2018 | NORTHWEST FALL/WINTER

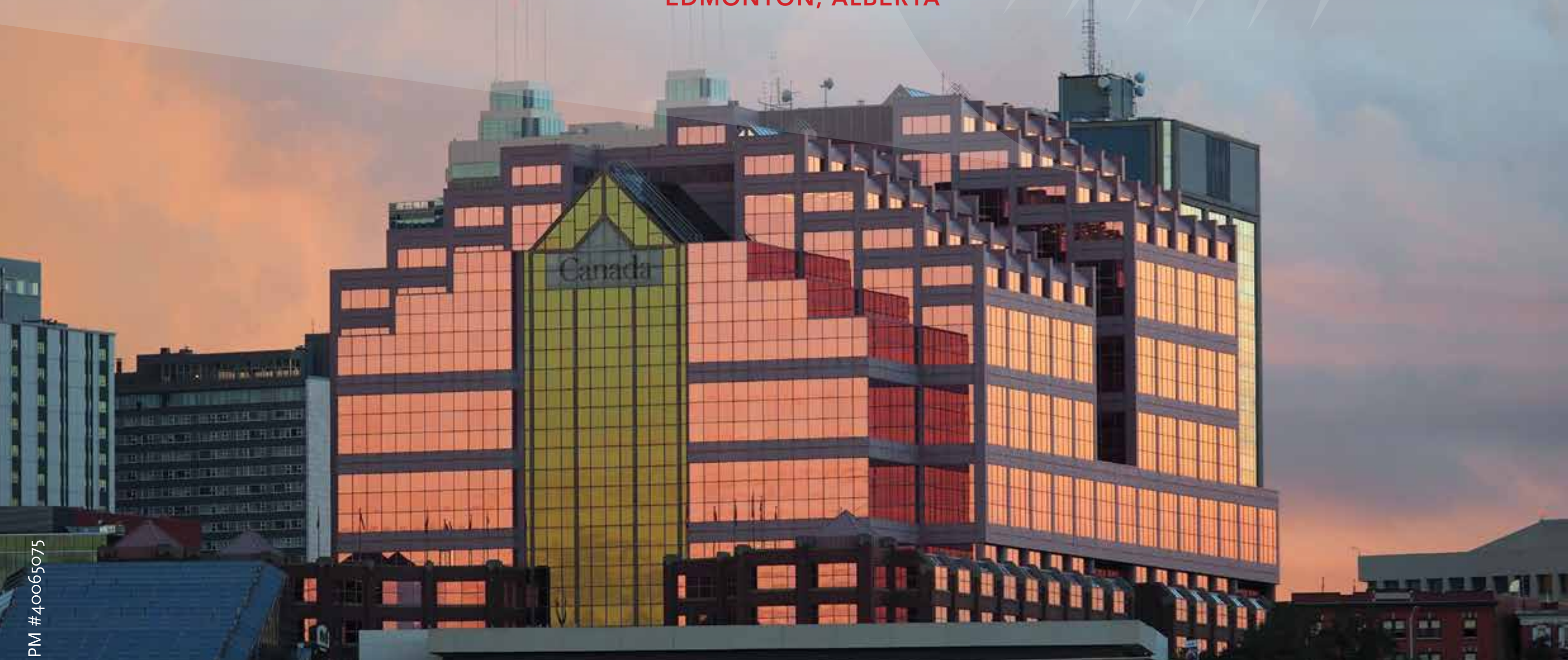
TRENCHLESS JOURNAL

THE OFFICIAL PUBLICATION OF THE NORTHWEST CHAPTER OF
THE NORTH AMERICAN SOCIETY FOR TRENCHLESS TECHNOLOGY

2018 TAC/NASTT-NW

Tunnelling and Trenchless CONFERENCE

NOVEMBER 7 TO 9, 2018
EDMONTON, ALBERTA



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ANALYSIS OF JACKING LOADS FOR MICROTUNNELING IN WESTERN CANADA

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TIME FLIES WHEN YOU ARE HAVING FUN

As we all come to the realization that the summer of 2018 is over, we are inching our way even closer to the trenchless event of the year for Canada, TT2018 – **TAC/NASTT-NW Tunnelling and Trenchless Conference. This national conference will be held in Edmonton at the Fantasyland Hotel on November 8 and 9.** The conference planning committee is well underway in finalizing the program for this two-track, two-day conference. In addition to the two-day conference, this conference will also feature a two-day trade show and a pre-conference short course. This year's short course, Microtunnelling Short Course: Design Considerations and Case Studies, was specifically developed for this conference. This is a great opportunity, especially for new members, to come out and network with your colleagues and get to know your NASTT-NW Board of Directors as well as some NASTT National Board Members. For more information on the above and the other events that will take place during this conference **please visit the Conference's webpage:** *www.tt2018.ca*.

> "This year's short course, Microtunnelling Short Course: Design Considerations and Case Studies, was specifically developed for this conference."

Our Chapter's Technical Lunch Programs in both Edmonton and Calgary have resumed after our summer break, and I encourage all of our members to take part and bring a friend or college to these great networking events! At these lunches, we not only highlight our great local projects but also new products, new techniques and national projects. Watch your emails and our website, *www.nastt-nw.com* for additional information on upcoming technical lunches. We would also like to extend an invitation to our members and remind you all that we are always looking for great topics and new presenters to become active and participate in our Chapter!

We are always looking for volunteers, fresh ideas, and new perspectives! If you wish to participate as a volunteer or just provide suggestions on how to improve our Chapter, please do not hesitate to contact me directly at *gtippett@nastt-nw.com*.

Greg Tippett
Chair, NASTT – Northwest Chapter

TREMENDOUS GROWTH IN OUR INDUSTRY

The trenchless industry continues to grow and expand our reach to more and more communities every year. 2018 has seen this growth and as we've talked with our membership we've heard many good news stories about trenchless project successes. As evidenced by this growth, NASTT's 2018 No-Dig Show held in Palm Springs this past March was a superb success and a highlight of the year. We welcomed more than 2,000 attendees from all over the world. We presented a top-notch technical program and completely sold out our exhibit hall, once again! None of this would be possible without our dedicated volunteer membership including your Northwest Chapter members.

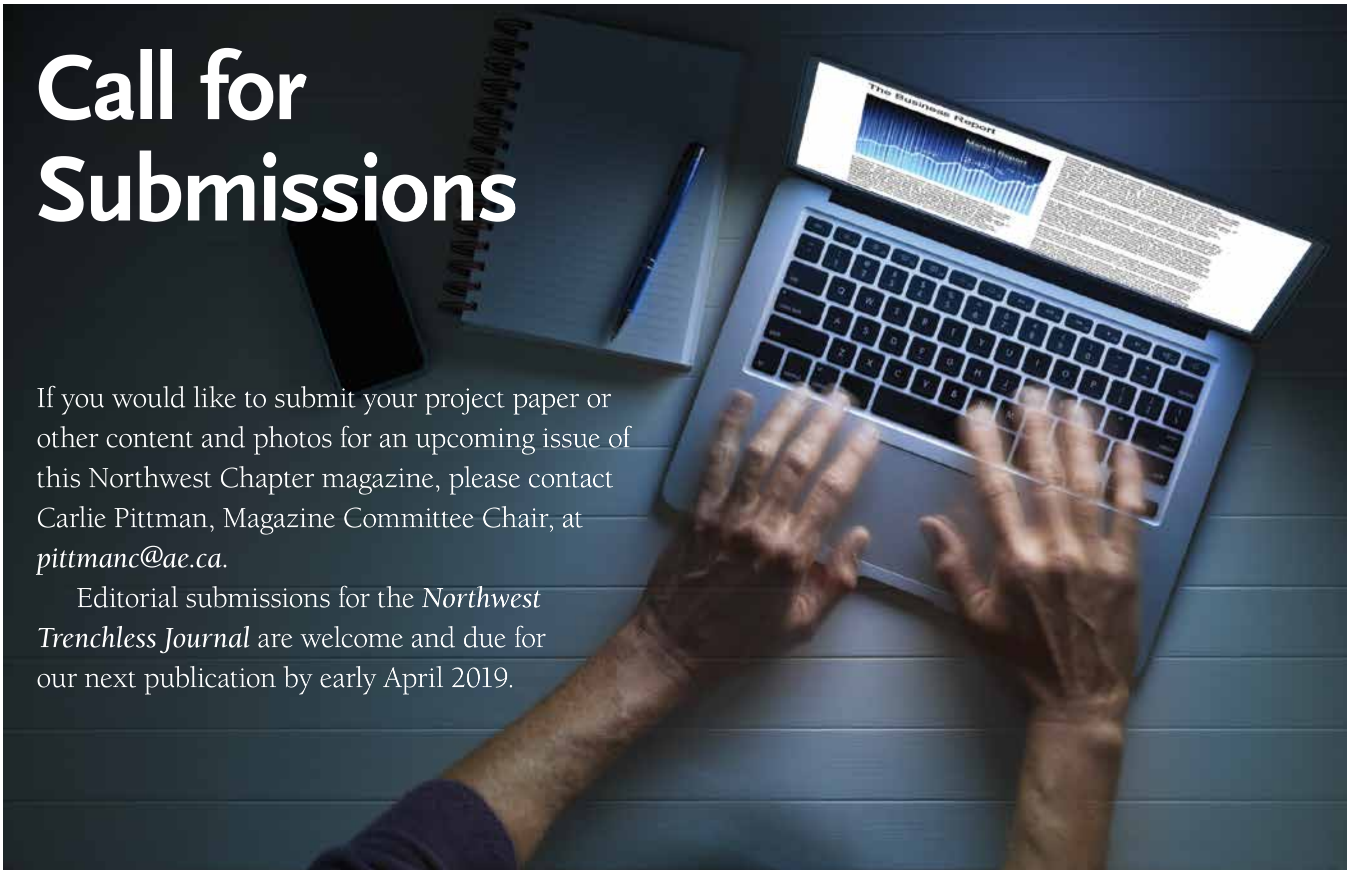
Looking ahead to November, I am particularly excited to be able to join you once again at the upcoming 2018 Northwest Chapter Trenchless Conference in Edmonton, Alberta. This will be the Chapter's 22nd annual conference! This year the conference has expanded to two days – another example of the tremendous growth in our industry! This conference will offer a variety of learning and networking opportunities for trenchless industry professionals. The event includes technical presentations and an exhibit hall bringing you industry innovations for trenchless products and services.

As you can imagine, plans for NASTT's 2019 No-Dig Show in Chicago, Illinois, March 17 to 21, are well under way. The 2019 technical paper program will have more than 160 informative and innovative presentations. Of course, our exhibit hall will be full of new products and services to support the trenchless industry as well. We will also host our Good Practices training program, which includes seven different specialized full- and half-day courses. This is an event you simply cannot miss! If you are a municipal or public utility employee, be sure to apply for NASTT's Municipal & Public Utility Scholarship Program Award. You can find all the details at *nastt.org*. The application deadline is November 1.

> "I am particularly excited to be able to join you once again at the upcoming 2018 Northwest Chapter Trenchless Conference in Edmonton, Alberta."

Again, I cannot thank our Northwest Chapter volunteers and members enough for your dedication and support. Your Chapter embraces the mission and vision of NASTT and we value you all as true Trenchless Champions. I look forward to joining you in Edmonton for the regional conference as well as seeing you in Chicago next March.

Michael J. Willmets
NASTT Executive Director



Call for Submissions

If you would like to submit your project paper or other content and photos for an upcoming issue of this Northwest Chapter magazine, please contact Carlie Pittman, Magazine Committee Chair, at *pittmanc@ae.ca*.

Editorial submissions for the *Northwest Trenchless Journal* are welcome and due for our next publication by early April 2019.


ANY SIZE. ANY LENGTH.
ANYWHERE.

2018 TAC/NASTT-NW

Tunnelling and Trenchless CONFERENCE

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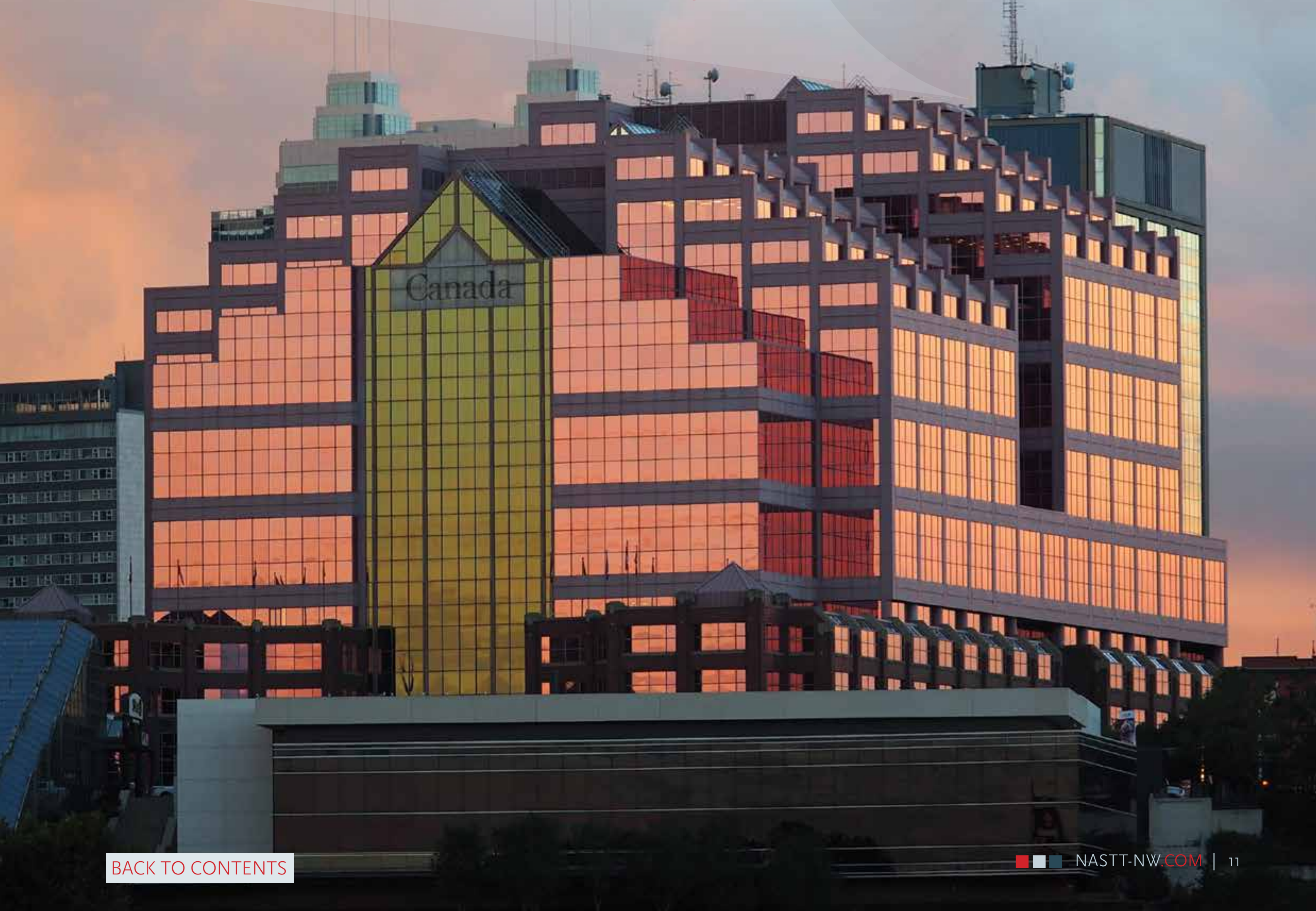

Conference Details

The Chapter is proud to be jointly presenting the TT2018 – TAC/NASTT-NW Tunnelling and Trenchless Conference in partnership with TAC featuring the theme Innovation in Underground Infrastructure. The Conference will take place in Edmonton, Alberta from November 7 to 9, 2018 at the Fantasyland Hotel at West Edmonton Mall.

Wednesday, November 7 will feature a microtunnelling short course during the day. Thursday, November 8 and Friday, November 9 will include all keynote and theme lectures, concurrent technical sessions, and panel discussions. The TAC AGM will take place at the end of the technical sessions on November 8, followed by the 2018 TAC Awards Banquet that evening. The NASTT-NW Project of the Year will be presented on November 9. For more information on sponsorship opportunities, trade show booth sales, and delegate registration please visit the Conference's webpage: *www.tt2018.ca*.

For more information, email *gtippett@nastt-nw.com*.

SHORT COURSE DETAILS

The Chapter is proud to be jointly presenting the TT2018 – TAC/NASTT-NW Tunnelling and Trenchless Conference in partnership with TAC featuring the theme Innovation in Underground Infrastructure.TT2018 is pleased to offer a microtunnelling short course on Wednesday, November 7 as an added element to the Thursday and Friday technical program. The short course will take place at the Fantasyland Hotel.

Microtunnelling Short Course: Design Considerations and Case Studies

Lead Instructor: Glenn Boyce – McMillen Jacobs Associates
Time: 8:30 a.m. – 4:30 p.m.
Cost: TAC/NASTT Members $375, Non-members $450, Students $150

This course is geared towards engineers and owners to provide an overview of microtunnelling design and construction considerations applicable to those planning and considering utilizing this technique on their infrastructure projects. This course will be led by Dr. Glenn Boyce, a recognized expert in the design of microtunnelling projects, and includes local geotechnical and contracting experts that will provide complementary local case studies and discussion pertaining to the various course topics.

Your course registration fee includes:

- Continental breakfast, breaks, and lunch
- CEU certificate issued by Louisiana Tech University
- Comprehensive, consensus-based information, non-commercial presentation
- Expert course instructors who are leaders in their respective fields and can help answer your questions not outlined in the course agenda

Register for this event today at *www.tt2018.ca*.

For course content questions: contact *gtippett@nastt-nw.com*.

REGISTRATION

Conference Registration – November 8–9, 2018:

- Full Conference with TAC Awards Banquet – TAC/NASTT Member $550
- Full Conference with TAC Awards Banquet – Non-member $650
- Full Conference without TAC Awards Banquet – TAC/NASTT Member $450
- Full Conference without TAC Awards Banquet – Non-member $550
- Full Conference – Student Delegate $150 (valid student ID card required)

Short Course Registration – November 7, 2018:

- Microtunnelling Short Course – TAC/NASTT Member $375
- Microtunnelling Short Course – Non-member $450
- Microtunnelling Short Course – Student $150 (valid student ID card required)

Conference registration is now OPEN. To register, go to *www.tt2018.ca*. Note: Registration for the short course is not included with general registration for The 2018 TAC/NASTT-NW Tunnelling and Trenchless Conference, and vice versa.

SPONSORS AND EXHIBITORS

The Tunnelling Association of Canada and the North American Society for Trenchless Technology – Northwest Chapter have a history of providing sponsors with excellent value for their investment. This year's conference includes a relevant and timely technical program with the theme Innovation in Underground Infrastructure. The trade show and social events combine to provide sponsors with opportunities to deliver their message and connect with this highly targeted audience of tunnelling leaders and stakeholders.

The trade show will open the evening of Wednesday, November 7, 2018 to host the Opening Reception and run until the end of the afternoon coffee break on Friday, November 9, 2018. Exhibitors will have the opportunity to reach 200+ delegates over this two-day period.

Depending on the level of sponsorship, delegate registrations may be included, as well as to each single booth exhibit space. Sponsors and exhibitors will be acknowledged on table cards, signage, and slideshows during breaks at the conference. Exhibitor booth assignment will be on a first-come, first-serve basis.

If your company is interested in sponsoring the conference or exhibiting at the trade show, the sponsor registration form is available at *www.tt2018.ca*. If you

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have any questions, please contact us at *sponsors@tt2018.ca*.

Special event sponsorship opportunities, such as for meals or coffee breaks, are limited, so early sponsorship registration is encouraged.

GENERAL INFORMATION

Short Course, November 7

The Chapter is proud to be jointly presenting the TT2018 – TAC/NASTT-NW Tunnelling and Trenchless Conference in partnership with TAC featuring the theme Innovation in Underground Infrastructure.TT2018 is pleased to offer a microtunnelling short course as an added element to the Thursday and Friday technical program. The short course will take place at the Fantasyland Hotel.

In conjunction with TT2018 – TAC/NASTT-NW Tunnelling and Trenchless Conference, the NASTT-NW Chapter is proud to be presenting a short course on Wednesday, November 7. This year's short course will be Microtunnelling. Please go to *www.tt2018.ca* for more information regarding the short course, including the technical agenda for the day.

Note: Registration for the short course is not included with general registration for the 2018 TAC/NASTT-NW Tunnelling and Trenchless Conference

Trenchless Conference. Conference, November 8–9

The two-day conference offers excellent learning and networking opportunities for trenchless industry professionals, and includes several technical presentations and a trade show. Technical presentations will cover various trenchless topics. Arrive early on November 8 to complete your registration and have breakfast while checking out the trade show. Prize draws will be held throughout the day.

NOVEMBER 8–9 CONFERENCE AGENDA

This year will contain two tracks with a total of 40 presentations including two keynote addresses. Following the program theme of Innovation in Underground Infrastructure, this year has brought a diverse set of papers and presentations. Accepted abstracts have been posted on the conference website *www.tt2018.ca*, and the full program agenda was released late September. Topics for this year's presentations include: Case Histories - Lessons Learned; Condition Assessment and Rehabilitation; Planning and Design; Research and Innovation; and Urban and Environmental Challenges.

PLANNING COMMITTEE

- Greg Tippett, Stantec Consulting Ltd, Conference Planning Committee Co-Chair
- Heinrich Heinz, Thurber Engineering, Conference Planning Committee Co-Chair
- Paul Dedeluk, Associated Engineering, Technical Program Chair
- Dave Krywiak, Stantec Consulting Ltd.
- Chris Jones, Stantec Consulting Ltd.
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- Robyn Barnett, Tetra Tech
- John Balla, Michels Canada
- Remco Kleinlugtenbelt, Thurber Engineering
- Erik Eberhardt, University of British Columbia

FOR GENERAL INFORMATION

Contact Greg Tippet, Co-Chair – 2018 TAC/NASTT-NW Tunnelling and Trenchless Conference: *gtippett@nastt-nw.com*.

"Arrive early on November 8 to complete your registration and have breakfast while checking out the trade show. Prize draws will be held throughout the day."

This Year's Keynote Speakers

TITLE: Transforming Edmonton with Urban LRT

PRESENTER:
GUY BOSTON, P. Eng.
Transit Oriented Development (TOD) Manager
Integrated Infrastructure Services, City of Edmonton

BIO

In his new role as Transit Oriented Development (TOD) Manager, Guy will be actively working to promote the investment and development opportunities that the LRT corridors have to offer with the goal of supporting Council's vision for the City of Edmonton. The role is essential to realizing Edmonton's Urban Transformation vision by leveraging the City's significant investment in LRT as a catalyst for change. TOD is an exciting approach to building a city. It concentrates housing, shopping, and employment along a network of walkable and bikeable streets within a five-minute walk of LRT stations, or 400 metres in any direction

Previously Guy was responsible for the development and delivery of the City's LRT expansion program, body of knowledge on Public-Private-Partnership (P3), and the delivery of one of the largest capital programs in Canada and the largest in the City's history.

Guy has a wide breadth of senior management experience in both the public and private sectors, has regional experience in economic development, and brings a deep appreciation and understanding of the critical business success factors required for City-building. This combination positions him with the knowledge and expertise development partners and investors need to be able to successfully implement TOD.

ABSTRACT

The vision for the City of Edmonton of the future is being catalyzed with a significant investment in LRT infrastructure. The 13 kilometer southeast leg portion of the 27 kilometer Valley Line is now under construction with much more of the LRT network poised to be built in the not too distant future. The portfolio of 'urban' LRT projects is designed to not only move people but also intended to spur on transit oriented development supporting the City vision of re-developing in a denser urban form. This presentation will touch on the planning, engagement, design and procurement processes of the entire LRT network and provide construction updates on the Valley Line Southeast project.

TITLE: Considerations for Increasingly Higher Pressure EPB Tunnelling in Challenging Ground

PRESENTER: Steve Skelhorn

BIO

Steve Skelhorn is a Project Sponsor with McNally Construction Inc. and is also the Vice President East, Tunnelling Association of Canada.

Graduating in Mining Engineering in the UK in 1984, Steve has more than 30 years' experience in soft ground segmental lined tunnels and has worked on various projects in the UK, USA, and Canada.

Recent projects have included Toronto Sheppard Subway the South Edmonton LRT, Spadina Subway Tunnels in Toronto, Big Walnut Creek in Columbus Ohio, Coxwell Trunk Emergency Bypass in Toronto, and most recently the Port Mann Water tunnel in Vancouver – a high pressure EPB tunnel beneath the Fraser River.

ABSTRACT

Over the past 30 years, pressurized face tunnelling has progressed leaps and bounds and has allowed for tunnelling in some extremely challenging ground. As the technology progresses, so does the demand for pressurized tunnels, which in many cases is pushing the envelope of what is possible.

Conventional wisdom considers two types of pressurized tunnelling: Earth Pressure Balance (EPB) for ground with high fines content and Slurry for granular material and areas of high hydrostatic head. However, today's technology has narrowed, if not eliminated, the differences in capability between these two technologies. Tunnelling at pressures over 6 bar and through ground with low fines content, is not only possible with EPB machines, but in some cases is more desirable when compared with slurry methods.

Steve Skelhorn has been working in soft ground tunnelling for over 30 years with specific experience in EPB tunnelling for 25 of those. This keynote lecture is based on his experience and observations of TBM behaviours through the development of pressurized machines. The key elements surrounding EPB tunnelling will be discussed from a practical viewpoint through case studies, and the balance with respect to selection of EPB versus Slurry TBMs will be considered.

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Technical Presentations Preview

The following is a sneak peek at the featured presentations offered at this year's conference.

AUTHOR	COMPANY	TITLE
Michelle van der Pouw Kraan	McMillen Jacobs Associates	Ashcroft Lateral Pipeline HDD Construction: Lessons Learned on the Use of a Surface Casing
Joe Anderson	Golder Associates	Soft Ground Tunnelling Techniques for Mine Access Development
Mark Stephen Diederichs	Queens University	The Evolution of Yield, Closure and Support Analysis for Rock Tunnelling
Karin Bäppler	Herrenknecht AG	4 Double Shielded Hard Rock TBMs In Use for the Oslo Follo Line – Project Challenges and TBM Solutions
Karin Bäppler	Herrenknecht AG	The New Jet Pump Technology, Ideal for Long-Distance Pipe Jacking and HDD Crossing with Highly Permeable Soils
Michael Duton	Hatch	Ashbridges Bay Treatment Plant Outfall – Designing for Time Dependent Deformations in PCTL
Andre Solecki	Hatch	Ashbridges Bay Treatment Plant Outfall – Design Innovations
Mehdi Bakhshi	AECOM	Tunnel Segmental Lining Durability
Remco Kleinlugtenbelt	Thurber Engineering	Following Canadian Pacific Railway protocol for a trenchless crossing in Calgary, Alberta
Stefan Goerz	CCI Solutions	A New Perspective in Hydro Fracture Analysis
Richard Humphries	Golder Associates	Design and Construction of Unlined Water Tunnels – An Update
Loic Galisson	SIXENSE Solutions Canada Ltd.	Reducing the Intrusion: Instrumentation and Monitoring for Urban Excavation with Non-Contact Technologies
Ray Offman	KGS Group Consulting Engineers	Winnipeg's First Large Diameter Microtunnelling Project – 2,700 mm Trunk Sewer: A Case History
Don Del Nero	Stantec Consulting Services, Inc.	Pedestrian Tunnels – The Mode of the Future
Leila Sunderani	R.V. Anderson Associates Limited	The 1905 Toronto Cross Harbour Watermain Tunnel
Carlie Pittman	Associated Engineering	Confederation Way Sanitary Sewer Bypass – Phase 2, Fort McMurray, Alberta
Samuel Wilson	CCI Solutions	940 m NPS 42 HDD Crossing of the Victoria Harbour
Neda Dadashzadeh	Queens University	Effect of Rock Strength Components' Evolution Rate on the Mechanism of Failure in Brittle Rocks
Lars Henning Babendererde	Tunnelsoft of Babendererde Engineers LLC	Data Management in TBM Tunneling – From Table List to BIM Source
Christopher Kevin Lamont	Associated Engineering	Stormwater Management Facility Upgrades at Easgate Lake
Giacomo Falorni	TRE ALTAMIRA	Satellite InSAR Monitoring in Urban Tunneling Projects
Nick Gannon	Allstream Waste Solutions Inc.	Novel Solidification Technology and Tracking Software Solves Waste Management Problem for Large HDD in Urban Environment
Ali Bayat	University of Alberta	Effect of Kaolinite and Bentonite on the Clogging Potential of Edmonton Clay
Paul Dedeluk	Associated Engineering	Beneath the City of St. Albert: Microtunnelling the 1,500 mm North Interceptor Sanitary Trunk

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AUTHOR	COMPANY	TITLE
George Bontus	Aegion Corporation	Cured-in-Place Pipe Liners for Pressure Applications – What the Industry is Doing to Standardize Structural Design and Seal at Services and Ends
Filippo Mira-Catto	Bauer Foundations Canada Inc.	Ground Freezing as Temporary Excavation Support: A Sustainable Geotechnical Technique
Daniela Garroux Goncalves de Oliveira	Herrenknecht AG	Laboratory Assessment of Flow Behaviour and Clogging Associated with EPB Machine Excavation
Mario Galli	PORR Deutschland GmbH	Material Flow in EPB Tunneling – Characterization and Importance
Guido Martin Perez Manfredini	MST Global	Unified Communication and Data Network for Tunnels
Stefan Lemke	Renesco Group	European Implementation of Automation and Digitization in Tunnel Waterproofing and Grouting Practices
Mehdi Bakhshi	AECOM	Tunnel Segmental Lining Geometry, Tolerance and Measurement
Chris Sivesind	Akkerman	Pilot Tube Guided Auger Boring to Solve Project Challenges, and Go Further in Harder Geology
Tom Fuerst	The Robbins Company	Lessons Learned at Montreal's Rue Jarry Project: Overcoming Flooding and Rebuilding a TBM to Finish on Schedule
Christina Lee Lindstrom	Obayashi Corporation	Analysis of Cognitive Response and Accident Prevention

We hope you can join us in November!


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ANALYSIS OF JACKING LOADS FOR MICROTUNNELING PROJECTS IN WESTERN CANADA – A Case Study

EREZ ALLOUCHE, PhD, P.Eng., Stantec Consulting Ltd., Edmonton, Alberta
OLUGBENGA IBIKUNLE, PhD, Stantec Consulting Ltd., Edmonton, Alberta

ABSTRACT

This paper presents a state-of-the-art review of design methods commonly used by practitioners to estimate the maximum jacking loads anticipated to develop during microtunneling projects. Knowledge of the magnitude of the jacking force required to successfully complete a given installation is needed for the contractor and engineer to:
a) determine the appropriate wall thickness for the product pipe; b) determine the appropriate jacking system configuration; c) properly design the thrust block; and d) determine the number and location of intermediate jacking stations, if needed; (e) determine the appropriate overcut for the jacking machine.

The accuracy and generality of these predictive models are evaluated by comparing their predictions with jacking load measured on five microtunneling drives, ranging in length from 50 m to 560 m, and in diameter from 2,050 mm to 2,250 mm, recently completed in Canada utilizing full face excavation machines with a hydraulic slurry circuit. These

installations were completed in a wide range of geological formations including shale, clay till, saturate poorly graded sand, and high-plastic silty-clay formations, each presenting a unique set of challenges to the contractor. Recommendations are made regarding coefficients that can be used for calculating penetration resistance and frictional resistance for selected geological formations commonly encountered in Western Canada.

INTRODUCTION

Deteriorating conditions of urban infrastructure systems, rising restoration costs, and increasing public pressure to mitigate construction-related impacts on normal day-to-day activities have led to the increased use of trenchless construction methods. In cities around the world, microtunneling has gained popularity as a suitable method for the installation of gravity sewers in densely populated urban areas and environmentally sensitive locations. A key design parameter in a microtunneling project is the jacking forces generated throughout the course of the installation. Knowledge of the magnitude of the jacking force required to successfully complete a given installation is needed for the contractor and/or engineer to (i) determine the appropriate wall thickness for the product pipe; (ii) determine the location of intermediate jacking stations, if needed; (iii) determine the appropriate jacking system configuration; (iv) properly design the thrust block; and (v) determine the appropriate overcut for the jacking machine.

This paper provides an overview of design methods proposed by researchers and practicing professionals around the world. Notations used in the various design equations are elaborated on in Appendix 'A' provided at the end of this paper. Thereafter, selected models for which sufficient input data is available are used to predict jacking loads for the five case histories. Tables 1 summarizes the project characteristics for each of the case histories. The predicted and measured values are compared and observations regarding the accuracy and consistency of the models are made. The case histories are from sanitary sewer and water feeder main projects in southeast Calgary, Alberta.

PARAMETERS CONTRIBUTING TO JACKING LOAD

The jacking load is the sum of the pressure at the cutting face of the boring machine and the friction between the product pipe and the surrounding geological formation. Because geological conditions can vary over the drive length of a microtunneling project, jacking loads may also vary due to changes in values of the factors involved. Factors that could affect jacking loads during a particular operation include: (i) resistance at the cutting face of the excavation machine; (ii) pipe characteristics, such as diameter, roughness and lack of straightness; (iii) location and use of intermediate jacking stations; (iv) amount of overcut; (v) use of lubrication; (vi) frequency of stoppages during the operation; (vii) elevation of the groundwater table; (viii) profile of the project path, such as horizontal or vertical curves; (ix) internal and external loads on the product pipe; and (x) changes in soil characteristics along the installation path.

Face Pressure Component

The face pressure, also known as the penetration resistance component of the jacking force is the force needed to advance the boring head of the microtunneling machine into the formation by a unit length. When an auger system or an open jacking shield is used, the face pressure is referred to as the cutting-edge resistance. If a slurry system is used to facilitate spoil removal, the face pressure is referred to as the face resistance. In many cases, the face pressure is small when compared to the total jacking force, but it can have a significant effect on the total jacking force in situations where: (i) the microtunneling operation occurs in rock or hard clay formations; (ii) groundwater levels are high; and/or (iii) the microtunneling operation occurs over a short drive length.

Friction Component

The friction component of the jacking force, also known as the skin friction, is the force needed to overcome the friction between the external surface of the product pipe and the soil in which the microtunneling operation is taking place. The friction force increases as the drive length increases, and depends on both the normal stresses acting on the pipe and the friction coefficient at the soil-pipe interface. Site conditions such as soil characteristics, depth, and groundwater can significantly affect the friction force. Other characteristics such as pipe diameter, roughness, lubrication, overcut, and misalignment can also affect the magnitude of the friction force during a particular drive.

METHODS FOR ESTIMATING THE TOTAL JACKING LOAD

The 'Rule-of-Thumb' Method

The following equation is known as the "rule-of-thumb" method for estimating the jacking load for a microtunneling project:

$$F = \pi \cdot D_o \cdot L \cdot f_r \quad [1]$$

This method ignores the contribution of face pressure to the total jacking load. Also, factors such as soil characteristics or conditions, depth, groundwater, overcut, misalignment, and lubrication are either ignored or included in the

Table 1 – Characteristics of the Case Histories

Site Locations	Length (m)	*h* (m)	Pipe OD (m)	γ (kN/m³)	K_h (1-Sinϕ')	μ	ϕ' (°)	Soil Type
MH104-100	559.74	1049.49	2.050	22.5	0.4264	0.2	35	Siltstone / Sandstone
MH104-106	249.97	1047.84	2.050	21.5	0.5616	0.2	26	Bedrock/silty clay till
MH109-106	414.92	1048.17	2.224	21.5	0.5616	0.2	26	Silty Clay Till (Stiff to hard) / Sedimentary Rock
MH109-112	390.95	1046.54	2.224	22.5	0.4264	0.2	35	Siltstone (Moderately strong)
MH118-117	50.00	1035.82	2.224	20.5	0.4701	0.2	32	Silty-sand

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jacking stress value (Collier et al.1996). For these reasons, some scholars (e.g., Sterling and Thorne, 1999) advised that the "rule-of-thumb" method should be avoided. Nevertheless, Equation 1 enjoys widespread use due to its simplicity.

KHAZAEI ET AL. (2004) METHOD

Khazaei et al. (2004) presented methods for estimating the jacking load, or thrust, for both straight and curved paths. In both cases, a slurry machine is assumed to be used. It is given that the general form of the jacking load equation is as follows:

$$[2] \quad F = F_i + u_1 \cdot \tau_1 \cdot L$$

Assuming a slurry machine is used, Equation 2 takes the following form:

$$[3] \quad F = F_i + (\tau_1 u_1 + \tau_2 u_2) \cdot L$$

The initial thrust, F_i, is dependent on the slurry pressure, P_s (kPa), and the area of the tunnel face, A (m²), as shown in Equation 4.

$$[4] \quad F_i = P_s \cdot A$$

Pipe Jacking on Straight Path

When jacking along a straight path, the equation used to estimate the jacking load depends on whether or not the product pipe rests on the bottom of the borehole. If the pipe does not rest on the bottom of the borehole, the jacking load can be estimated as follows:

$$[5] \quad F = P_s \cdot \left(\frac{D_o}{2}\right)^2 \cdot \pi + \pi \cdot D_0 \cdot (P_s \cdot \mu_2 + C_2) \cdot L$$

Where the term $P_s(Do/2)^2\pi$ represents the face pressure component of the jacking load. The term $\pi Do(Ps\mu_2+C_2)L$ represents the friction component of the jacking load.

Pipe Jacking on Curved Path

Khazaei et al. (2004) use the following approach to estimate the jacking load needed for a curved alignment. From Figure 1, the initial thrust, F_i, is used to determine the jacking load in the first section of pipe in the following manner:

$$[6] \quad F_1 = F_0 + (F_0 \cdot \mu_1 \cdot \sin\beta_1) + (P_s \cdot u_2 \cdot L \cdot \mu_2)$$

The jacking load for the second section of pipe is given by the expression in Equation 7.

$$[7] \quad F_2 = F_1 + (F_1 \cdot \sin\beta_1 \cdot \mu_1) + (P_s \cdot u_2 \cdot L) \cdot \mu_2$$

By combining Equations 6 and 7, Equation 7 takes the following form (i.e., Equation 8):

$$[8] \quad F_2 = F_0 \cdot (1 + \mu_1 \cdot \sin\beta_1)^2 + 2 \cdot (P_s \cdot u_2 \cdot L) \cdot \mu_2$$

The jacking load for the third section of pipe can be calculated from Equation 9. The same process can be carried out to determine the jacking load in any n number of pipe sections, as shown in Equation 10.

$$[9] \quad F_3 = F_0 \cdot (1 + \mu_1 \cdot \sin\beta_1)^3 + 3 \cdot (P_s \cdot u_2 \cdot L) \cdot \mu_2$$

$$[10] \quad F_n = F_0 \cdot (1 + \mu_1 \cdot \sin\beta_1)^n + n \cdot (P_s \cdot u_2 \cdot L) \cdot \mu_2$$

CHAPMAN AND ICHIOKA (1999) MODEL

Chapman and Ichioka (1999) proposed a general expression for determining the total jacking load, F, for slurry, auger, and push-in machines.

$$[11] \quad F = f_0 + \pi \cdot D_o \cdot F_r \cdot L$$

Equation 12 gives an expression for calculating the primary resistance, f_o. For slurry machines, the frictional resistance, F_r, given by Equation 13, is dependent on the external diameter of the product pipe and the type of soil in which the jacking operation is taking place.

$$[12] \quad f_0 = \frac{\pi \cdot D_o^2}{4} \cdot R_f$$

$$[13] \quad F_r = a + 0.38 \cdot D_o$$

OSUMI (2000) MODEL

This model provides equations for calculating the jacking force for slurry type and the earth pressure balance type microtunneling construction methods. In the case of 'Slurry Type Jacking Method,' Equation 14 is used to calculate the total jacking load, F, while Equation 15 provides an expression for calculating the penetration resistance, R_f.

$$[14] \quad F = R_f + \pi \cdot D_o [(\alpha_1 \cdot q + W_3) \cdot \mu_1 + C_a] \cdot L$$

$$[15] \quad R_f = (P_j + P_w) \cdot \left(\frac{d_o}{2}\right)^2 \cdot \pi$$

The point resistance, P_j in Equation 15, is taken to be 150 kN/m² for ordinary soil and 300 kN/m² for gravel. Note, the slurry pressure, P_s, is taken to be (P_j + 20) kN/m². For the earth pressure balance type jacking method on the other hand, Equations 16 and 17 can be used respectively to calculate the total jacking force and the corresponding penetration resistance, R_f.

$$[16] \quad F = R_f + \beta_2 \cdot [(\pi \cdot D_o \cdot q + W_3) \cdot \mu_1 + \pi \cdot D_o \cdot C_a] \cdot L$$

$$[17] \quad R_f = \alpha_2 \cdot P_e \cdot \left(\frac{d_o}{2}\right)^2 \cdot \pi$$

The excavated earth pressure, P_e, depends on the type of soil that is being excavated. For instance, the earth pressure at rest is used for cohesive soil; while for sandy soils, the excavated earth pressure is taken as the sum of the active earth pressure, hydraulic

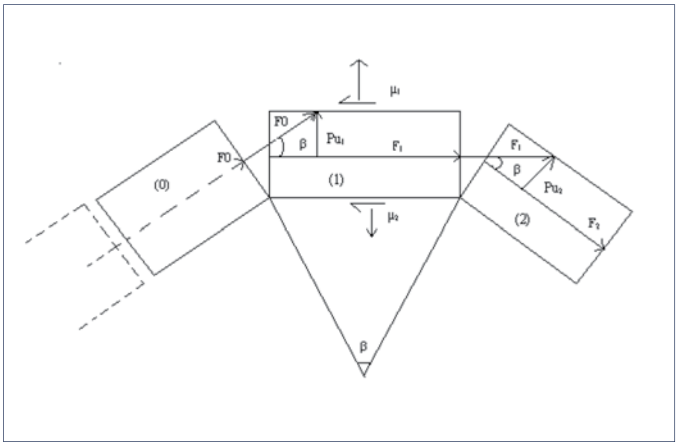

Figure 1 – Sections of Curved Pipe (Khazaei et al., 2004)

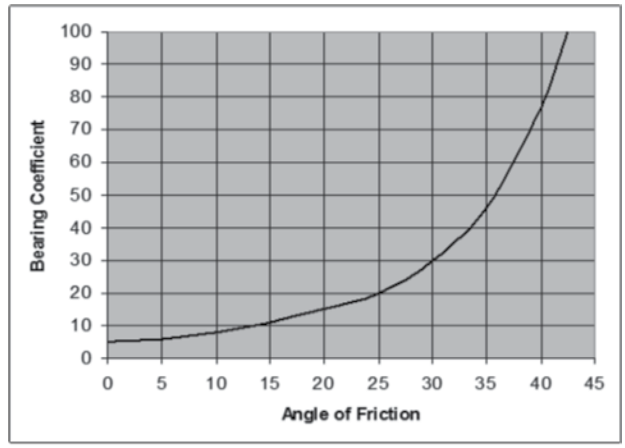

Figure 2 – Coefficient of Load Bearing Capacity, λ_c (Pecora and Sheahan, 2004)

pressure, and ΔP (where ΔP is equivalent to 20 kN/m^2).

METHODS FOR CALCULATING COMPONENTS OF THE JACKING LOAD

The two components of the jacking load are face resistance and friction resistance. Common methods used to calculate each component of the jacking load are described in the following sections:

Methods for Estimating the Face Pressure

Cutting Edge Resistance

The Herzog (Atalah et al., 1994) method of determining cutting edge resistance uses an empirical tip resistance value, p_s, for calculating the load. Table 2 shows typical tip resistance values based on soil type, these values were statistically determined from studies of previous jacking projects. The Herzog method is based on Equation 18 and it considers only the pipe's circumferential area as the penetrating area.

Soil Types	P_s (kPa)
Rock-like soil	119969
Gravel	69982
Sand, dense bedding	59984
Sand, medium dense bedding	39990
Sand, loose bedding	19995
Marl	29992
Tertiary clay	9997
Silt, Quaternary clay	3999

Table 2 – Tip Resistance Values, P_s (Bennett and Cording, 2000)

[18] $P_c = \pi \cdot D_o \cdot t \cdot p_s$

Another common method is the Scherle method (Pecora and Sheahan, 2004), which estimates the cutting resistance from Equation 19:

[19] $P_c = \dfrac{\pi \cdot D_o^2}{4} \cdot f_1$

The cutting resistance factor, f_1, depends on the density of the soil and can range from 6,265 psf (300 kPa) to 12,531 psf (600 kPa). Loose silts, clays or sands generally have a low penetration resistance, while penetration resistance is high for dense sand, gravel, and soft rock. Scherle method considers the entire machine's cross-sectional area to be the penetrating area, therefore, it is considered best for estimating the cutting resistance for projects involving closed face pipe jacking. The Weber method or shear strength resistance method (Atalah et al. 1994), expressed in Equation 22, is developed based on laboratory tests and statistical data collected from construction site records (Pecora and Sheahan, 2004). It is commonly used for operations using a boring or cutting head. It assumes that the tip resistance is equivalent to the shear strength of the soil. Values for the coefficient of load bearing capacity, λc, in Equation 20 can be obtained from the plot in Figure 2.

[20] $P_c = [\gamma \cdot H \cdot \tan(\phi) + c] \cdot \lambda_c \cdot D_o \cdot t$

Lastly, similar to the Herzog method, 'the passive earth pressure method' (Equation 21) uses tip resistance to help determine the cutting resistance. However, this method assumes that the tip resistance is equal to the passive earth pressure of the soil. In general, it yields higher tip resistance values than those obtained with the Weber method.

[21] $P_c = [\pi \cdot D_o \cdot t] \times \left[\gamma \cdot \left(H + \dfrac{D_o}{2}\right) + \tan^2\left(45 + \dfrac{\phi}{2}\right)\right]$

Face Resistance

The face resistance, R_p, is composed of two components: boring head contact force, P_b, and hydraulic force, P_w. Equation 22 presents an expression for calculating P_b, however, to prevent surface heave, settlement, or slumping of the boring face, the relationship in Equation 23 should be satisfied, which states that the boring head contact force must be smaller than the active earth pressure, but greater than the passive earth pressure.

[22] $P_b = \dfrac{\pi}{4} \cdot d^2 \cdot p_b$

[23] $\gamma \cdot \left(H + \dfrac{d}{2}\right) \cdot k_A > P_b > \gamma \cdot \left(H + \dfrac{d}{2}\right) \cdot k_P$

The hydraulic force on the other hand, constitutes the force that equalizes those of the face and hydrostatic pressure. Atalah et al. (1994) recommended that the hydraulic force should be 10% to 20% greater than the force generated by the water pressure, as represented by Equation 24.

[24] $P_w = \alpha_3 \cdot \dfrac{\pi}{4} \cdot d_i^2 \cdot p_w$

The water pressure, p_w, can be calculated by multiplying the density of water by the distance between the top of the ground water table and the pipe's invert. Furthermore, as an alternative for computing the boring head contact force

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Soil Parameter	Terzaghi (1943)	ATV	PJA	Staheli (2006)
b	$D+2D\cdot\tan\left(\frac{\pi}{4}-\frac{\phi'}{2}\right)$	$D\sqrt{3}$	$D\cdot\tan\left(\frac{3\pi}{8}-\frac{\phi'}{4}\right)$	$D\cdot\cos\left(\frac{\pi}{4}+\frac{\phi'}{2}\right)$
δ	ϕ'	$\phi'/2$	ϕ'	ϕ'
K	1	0.5	$\frac{1-\sin\phi'}{1+\sin\phi'}$	1

Table 3 – Soil Parameters used to calculate the vertical loads (Source: Meskele, 2013)

and the hydraulic force, Atalah et al. (1994) presented the following empirical method for calculating the total face resistance:

[25] $R_t = 13.2\cdot\pi\cdot D_o\cdot N$

METHODS FOR ESTIMATING THE FRICTION RESISTANCE

Various methods for estimating the friction resistance, F_r, component of the jacking load exist (e.g., Pellet and Kastner, 1998; Pecora and Sheahan, 2004; Atalah et al., 1994 and Bennett and Cording, 2000). Despite some variations, all the methods use the same rudimentary theory of friction as a basis for calculating the friction resistance, F_r. Equation 26 is the basic equation for F_r, it depends on the force normal to the pipe surface, N, and roughness coefficient, μ.

[26] $F_r = \mu\cdot N$

The term 'μN' is usually referred to as the skin friction. Equation 26 can be extended as Equation 27 to calculate the friction resistance a pipe. In this case, the coefficient of friction will depend on the characteristics of both the pipe material and soil.

[27] $F_r = \mu\cdot\sigma_n\cdot\pi\cdot D_o\cdot L$

Following Equation 27, the 'Iseki Poly-Tech Method' (Equation 28) was developed to determine the friction resistance in cohesive soils. This method differentiates between friction and cohesion, both of which are components of friction resistance for cohesive soils (Atalah et al. 1994).

[28] $F_r = (\mu\cdot\sigma_n + C_a)\times\pi\cdot D_o\cdot L$

Japan Sewerage Association modified formula (Equation 29) method is also commonly used, it is similar to the Iseki Poly-Tech method, but assumes that the friction resistance and the shear resistance of the soil and pipe are the same.

[29] $F_r = \pi D_o\cdot(C_a + \mu\cdot\sigma_n)\cdot L$

Another method for estimating the friction resistance was proposed by Terzaghi. According to Terzaghi, the vertical stress, P_{EV}, on a pipe is related to four loads acting on a horizontal slice of ground above the pipe, namely: (i) the weight of the soil above the ground slice, P; (ii) the weight of the ground slice, dP; (iii) the shear resistance, T or τ; and (iv) the reaction to each of the above loads, $P+dP$. The vertical load on the pipe, given by Equation 30, is found by differentially solving the equilibrium equation for the four loads. Equation 31 gives the vertical load for non-cohesive soil. The reduction factor, calculated according to Equation 32, takes the supporting effect of the soil into consideration (Atalah et al. 1994).

[30] $P_{EV} = \dfrac{b\cdot\left(\gamma - 2\cdot\frac{c}{b}\right)}{2\cdot k\cdot\tan(\delta)}\times\left(1 - e^{-2\cdot k\cdot\tan(\delta)\cdot\frac{H}{b}}\right)$

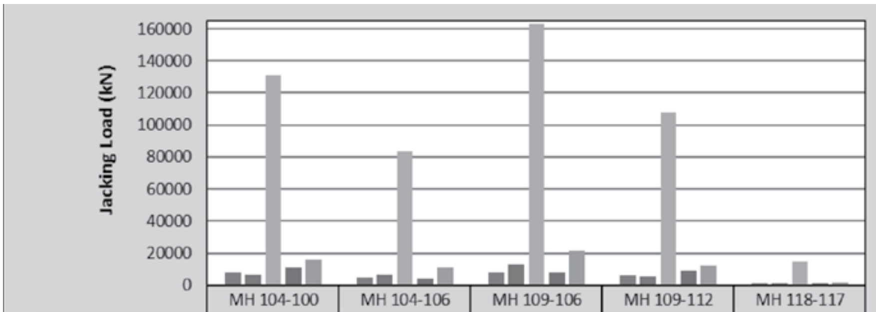
[31] $P_{EV} = \gamma\cdot H\cdot\lambda$

[32] $\lambda = \dfrac{1 - e^{-2\cdot k\cdot\tan(\delta)\cdot\frac{H}{b}}}{2\cdot k\cdot\tan(\delta)\cdot\frac{H}{b}}$

When calculating vertical loads using Terzaghi's method, the recommendations of other researchers and design codes for physical parameters of K, δ, and b are presented in Table 3.

The Kubota manual method is also used for estimating the friction resistance, F_r, component of the jacking load, it assumes that the normal force acting on a pipe is the average of the vertical earth pressure and the active horizontal earth pressure at both the top and bottom of the pipe. Instead of having the pipe carry the entire weight of the depth of cover, the Kubota manual method assumes that the soil above the pipe forms an arch. It is only the weight of the soil within this ground arch that is carried by the pipe (Atalah et al. 1994). Thus, the friction resistance is calculated as follows:

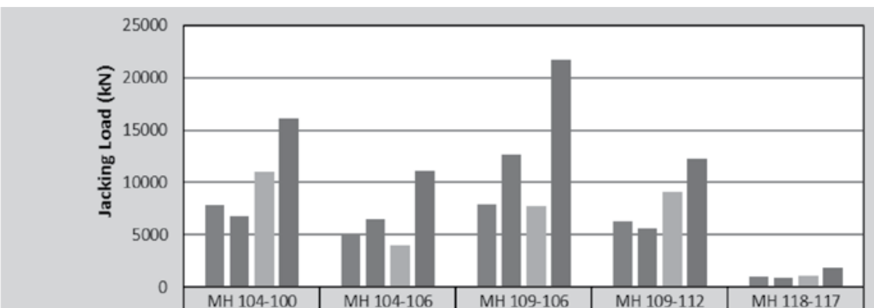
[33] $F_r = 0.5\cdot\mu\cdot[W + 0.5\cdot(W_1 + W_2)]\cdot\pi\cdot D_o\cdot L$



Model	MH 104-100	MH 104-106	MH 109-106	MH 109-112	MH 118-117
Measured	7800.8	5001.9	7921.4	6285.6	984.3
Terzaghi (1943)	6784.2	6493.2	12650.9	5595.8	885.3
Terzaghi (ATVA 161)	130621.3	83784.9	163243.2	107606.6	14652.9
Terzaghi (PJA-UK)	10986.3	3955.8	7705.3	9094.6	1020.6
Staheli (2006)	16125.2	11130.1	21667.6	12250.5	1858.8

Model

Figure 4 – Comparison of Total Jacking Load from Four Terzaghi Based Models (with ATVA 161)



Models	MH 104-100	MH 104-106	MH 109-106	MH 109-112	MH 118-117
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Models

Figure 5 – Comparison of Total Jacking Load from Four Terzaghi Based Models (without ATVA 161)

Similar to the Kubota manual model, the Bennett and Cording (2000) Model is another commonly used model. This method estimates F_r based on Terzaghi's arching theory, by calculating the skin friction portion of the friction resistance with the following equation:

$$[34]\quad F_s = \sigma'_n \cdot \mu_3 \cdot A_c \cdot L$$

Introducing Terzaghi's arching factor, C_a, the normal stress σ'_n can be calculated as follows:

$$[35]\quad \sigma'_n = C_a \cdot \gamma' \cdot D_o$$

With this model, the friction factor acting on the shield and pipe is determined by applying a reduction factor to the soil friction angle, as shown in Equation 36.

$$[36]\quad \mu_3 = \tan(C_f \cdot \phi)$$

COMPARISON OF JACKING LOAD ESTIMATION METHODS

Based on the available data, predictions from the Terzaghi (1943) model and its derivatives (Table 2) have been calculated and compared with field measured jacking data. Figures 4 and 5 show the comparison of the measured jacking loads during the microtunneling operations and those predicted by the four models. Terzaghi (1943) and Terzaghi (PJA-UK) models provide predictions that are in good agreement with the field measured values, while Terzaghi (ATVA 161) model were found to be overly conservative. The model proposed by Staheli (2006) was found to be conservative for all cases examined, irrespective of the anticipated geological conditions.

CONCLUSION

When compared, predictions made by the Terzaghi-based models varied widely from each other. It is assumed that these variations could be attributed at least partially to the extent in which the effect of lubrication is been accounted for by the various models. Of the models evaluated and for the case studies considered, the Terzaghi (1943) and Terzaghi (PJA-UK) models appear to overall provide better agreement with field measured values.

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APPENDIX 'A': NOTATIONS

a = soil factor
= 0.153 for clay soil
= 0.243 for sand
= 0.343 for sand and gravel
A = area of tunnel face
A_c = circumferential area of pipe
b = width of ground slice above pipe
c = soil cohesion
C_a = adhesion between the soil and pipe
C_f = reduction factor
C_1 = cohesion between soil and pipe
C_2 = cohesion between slurry and pipe
d = boring head diameter
d_i = inner diameter of excavating equipment
d_o = outer diameter of excavating equipment
D_o = pipe outer diameter
f_o = primary resistance
f_r = jacking stress
f_1 = cutting edge resistance factor
F = jacking load
F_i = initial thrust
F_o = thrust for straight distance before curve
F_r = friction resistance
F_s = skin friction
H = depth of cover
k_A = coefficient of active earth pressure
k_P = coefficient of passive earth pressure
K_h = coefficient of horizontal passive earth pressure
L = length of microtunnel drive
N = standard penetration number
p_b = boring head contact pressure
p_s = tip resistance
p_w = water pressure
P_b = boring head contact force
P_c = cutting resistance
P_e = excavated earth pressure
P_{EV} = vertical stress
P_j = jacking force per area of cutting face
P_s = slurry pressure
P_w = force caused by water pressure
q = uniform load carried by pipe
R_f = face resistance
R_t = total face resistance
t = cutting edge thickness
u_1 = contact length between soil and pipe
u_2 = contact length between slurry and pipe
W = vertical earth pressure
W_1 = horizontal earth pressure at top of pipe
W_2 = horizontal earth pressure at bottom of pipe
W_3 = weight per unit length of pipe
α_1 = coefficient (0.75 ~ 2.70)
α_2 = soil coefficient
= 1.5 for silt and cohesive soil
= 2.0 for sands or sandy soil
= 3.0 for gravel and solid soil
α_3 = coefficient (1.1 ~ 1.2)
β_1 = angle of misalignment
β_2 = reduction coefficient for lubricants
= 0.7 ~ 0.8 for silt and cohesive soil
= 0.8 ~ 0.9 for sandy soil
= 0.9 ~ 1.0 for gravel
δ = angle of wall friction
ϕ' = angle of internal friction
γ' = effective unit weight of soil
λ = reduction factor
λ_c = coefficient of load bearing capacity
μ = roughness coefficient
μ_1 = coefficient of friction between soil and pipe
μ_2 = coefficient of friction between slurry and pipe
μ_3 = average friction factor acting on shield and pipe
σ_n = normal stress along surface of pipe
σ'_n = average effective normal stress acting on shield and pipe
τ_1 = friction resistance between soil and pipe
τ_2 = friction resistance between slurry and pipe

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2019 Edmonton Technical Lunch Program

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- Thursday, January 24, 2019
- Wednesday, February 28, 2019
- Thursday, March 28, 2019
- April 2019 TBD

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