of using different excavation methods related to specific geologic conditions in the Istanbul area <i>C. Balci & N. Bilgin</i>	1641

Critical issues in selecting conventional and mechanized tunnelling methods, lessons learned from the past	1648
<i>N. Bilgin & C. Balci</i>	
Computational modeling of cutting disc-rock interaction in mixed ground conditions	1654
<i>S.N. Butt, J. Rostami & G. Meschke</i>	
Pumice mineral using as a backfill grout injection in TBM excavations	1663
<i>U.C. Çalışkan, S. Beyhan & H. Ergin</i>	
Performance analysis of TBM excavation parameters related to small-diameter horizontal and inclined tunnels	1669
<i>M. Cardu, C. Todaro, O. Farzay, A.D. Giovanni & S. Saltarin</i>	
Wear prediction of disc cutter tools during shield tunnelling in composite stratum based on improved deep learning method	1675
<i>J. Chang, D. Zhang & H. Huang</i>	
A modified foam half-life time test method for EPB shield tunnelling	1682
<i>Z. Chen, A. Bezuijen & Y. Fang</i>	
Automatic excavation system for directional control in shield tunneling using machine learning techniques	1687
<i>J. Chen, H. Kamada, N. Takamoto, H. Sugiyama, S. Yamamoto & T. Aoyama</i>	
Influence analysis and control measures of super-large diameter shield tunnel undercrossing the existing tunnel in upper-soft and lower-hard composite stratum	1694
<i>J. Chen, Z. Lv & H. Lou</i>	
Influence of TBM cutter configurations on gravel excavation characteristics revealed by discrete element method	1698
<i>Y.-F. Chen, T.-T. Wang & F.-S. Jeng</i>	
Research on the application of high-strength burn-free building blocks made from shield muck	1705
<i>H. Chen, Y. Xiao, B. chen, A. Lin & X. Liu</i>	
The key technology of large section pipe jacking for main structure of station in complex water-rich sand bed	1711
<i>B. Cheng, W. Huang, X. Shuai & Y. Tan</i>	
Box jacking construction technology for large cross-section box culverts passing under existing high-speed railways	1719
<i>C. Cheng, J. Wang & Y. Li</i>	
City Rail Link – bored tunnel challenges in Auckland city centre, New Zealand	1728
<i>T. Cheung, S.F. Chau, T. Ireland & S. Eratne</i>	
Research and application of multi-curve small turn continuous belt conveyor	1737
<i>L. Cui, H. Xu, J. Shen, J. Cheng, P. Song, Q. Qin & W. Yang</i>	
Slurry treatment technology based on calcium oxide and seawater of extra-large diameter slurry balance shield machine in Zhuhai area muddy silty clay stratum	1742
<i>R. Dong, Z. Zhou & W. Liao</i>	
Field monitoring and numerical modelling of ground heaves due to shield tunnelling in soft ground conditions	1750
<i>O. Duangsano, A. Chayaroon, P. Yensri, A. Asanprakit & N. Phienwej</i>	

Research and application of key technologies for the TBM tunnel construction under extremely complex geological conditions	1759
<i>H.H. Feng & K.R. Hong</i>	
Evaluations and considerations on the squeezing rock tunnelling in twin TBM tunnel of Rishikesh to Karanprayag railway project in Himalaya	1768
<i>M. Forooghi, V. Bansal, M. Tajik, S. Jain, S. Batuman & P. Aggarwal</i>	
Structural behaviour mechanism of vertical jacking method on large sections and influencing factors analysis	1777
<i>Y.-M. Gao, X. Liu, Z. Liu, G. Ramos & J. Turmo</i>	
Research on the automatic and synchronous construction technology of fully prefabricated internal structures inside large-diameter shield tunnels	1784
<i>Z. Ge, Z. Tang, C. Chen & X. Liu</i>	
The Sicilian job, 21 TBMs simultaneously at work to modernize the railway infrastructure of the largest island in the Mediterranean Sea	1792
<i>R. Grandori & R. Bono</i>	
Evaluating TBM design and performance, 30 years apart: The Lesotho Highlands Water Tunnel, phase 1 and phase 2	1800
<i>B. Grothen</i>	
Load condition effect based on functional model for the ultimate bearing capacity of segmental lining	1806
<i>C. Guo, R. Dong, X. Dong, C. He & Y. Cai</i>	
Negligible ground surface movement with EPB TBMs in Singapore marine clay and fluvial sand	1814
<i>G.C. Hangadi, L.J. Pakianathan, C.K. Poh, J. Lim & R. Koh</i>	
Development and application of supersized tunnelling technology for China's large-scale construction of underground infrastructure	1820
<i>S. Hu, J. Hoss & W. Sun</i>	
Failure analysis and coping suggestions for TBM tools under complicated geological conditions	1828
<i>H. Huan Feng, S. Ying Wang, L. Wei Yang & Y. Dong Yang</i>	
Construction method for rapid construction of station by use of large-diameter shield tunneling machines expanding small-diameter shield tunnels and its application	1837
<i>L. Huang, K. Jia, J. Zhang, D. Yu & T. Song</i>	
Breaking the tunnel vision: Generalizing TBM performance prediction across projects	1843
<i>S. Huang, R. Sousa & G. Korfiatis</i>	
Study on soil discharge efficiency of earth pressure balance shield tunneling in deep buried depth sandy stratum	1850
<i>S. Huang, X. Zhong, Z. Zhou & T. Feng</i>	
Muck discharge efficiency depending on soil conditioning by laboratory-scale model test	1860
<i>B. Hwang, A. Bae, D. Lee, K. Lim & H. Choi</i>	
Use of biomass as soil conditioner to improve clay rheology in EPB tunneling	1866
<i>M. Ishaq, B. Appleby, J. Rostami, J. Samaniuk</i>	
TBM jamming and statistical estimators: Case of a long and deep tunnel	1875
<i>D. Kasal, A. Flor, F. Amadini & A. Oss</i>	

Construction of a Horseshoe-shaped trenchless tunnel using the rectangular element propulsion method	1884
<i>D. Koizumi, T. Shimotsu & T. Tanaka</i>	
Decision-Making approach for parallel earth pressure balance machine advancements for tunnel construction	1893
<i>N. Kumbhar & S. Tirpude</i>	
Short launch of TBM to overcome economic and logistic difficulties in Sri Lanka	1902
<i>D. Lees, J. Sánchez, Y. Chengzhi, S. Banda, D. Denman & P. Muniyandy</i>	
Adaptability design and application of TBM cutterhead in Beishan extremely hard rock geological conditions	1909
<i>J.F. Li</i>	
Real time estimation and early warning of rock mass strength and integrity in TBM tunneling	1916
<i>Q. Li, L. Du, Y. Yang, X. Zhao, Y. Zhao, Y. Quan & S. Su</i>	
Three-dimensional centrifuge modelling of the effects of TBM on adjacent piles	1926
<i>X. Liang & S. Haigh</i>	
Geotechnical dimensioning of TBMs and new technological challenges	1935
<i>G. Lunardi, G. Cassani, M.C. Gatti & A. Zimbaldi</i>	
Line 2 y Ramal - Red Básica Metro Lima y Callao – Conditioning of different types of soils encountered during the tunnel excavations with 2 TBMs (EPB and Variable Density)	1944
<i>J.L. Magro, M. Calleja, R. Bono & S. Iacullo</i>	
Large diameter slurry TBM tunnels with very low cover: A comparison of approaches	1953
<i>M. Mains, S. Sánchez, L. Içik & C. Mora</i>	
The mechanised excavation of the exploratory tunnel of the Brenner Base Tunnel: The major challenges	1959
<i>D. Marini, A. Lussu & G. Venditti</i>	
Excavation management system for mechanized tunnelling in urban areas	1967
<i>M. Marotta, J. Kumarasamy, A. Sim, C.K. Poh & K.B. Chang</i>	
Advancing mechanized tunneling through integrated digital design, simulation, and data-driven techniques	1974
<i>G. Meschke, Y. Zendaki, A. Alsahly & B.T. Cao</i>	
TBM design and special features for boring through highly squeezing ground	1981
<i>M. Monina, M. D'Ambrosio & F.D. Rossi</i>	
The application of tunnel boring machines in the execution of incline and decline tunnels in mining projects	1987
<i>M. Nasiri, H. Moammeri & G. Stripp</i>	
Soil conditioning for TBM performance advancement in mixed geology	1994
<i>E.D. Negro, A. Boscaro, E. Barbero, A. Menghini & C. Butterworth</i>	
Tunnel excavation with EPB: Development of new conditioning agents to reduce the amount of water required for soil conditioning	2003
<i>E.D. Negro, A. Boscaro, E. Barbero, C. Todaro & D. Peila</i>	

Managing tunnelling risks in urban environment using first earth pressure balance/variable density slurry Tunnel Boring Machine (TBM) in Hong Kong for the MTR East Rail Line Cross Harbour Extension of the Shatin Central Link project	2012
<i>N. Ng, D. Kwork, K. Kwork & D. Jacques</i>	
Is a large TBM diameter unfavourable under squeezing conditions?	2020
<i>A.N. Nordas, T. Leone & G. Anagnostou</i>	
Developments in large diameter subaqueous tunnels	2028
<i>O. Ozgur, T. Ma & J. Cheung</i>	
Design and construction excellence at Tuen Mun-Chek Lap Kok Link tunnels: An engineering marvel beyond boundaries	2035
<i>W.H. Patrick, E. Baranger, K. Choi, P. Thompson & A. Raine</i>	
TBM Sub-sea tunnelling in the Arabian Gulf	2043
<i>G. Peach, H. Vigil & K.S. Al-Khayareen</i>	
Green TBM: Design targets, features and power efficiency	2049
<i>A. Petriccioli, L. Tafuri & R. Grandori</i>	
On the interplay between face extrusion and shield loading in squeezing conditions	2056
<i>Th. Pferdekämper & G. Anagnostou</i>	
Research on curved tunneling and bending angle calculation of articulated shield tunneling machine	2062
<i>W. Qiao, X. Zhou & X. Liang</i>	
Analysis of motion characteristics of large-sized irregular particles in long pipelines	2070
<i>Z. Ren, S. Wang, Y. Wang & X. Zhou</i>	
Experimental study and simulation verification of slurry penetration process	2076
<i>Z. Ren, L. Ye, X. Zhou, Y. Wang & S. Wang</i>	
Passage of TBM EPB under buildings with deep foundations, with physical interference	2082
<i>H. Rocha, F. Hirata, G. Robbe, W. Giannotti & T. Pires</i>	
TBM performance in rock conditions of water diversion tunnel constructions (Mae Ngad-Mae Kuang tunnel) in Chiang Mai Province, Thailand	2087
<i>K. Sarapagdee, A. Laddakul & T. Saelao</i>	
A new AFTES guideline: Suitability and selection process of pressurized TBMs in urban contexts	2099
<i>M. Schivre & F. Renault</i>	
JWPCP effluent outfall tunnel in Los Angeles, California – Anticipated challenges and slurry TBM performance in the soft ground section of the alignment	2108
<i>M. Scialpi, M. Piemontese, R. Schürch, M. Kendall & N. Karlin</i>	
A review of deterministic approaches in the performance evaluation of Raise Boring Machines (RBMs)	2116
<i>A. Shaterpour-Mamaghani, H. Copur, C. Balci & D. Tumac</i>	
Distinctive considerations in the design and construction of large diameter TBM-built tunnels in urban environment – a UK perspective	2122
<i>S. Shen</i>	

Smarter, larger, leaner, greener – trends of the tunnelling industry towards a sustainable future in the United Kingdom	2130
<i>S. Shen & A. V. Serin</i>	
Tunneling successes in West Los Angeles - Purple Line Project Section 3	2139
<i>E. Sillerico, M. Ellwood, C. Davis, A. del Amo & E. Whitman</i>	
Application of EPB-TBM dual-mode shield tunneling technology in Shenzhen Metro	2148
<i>T. Song, J. Yang, L. Huang, J. Lei, K. Jia, J. Huang & J. Lu</i>	
A newly developed reduced CO ₂ backfill grout system for TBM operations	2157
<i>M. A. Sposetti</i>	
Successful tunnelling in the desert, Wakrah and Wukair Drainage Tunnel, Doha, Qatar	2162
<i>J. B. Stypulkowski & K. S. F. S. Al-Khayareen</i>	
TBM design for operation in gassy formation	2170
<i>L. Tafuri, O. Bonfanti & A. Lisardi</i>	
Successful steering control with partial soil excavation for station crossing of a 13.08 m diameter EPB TBM in Lodz, Poland	2179
<i>M. Tomaszewski, S. Nortoft, F. Bove & M. D'Ambrosio</i>	
Planning, design and construction for mechanised cross passage excavation	2185
<i>C. K. Tsang, T. J. Sia, Z. G. Zhang, L. Sun & K. Chen</i>	
A study on intelligent assembly technology for Mid-partitions in shield tunnels and application	2193
<i>H. Wang</i>	
Creative design for Herrenknecht TBM used in Jiangyin Jingjiang Yangtze River crossing tunnel construction	2202
<i>H. Wang, R. Jin, G. Lin & W. Sun</i>	
Research on settlement control of large diameter shallow buried shield tunnel crossing railway and reservoir embankments	2209
<i>J. Wang, S. Yan, C. Wang, Q. Yang, J. Sun & S. Xue</i>	
Slaking characteristics of clay blocks and the influence of dispersant	2215
<i>S. Wang, H. Zhu & P. Liu</i>	
Revealing inherent mechanism affecting loess-metal interface adhesion properties: Insights from macro- and atomic-scale tests	2222
<i>B. Wu, W.-C. Cheng & X.-D. Bai</i>	
Challenges and solution of super large diameter TBM tunnel construction in urban center	2229
<i>X. Xiao, L. Jiao & Y. Li</i>	
Research on vertical dry tailings conveying technology and equipment of shaft boring machine	2239
<i>C. Yang</i>	
Study on classification prevention and control technology of hard rock rockburst in TBM construction	2244
<i>Y. Yang, L. Du, C. Gong, Y. Song, Q. Li & M. Wang</i>	
Prediction model of TBM tunneling speed based on geological parameters	2253
<i>Y. Yang, L. Du, R. Tang, F. Wei & H. Zhang</i>	
Research on prefabricated metro station structure and key assembly technologies	2262
<i>X. Yang & F. Lin</i>	

Numerical investigation of the excess pore water pressure generated by TBM tunnelling in saturated and unsaturated aquifers: A comparable study <i>C. Zhang & A. Bezuijen</i>	2271
Launching technology with shallow overburden for super-large diameter slurry shield <i>B. Zhang, H. Wang, X.B. Xie, Y. Y. Lu & Z. Chen</i>	2280
Experimental research on foam performance and intelligent injection control of foam additive system of tunnel boring machine <i>C. Zhang & Y. Zhai</i>	2286
Visualization study on stability of shield tunnel face with transparent soil model <i>H. Zhao, Z. Jia & Y. Liu</i>	2294
Application study of combined machining in the cutterhead design for hard rock tunnel boring machine <i>M.B. Zhou</i>	2302
Shield self-driving technology and its application <i>W. Zhou, M. Hu, H. Wu, B. Wu & J. Lu</i>	2309
Research on frontier technology of shield machine/hard rock machine selection and mode innovation <i>W. Zhu, J. Wang & W. Xie</i>	2316
Development and application of a synchronous shield tunnelling technology combining advancement and segment fabrication <i>Y. Zhu, Y. Zhu, X. Bi, X. Wang, Z. Zhang, J. Chen, Y. Qin & S. Duan</i>	2323
 <i>Immersed tunnels</i>	
Achieving sustainable immersed tunnel projects <i>J. Baber</i>	2333
Research on fire resistance limit standard of steel-encased concrete immersed tunnel structure <i>P. Cao, S. Song, M. Wu, S. Jiang & E. Liu</i>	2342
Stability and deformation analysis of dry dock slope in Haihe Tunnel, Tianjin, China <i>C.N. He, Y. Qu, E.C. Qing & J.Q. Shen</i>	2349
Research on online intelligent prediction of service status of immersed tunnel based on artificial intelligence <i>H. Ding & P. Cao</i>	2358
Key developments of world's immersed tunnel design and construction solutions <i>A. Doorduyn, Y. Li, H. de Wit, M.T. Hart & W. Chen</i>	2366
Structural optimization design of seamless expansion joint based on finite element analysis <i>W. Jiang, S. Zhang, Y. Wang, R. Bao & J. Shan</i>	2376
Analysis and research on seismic effects of immersed tunnel joints of Shenzhen-Zhongshan Link <i>Z. Li, Z.J. Chen & H. Chen</i>	2388
Seismic resilience assessment for longitudinal response of immersed tunnels <i>X. Li & H. Yu</i>	2394
Void detection method and its application for steel shell-concrete interface of immersed tube tunnel <i>S. Li, Y. Zhang & S. Feng</i>	2400

Assessment of operational limits for tunnel element transport using a shallow draft semi-submersible barge	2407
<i>M. Lin, Z. Ying, W. Shen & X. Wang</i>	
Research and application of steel intelligent manufacturing of Shen-Zhong Link steel sandwich immersed tunnel	2414
<i>H. Long, W. Rui & Y. Xie</i>	
Research and application of transportation and landing technology for Shen-Zhong Link super large steel shells of immersed tunnel	2421
<i>H. Long, W. Rui & G. Zhang</i>	
Innovative research on key technologies for dredging construction of immersed tunnel	2429
<i>D. Ma, P. Zhang, Z. Li & Y. Yao</i>	
Immersed tunnels – knowledge sharing in the past showing the way towards sustainable solutions in the future	2434
<i>T. Olsen</i>	
Small-scale model test for the dynamic behavior of submerged floating tunnels considering the coastal connection with subsea bored tunnels	2442
<i>J. Park, S.-J. Kang, J.-B. An, J. Kim & G.-C. Cho</i>	
Mechanical behaviors of steel-concrete-steel immersed tunnel composite structures	2450
<i>S. Song, X. Nie, J. Fan, Y. Guo & H. Zhang</i>	
Key technologies of concreting construction of super-wide steel-concrete-steel sandwich immersed tunnel element tubes in Shenzhen–Zhongshan Link	2457
<i>Z.-X. Su, X.-D. Wu, C.-L. Zhang & S.-Y. Song</i>	
Experimental study on the typhoon resistance by placing Shenzhen-Zhongshan Link immersed tunnel element on the seabed	2466
<i>S.-P. Sun, Q.-A. Ou Yang, W.-H. Li & J.-J. Ma</i>	
Assessing the suitability of coarse sand for the sand flow method in immersed tunnel foundations	2475
<i>X. Szadkowski, M. van der Molen, R. Hermsen & R. Montijn</i>	
Ventilation and smoke exhaust technical scheme of super wide section immersed tunnel	2483
<i>X. Yang, L. Cheng & M. Zhong</i>	
Fire prevention and rescue technologies used in ultra-wide cross-section immersed tunnel	2487
<i>X. Yang, L. Yin, M. Zhong & L. Cheng</i>	
Quantitative detection method and practice of voids at the interface of steel-shell concrete with complex structure	2492
<i>H. Zhao, G. Liu, Z. Fan, L. Sun, L. Meng & L. Wang</i>	
Research on settlement calculation method for DCM composite foundation of immersed tunnel in Shenzhen-Zhongshan Link	2500
<i>J.-J. Zhou, F.-Y. Xia, Z.-J. Chen, X.-N. Gong, D. Liu & J.-L. Yu</i>	
<i>Waterproofing and drainage</i>	
Next generation tunnel waterproofing	2509
<i>Y. Boissonnas</i>	
Mitigation of the sources of infiltration in the segment sealing gasket	2517
<i>G. Bomben</i>	

Analysis of cement grout hydraulic erosion in a homogeneous fracture <i>H. Duan & L. Zou</i>	2522
Seepage and drainage study of underwater tunnel connecting section with combined method <i>H. Fu, K. Hu, Y. Wu, Y. Yu & W. Liu</i>	2529
Comparison of double shell and sprayed single shell waterproofing methods in tunneling <i>I.U. Gök, E. Karahan & B. Ünver</i>	2539
Constitutive model of aged EPDM rubber in subsea shield tunnel <i>C. Gong, C. Xie, Y. Ge & J. Song</i>	2548
Research and application of joint waterproofing technology for prefabricated metro station structures <i>M. Huang, Q. Fan, X. Yang & L. Fang</i>	2554
Innovative waterproofing system for shallow underground structures <i>D.S. Konyukhov, T.E. Kobidze & O.B. Krymov</i>	2561
Tunnel drainage system and the possibility of non-destructive remediation <i>J. Ortuta & V. Tóth</i>	2567
Step effects of hydraulic pressure of tunnels in loess under high-pressure seepage <i>J. Qiu, K. Tang, Z. Zhao, Y. Bai, N. Zhang, Y. Chen & S. Ding</i>	2575
ITAtch design guidance chapter for composite Sprayed Concrete Lined (SCL) tunnels waterproofed with sprayed membranes <i>J. Su</i>	2584
Self healing materials for preventing tunnel crystalline damage: Anti-calcium leaching, mechanical performance, self-healing mechanism <i>Y. Tong, F. Ye, C. Tian, Y. Jiang, J. Zhang, H. Wang, B. Wu & X. Han</i>	2593
Analysis of viscous fingering between water and cement-based grout in tunnels <i>S. Zhang, F. Johansson & L. Zou</i>	2602
Analysis of cement grout propagation with varying fracture apertures <i>L. Zou, G. Zirgulis, A.N. Ghafar, U. Håkansson & V. Cvetkovic</i>	2610
 <i>Instrumentation and monitoring/testing and inspection</i>	
Design and development of tunnel liner void detection system <i>A. An, W. Luo, G. Tian, Y. Xu, L. Gao & J. Zheng</i>	2619
Tunnel condition assessment: State-of-the-art <i>S. Behbahani, J. Steinkuehler, J. Rostami, X. Wang & T. Iseley</i>	2624
Ground movement due to shaft construction and dewatering at Bengeworth road for the London Power Tunnels 2 scheme <i>O. Brown, A. Simic & J. Ellis</i>	2630
Application of Acoustic signal to quantify the damage of the lesser Himalayan sandstone under unconfined compression loading and its implementation in the micromechanical damage-plasticity model <i>S. Chajed & A. Singh</i>	2639
Tunnel detection and monitoring technology based on terrestrial laser scanning <i>Y.-J. Cheng, C. Wang & W.-G. Qiu</i>	2644

Bored tunnels: Automated extraction of segment edge location from scan data <i>J. Douglas, O. Côté & S. Jain</i>	2650
Cavity detection model from GPR images considering reinforcing bars in tunnel segment lining <i>C. Hwang, S. Yang, S. park, H. Kim & H. Choi</i>	2658
Combination of modelling and monitoring in assessing stability of a tunnel constructed in highly deformable rock and fragilized by fire <i>T. Kazerani & E. Garin</i>	2664
Field measurement of pile transient lateral response to advancing tunnel <i>C.M. Khoo, H. Mohamad, B.P. Tee & M.F. Ghazali</i>	2672
Model experiment on load-bearing performance and failure process of newly proposed invert to reduce volume of excavation <i>Y. Koizumi, A. Kusaka, N. Isago, K. Kawata, T. Otsu & N. Mikami</i>	2681
A noncontact mobil system using camera module for tunnel inspection <i>C. Lee, D. Kim & D. Kim</i>	2689
Tunnel indirect monitoring and damage identification method based on SET-Swin transformer <i>Q. Li, X. Xie & K. Zeng</i>	2696
Effectual approach to characterize rock fracture: Insight from calculating method of fractal dimension <i>B. Li, W. Zhang, Y. Xue, K. Li, J. Zhao, Y. Chen, R. Kong & G. Wang</i>	2702
Research on integrated monitoring platform of composite steel-concrete immersed tunnel <i>X. Mao, Z. Zhang & L. Li</i>	2717
Study for health monitoring of mountain tunnels operation using distributed fiber optic sensing technology <i>H. Nonaka, Y. Miyajima, N. Sakamoto, Y. Taira, T. Yamamoto, M. Imai, K. Koike, K. Kishida, H. Shinbo & J. Kawabata</i>	2724
Development of wear detection device using dye <i>Y. Omae, Y. Imaoka, H. Ueda, A. Nakamoto & R. Fukui</i>	2731
Structure health sensing network layout and monitoring based on wireless sensor network in undersea tunnel <i>L. Ouyang, H. Huang, D. Zhang, C. Wang & S. Zhu</i>	2737
Innovative shaft inspection system for the Gotthard Base Tunnel <i>M. Puglia, P. Spohn, K. Wachter, L. Chelini & S. Xiao</i>	2745
Fault diagnosis system for tunnel boring machines based on electrical energy monitoring <i>Y. Qin, C. Zhang, S. Huang, Z. Wu, H. Shen & J. Sun</i>	2751
Pivotal role of instrumentation & monitoring in construction of Mumbai Metro Line 3 in an urban setting <i>A. Rawat, R.R. Kumar & S.K. Gupta</i>	2757
Geotechnical instrumentation for road tunnels: Success cases in Colombia <i>V. Restrepo, H. Salazar & J. Piedrahita</i>	2763

Analysis of laboratory tests for the determination of the clogging risk in mechanized tunnel excavation in fine-grained soils	2771
<i>D. Sebastiani, S. Mangifesta, A. de Lillis & S. Miliziano</i>	
Information entropy based Robust Sensor Placement (RSP) method for wireless sensing of shield tunnel deformation	2778
<i>J. Shi, H. Huang & Z. Guan</i>	
Design and key features of shaft and tunnel excavation monitoring system implemented in Singapore's Deep Tunnel Sewerage System Phase 2 Project	2784
<i>A.K.K. Soe, L.L. Woo, K. Khin, P.C. Koh, A. Maxwell & E. Valdez Jr</i>	
Research on concrete strength detection method based on digital drilling and machine learning	2792
<i>R. Wu</i>	
Development and application of similar materials to cobble stratum for solid-fluid coupling model test	2800
<i>W. Zan, W. Zhang & Q. Yang</i>	
Study on the deformation and stress law of single shell lining in subsea rock tunnels	2809
<i>W. Zhang</i>	
Using the acoustic emission and infrared thermal imager to identify the precursor of rock violent failure	2817
<i>S. Zhu, D. Zhang, H. Huang, C. Wang & L. Ouyang</i>	
<i>Digital and information technology</i>	
BIM Modelling & reality capture in underground drill and blast caverns	2825
<i>P.R. Antón, I.J.F. Teixeira, A. Barbeta, B.B. Vieira & F. Abreu</i>	
The Sotra Link Project (Norway): An application of the BIM methodology in tunneling design and construction	2834
<i>G. Barbieri, E.D. Panics, G. Bella, D.D. Femina, A. Biagi & M. Giani</i>	
INFRA-BIM interoperability for Tunnel Renewal	2841
<i>M. Catapano, A. Poli, R. Roncoroni & A. Reis</i>	
Design and implementation of a mobile welding robot for TBM cutterhead: Enhancing efficiency, precision, and safety	2848
<i>P. Chen, J. Chen, J. Mao, J. Shu, M. Yang & S. Guo</i>	
Enhancing management and construction quality for a 5km long sandwich immersed tunnel through digital and intelligent methods	2857
<i>W. Chen & J. Liu</i>	
Digital strategies-driven optimization of infrastructure maintenance: The case study of the rehabilitation of a disused tunnel in northern Italy	2863
<i>F. Foria, E. Moschetti, M. Calicchio, V. Grigoras & B. Boyaci</i>	
Intelligent technologies and applications on TBM tunnel construction	2868
<i>W. Guo, K. Hong, P. Gao & F. Li</i>	
Research and application of the bim-based fine management in shield tunnelling construction of rail transit engineering	2876
<i>Y. Huang, Z. Zhang, K. Jia, H. Lai & Y. Li</i>	

Innovative design and practice of full life cycle of complex underground engineering equipment based on digital twin <i>F. Liu</i>	2885
Research on intelligent construction technology and grading method of railway shield tunnel <i>G. Lu, T. Wang, J. Liu & W. Wang</i>	2893
The interface between construction site and Tunnel Information Model: The case of the Brenner Base Tunnel <i>D. Marini & G. Venditti</i>	2902
Integrated design of precast concrete linings for mechanized tunnels <i>A. Menozzi, B. Tiberi, D. Maturi & R. Comini</i>	2910
Data-driven underground construction management: a case study of the Big Circle Metro Line in Moscow <i>M.D. Nadot, V.V. Vyazovoy, M.A. Lvovskaya & A.G. Polyankin</i>	2917
Research on construction collaborative control method based on drilling and blasting tunnel equipment <i>Q. Nianwen, Z. Miaojun, J. Weiliang</i>	2920
Trusted elements in the digital model of the tunnel <i>G. Paskaleva, P. Beronneau & T. Bednar</i>	2927
Why is it worth using BIM in tunnelling? <i>F. Robert & N. Dias</i>	2935
Digital automation in the structural modelling process for tunnel linings – A digital tool-based case study <i>A. Shivasami & G. Heath</i>	2944
Demonstration of parametric analyses in ground models by applying programming logics using a digital tool named ParaRanger <i>A. Shivasami, R. Nair & L. Dunbar</i>	2951
Streamline field management processes to improve labor productivity and reduce material loss <i>H. Umeyama, S. Kitagawa, T. Arai, T. Fukuda, S. Taniguchi, F. Ito & H. Nagamatsu</i>	2959
Research on integrated management platform of shield construction based on digital twin and application in subway engineering <i>X. Wang, J. Wang, Y. Zhang & S. Jiang</i>	2965
A study of digital quantitative evaluation system for the safety risk management in the construction activities of transportation hubs <i>R. Wen, D. Gao, W. Yang & W. Mou</i>	2972
Research on data management and analysis of BIM technology <i>Y. Zhaofeng</i>	2980
A study on 3D reconstruction of tunnel based on NeRf: A case study of Shanghai Metro Line 18 Tunnel <i>Z. Zheng, Y. Xue, Y. Guo, J. Liu & L. Zhao</i>	2985

Machine learning

- Development of a hard rock TBM performance prediction model using RMR input parameters 2995
A. Dardashti, J. Rostami, R. Ajalloeian, J. Hassanpour & A. Salimi
- Performance analysis of supervised algorithms on encoded data for predicting tunnel strain classes 3005
A. Dewangan, D.R. Sahoo & J. Karlovsek
- Automatic classification and segmentation of tunnel cracks based on deep learning and visual explanations 3014
Y. Feng, X. Zhang, S. Feng, Y. Zhao & Y. Chen
- TBM machine parameters estimation: From design approach to on-field results. A concrete example based on Kalman Filter approach 3023
C. Iasiello & J. Rodríguez-Sánchez
- An intelligent decision support system for tunnel structural defects maintenance with combining knowledge graph and deep learning 3029
F. Jia, Y. Xue, Q. Zhang & L. Qu
- Prediction of disc cutter wear considering ground conditions and TBM operating parameters 3037
Y.S. Kang, S.J. Park, J.H. Hwang, J.P. Hong & T.Y. Ko
- Leakage prediction and post-grouting assessment in headrace tunnel of a hydropower project 3044
T.B. Katuwal, K.K. Panthi, C.B. Basnet & S. Adhikari
- A novel machine-learning model for estimating disc cutter life in TBMs considering individual cutter travel lengths 3053
D. Kim, Y. Shin, D. Kim, C. Lee, K. Kwon & H. Choi
- Segment segmentation of tunnel ring point clouds using 3D deep learning 3059
W. Lin, B. Sheil, X. Xie, K. Li & G. Niu
- Forecasting the driving speed of the TBM using machine learning algorithms 3067
M. Miller, Y. Fang, H. Luo, Y. Wang, G. Xu, B. Leng, S. Kharitonov, V. Akulich, Y. Ma & F. Zou
- Intelligent tunnel asset management of CERN underground facilities 3073
V.D. Murro, A. Ouyang, J.A. Osborne & Z. Li
- Research and practice of digital lean construction mode of tunnelling based on shield self-driving technology 3079
L. Pei, H. Wu, M. Hu, J. Lu, B. Wu & G. Li
- Study on machine learning method for supporting conventional tunnel engineering judgement 3086
K. Sakai, S. Miyanaga & M. Yamagami
- Assessment of TBM performance in different types of rocks using supervised learning techniques 3095
H. Samadi, J. Hassanpour, J. Rostami & A. Moghbeli
- Hyperspectral imaging features for concrete compressive strength assessment: Experimental study 3104
C. Wang, H. Huang, M. Zhou & S. Zhu
- An energy-efficient tunnel ventilation control algorithm combining dynamic neural network and fuzzy control 3113
H. Wang, Z. Li, Y. Zhang & J. Zhang

Intelligent surrounding rock classification and mechanical parameters analysis method based on drilling parameters of tunnels	3122
<i>M. Wang, S. Zhao, W. Yi & X. Peng</i>	
Investigation on surrounding rock quality prediction based on incomplete multi-source dataset and tree-augmented naïve Bayesian network	3131
<i>C. Wu, H. Huang, H. Tong, M. Zhou, L. Zhang & Y. Tong</i>	
Machine learning-informed soil conditioning for mechanized shield tunneling feature engineering, model selection, and uncertainty quantification	3139
<i>X. Yuan, S. Wang & T. Qu</i>	
 <i>Underground caverns/underground space use</i>	
Planning and support estimation of underground powerhouse in the Himalayas	3149
<i>S. Adhikari, C.B. Basnet, K.K. Panthi & T.B. Katuwal</i>	
A conceptual framework for the creation of an integrated planning system for the strategy of implementing technologies for underground urban construction	3157
<i>V. Agafonov, D. Konyukhov & E. Kulikova</i>	
Deep powerhouse caverns design development and challenges – Snowy 2.0 experience	3160
<i>I. Ching, M. Diederichs, B. Chapman & G. Cardone</i>	
Minimising impacts on the local habitat in relocation and construction of a large cavern for track crossover at Acharya Atre Chowk Metro Station of the Colaba-Bandra-Seepez (Line 3) in Mumbai, India	3169
<i>S.K. Gupta, R. Mittal, M. Dange & R. Tilak</i>	
Innovation practice of indoor space of rail transit hub	3174
<i>L. Ji, Y. Li, K. Wei, Y. Deng & Y. Fu</i>	
Hexane section and its section combination honeycomb type underground structure system. Design and implementation of the program study	3180
<i>Q. Jiao, L. Guo & W. Chen</i>	
Harnessing the potential of underground space for climate-neutral cities: Energy geostructures in metro tunnels	3187
<i>A. Koliji, E. Garin, T. Kazerani, B. Schenk & J. Senn</i>	
Research on complete technologies for the construction and utilization of super large caverns in Hong Kong	3194
<i>Y. Li, Z. Hong, W. Li & F. Xu</i>	
Challenges in planning, design, and construction of the underground power plant station cavern Kūhtai 2	3202
<i>A. Morocutti, P. Wetzlinger & R. Steiger</i>	
The use of underground space in greater Kuala Lumpur	3207
<i>T.-A. Ooi & C.-M. Khoo</i>	
SMART tunnel revisited – after 15 years in operation	3215
<i>T.-A. Ooi & C.-M. Khoo</i>	
Large diameter surge shaft in weak foliated rock mass; excavation and support with real-time investigation and pre-excavation support strategy in the lesser Himalayan Slate	3223
<i>B. Parajuli, E. Christakis, A. Marasini & X.-Y. Yang</i>	

Gangxia North Hub innovation highlights <i>X. Qie & L. Qi</i>	3232
Contract Korsvägen - part of the new Westlänken Commuter Rail Project in Gothenburg, Sweden. Challenges of drill & blast Tunnelling and cut & cover construction in heterogeneous ground conditions <i>K. Rieker</i>	3236
The cross river rail project as a PPP model in Brisbane, Australia. Experiences in cavern construction for 3 underground stations and tunnelling with double shield machines <i>K. Rieker</i>	3243
Mechanized shaft sinking with VSM: Developing underground space for U-Park® systems <i>P. Schmäh, S. Frey & M. Peters</i>	3249
Snowy 2.0 – Implementation of a “twin numerical model” as computational tool of the “observational method” during the excavation of a large cavern under high in situ stress <i>P.L. Tonioni, A. Toussaint, P. Lignier, K. Thermann, A. Lambrughì & I. Ching</i>	3255
Rock engineering in Sweden - Mining, hydropower and railways <i>P. Vedin, T. Dalmalm & J. Brantmark</i>	3262
Integration of stations and cities plan and research on technological innovation of Shenzhen Dayun comprehensive transportation Hub <i>M.-S. Wang, C. Liu, R.-Z. Fei, W.-R. Liu, Y.-Y. Fu & Y.-Z. Deng</i>	3267
Comprehensive development and utilization of underground space of Xiangya Road River-crossing Tunnel project in Changsha City <i>H. Wang, J. Ma, X. Zhang & M. Zhou</i>	3276
A broad review of cavern engineering approach in meta-sedimentary rock in Northern Hong Kong <i>J.C.F. Wong, L.W.H. Tsang, H.H.M. Suen, D.C.W. Mak, F.K.L. To & H.H.C. Poon</i>	3282
Key technology for the construction of the Shen-Zhong Link tunnel under the existing operating expressway <i>X. Zhou, X. Cheng & Q. Xu</i>	3290
<i>Operational safety, maintenance and repair</i>	
The 365 km tunnels assessment along ASPI Motorways Network – Key findings addressing risk analysis procedures and structural conditions evaluation and strategy of interventions <i>C. Alessio, L. Baccolini, D.D. Fiore, M. Conte, M. Mazzola & D. Peila</i>	3303
Conservative rehabilitation interventions of masonry highway tunnels along the historic Genoa-Po valley motorway in Genoa (Italy) <i>C. Alessio, R. Pittalis, A. Poli, G. Attianese, B. Chiaia, D. Ferretti, E. Zanazzi, L. Ferrari & E. Coisson</i>	3312
Colle Marino left tunnel renewal project: The first case-history of full lining reconstruction - from invert to crown - under difficult geotechnical conditions and future developments for working under traffic <i>C. Alessio, B. Spigarelli, M. Mazzola, C. Ceccarelli, A. Poli & P. Iuculano</i>	3320
Lessons learned from longitudinal ventilation worldwide and CFD-based solutions <i>A.B. Amado, Y. Zhao & E.Q. Ruiz</i>	3328

Italian guidelines for the risk classification, safety evaluation and monitoring of existing tunnels: An overview	3333
<i>A. Carigi, C. Todaro & G. Silvestri</i>	
A computer-vision-based model updating strategy for shield tunnels with cracks	3342
<i>X. Chang, Y. Zhang & Y. Fu</i>	
Evolution of safety situation and repair scheme for punctured shield lining	3350
<i>Z. Dai, R. Hu & Z. Wang</i>	
Smart tunnel in industry 5.0: Improving road tunnel resilience by dynamic risk analysis	3359
<i>A. Focaracci, L. Martirano & F. Zacchei</i>	
Tunnel asset management: Risk analysis through the MIRET approach	3365
<i>F. Foria, G. Miceli & M. Calicchio</i>	
Tunnel renewal strategy – The evaluation of the advantages through LCA	3371
<i>S. Frisiani, M. Pierani, F. Magnelli, L. Baccolini & A. Poli</i>	
Development of cementitious repair material for tunnel concrete structures of operating railroad in salt-affected environment	3379
<i>Y. Kose, K. Miyake, A. Hosoda, M. Saito & H. Utsugi</i>	
Ventilation for a long underground road tunnel system from a modern perspective	3388
<i>T.K. Lam & E. Hataysal</i>	
Study on fire smoke exhaust strategy in daliangshan no.1 super-long expressway tunnel	3394
<i>F. Lan, H. Zou, L. Wu, Y. Wang & Y. Deng</i>	
Positioning and autonomous control of intelligent hydrodemolition robot	3401
<i>W. Liang</i>	
Research on information perception mechanism and evaluation method of tunnel lighting environment	3409
<i>B. Liang, J. Niu & C. Qin</i>	
Research and realization of equivalent lighting environment for tunnels	3418
<i>B. Liang, C. Qin & J. Niu</i>	
A numerical investigation on the long-term stability of tunnels excavated in the upper stratum of expansive layer	3428
<i>S. Ma, Y. Cui</i>	
Subway ventilation system design and the importance of predicting the long-term wall surface temperature	3437
<i>I.K. Mbaye</i>	
Approach in structural fire resistance of the existing North-South Railway Tunnel in Brussels	3444
<i>B.D. Pauw, C. Timperman & S. Devriese</i>	
A seismic damage classification for post-damage assessment of rock tunnels	3451
<i>D.A. Reddy & A. Singh</i>	
The numerical-physical coupling method in investigation of the response of the tunnel structure under fire scenarios	3456
<i>L. Wang & Z. Yan</i>	

Research on fire compartmentation of hyperscale public area in underground rail transit hub <i>K. Wei, L. Ji, Y. Fu & Y. Deng</i>	3465
Experimental study on the applicability of the combined tunnel ventilation system of complementary ventilation and shaft <i>Y. Xin & Y. Wang</i>	3472
Study on the influence of longitudinal slope on the temperature field inside railway tunnels in cold regions and engineering counter measures <i>C. Yang, S. Tian & Z. Ma</i>	3480
The impact of landscape belt design inside extra-long highway tunnel on driving comfort: A driving simulation study <i>F. Ye, J. Liu, W. Zhu, E. Su, X. Wen, X. Han, Z. Jiao & P. Sun</i>	3489
Full life cycle multi-hazard scenarios and structural response analysis of metro shield tunnels <i>T. Yu, Z. Yan & H. Zhu</i>	3497
Research on China's extra-long separate construction tunnel emergency evacuation and rescue technology <i>Y. Yuan & S. Chen</i>	3504
Concept of a thermoelectric power system in high geothermal tunnel: Preliminary design with numerical simulation <i>Y. Yuan, P. Cui & Q. Wang</i>	3511
Development and application of complete equipment for mechanized construction of defect remediation in existing railway tunnels <i>W. Yuan, F. Gui, L. Zhang & P. Zhang</i>	3520
Research trend and prospect of reconstruction and expansion technology of existing highway tunnels <i>Z. Zhang</i>	3528
Reliability study of full jet longitudinal smoke exhaust system for a road tunnel over 5 km long <i>X. Zhang, L. Tao, M. Luo & Y. Zeng</i>	3538
Resilience assessment of shallow-buried subway stations under earthquake disasters <i>C. Zhang, D. Zhang & Z. Huang</i>	3545
<i>Contractual practices and risk management</i>	
Development of a tunnel asset management tool from a risk-based approach <i>C. Alessio, D. Di Fiore, L. Baccolini, B. Chiaia & M. Conte</i>	3557
SMART-Systemic approach to risk management of tunnels <i>E. Andrés Marulanda</i>	3567
Risk management of tunnel projects: From qualitative to quantitative probabilistic risk analysis <i>A. Antiga, M. Chiorboli & M. Dotti</i>	3572
Strong financial and improved procurement strategies for the success of the Grand Paris Express <i>A. de Pommerol</i>	3581
A methodology of risk management to urban tunnels and its application to Bogota subway <i>J. Esteban Alarcón G & A.P. de Assis</i>	3585
The use of a reference cost system for contracting underground public works <i>E.A.P. Filho, C.K. Miyazato & P.M. Neto</i>	3594

Development of an early contractor involvement selection tool for public owners <i>C.P. Friedinger & P. Sander</i>	3600
Pawtucket CSO tunnel design build - From managing risk and quality to design and construction innovations <i>I. Halim, S. Polycarpe & V.E. Gall</i>	3608
Comprehensive risk management for slurry shield TBM tunneling using fuzzy set theory <i>K. Kwon, M. Kang, H. Park, Y. Ma & H. Choi</i>	3617
Geotechnical risks management associated with a tunnel launch in complex geological conditions <i>C.L. Ng, C.M. Khoo & N.A. Abdul Rahman</i>	3623
Comparing underground construction risk for urban transportation and hydropower projects – A lender’s technical advisor’s perspective <i>A. Noble</i>	3632
Underground risk and ESG aspects in pumped hydro and hydropower projects – what worries the lenders? <i>A. Noble</i>	3639
Research on risk management and control of undersea tunnel construction based on blockchain technology <i>L. Qu, S. Liu, M. Tan & H. Huang</i>	3647
Study on the major risk control elements under EPC management mode of rail transit <i>Z. Shi, J. Huang & L. Ding</i>	3652
Tunnel Euralpin Lyon Turin: The design and contract challenges for a modern Alpine base tunnel <i>D. Stocker, P. Gilli & M. Falanesca</i>	3659
Risk limiting in urban tunnel contracts <i>H. Wagner</i>	3668
Author index	3673



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Preface

The World Tunnel Congress 2024 and the 50th ITA-AITES General Assembly are held in Shenzhen, China, from 19–25 April, 2024. The China Civil Engineering Society (CCES) is honoured to host this prestigious and significant event which is not only a milestone in the history of the ITA, marking its 50th anniversary but also a testament to the enduring commitment and collaboration within the international tunnelling community.

With the visionary theme of “Tunnelling for a Better Life,” WTC2024 is set to spotlight the pivotal role of tunnelling and underground works in creating sustainable, efficient, and resilient environments. This theme is a call to the global community to leverage the latest in innovation and technology, addressing the era’s most pressing challenges, including climate change, urbanization, and the quest for low-carbon, intelligent infrastructure solutions.

The proceedings encompass a wide array of critical topics in tunnelling and underground space, reflecting the latest trends, insights, and innovations. WTC2024 has received more than 1,000 abstracts and 540 full papers from authors of 46 different countries. After the peer review by the Scientific Committee which was composed of 145 experts from 39 countries, 486 papers from 40 countries were accepted for publication in the WTC2024 Proceedings. From integrating low-carbon technologies to applying intelligent systems in the design, construction, and management of tunnelling and underground works, the contributions within these pages showcase a forward-looking approach to tackling the complexities of modern urban development. The sustainable solutions presented within the proceedings illuminate a path toward resilient, low-carbon, and eco-friendly practices, reflecting our commitment to minimizing environmental impact and underscoring our dedication to efficiency and progress in the intelligent and digital era. The WTC2024 proceedings will inspire and guide our community toward realizing the potential of underground spaces to create a better, more sustainable life for present and future generations.

As we gather in Shenzhen, a city renowned for its dynamic innovation and rapid growth, we are reminded of the power of collaboration and the importance of knowledge exchange in advancing our field. The WTC2024 serves as a platform for experts, practitioners, and stakeholders from across the globe to come together, share insights, and forge partnerships that will drive the future of tunnelling and underground space development.

On behalf of the organizing committee and the CCES, we express our deepest gratitude to all participants, contributors, and sponsors who have made this event possible. As we celebrate the 50th ITA-AITES anniversary, WTC2024 in Shenzhen will provide invaluable opportunities for the international tunnelling community to explore the depths beneath our cities and the heights of our aspirations for a sustainable future and a better life.

Yi Jun
Chair of the WTC2024 Organizing Committee
President of the China Civil Engineering Society (CCES)
Shenzhen, April 2024



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Marble sludge in two-component grout applications

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ABSTRACT: The two-component grout is currently the most used backfilling technology in shield tunneling applications. The technology is widely used all around the world thanks to its versatility. In fact, by properly calibrating dosages and types of raw ingredients, the technical specifications proper of a certain construction site can be easily satisfied. In this work, an innovative two-component grout mix design is introduced, in which a marble sludge is added to component A of the two-component grout system as a new ingredient. The marble sludge, obtained during the cutting process of ornamental stones in marble quarries is commonly considered a waste, an environmental problem that must be correctly managed. The idea of the authors was, hence, to use the marble sludge as an ingredient in the two-component grout, by physically blocking it in the gelling reaction and making it permanently part of the backfilling material, confined between the bored medium and the lining extrados.

In this paper, a laboratory test campaign on the potential use of marble sludge in the two-component grout technology is reported. A standard two-component grout and the innovative one have been compared according to standardized testing protocols. Outcomes highlight that the innovative grout has similar properties compared to the standard one and that the addition of marble sludge does not worsen the grout's properties.

Keywords: two-component grout, backfilling, marble sludge, waste reduction

1 INTRODUCTION

At present times, the two-component grout is the most used backfilling technology in mechanised tunnelling, using shielded machines.

During the tunnel excavation and the machine advancement, a gap is continuously created from the difference in diameter between the head of the machine and the lining extrados. This gap is inevitable since this geometrical peculiarity is essential and allows for the assemblage of the segments in linings under the protection of the shield, as well as avoiding potential machine block due to convergence of the excavated medium.

This gap, commonly called annulus, has an order of magnitude of centimetres and is schematically shown in Figure 1.

Different technologies can be used for the complete filling of the annulus (Grasso et al., 2023) but two-component grout is undoubtedly the most popular all around the world, due to its aptitude for preventing and controlling surface settlements (Fagnoli et al., 2013). This feature is guaranteed by an almost instantaneous gelation of the grout: the material after the

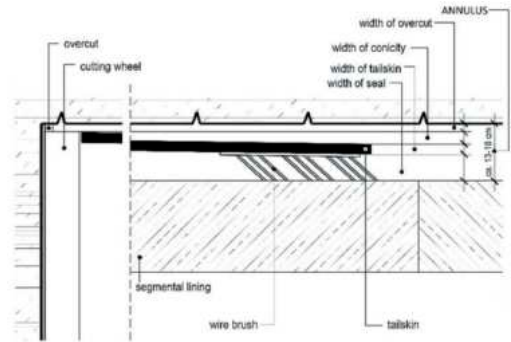


Figure 1. Annulus. Modified from thewes and budach (2009).

gelation starts immediately to improve its mechanical and elastic properties (Oggeri et al., 2021; Todaro and Pace, 2022).

The technology is based on two liquid components: the component A and the component B. The first is a cement-based material made up of cement, water,

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bentonite and retarding/fluidifying agent, while the second is commonly a solution of sodium silicate. Recently, new ingredients have been experimentally introduced to component A production such as, for example, fly ash, blast furnace slag, and industrial solid waste (André et al., 2022; Schulte-Schrepping and Breitenbücher, 2019; Song et al., 2020, Song et al., 2022).

These last studies were the starting point for this research, meaning that the idea to re-use something considered industrial waste was followed. In detail, the new ingredient selected to produce the component A has been the marble sludge, typical waste coming from the cutting process of ornamental stones. The choice was dictated by the nature of the marble sludge, composed mainly of calcium carbonate (CaCO_3) and directly available with a grain size distribution suitable for the proposed application. This material is produced in large amounts in marble quarries (Cobo-Ceacero et al., 2019): On average, for each cubic metre of marble exploited, 50-95 L of marble sludge is obtained. This material must be correctly managed, and the cost for its disposal significantly impacts the marble quarry business.

In this work, a preliminary test campaign is presented concerning the use of marble sludge powder as a raw ingredient for the production of component A. In the following paragraphs, the term “marble sludge” refers more specifically to the powder of marble, naturally produced during the cutting operation performed in a dry way (no water or other lubricants added).

Starting from a mix design typically used in construction sites for the two-component grout production, two different dosages of marble sludge have been tested to produce the grout. To verify the feasibility of using this new ingredient in the two-component grout technology, the component A properties, the reaction of gelation, and the hardened grout have been tested according to a standardised testing protocol (Todaro et al., 2019). The results of the grout prepared with the marble sludge have been compared to those of the reference mix.

2 THE ISSUE OF THE MARBLE SLUDGE

Considering the ornamental stone processing chain, the cutting operations are important since blocks of huge dimensions (m^3 of order of magnitude) are split into easily transportable slabs, suitable for further processing (Figure 2, left). Taking into account the Italian scenario, marble quarries are by far the most common, yet other types of ornamental stone quarries are also present on the national territory. For the reason of “abundance”, authors have selected marble sludge as an experimental ingredient in this study (Figure 2, right).



Figure 2. Chain cutting machine used for splitting the marble blocks in slabs (on the left) and the marble sludge obtained during this cutting operation (on the right).

Considering only the Carrara marble basin, hundreds of thousands of tons of marble sludge are produced every year due to the huge production of blocks (about 900,000 tons/year) of one of the finest marbles in the world. This big production inevitably leads to big amounts of produced marble sludge. Additionally, the environmental problem associated with marble sludge disposal is challenging, especially in the area where quarries operate.

From this scenario, the authors’ idea has been conceived, while considering the new big tunnel projects that are going to start in the next years in Italy according to the National Recovery and Resilience Plan funding: use the marble sludge in the backfilling phase in shielded mechanised tunnelling.

If, from one side, the environmental positive impact of “trapping” the marble sludge in a grout is practical, the calibration of the two-component grout mix design for using the marble sludge as an ingredient is a complex phase from the other side, considering the sensitive balance between compounds. The two mix designs presented have been calibrated not only to maximize the dosage of marble sludge but also to try to improve the mechanical performances of the obtained grout.

3 MATERIALS AND METHODS

The test campaign has been organised in two different parts: the first aimed to assess the properties of component A only and the gel time, while the second aimed to test the mechanical performance of the gelled grout at a short curing time. The short curing time is intended for no more than 3 hours after the casting. The procedure for preparing component A, for the sample casting and the used mix designs are reported in the following.

3.1 Used materials

To produce the two-component grout, Portland Cement type CEM I 52.5 R (CEN, 2011) was used. The accelerator, retarding/fluidifying agents, and

bentonite were provided by Mapei company. The marble sludge was instead provided by the “Rock cutting laboratory”, part of the “Geomechanics and Geotechnology laboratory” of the Politecnico di Torino.

3.2 Component a production and sample casting

The component A production was carried out by using a laboratory stirrer, according to the procedure described in Todaro et al. (2019) and hereinafter shortly summarised in Table 1.

Table 1. Mixing procedure.

Phases	Impeller rotation speed (rpm)	Duration (min)
Start – only water	800	/
Bentonite mixing phase	2000	7
Marble sludge mixing phase	2000	if the marble sludge is added, the mixing time should be calibrated for obtaining a suitable mix
Cement mixing phase	2000	3
Mix of retarder/ fluidifying agent – End	2000	2

The mix designs used are reported in Table 2. Those where the marble sludge is used are “1M” and “2M”, while “R” is the reference mix design. Dosages are expressed in kg/m^3 .

Table 2. Mix designs.

Ingredient	1M	2M	R
Cement	230	230	230
Bentonite	30	30	30
Marble sludge	50	100	/
Water	834	816	853
Retarding/fluidifying agent	3.5	3.5	3.5
Accelerator	81	81	81

When component A was obtained, the sample casting was performed manually. The metered amount of components A and B were prepared in two different tanks, followed by quickly pouring component A inside the tank holding the component B, and later pouring all the grout into the empty tank, which led to the final step of emptying the grout (still liquid) into the sample moulds.

Used samples have dimensions in compliance with CEN (2016) (40*40*160 mm).

3.3 Performed test

The characterisation of component A, the reaction between components A and B, and the hardened grout at short curing time have been studied in accordance with the well-established, detailed procedure reported in Todaro et al. (2019). Briefly, the characterisation of component A was assessed by measuring the unit weight and the flow time on the fresh component A (i.e. within 10 minutes after the production) while the bleeding was assessed after 1, 3, and 24 hours after the component A production. The gelation of the grout obtained by turbulently mixing component A and component B has been assessed by measuring the gel time. Finally, the hardened grout has been characterised by assessing the surface compression strength (SCS) after 1 and 3 hours of curing.

3.3.1 Unit weight

The unit weight was assessed by using a mud balance (Figure 3), according to the standard ASTM D4380 (2020).



Figure 3. Mud balance used for the unit weight assessment. (Todaro et al., 2023).

3.3.2 Flow time

The flow time was assessed by using the Marsh funnel (Figure 4), in line with UNI 11152-13 (2005). This test provides indications on the viscosity of the tested material. The outcome of the test is the time spent by 1 L of mortar to flow through the funnel. The higher the viscosity of the mortar, the higher the flow time.



Figure 4. Marsh funnel used for the flow time assessment (Todaro et al., 2023).

3.3.3 Bleeding

The bleeding test allows the evaluation of the physical stability of component A. The test has been carried out according to UNI 11152-11 (2005). A standardised cylinder is filled with 1 L of component A, to which particles of cement tend to settle on the bottom of the cylinder due to the gravity force, leaving a layer of water on the top of the surface. After a certain time, the volume of the segregated water is measured (V_w), and by computing the ratio on the whole volume of 1 L (V_t), the bleeding index is computed, expressed as a percentage according to equation (1):

$$\text{Bleeding} = \frac{V_w}{V_t} (\%) \quad (1)$$



Figure 5. Bleeding assessment. (Todaro et al., 2023).

3.3.4 Gel time

The gel time has been assessed by following the experimental procedure proposed by Todaro et al. (2019) and used also by André et al. (2022). Once the quantities of components A and B are metered and prepared according to the mix design, component A is poured into component B; after that the whole material is quickly poured again in the empty tank and so on with subsequent series of pouring. The time recorded started when the first contact between components A and B occurred, and ended when the grout is not able to flow.

3.3.5 Surface compression strength (SCS)

The surface compression strength (SCS) has been assessed according to the procedure proposed by Todaro et al. (2020). A dynamometer was equipped with a flat circular bit having a surface of 177.9 mm^2 (A in equation 2) (Figure 6).

The test consists of the penetration of the bit orthogonally on the cast surface of the grout (previously cast in moulds with the shape in compliance to CEN (2016) and cured for 1 or 3 hours in a sealed environment) till a penetration of 5 mm is reached. The maximum force (F in equation 2) reached during the test is recorded. SCS is consequently computed according to equation (2) where F is expressed in N.



Figure 6. Dynamometer used for the surface compression strength assessment during the test. Todaro et al. (2020).

$$\text{SCS} = \frac{F}{A} \quad (2)$$

According to the reference standard, tests have been performed without demould samples. At least 6 tests were carried out for each assessment performed after 1 hour, while between 3 and 6 determinations were performed for testing after 3 hours of curing. The reason for a higher number of assessments at 1 hour of curing is related to the higher dispersion observed.

4 RESULTS

The obtained outcomes are summarised in Table 3.

Table 3. Used mix designs.

Mix design	1M	2M	S
Unit weight (kg/L)	1.20	1.27	1.17
Flow time (s)	36.0	38.0	34.5
Gel time (s)	7	4	8
SCS 1h (MPa)	0.38	0.45	0.41
SCS 3h (MPa)	1.65	1.71	1.62
Bleeding 1h (%)	0.3	0.0	/
Bleeding 3h (%)	0.68	0.00	1.04
Bleeding 24h (%)	3.10	2.40	2.09

5 DISCUSSION

Taking into account the unit weight, an increment of values is recognised for 1M and 2M compared to R. The higher weight for a fixed volume of the considered component A is due to the replacement of a certain amount of water with the marble sludge. However, values of 1.2-1.3 kg/L are typically

accepted in construction sites, therefore it can be stated that compliance has been respected.

On the other hand, a significant reduction in gel time was observed. If for 1M the reduction is only of 1 s (a time lapse consistent with the test error), the gel time of 2M is half of those of R. The value of 4 s is very short, hardly applicable in standard practices, and not commonly acceptable in construction sites. Probably, the gelation between components A and B is affected by the presence of the marble sludge that plays an active role as a further booster of the reaction.

Considering the flow time, a slow increase has been observed (about 4 % and 10 %, respectively for 1M and 2M) compared to the flow time of the mix R, but then again, these values are accepted in common practice.

Optimal results have been obtained for the bleeding test, despite the presence of the marble sludge and consequently the tendency of these particles to segregate (similarly to the concrete ones), bleeding values are lower than 1% after 3 hours and abundantly lower than 8% (the threshold commonly fixed for construction sites) after 1 day.

As for the strengths at short curing time, 2M seems to be more performant than R: values greater than about 10 % and 6 % compared to the reference mix design have been obtained for a curing time of 1 hour and 3 hours respectively. Differently, 1M exhibits similar results compared to R (for 1 hour of curing, the strength was lower than that of the reference mix).

6 CONCLUSIONS

This work describes a preliminary test campaign where marble sludge, a material considered as waste in the ornamental stone supply chain, is reused in a tunnelling application. The preliminary nature of the work is related to the used mix designs; in fact, starting from a real two-component grout mix, no variations on dosages of raw ingredients have been applied: only the water has been replaced by the marble sludge in a quantity dictated by the sludge dosages and the respective unit weights. This choice was dictated by the need to check the potential impact of the new ingredient on the two-component grout technology by monitoring the reference parameters and their “fluctuations” in presence of the new ingredient.

Despite this limitation, the results highlighted the concrete possibility of giving the marble sludge a noble use as an ingredient in the two-component grout technology, as backfilling in tunnelling applications. No breach has been actually identified, granted that the gel time could extend by increasing the dosage of the retarding/fluidifying agent. It is also important to note that an increment of the retarding/fluidifying agent could allow the increase of the marble sludge dosage that, according to the

presented results, could turn into higher strength performances. In conclusion, the preliminary outcomes reported in this study highlight that the innovative grout has similar properties to the standard one and that adding marble sludge does not worsen the grout's properties.

Results presented in this paper should be considered as a first step of the research since further analyses on mechanical and elastic performance at long curing time should be carried out before transferring the technology to a pilot construction site.

The research is currently on-going.

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