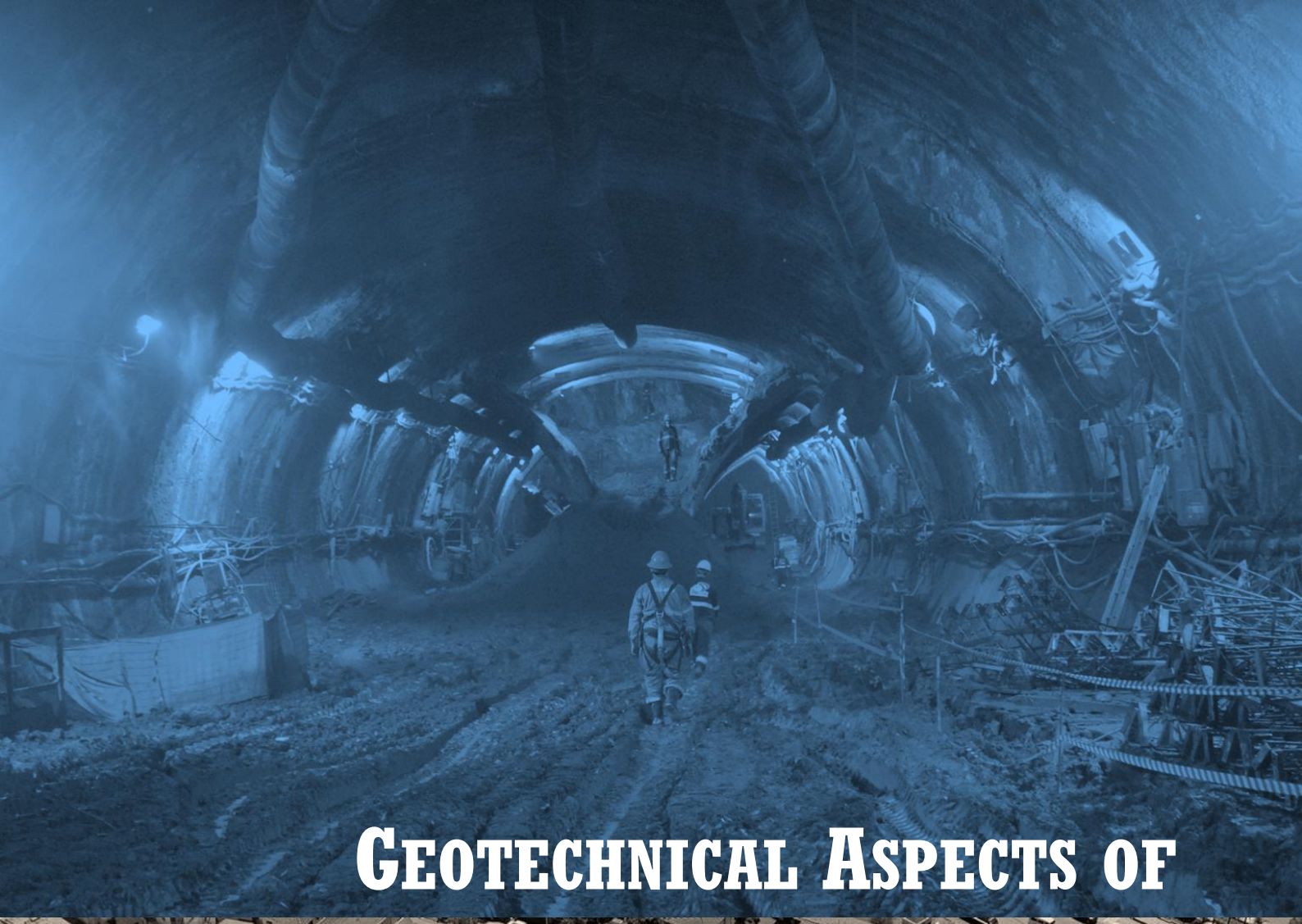

Geotechnical Aspects of Underground Construction in Soft Ground

editors
Arsenio Negro Jr.
Marlísio O. Cecílio Jr.

BRAZILIAN TUNNELLING COMMITTEE

CBT COMITÊ BRASILEIRO DE TÚNEIS

ABMS

9th International Symposium on
Geotechnical Aspects of Underground Construction in Soft Ground
IS – Sao Paulo 2017

Book of Abstracts

editors
Arsenio Negro Jr.
Marlísio O. Cecílio Jr.

Sponsored by

CAPES

CNPq
Conselho Nacional de Desenvolvimento Científico e Tecnológico

SUMMARY

FUJITA LECTURE

KEYNOTE LECTURES

TECHNICAL SESSIONS

Deep Excavations

Interaction with Adjacent Structures

Mechanized Excavations

Sequential Excavations

Physical Modelling and Field Tests

Case Histories

Fujita Lecture

Amazing underground construction technology in Japan

Prof. Hirokazu AKAGI
Waseda University, Department of Civil and Environmental Engineering, Tokyo, Japan
Core member of TC204, ISSMGE
Chair of Japanese Geotechnical Society national committee for TC204

This second Fujita lecture covers the current underground construction in Japan, which amazes the international underground construction engineers with opening their eyes. The six amazing case histories are introduced with the large-size and novel underground construction technologies used in these case records and the planning. The metropolitan area outer discharge channel tunnel (MAODC) featured by the large underground shrine cavern, the metropolitan expressway and the Gaikan projects including large diameter Shied TBM tunnelling and large size open excavation, the Maglev bullet train Shinkansen, the new connecting train network system and the refurbishment of Tokyo metro train station are introduced.

Keynote Lecture

Case studies and Monitoring of Deep Excavations

Dr. Mandy KORFF
Deltares, Delft, Netherlands
Delft University of Technology, Delft, Netherlands

Several case histories from Dutch underground deep excavation projects are presented in this paper, including the lessons learned and the learning processes involved. The focus of the paper is on how the learning takes places and how it is documented. It is necessary to learn in a systematic and active way from real and on-going projects because of the high failure costs in the industry, not excluding the underground construction part of it.

Keynote Lecture

EPB Granular Soil Conditioning under Pressure

Prof. Michael A. MOONEY
Colorado School of Mines, Golden, USA

Yuanli Wu & Dhrupad PARIKH
Colorado School of Mines, Golden, USA

Lisa MORI
Jay Dee Contractors, Seattle, WA, USA

This paper provides an overview of recent experimental results regarding the influence of pressure on foam and foam-conditioned sands. A series of experimental investigations were performed using pressurized chambers and a foam capture device to investigate the fundamental and engineering properties of foam and foam-conditioned sand. Foam development experiments reveal significant energy losses through the bead-filled generator and foam transport pipe. Energy loss in the generator increases with foam/air velocity, pressure and generator length. The hydraulic gradient in the foam transport pipe increased sharply with a decrease in pipe diameter, affiliated with a decrease in foam bubble size. An investigation of foam stability showed that foam and air volume loss with time is insignificant during significant liquid volume loss. During this period of time, air bubbles are coalescing to form bigger bubbles yet very little air (e.g. less than 2-3%) is released to the atmosphere. The corresponding engineering properties of foam, such as compressibility, elasticity and plastic strain accumulation do not change appreciably. Foam was also found to be much less time-varying under higher pressure, largely due to smaller, more uniform bubbles. A series of conditioned sand experiments under pressure confirmed the role of relative density of conditioned soil in assessing the efficacy of conditioning. The transition pressure, above which the foam governs behavior and below which the soil governs behavior, increases with increasing foam. Shear strength and abrasivity increase rapidly at chamber pressures above the transition.

Keynote Lecture

Influence of the Trough Shape on Settlement Prediction and Analysis

Prof. Tarcísio B. CELESTINO
School of Engineering of Sao Carlos – University of Sao Paulo, Sao Paulo, Brazil
Themag Engenharia, Sao Paulo, Brazil

The importance of the shape of the settlement trough has been recognized for a long time. However, most of the procedures for the prediction and analysis of settlement data have adopted Gaussian curves. They are unable to fit real settlement data in many situations, including the cases of tunnels excavated through granular materials, or very shallow tunnels excavated through any type of ground. This has led sometimes to scattered evaluations of ground distortion and unsafe predictions of damage to adjacent buildings. After the use of yield density curves was introduced, other curves were also proposed, however Gaussian curves are still most frequently used. The lecture will show the performance of different curves which have been recently proposed to fit real settlement data and errors which can result in ground distortion evaluation.

Keynote Lecture

Recent Underground Construction Projects in Korea – From Rock to Soft Ground

Prof. Chungsik YOO
Sungkyunkwan University, Suwon, Korea

This paper presents design and construction aspects of recent large underground construction projects executed in Korea. Two projects were presented; one for an underground low and intermediate level nuclear waste repository construction project and the other for a large diameter railway tunnel construction project executed under a domestic airport. A number of design and construction issues were brought up when executing these projects due largely to difficult ground conditions and construction constraints. The first case history illustrates implementation of large scale finite element computing for design of the underground nuclear waste repository which involved with construction of six mega size underground silos in complex, unfavorable geological conditions with high initial in-situ stresses. The second case history involves construction of the railway tunnel directly under the domestic airport, where excessive settlements occurred due to inappropriate groundwater control during tunnelling, which eventually raised significant concerns over operational safety of the airport facilities situated in the settlement affected area. This paper presents details of the design and construction aspects of the two case histories together with practical implications of the findings.

TECHNICAL SESSIONS

Deep Excavations

Design and Construction of the Substructure of a Commercial Development in Bogotá City Using a Top-Down Sequence

G. Clavellina-Miller
CIMESA Soletanche-Bachy, México
O. Martínez-Galvis
GEOFundaciones, Colombia
J. Paulín-Aguirre
SolExpert International, México
T. Jeanmaire, J.I. López
Group Design Office, Soletanche Bachy, France

This paper presents the foundation design (mixed solution: barrettes and foundation slab), and the design and back analysis of the diaphragm wall forming the basement retaining wall of a major commercial development in Bogota, Colombia. The development consists of 4 eleven-story office towers each, and 4 basements for car parking use, occupying the entire venue area (18,000 m² per basement). The design considers a permanent structural diaphragm wall, 60cm thick, 40m in depth, a substructure built with a Top-Down construction sequence, using basements slabs as horizontal elements of support. The Maximum Excavation Level is -15.0m to enable the construction of the slab foundation with Finished Floor Level at -13.5m. The ground profile consists mainly of very soft clay with natural water content up to 200%. The water table was detected at 4m depth. An important number of in-situ shear vane tests and laboratory tests were performed as part of an additional ground investigation in order to have more accuracy in the undrained shear strength of the clays. The project is heavily instrumented with inclinometers, piezometers, extensometers and topographical survey. The excavation is complete and the theoretical results obtained during the design stage are compared with the instrumentation measurements. This back analysis was used in the form of adjusted sets of soil parameters for traditional elasto-plastic modelling and finite element modelling of the excavation sequence.

Deep Excavations Stabilization with Ground Improvement or Cross Walls: a Comparison of Both Stabilization Methods

G. A. Pittaro
Mott MacDonald, Singapore

Deep excavations in soft ground often need stabilization. One of the stabilization method is to use cross walls (CW). The CWs act as mega props to reduce wall deflection effectively. The use of CW in deep excavation in Singapore has become more and more popular nowadays due to the highly developed urban landscape and the widespread presence of soft clay. Another popular stabilization method used in Singapore is the ground improvement (GI) inside the excavation. This method is based on the gaining of stiffness and resistance by mixing soil, water and cement. The main difference between GI and CW is that the first is based on the improvement of the soil by mixing it with other materials, while the second is based on the improvement of the soil by replacing it with other materials. The objective of this paper is to compare CW and GI as stabilization methods. To do so, firstly the CW and GI stabilization methods will be described, subsequently the pros and cons of the use of each method are presented. This paper does not define a “right and wrong” method; however, it can be used to understand some of the factors that can define the use of one stabilization method or the other.

Ground Movement Estimation for Underground Box Structures: Movements at Corners

J. McCallum
Mott MacDonald Limited, Singapore
G.R. Taylor, J. Birks, Y.S. Hsu
Mott MacDonald Limited, Croydon, United Kingdom

When assessing the feasibility of underground construction works impact assessment is usually undertaken in the first instance employing empirical means for the determination of excavation-induced ground movements as part of the widely-accepted 3-stage procedure for potential impact assessment. Ground movements generated by the excavation of boxes and shafts are predicted using an empirical approach validated by data from case studies of similar excavations. Vertical and horizontal ground movements are estimated on the basis of conservative greenfield assumptions. For box excavations, ground movement depends on the depth of the excavation and support system stiffness. The values for settlement at the wall and the extent of the settlement trough are expressed as functions of the support system stiffness and the excavation depth. One of the key limitations of the current approaches is the estimation of ground movements around the corners of box excavations. The increased stiffness evident at the corners of box structures should result in reduced excavation-induced ground movement behind the embedded retaining walls in these zones; field measurements support this assertion, the observations of wall deformations and ground movements at the corners of box structures being lower than elsewhere within the footprint of the box. However, this beneficial effect is largely ignored in the initial phases of the impact assessment process; the assumption that the ground movements are constant around corners is commonly made. A methodology for incorporating the reduction in ground movement evident behind the corners of box structures is presented in this paper. The use of this methodology in conjunction with other complementary empirical methods allows for more informed decision-making and early discussion with affected Third Parties whose approval will be sought as part of project implementation.

Analytical Calculation of Lateral Earth Pressure in Finite Soils Considering Displacement of Retaining Wall

X. Yang, G. Liu
Department of Geotechnical Engineering, Tongji University, Shanghai, P. R. China

Based on the relationship between lateral earth pressure and displacement of retaining wall, a formula has been introduced for the calculation of lateral earth pressure. Then the formula was testified by monitored data from centrifuge test and realistic project. Furthermore, the formula was applied to the calculation of lateral earth pressure for finite soils where the width of soils behind retaining wall is limited. With field data from a deep excavation in Shanghai, the characteristics of lateral earth pressure for finite soils were acquired in consideration of wall displacement s, width of finite soils, d, and friction angle between soils and wall, δ. The results show that (1) the lateral earth pressure in finite soils was smaller than Rankine active earth pressure; (2) the influence of wall displacement on lateral earth pressure varied in different soils; (3) both d and δ played a key role in the distribution of lateral earth pressure but within a certain scope.

Interaction with Adjacent Structures

Effects of Deep Soil Mixing and Jet Grouting on Adjacent Retaining Walls and Ground

Y. P. Dong
Singapore-MIT Alliance for Research and Technology, Singapore
A. J. Whittle
Massachusetts Institute of Technology, Cambridge, USA

Ground improvement methods such as Deep Soil Mixing (DSM) and Jet Grouting Piles (JGP), are widely used to stabilize soft soils in underground construction. However, DSM and JGP construction processes themselves cause movements and pore water pressure changes in the adjacent ground, and can potentially impact adjacent structures. To mitigate these detrimental effects, the mechanisms of ground movements during DSM and JGP processes need to be well understood and controlled during construction. This paper summarizes data from a deep excavation within underconsolidated marine clays, where DSM and JGP were designed to stabilize the excavation. Field measurements show that significant ground movements and wall deflections occurred during DSM and JGP installation (prior to excavation). We have simulated the ground improvement processes using simplified 2D finite element analyses. The analyses assume a net volume change associated with deep soil mixing (reflecting pressure differences between the wet 'soilcrete' and surrounding clay), while much larger movements occur due to jet grouting in the space between the previously installed DSM columns and the perimeter diaphragm wall panels. This behavior is reasonably simulated by introducing a set of boundary pressures to represent JGP construction. Further research is now needed to establish how the jet grouting process can be controlled to limit potential ground movements in very soft clays.

Parametric Study of the Impact of Deep Excavation on an Existing Metro Station

M. Mitew-Czajewska
Warsaw University of Technology, Warsaw, Poland

In the paper, a parametric study (back analysis), concerning the estimation of 13m deep excavation influence on an existing metro station is described. FEM model of the excavation, surrounding soil body and existing metro station was built in order to estimate the range of the impact zone as well as to calculate values of vertical and horizontal displacements of excavation walls and adjacent structures. The displacements of the diaphragm wall as well as displacements of the existing metro station obtained from the analysis were compared to the measurements performed during construction. A significant difference was observed, especially in terms of vertical displacements of the metro station. In order to obtain more accurate results, further calculation series were made with the modification of material model of the soil body (MC, MMC, DP), modulus of elasticity of soils and the ranges of the FEM model.

Pile Tunnel Interaction: an Analytical Framework

T.G.S. Dias
Ghent University, Gent, Belgium
A. Bezuijen
Ghent University, Gent, Belgium / Deltares, Delft, The Netherlands

The underground space of densely populated cities contains parts of buildings, utility installations, deep foundations, tunnels, and deep excavations. It is possible, and increasing more probable, that new underground constructions will be built within close proximity of existing pile foundations. This paper presents a framework for pile analysis to predict the consequences of new underground constructions on piles, specifically through the induced ground displacements, calculated using an analytical solution for a tunnel excavation. Pile deformations are calculated with a modified version of the load transfer method. Pile settlement is found to be inversely proportional with the distance from the tunnel. The calculated pile settlement was between 0.3 and 3% of the pile diameter for 1% volume loss during tunnelling.

Pile Tunnel Interaction During Mechanized Tunnelling

T.G.S. Dias
Ghent University, Gent, Belgium
A. Bezuijen
Ghent University, Gent, Belgium / Deltares, Delft, The Netherlands

The underground space of densely populated cities contains parts of buildings, utility installations, deep foundations, tunnels, and deep excavations. It is possible, and increasingly more probable, that new underground constructions will be built within close proximity of existing pile foundations. This paper presents a framework for pile analysis to predict the consequences of new underground constructions on piles, specifically through the induced ground displacements. A numerical calculation for mechanized tunnels, where the pressures during tail void grouting are calculated iteratively with the ground displacements, is used to predict the settlements. The calculated ratio between the pile and the surface settlements was generally higher than 1 for a pile located above the tunnel, and smaller than 1 at a lateral distance larger than one tunnel diameter. The results agree with the literature on pile tunnel interaction and offer a rational framework to understand the different pile responses around a tunnel excavation.

Mechanized Excavations

Slurry Infiltration Ahead of Slurry TBM's in Saturated Sand: Laboratory Tests and Consequences for Practice

T. Xu
Ghent University, Ghent, Belgium
A. Bezuijen
Ghent University, Ghent, Belgium / Deltares, Delft, The Netherlands
T.G.S. Dias
Ghent University, Ghent, Belgium

During mechanized tunneling with a slurry shield in saturated sand, pressured bentonite slurry is often used to counteract soil and water pressures in front of the tunnel face. Due to the pressure difference between the mixing chamber and the ground, the bentonite slurry will penetrate into the sand. This study focuses on the two key processes in bentonite slurry infiltration: mud spurt and filter cake formation. A series of bentonite slurry infiltration tests in saturated sand are presented. The experiments show that the excess pore water pressure will only be present in the sand during mud spurt. After that, the filter cake will form on the sand surface. The distribution of pore water pressure in the sand depends on the bentonite content of the slurry. The differences between the stages of mud spurt and filter cake formation were clearly noticed.

A Simplified Chamber Pressure Model for EPB TBM Tunneling in Granular Soil

H. Yu, M. Mooney
Colorado School of Mines, Golden, USA
A. Bezuijen
Ghent University, Belgium / Deltares, Delft, the Netherlands

In this paper, we propose a simplified chamber pressure model for earth pressure balance (EPB) tunnel boring machine (TBM) tunneling in granular soils, both during excavation and standstill. Three physical processes, (1) muck compression/decompression; (2) chamber fluid seepage; and (3) rotation induced unlevel muck surface, are identified and modeled. The model satisfies the muck mass conservation constraint, but relaxes its motion equation by assuming quasi-static condition and gas substance even distribution. The model is designed as a state machine, with total chamber gas volume, liquid volume and gas substance amount chosen as the state variable to characterize the chamber pressure distribution. TBM operations are used to update the state variable and track the chamber phase evolution over time. The model is implemented with data from the N125 tunneling project in Seattle for model demonstration and evaluation.

Excavation Cycle Dependent Changes of Hydraulic Properties of Granular Soil at the Tunnel Face During Slurry Shield Excavations

Z. Zizka, B. Schoesser, M. Thewes
Ruhr-University Bochum, Bochum, Germany

Increased pore pressure heads in front of the tunnel face are frequently observed during excavations with slurry shields. It is expected that the excess pressures are caused by a flow in front of the tunnel face resulting from the interaction between the face supporting fluid (bentonite slurry) and the soil. The flow is assumed to be unsteady from two points of view. First, it is influenced by a time dependent change of hydraulic properties of the soil at the tunnel face. The time dependent change is governed by the interaction with bentonite slurry. Second, the area of the soil on the tunnel face with changed hydraulic properties is disturbed periodically by passing cutting tools which are rotating with the cutting wheel. After each passing of the cutting tool through a particular point at the tunnel face, new local flow is induced. The aim of this paper is to investigate experimentally the transient changes of hydraulic properties of granular soils due to interaction with bentonite slurries. The time dependent change of the soil properties is compared with excavation data of real shield machine describing the time scale of the cutting process. Based on the comparison, the hydraulic properties of soil on the real tunnel face during excavation can be evaluated. Thus, a better assessment of the pore pressure heads in front of the tunnel face can be performed.

Rheology of Foam-conditioned Sands: Transferring Results from Laboratory to Real-world Tunneling

S. Freimann
Institute for Tunneling and Construction Management, Ruhr-Universität Bochum, Germany
M. Galli
Ingenieurbüro Dipl.-Ing. H. Vössing, Düsseldorf, Germany
M. Thewes
Institute for Tunneling and Construction Management, Ruhr-Universität Bochum, Germany

When tunneling with EPB shields in coarse-grained soils, the flow behavior of the support medium is a decisive criterion for effective face support. On one hand, the support material should possess fluid-like properties ensuring a homogeneous pressure transfer to the face and on the other hand, it needs to exhibit sufficient stiffness for transportation and tipping. Usually, the flow behavior of conditioned soils is assessed using a concrete slump test, whereby a slump range of 10 to 20 cm is recommended by literature. The rheological characterization of soil-foam-mixtures is evaluated analytically. For this, measurements from numerous slump tests are considered. In addition, numerous rheological investigations with Ball rheometers are considered with conditioned sands to get direct measurements of rheological properties. These results can be used for the calibration of a large scale experimental setup. By conducting experiments on different scales, information on the flow behavior of conditioned soil can be transferred from the laboratory scale to the real-world TBM scale.

Grout Pressure Distribution During TBM Tunnelling

T. G. S. Dias
Ghent University, Gent, Belgium
A. Bezuijen
Ghent University, Gent, Belgium / Deltares, Delft, The Netherlands

Mechanized tunnels are constantly used in urban spaces, and have become a viable option for projects with strict limits of disturbance, where underground solutions were deemed unsuitable in the past. However, several mechanisms of the excavation cycle are still not taken into account in tunnel design or in risk assessments, where an accurate prediction of the soil displacements is important. This paper presents how two models, for the grout flow and consolidation, can be associated with a finite element model to calculate the induced soil displacements during tail void grouting. These models were used to compute different examples of a tunnel excavated between two layers of sand, modelled as elastoplastic materials. The results reproduce the basic mechanisms of the process, identified in the field measurements.

Numerical Investigation of Hydromechanical Interactions at the Tail Void of Bored Tunnels due to Grouting

A.A. Lavasan, T. Schanz
Faculty of Civil and Environmental Engineering, Ruhr-Universität Bochum, Bochum, Germany

The hydro-mechanical incidents that occur at the vicinity of the tunnel boring machine (TBM) affect the ground settlement and the structural forces in the lining. In other words, the generation and dissipation of excess pore pressure in conjunction with the mechanical pressures in the grout mortar and surrounding soil significantly influence the process of the fluid flow around the tunnel. In addition, the mechanized tunneling process induces volume loss around the tunnel that triggers a stress redistribution. The main challenge in the design of tunnels in saturated soil is how to adequately simulate the volume loss and backfill grouting. Therefore, this research studies the influence of the numerical simulation technics along with idealized assumptions to address the stress redistribution and HM interactions around the tunnel on the model responses. Based on the results, depending on the expected level of accuracy for a given model response, appropriate technique can be chosen.

Numerical Study of Segmental Tunnel Lining Behavior During Mechanized Tunneling

S. Fabozzi, E. Bilotta
University of Naples Federico II, Napoli, Italy

During mechanized tunneling, the surrounding soil and the tunnel lining undergo a continuous changing of their state of stress and strain before reaching an equilibrium condition when the front of excavation is far enough not to induce any further effect. The impact of the construction process on the lining behavior has been investigated in this work by numerical modelling. The influence of several aspects was considered, such as the grouting pressure, the grout consolidation, the shield tapering, the segmental layout of the lining and the jacking forces. The numerical results are shown in the paper and discussed also in the light of measurements recorded during tunnel construction for a metro line.

Operative Techniques for Earth Pressure Balanced Shield in Saturated Soft Soils

C. Chanchaya
Chor Karnchang (Public) Company Limited, Bangkok, Thailand

This paper aims to explain about operation control of Earth Pressure Balanced Shield in tunnelling, focus to the principal of soil face pressure maintenance at shield face during shield advancing as correctly in soil mechanics. Determine important of face pressure monitoring and evaluate face stability in real time by empirical method while shield tunneling. Adjusting the other parameters such as screw conveyor speed, shield jack speed and soil excavation volume related to the changing of face pressure by presenting in simple chart and grout filling control correctly. However, to explain factors affect general problems during shield tunneling as type of excavation mode, airlift effect in borehole, amount and position for injected soil conditioning, assessment condition of soil excavation discharged from screw conveyor and grout leakage into shield to improve these procedures before or during tunneling in Bangkok subsoils by case study of MRT Blue Line Extension project, Thailand. This study is guideline in shield tunneling efficiency for another tunnel works and underground project in the future to reduce ground loss which causes minimum building damage on ground.

Tropical Residual Soil Data Compilation as Guidance for Laboratory Tests and EPB Excavation Process Simulation

D.G.G. de Oliveira, M. Diederichs
Queen's University, Kingston, Canada
L.L. Rasmussen
Brasília University, Brasília, Brazil
M.O. Cecílio Jr.
Tüv Süd - Bureau de Projetos e Consultoria, Sao Paulo, Brazil

The current trend of intense urban growth around the world has brought an increase in the demand for underground infrastructures including urban tunnels. In many cities, tropical residual soils are the main ground type in which tunnels are driven. Therefore, a thorough understanding of the residual soil engineering behaviour is crucial for planning and design. Considering the large increase in the use of tunnel boring machines, such as the Earth Pressure Balance (EPB), the need for more studies related to this type of construction method when applied to tropical residual soils is undeniable. To characterize the variability of tropical residual soil properties, a database of worldwide published data on laboratory and in-situ testing has been elaborated. This paper presents the results of this compilation together with statistical analyses of its content.

Sequential Excavations

Tunneling Through the Rock-Soil Interface

W. Bilfinger
Vecttor Projetos Ltda., Sao Paulo, Brazil
L.G.F.S. de Mello
Vecttor Projetos Ltda., Sao Paulo, Brazil / University of Sao Paulo, Sao Paulo, Brazil

Constructive methods, soil treatment and conditioning, and tunnel lining depend fundamentally of ground and hydro-geological conditions. In homogeneous ground, after adequate definition of the parameters above, independent of specific difficulties, construction becomes, after the initial learning curve, a repetitive, uniform and, normally, controlled process, either using conventional or mechanical tunneling method. Normally difficulties arise when varying ground conditions are encountered along the tunnel alignment, especially if ground behavior presents significant contrasts in deformability, shear strength and permeability. In geological environments where soft ground overlays rock and tunnels have to be built crossing this interface, the above mentioned contrasts occur at the same location. Some of the most significant recent tunnel failures in Brazil occurred close to rock soil interface, showing the necessity of a review of current design and construction practice. This paper intends to discuss main challenges associated to the rock-soil interface in the light of recent tunnel failures and present suggestions for robust design and construction methods.

A New Method for the Prediction of Settlements due to Urban Tunneling in Soft Ground

N. Gilleron, A. Saïtta
Egis, Saint-Quentin-En-Yvelines, France
E. Bourgeois
Université Paris-Est, IFSTTAR, COSYS, Marne-La-Vallée, France

In a context of global risk analysis for tunnel projects, the prediction of settlements due to shallow tunneling is a huge challenge for design firms. The finite element simulations, in two or in three dimensions, tend to provide poor predictions of the settlements induced at the surface. This is why the empirical method, based on Peck's works, is often privileged. This paper illustrates on an example the use of a new method to predict settlements due to urban tunneling. The method is grounded on finite element simulations based on a new constitutive model for soil. It discusses also the modeling and influence of pre-support structures. This example highlights the capacity of this new way of modeling to help the designer to choose the right construction process to manage the risk of settlement on surface structures.

Deformations Caused by the Excavation of Twin Tunnels

A. Pedro, T. Cancela, J. Almeida e Sousa, J. Grazina
University of Coimbra, Coimbra, Portugal

The use of the underground has been a growing solution found for the installation of infrastructure and (or) transport networks in the last decades. In these networks it is common to sequentially excavate tunnels in close proximity. Several case studies reported that the deformations associated with the excavation of a second tunnel were higher than those recorded in the first, showing that in this scenario there seems to have an interaction between tunnels. In order to predict the settlement profile induced by the excavation of the second tunnel several methods have been proposed based on numerical, centrifuge and small scale models. In this paper the results obtained with a numerical analysis of the excavation of two twin tunnels are presented and compared against those proposals. The results confirm that the presence of the first tunnel influences the excavation of the second tunnel. Based on a parametric study carried out it was possible to verify that interaction occurs regardless of the depth of the tunnel, though it is strongly dependent on the pillar width between tunnels.

K_0 Parameter Influence in Tunneling Superficial Settlements and in Liner Stresses

V. Armigliato, A.C.G. da Silva, C.M.A. Prado
Arcadis Logos, Sao Paulo, Brazil

This paper describes the influence of the K_0 parameter (ratio between vertical and horizontal "in situ" stresses) in superficial settlements and liner stresses caused by NATM tunnel excavation in a residual soil ground in São Paulo Line 4 Yellow Subway expansion. Two-dimensional numerical analyses using Finite Diferences Method implemented in FLAC software are presented for the construction method simulation. The soil behavior is simulated by Linear Elastic model with Mohr-Coulomb envelope.

Analytical and Numerical Models for Evaluation of Tunnel Excavation Stability in a Multi Layered Soil Profile with Groundwater Flow

L.E. Sozio
Geotechnical Consultant, Sao Paulo, Brazil

Analytical and numerical models to evaluate tunnel excavation stability are discussed. Multi layered soil profiles and groundwater flow are included into these models. Collapse and blow out type of failures, for both drained and undrained conditions, are considered. Comparative example applications are given. Analytical model calculations are straightforward and suited to preliminary studies. However, due to a series of limitations, analytical models should be replaced by more accurate three dimensional numerical models, as design progresses into detailed stages.

Investigation of Influence Zones Induced by Shallow Tunnelling in Soft Soils

M.N. Vu, W. Broere, J.W. Bosch
Delft University of Technology, Delft, The Netherlands

The extent of the influence zone affected by shallow tunnelling depends on the value of volume loss which normally represents the amount of over-excavation and stress changes induced in the soil. This paper combines upper and lower estimates of volume loss for different soft soils and cover-to-diameter ratios in order to identify the extent of zones around the tunnel influenced by tunnelling. These zones are combined with risk categories of damage of existing buildings in order to determine whether applying mitigating methods or taking additional control measures during tunnelling would be needed for a safe and damage-free tunnel construction. The effects of soil parameters on the influence zones are also investigated to identify their impact and quantity of the requirements for mitigating measures.

Effect of Construction Sequence of Three-Arch Tunnel on Center Structure: Numerical Investigation

J.H. Choi, J.S. Song, Q. Abbas, C. Yoo
Sungkyunkwan University, Suwon, Korea

This paper concerns the behavior of 3-Arch tunnels constructed in difficult ground conditions. A three-arch tunnel section adopted in a railway tunnel construction site was considered in this study. A calibrated 3D finite element model was used to conduct a parametric study on a variety of construction scenarios. The results of analyses were examined in terms of load and stress developed in center column in relation to the side tunnel construction sequence. The effect of the side tunnel construction sequence on the structural performance of the center structure was fully examined. Fundamental governing mechanism of three-arch tunnel behavior is also discussed based on the results.

Assessment of Train-Load-Induced Ground and Tunnel Settlement with the Effect of Leakage

Z.K. Huang, D.M. Zhang, H.W. Huang, Y. Li, S.J. Feng
Department of geotechnical Engineering, Tongji University, Shanghai, China.

The ground and tunnel settlement significantly degrade both the serviceability and safety of tunnel and its surroundings. In this paper, a typical numerical analysis is conducted to study the ground and tunnel settlement due to train load coupled with tunnel leakage in soft soil deposit of Shanghai. Two typical models are established according to the tunnel leakage conditions, namely without tunnel leakage and with uniform tunnel leakage. The development of excess pore pressure of the soil around the tunnel is analyzed. The long-term ground and tunnel settlement is predicted using the Gaussian curve based on the numerical calculation results. The results shows that the cumulative train-load-induced tunnel settlement increases as the operation time increases and the tunnel leakage can significantly increase the long-term ground and tunnel settlement.

Numerical Analysis of Large-sectional Pipe Arch Aided Tunneling from Ground Movement Perspective

X. Xie
Dept. of Geotech. Eng. of Tongji Univ., Shanghai, China
Z. H. Li
Guangdong Nanyue Communication Investment and Construction Co., Ltd., Guangzhou, China
D. M. Zhang, H. W. Huang
Dept. of Geotech. Eng. of Tongji Univ., Shanghai, China

The Gongbei tunnel is the connection of Hong Kong-Zhu Hai-Macao Bridge to Zhuhai mainland which has a large cross-section area of 345m². Under the support of pre-supporting system built with Freeze-Sealing Pipe-Roof (FSPR) method, tunnel is excavated with bench cut method. In this paper, numerical analysis of the tunneling process using the ABAQUS software is presented. General trend of the ground movement has been investigated from the numerical results. By comparison of the three models, i.e., green field, tunneling under the existence of raft foundation and tunneling under the existence of pile foundations, it can be concluded that the existence of the raft foundation and the pile foundation has relative little effect on the internal force of the tunnel lining. On the contrary, tunneling process has significant effect on raft foundation and pile foundation due to the ground movement induced by the tunneling. In the end of this paper, monitoring settlement has been analyzed and compared with the numerical simulation results.

Physical Modelling and Field Tests

Study on Potential Area of Chloride Ion Attack in Subway Tunnel from View Point of Chloride Ion Penetration Route in Ground and Concrete of Tunnel Lining

S. Konishi, T. Kawabata
Infrastructure Maintenance Dep., Tokyo Metro Co. Ltd., Tokyo, Japan
K. Kamei
Civil Engineering Sec., Infrastructure Maintenance Dep., Tokyo Metro Co. Ltd., Tokyo, Japan

Chloride attack is the main cause for deterioration of subway tunnels. Tokyo Metro studied on the potential area of chloride induce deterioration in the box type tunnel with investigating positional relations between tidal rivers and saltwater leakage parts. As the results, it is found that the influenced areas are within the range of 50m from edge of the tidal river. And we confirmed generality of the result by a ground water density flow analysis. Moreover, it is also found that the area of chloride ion attack is limited on area of leakage and trace part of it on the lining. For chloride penetration route, it is cleared that chloride ion in the tidal river move into underground, enter into subway tunnel through clacks or joints of tunnel lining and penetrate into lining from inside surface of the tunnel. The report describes procedure and results of the study.

Predictions of Changes in Pore-Water Pressure Around Tunnels in Clay

S. Divall, R.N. Taylor, S.E. Stallebrass, R.J. Goodey
City, University of London, London, UK

Any underground construction causes changes to the stress state in the ground and this change generally causes the generation of excess pore-water pressures in saturated fine grained soils. Subsequent dissipation of these pressures can lead to settlements and potential damage and hence there is a need to understand and predict these changes in pore-water pressure. Simple plasticity and non-linear elastic solutions have been used to calculate pore-water pressure changes as a tunnel is constructed in clay. These are compared with previous centrifuge tests involving the simulation of tunnel excavation as well as new tests specifically designed to investigate the generation and subsequent dissipation behaviour of excess pore-water pressures. The paper reports on the new tests, presents the findings within the simple plasticity and non-linear elastic analysis framework.

The Role of Building Dimensions and Position on the Response of Buildings to Tunnelling Subsidence: Centrifuge Modelling

S. Ritter
Department of Engineering, University of Cambridge, Cambridge, United Kingdom
G. Giardina
Department of Architecture and Civil Engineering, University of Bath, Bath, United Kingdom
M.J. DeJong, R.J. Mair
Department of Engineering, University of Cambridge, Cambridge, United Kingdom

In urban tunnelling it is essential to predict the performance of surface structures to tunnelling induced ground movements. Existing methods to assess potential building damage assume that a building located within the hogging and sagging region of the settlement trough can be subdivided into its sagging and hogging parts, which are then analysed separately. Netzel (2009) importantly identified that this splitting of a building can underestimate the structural damage. This paper examines the effects that both the building length perpendicular to the tunnel axis and the building location relative to the tunnel have on the building response to tunnelling in dry sand. A series of centrifuge model tests, performed on 3D printed surface structures with different building stiffness, are discussed. The findings confirm that potential structural damage caused by tunnelling-induced ground movements significantly depends on the building length and the location of the building within the settlement trough. Importantly, structures that span the sagging/hogging transition zone were found to be more vulnerable to building damage (in the form of cracking) than equal length structures wholly located in either the hogging or sagging region. Longer structures that span the sagging/hogging transition zone were found to be even more vulnerable. As a consequence, experimental results indicated that partitioning a structure into its sagging and hogging parts can lead to underestimation of building damage.

The Role of Building Position on the Response of Buildings to Tunnelling Subsidence: Numerical Modelling

G. Giardina
Department of Architecture and Civil Engineering, University of Bath, United Kingdom
S. Ritter, M.J. DeJong, R.J. Mair
Department of Engineering, University of Cambridge, United Kingdom

The potential damage caused by tunnel excavations to surface buildings can be effectively investigated by centrifuge testing. However, for practical reasons only a limited number of geometrical configurations can be tested in a geotechnical centrifuge. Therefore, numerical modelling provides an essential tool to generalise the laboratory results. This paper illustrates the performance of a 2D finite element model of masonry buildings subjected to tunnelling in sand. The results of the first series of centrifuge tests performed on complex 3D printed masonry structures and presented in the companion paper were used for the model validation. The model includes nonlinear constitutive laws for both the soil and the building. Differently than previous works, this paper focuses on the accurate simulation of the building response by using structural parameters specifically defined for the assessment of building deformations. The results provide insights into the effect of different building positions relative to the tunnel on the structural response. The validated model can be used to investigate the effect of different building conditions on the soil-structure interaction mechanism.

Centrifuge Modelling of Shaft Excavations in Clay

N.E. Faustin, M.Z.E.B Elshafie, R.J. Mair
University of Cambridge, United Kingdom

Circular shafts are an integral component of tunnelling projects and can be located very close to buildings and services in urban environments. They enable access of equipment, personnel and material to the tunnel horizon and also provide ventilation and/or emergency access to the completed tunnel. The current state of knowledge concerning the behaviour of circular shafts and the ground movement associated with their construction is limited. Consequently, any conservative assumptions made in the design of the shaft lining or to estimate ground movement due to their construction can have considerable cost implications for tunnelling projects. This paper describes a small-scale model test performed in a geotechnical centrifuge to simulate shaft excavation in clay. The centrifuge model and procedure developed to excavate the shaft in-flight are described. Measurements are presented for instruments used to monitor the response of the shaft lining as well as the adjacent ground.

Field Measurements of Ground Movements Associated with Circular Shaft Construction

N.E. Faustin, R.J. Mair, M.Z.E.B Elshafie
University of Cambridge, Cambridge, United Kingdom
C.O. Menkiti
Geotechnical Consulting Group, London, United Kingdom
M. Black
Crossrail Limited, London, United Kingdom

Circular shafts are an integral component of infrastructure development schemes which exploit underground space. However, limited design guidance exists for such structures and the cautious approach often adopted by designers can have significant impact on the shaft construction costs and the protective measures implemented for adjacent buildings and services. In the UK, Crossrail is a major tunnel construction project underway to improve transportation links across London and the South East. Several deep circular shafts were constructed to facilitate access and egress of plant and personnel to and from the tunnel horizon. This paper describes the findings from a comprehensive review of field observations associated with construction of four of the Crossrail shafts. The data is invaluable to understanding the behaviour of circular shafts and the adjacent ground. Different techniques for constructing shafts are evaluated and the important effect of dewatering is highlighted.

Effects of Wall Embedment on Base Heave Failure Arising from Deep Excavations in Soft Soils

J.P. Panchal, S.E. Stallebrass, A.M. McNamara
City, University of London, London, United Kingdom

There is an increasing demand for basement construction in congested areas and the successful execution of this relies heavily on mitigating ground movements. The three primary causes of ground movements include wall bending, wall displacement and base heave, thus parameters such as wall stiffness, embedment and excavation support systems can influence movements. Physical modelling was used to focus on preventing basal heave at the formation level and subsequently reduce movements adjacent the excavation. To investigate the significance of wall embedment in soft soils control measures were in place to isolate displacements typically observed from wall bending or inadequate prop stiffness. A 160g centrifuge test was performed to observe ground movements during an excavation of a wall retaining 12m soil and of 8.8m embedment. Measurements from this experiment were used in the upper bound analysis of a fan mechanism and indicated that the factor of safety against basal heave was 1.25.

Collapse Behaviour of Large Rectangular Tunnel in Cement-Admixed Soils

M.F.B. Zulkefli
Building and Construction Authority, Singapore
A. Tyagi, F.H. Lee
National University of Singapore, Singapore

Tunnelling in soft soils is difficult and constructing large vehicular tunnels in such soils is even more challenging. Ground improvement is often used to strengthen the soil surrounding the tunnel opening, however, failure mechanisms and stability of large vehicular tunnels in improved soils are still unknown. This paper presents centrifuge modelling of a rectangular tunnel of vehicular dimensions in cement-treated soils. The strength and thickness of improved soil zone surrounding the tunnel were varied to study the possible failure modes. From post-test examination, bending or flexural leading to roof collapse was found to be a dominant failure mode. The stability increased with strength or thickness of improved soil zone surrounding the tunnel, however the failure mechanism did not vary much for different tests. Based on the failure mechanism, an analytical method was proposed for finding the critical tunnel support pressure at the springline of a tunnel.

Case Histories

Large-Scale Improvement of Converting a Japan's First Subway Station Constructed by the Shield Tunneling Method into that of an Open-Cut Method: Kiba Station on the Tozai Line

K. Hiromoto, H. Hashiguchi, Y. Arai
Tokyo Metro Co.,Ltd, Renovation & Construction Department, Tokyo, Japan

Tokyo Metro has constructed subway lines since the 1950s to develop a subway network in the central part of the Tokyo Metropolitan Area. At present, it operates a 200km network of nine subway lines, which was, for the most part, completed when the entire Fukutoshin Line was opened for service in 2008. Tokyo Metro is now working to enhance safety and raise customer satisfaction by upgrading the quality of service. This paper reports on the contents and the construction methods used to achieve a seamless flow of passengers at Kiba Station on the Tozai Line. This is an example of the improvements being made in the existing subway network to help establish an affluent society in the future.

Ground response to tunnel construction for Jakarta Mass Rapid Transit Project

H. Hendarto, J.R. Standing
Imperial College London, London, UK

The Jakarta Mass Rapid Transit (MRT) Project, currently under construction, to relieve traffic congestion within the city, has both elevated and underground sections with a transition between them immediately north of Sisingamangaraja station. The tunnel runs from there to Bunderan Hotel Indonesia for 4 km beneath major roads in central Jakarta. Four earth-pressure-balance (EPB) machines with outer diameters of ~6.7 m are being used to excavate the northbound and southbound tunnels. The tunnels are mostly located in dilluvial strata which comprise stiff to hard silts or clays. Surface settlement predictions have been performed and field measurements analysed to assess the ground response to tunnel construction around the Bunderan Hotel Indonesia. In the early stages of tunnelling, in the northern part of the project (CP106), small degrees of heave, up to about ~6 mm, occurred directly above the centre-line of the southbound tunnel, reducing with transverse distance to small settlements. Once the tunnel boring machine (TBM) reached about 320 m southwards, surface movements changed from heave to settlement. The responses suggest that vertical displacements (heave or settlement) depend on TBM variables such as face and tail skin grouting pressures in conjunction with depth of overburden.

Imposed Longitudinal Settlement on a Cast-iron Tunnel from the Excavation of a New Tunnel Beneath

M. Alhaddad
University of Cambridge, Cambridge, United Kingdom / Arup, London, United Kingdom
M.Wilcock
University of Cambridge, Cambridge, United Kingdom / CH2M, London, United Kingdom
C.Y. Gue, M.Z.E.B. Elshafie, K. Soga, R. Mair
University of Cambridge, Cambridge, United Kingdom
M. Devriendt
Arup, London, United Kingdom
P. Wright
CH2M, London, United Kingdom

This publication presents observed settlement of an existing cast iron tunnel that was influenced by the excavation of a new tunnel directly beneath and parallel to its axis for more than 100 m. The existing tunnel is 2.7 m in diameter and the new tunnel is up to 11 m in diameter. The clearance between the two was around 2 m. The new excavation took place in two stages: a 6 m diameter pilot tunnel, and a later enlarged to approximately 11 m in diameter. The longitudinal deformation of the existing tunnel due to these two stages was monitored using a newly developed 'digital image correlation' technique (CSattAR) and fibre optic sensing cables. This paper focuses on the CSattAR data which show that at subsurface level, the magnitude of the immediate longitudinal ground movement ahead of the tunnelling face in London Clay is likely to be less than empirical assessment methods suggest.

PAT TBM Improving: A Case of Study to Metro São Paulo

D. Agnella
GETAD Consult, Sao Paulo, Brazil
W. J. Giannotti, M. A. Rosatti Filho, T. Oliveira Pires
Companhia do Metropolitano de São Paulo - METRÔ, Sao Paulo, Brazil

In the final stage of Line's 5 tunnel construction - São Paulo Metro (Chácara Kablin Station – VSE Dionisio da Costa), by the use of TBM-EPB, a PAT (Plan for Advance of Tunnel) instrument has been generated for improving the previous referenced TBM face pressure, principally due to variation of the underground water level and to the new up-pressure contribution related to the load of a new building edified above the tunnel route, of 48m height and with 2 underground levels of 7m depth. The up-pressure contribution of the new building, in the face TBM pressure calculation, has been considered as part of the footing pressure, evaluate by model based on the theory of elasticity. The result of the TBM´s parameters recorded during the excavation, the monitoring data and the absence of building damage shows the integrity of the methodology used.