DERIVING ROCK MECHANICAL PROPERTIES FROM GEOLOGICAL FRACTURE OBSERVATIONS

KYT2018 Seminar

Paula Salminen, Pöyry Finland Oy

December 1, 2017

INSIGHTS FROM THE PARAMETRIZATION WORK FOR POSIVA

- Rock mechanical properties of the fractures and brittle deformation zones in ONKALO and in the vicinity of ONKALO have been analysed
- This was done to support rock mechanics site characterization of Olkiluoto
- The results of the parametrization work are also needed in the future modelling work

- In addition, a small-scale mapping campaign was conducted in ONKALO, e.g. to support the parametrization work

INSIGHTS FROM THE PARAMETRIZATION WORK FOR POSIVA

- The mapping data of ONKALO is chiefly based on the Q classification system. There are a lot of Q mapping data available

→the parametrization of the rock mechanical properties is also based on the Q system

- Rock mechanical properties of the fractures are characterized by
  – 1) **Mapped fracture parameters**
  – 2) **Indirectly derived fracture mechanical parameters**, which were estimated/calculated based on mapping data and laboratory data

- **Rock mechanical properties of brittle deformation zones** are also estimated based on the fracture mapping data

MAPPED FRACTURE PARAMETERS

- Following mapped parameters were considered in the parametrization work:
  - RQD values
  - The Q´ parameters
  - Fracture trace length
  - Fracture termination
  - Fracture undulation
  - Fracture fill minerals
  - Fracture orientations

MAPPED FRACTURE PARAMETERS

RQD values

- RQD = Rock Quality Designation
  - Originally developed for drill cores (Deere 1963, Deere et al. 1967): RQD is the percentage of intact core pieces longer than 100 mm
  - For tunnel sections, RQD values can be
    1. Calculated, e.g. using the equation of Palmström (2005)
    2. Obtained using artificial scanlines
    3. **Estimated visually (POSIVA)**
  - Five rock quality classes based on RQD values
  - RQD values are also used as an input parameter in the Q mapping system and the RMR mapping system

MAPPED FRACTURE PARAMETERS

Q classification system

- Q system can be used in the classification of the rock quality

→ **The Q value** (e.g. Barton et al. 1974, NGI 2015):

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF}$$

RQD = Rock Quality Designation
J_n = Joint set number
J_r = Joint roughness number
J_a = Joint alteration number
J_w = Joint water reduction number
SRF = Stress Reduction Factor

MAPPED FRACTURE PARAMETERS

Q classification system

- **The quotient RQD/J_n** represents the structure of the rock mass (Barton et al. 1974).
  - It describes the degree of jointing or the block size (NGI 2015).
- **The quotient J_r/J_a** is a measure of inter-block friction angle (shear strength) (Grimstad & Barton 1993, NGI 2015).
  - It represents the roughness and degree of alteration of the joint walls or filling materials (Barton *et al*. 1974)
- **The quotient J_w/SRF** is a measure of the active stress (Grimstad & Barton 1993, NGI 2015).
  - It represents the relative effect of water, faulting, strength/stress ratio, squeezing or swelling (Barton 2002).

MAPPED FRACTURE PARAMETERS

Q classification system, Q´ value

- The Q´ value can be used in the characterization of the rock mass quality
  - In the assumptions for the Q´ value, the rock mass is:
    - dry
    - subjected to “medium” stress conditions

$$Q' = \frac{RQD}{J_n} \times \frac{J_r}{J_a}$$

MAPPED FRACTURE PARAMETERS

Q classification system, Q´ parameters

- J_n = Joint set number
  - Can have values from 0.5 (massive, no or few joints) to 20 (crushed rock, earthlike)
- J_r = Joint roughness number
  - Its value depend on the profile and roughness of the fracture surface
  - The lower values indicate more planar surfaces, which are more susceptible to shearing than rougher fractures
  - It can have values from 0.5 to 4
- J_a = Joint alteration number
  - The lower values indicate less altered fractures, which are less susceptible to shearing compared to more altered fractures
  - A) Rock-wall contact: J_a 0.75-4
  - B) Rock-wall contact before 10 cm shear: J_a 4-12
  - C) No rock-wall contact when sheared: J_a 6-20
  - The degree of the joint alteration is connected to the thickness of the mineral fill and to the presence of certain minerals

INDIRECTLY DERIVED FRACTURE MECHANICAL PARAMETERS

- Indirectly derived fracture mechanical properties include:
  - Estimates of JRC and JCS values
  - Parameters based on Barton-Bandis Joint model
    - Stiffness parameters
    - Instantaneous friction angle and instantaneous cohesion
    - Peak dilation angle

INDIRECTLY DERIVED FRACTURE MECHANICAL PARAMETERS

Barton-Bandis joint model

- Barton-Bandis joint model (Barton & Choubey 1977)

$$\tau_p = \sigma'_n * tan\left(JRC\ log_{10}\left(\frac{JCS}{\sigma'_n}\right) + \phi_r\right)$$

  – τ_p = the peak shear strength (MPa)
  – σ'_n = the effective normal stress (MPa)
  – JRC = the Joint Roughness Coefficient
  – JCS = the Joint Wall Compressive Strength (MPa)
  – ϕ_r = the residual friction angle (º)

- In the original equation (Barton 1973, 1976), basic friction angle (ϕ_b) is used instead of the residual friction angle (ϕ_r)
  – For dry, unweathered surfaces, the residual friction angle is equal to the basic friction angle
  – For weathered/wet joint surfaces, residual friction angle can be significantly lower
  – The residual friction angle can be calculated from the basic friction angle if Schmidt hammer data is available

INDIRECTLY DERIVED FRACTURE MECHANICAL PARAMETERS

JRC values

- JRC = the Joint Roughness Coefficient
  - It represents a sliding scale of roughness, varying from 0 to 20 (Barton 1973)
  - It can be measured with **a comb** (a roughness profile tool)
  - **Indirect estimates** based on J_r values and J_r profiles (Salminen *et al.*, after Barton 1987)

Description	Profile	J_r	JRC 200 mm	JRC 1 m
Rough		4	20	11
Smooth		3	14	9
Slickensided		2	11	8
	Stepped			
Rough		3	14	9
Smooth		2	11	8
Slickensided		1.5	7	6
	Undulating			
Rough		1.5	2.5	2.3
Smooth		1.0	1.5	0.9
Slickensided		0.5	0.5	0.4
	Planar			

INDIRECTLY DERIVED FRACTURE MECHANICAL PARAMETERS

JCS values

- JCS = the Joint wall Compressive Strength
  - It represents the compressive strength of the fracture surface, measured on the wall of the fracture itself (see e.g. Barton 1973)
  - It can be measured using **the Schmidt hammer** (e.g. Deere & Miller 1966, Barton & Choubey 1977)
  - **Indirect JCS estimates** (Barton 1973, Barton & Choubey 1977):

$$JCS = \frac{UCS}{alteration}$$

  - UCS = the intact rock uniaxial compressive strength
  - Alteration = alteration factor
    - Alteration factors have been suggested by various authors (Alejano & Ramirez 2008, Bandis *et al*. 1983)
    - *In the parametrization work, an own scheme for alteration factors was defined*

INDIRECTLY DERIVED FRACTURE MECHANICAL PARAMETERS

JCS values continued

- Alteration values for the calculations of JCS values, Salminen *et al*.

J_r profile	Thickness of the mineral fill	Alteration
planar rough (PRO) undulating rough (URO) stepped rough (SRO)	< 0.5 mm	1
planar rough (PRO) undulating rough (URO) stepped rough (SRO)	≥ 0.5 mm	1.2
planar slickensided (PSL) planar smooth (PSM) undulating slickensided (USL) undulating smooth (USM) stepped slickensided (SSL) stepped smooth (SSM)	< 2 mm	1.2
planar slickensided (PSL) planar smooth (PSM) undulating slickensided (USL) undulating smooth (USM) stepped slickensided (SSL) stepped smooth (SSM)	≥ 2mm	1.5

INDIRECTLY DERIVED FRACTURE MECHANICAL PARAMETERS

Testing of the indirect estimates of the JRC and JCS values

- The applicability of the indirect JRC and JCS estimates for the conditions of the ONKALO facility was tested in a small-scale mapping campaign (Salminen *et al*. 2017, in press)
- It was difficult to find suitable test fractures, so only 6 fractures were studied
- The indirectly derived JRC values fit in the mapped ranges of JRC values
- The indirectly derived JCS values are not far away from the measured ones, when the uncertainties in the methods are taken in account

INDIRECTLY DERIVED FRACTURE MECHANICAL PARAMETERS

Stiffness parameters, instantaneous friction angle and cohesion, and peak dilation angle

- Calculated based on Barton-Bandis Joint model
- Input parameters for the calculations:
  - Indirectly derived JRC and JCS values
  - Residual friction angle from laboratory measurements based on Olkiluoto samples
    - Residual friction angle was used as an estimate of the basic friction angle

INDIRECTLY DERIVED FRACTURE MECHANICAL PARAMETERS

Fracture shear stiffness

- Stiffness is a measure of the resistance to deformation
- Fracture shear stiffness (Barton & Choubey 1977)

$$k_s = \frac{\tau_{peak}}{\delta_{h,peak}}$$

τ_{peak} = the peak shear strength (MPa)
$\delta_{h,\,peak}$ = the peak shear displacement

- Usually, peak shear strength is obtained when the peak shear displacement is ca. 1 % of the fracture length

→ $\delta_{h,peak} = L_n/100$

→ This leads to the following equation (Barton & Choubey 1977):

$$k_s = \frac{100}{L} * \sigma'_n * tan\left(JRC * \ log_{10}\left(\frac{JCS}{\sigma'_n}\right) + \ \phi_r\right)$$

L = the sample fracture length (m)

INDIRECTLY DERIVED FRACTURE MECHANICAL PARAMETERS

Fracture shear stiffness, continued

- The sample size often differs from the lab scale. Based on the results from lab studies, the shear displacement can be calculated with the following equation (Barton & Bandis 1990):

$$\delta_{h,\ peak} = \frac{L_n}{500}\left(\frac{JRC}{L_n}\right)^{0.33}$$

L_n = the field scale fracture length (m)

→**The shear stiffness can be calculated with the following equation (also used in the parametrization work):**

$$k_s = \left(\sigma'_n * tan\left(JRC * \ log_{10}\left(\frac{JCS}{\sigma'_n}\right) + \ \phi_r\right)\right) / \left(\frac{L_n}{500}\left(\frac{JRC}{L_n}\right)^{0.33}\right)$$

INDIRECTLY DERIVED FRACTURE MECHANICAL PARAMETERS

Fracture normal stiffness

- Fracture normal stiffness, k_n, is defined as the instantaneous slope of the effective normal stress vs. displacement curve (e.g. Barton *et al*. 1985).

- In parametrization work, normal stiffness was approximated based on the shear stiffness, using the following relation:

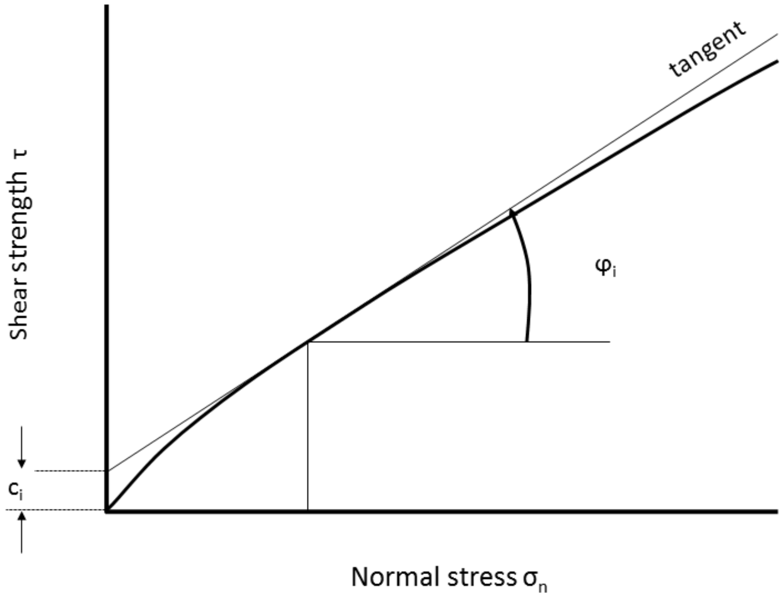
$$10\, k_s < k_n < 1000\, k_s$$

  – This relation is based on the results of Glamheden *et al*. 2007 and Hakami *et al*. 2008

INDIRECTLY DERIVED FRACTURE MECHANICAL PARAMETERS

Instantaneous cohesion and friction angle

- Instantaneous friction angle and cohesion can be used for stability analyses
- Definition of instantaneous cohesion (c_i) and friction angle ($ø_i$) (Hoek *et al*. 1995):



- In the parametrization work, the effective normal stress ($σ´_n$) and the peak shear strength ($τ_p$) were considered (instead of the total normal stress $σ_n$ and the shear strength τ).

INDIRECTLY DERIVED FRACTURE MECHANICAL PARAMETERS

Instantaneous cohesion and friction angle

- Instantaneous cohesion (c_i) (Hoek *et al*. 1995):

$$c_i = \tau_p - \sigma'_n \tan\phi_i$$

- Instantaneous friction angle ($ø_i$) (Hoek *et al*. 1995)

$$\phi_i = \arctan\left(\frac{\partial\tau_p}{\partial\sigma'_n}\right)$$

  – where

$$\frac{\partial\tau_p}{\partial\sigma'_n} = \tan\left(JRC\,\log_{10}\left(\frac{JCS}{\sigma'_n}\right) + \phi_r\right) - \frac{\pi\,JRC}{180\ln(10)}\left(\tan^2\left(JRC\,\log_{10}\frac{JCS}{\sigma'_n} + \phi_r\right) + 1\right)$$

INDIRECTLY DERIVED FRACTURE MECHANICAL PARAMETERS

Peak dilation angle

- Dilation angle can be calculated with the following equation (Barton 1971):

$$d_n = arctan\left(\frac{\delta_v}{\delta_h}\right)$$

  - where δ_v = the vertical displacement and the δ_h = the horizontal displacement

- Peak dilation angle can be calculated with the following equation (Barton & Choubey 1977):

$$d_{n-peak} = JRC\ log_{10}\left(\frac{JCS}{\sigma'_n}\right)$$

  - If the normal stress is sufficiently lower than the strength of the rock or the fracture wall → peak dilation angle is equal to the difference between the peak friction angle and the residual friction angle → the asperities will suffer almost no damage during shear

  - If the normal stress is high and the strength of the asperities is exceeded → asperities will be damaged → the dilation angle will be app. half of the peak dilation angle calculated with the above mentioned equation (Barton & Bandis 1990)

ROCK MECHANICS PROPERTIES OF THE BRITTLE DEFORMATION ZONES

- There are different methods for estimating the mechanical properties of the brittle deformation zones

→In Posiva´s work, this work was done using the mapped Q´ parameters

- Mapped Q´ parameters were converted to GSI (geological strength index) values

→Other parameters were calculated based on the GSI values

ROCK MECHANICS PROPERTIES OF THE BRITTLE DEFORMATION ZONES

Geological Strength Index, GSI

- GSI values can be directly mapped from the rock sections, using **GSI mapping charts** (e.g. Hoek & Marinos 2000)
- GSI values can be calculated from other parameters using different **conversion equations**
- In earlier works for Posiva, the following "conventional" equation (Hoek *et al*. 1995) was applied

$$GSI = 9 \ln Q' + 44$$

- In the current parametrization work, an alternative equation (Hoek *et al*. 2013) has been applied

$$GSI = \frac{52\ J_r/J_a}{(1 + J_r/J_a)} + RQD/2$$

  – Based on the results from a small-scale mapping campaign in ONKALO, this equation is the best one for the conditions of ONKALO
    – Best results were obtained, when RQD values <10 were converted to values of 10

ROCK MECHANICS PROPERTIES OF THE BRITTLE DEFORMATION ZONES

Hoek-Brown strength criterion

- Hoek-Brown strength criterion (Hoek *et al*. 2002) can be used in the calculations of the mechanical properties of the brittle deformation zones:

$$\sigma_1^{'} = \sigma_3^{'} + \sigma_{ci}\left(m_b \frac{\sigma_3^{'}}{\sigma_{ci}} + s\right)^a$$

σ'_1 = the major effective principal stress at failure
σ'_3 = the minor effective principal stress at failure
σ_{ci} = the uniaxial compressive strength of the intact rock material.
m_b = a reduced value of the material constant (m_i); it is given by following equation
s and a are constants for the rock mass

m_b, s and a can be calculated based on GSI value and a D factor, which depends upon the degree of disturbance to which the rock mass has been subjected by blast damage and stress relaxation.

ROCK MECHANICS PROPERTIES OF THE BRITTLE DEFORMATION ZONES

Mohr-Coulomb fit

- Friction angles and cohesion values were estimated by fitting *the Mohr-Coulomb linear failure envelope* to the Hoek-Brown failure envelope
- Young´s modulus was calculated based on GSI value and intact rock Young´s modulus (Hoek-Brown criterion)
- Shear modulus was calculated based on Young´s modulus and Poisson´s ratio

- In addition, in the parametrization work,
  - normal stiffness was calculated based on Young´s modulus and the width of the fault core zone
  - shear stiffness was calculated based on the shear modulus and the width of the fault core zone

SUMMARY

- **Q mapping data** from fractures was applied in the rock mechanics parametrisation of the fractures and the brittle deformation zones

- Some other fracture parameters have also been mapped and analysed
- Indirect estimates of fracture parameters based on the mapped parameters
  - Estimates of JRC and JCS values
  - Parameters based on the Barton-Bandis criterion

- The mechanical properties of the brittle deformation zones were calculated based on GSI values
  - GSI values were calculated based on Q´ parameters

THANK YOU !

paula.salminen@poyry.com

REFERENCES 1/5

The current parametrization work and the small-scale mapping campaign

- This presentations was chiefly based on the following reports/works:
  - Salminen, P., Mas Ivars, D., Mattila, J., Nordbäck, N., expected in 2018. Rock Mechanics Parametrization of Fractures and Brittle Deformation Zones in ONKALO Based on the Mapping Data. Working report 2016-23, Posiva Oy, Eurajoki.
  - Salminen, P., expected in 2018. Rock Mechanics Parametrization of Fractures and Brittle Deformation Zones in ONKALO Based on the Mapping Data – Synthesis. Posiva Report, Posiva Oy, Eurajoki
  - Salminen, P., Lindfors, U., Haapalehto, S., 2017, in press. GSI conversion equations and indirect estimates of JRC and JCS values – Applicability for the conditions of the ONKALO facility. Working report 2017-04, Posiva Oy, Eurajoki.

REFERENCES 2/5

References cited in this presentation

- Alejano L. & Ramírez P., 2008. Mecánica de Rocas: Fundamentos e ingeniería de taludes. Ed Red DESIR. In Spanish.
- Bandis, S.C., Lumsden, A.C. & Barton, N.R., 1983. Fundamentals of rock joint deformation. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts 20, 249-268.
- Barton, N.R, 1971. A relationship between joint roughness and joint shear strength. Symposium Soc. Internat. Mécanique des Roches, Nancy. Paper I-8.
- Barton, N., 1973. Review of a new shear strength criterion for rock joints. Engineering Geology 7, 287-332.
- Barton, N., 1976. The shear strength of rocks and rock joints. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts 13, 255-279. Also NGI Publ. 119, 1978.
- Barton, N., 1987. Predicting the behaviour of underground openings in rock. In: *“Manuel Rocha Memorial Lecture”.* Lisbon. NGI, Oslo, Norway.
- Barton, N., 2002. Some new Q-value correlations to assist in site characterisation and tunnel design. International Journal of Rock Mechanics and Mining Sciences 39, 185–216.
- Barton, N. & Bandis, S., 1990. Review of predictive capabilities of JRC-JCS model in engineering practice. International Society of Rock Mechanics, Symposium on rock joints, Loen, Norway (eds. Barton, N, & Stephansson, O.), pp 603-610.
- Barton, N., Bandis, S., Bakhtar, K., 1985. Strength, deformation and conductivity coupling of rock joints. Internatilnal Journal of Rock Mechacnics and Minining Sciences & Geomechanics Abstracts 22, 121-140.
- Barton, N. & Choubey, V., 1977. The shear strength of rock joints in theory and practice. Rock Mechanics 10, 1-54.
- Barton, N., Lien, R. & Lunde, J., 1974. Engineering classification of rock masses for the design of tunnel support. Rock Mechanics 6, 198-236.

REFERENCES 3/5

References cited in this presentation, continued

- Deere, D.U., 1963. Technical description of rock cores for engineering purposes. Felsmechanik und Ingenieurgeologie (Rock Mechanics and Engineering Geology), 1, 16-22.
- Deere, D.U., Hendron, A.J., Patton, F.D. & Cording, E.J., 1967. Design of surface and near surface construction in rock. Failure and breakage of rock: Proceedings of the 8th U.S. Symposium on Rock Mechanics (ed. C. Fairhurst), American Institute of Mining, Metallurgical & Petroleum Engineers, New York, pp. 237-302.
- Deere, D.U., Miller, RP., 1966. Engineering classification and index properties for intact rocks. Tech Rep Air Force Weapons Lab, New Mexico, no AFNL-TR, 65–116.
- Glamheden, R., Röshoff, K., Karlsson, J., Hakami, H. & Christiansson, R., 2007. Rock Mechanics Forsmark. Site descriptive modelling Forsmark stage 2.2. SKB- R-07-31. Svensk Kärnbränslehantering AB.
- Grimstad, E. & Barton, N., 1993. Updating of the Q-system for NMT. Proceedings of the International Symposium on Sprayed Concrete – Modern Use of Wet Mix Sprayed Concrete for Underground Support, Fagernes (eds. Kompen, Opsahl & Berg), Norwegian Concrete Association, Oslo.
- Hakami, E., Fredriksson, A., Lanaro, F. & Wrafter, J., 2008. Rock Mechanics Laxemar. Site descriptive modelling SDM-Site Laxemar. SKB-R-08-57. Svensk Kärnbränslehantering AB.

REFERENCES 4/5

References cited in this presentation, continued

- Hoek, E., Carranza-Torres C. & Corkum, B., 2002. Hoek-Brown failure criterion. 2002 edition. Proceedings of the 5th North American Rock Mechanics Symposium and 17th Tunneling Association of Canada Conference: NARMS-TAC 2002, July 7-10, University of Toronto, pp. 267-271.
- Hoek, E., Carter, T.G. & Diederichs, M.S., 2013. Quantification of the Geological Strength Index chart. In. Proceedings of the 47th US Rock Mechanics/Geomechanics Symposium, San Francisco, CA, USA, 23-26 June 2013. ARMA 13-672.
- Hoek, E., Kaiser, P. K. & Bawden, W. F., 1995. Support of underground excavations in hard rocks. Rotterdam: A. A. Balkema.
- Hoek, E. and Marinos, P. 2000. Predicting Tunnel Squeezing. Tunnels and Tunnelling International. Part 1 - November 2000, Part 2 – December, 2000.
- NGI 2015. Using the Q-system. Rock mass classification and support design. NGI, Oslo.
- Palmström, A. 2005. Measurements of and Correlationg between Block Size and Rock Quality Designation (RQD). Tunnels and Underground Space Technology 20, 362-277.

REFERENCES 5/5

The earlier parametrization work for Posiva

- Results of parametrization of fractures and brittle deformation zones have previously been reported in four working reports. Somewhat different input data and methodology have been applied in these reports.

  - Kuula, H., 2010. Geometrical and Mechanical Properties of the Fractures and Brittle Deformation Zones based on ONKALO Tunnel Mapping, 0–2400 m Tunnel Chainages. Working Report 2010-64. Posiva Oy, Eurajoki.
  - Mönkkönen, H., Rantanen, T. & Kuula, H., 2012. Geometrical and Mechanical Properties of the Fractures and Brittle Deformation Zones based on ONKALO Tunnel Mapping, 2400–4390 m Tunnel Chainages. Working Report 2010-64. Posiva Oy, Eurajoki.
  - Simelius, C., 2014. Geometrical and Mechanical Properties of the Fractures and Brittle Deformation Zones Based on the ONKALO Tunnel Mapping, 4390–4990 m Tunnel Chainage and the Technical Rooms. Working Report 2013-32. Posiva Oy, Eurajoki.
  - Salminen, P. & Simelius, C., 2016. Geometrical and Mechanical Properties of the Fractures and Brittle Deformation Zones Based on the ONKALO Tunnel Mapping, the Shafts and the Demonstration Tunnels. Working Report 2015-11. Posiva Oy, Eurajoki.

PÖYRY

The connected company

Consulting. Engineering. Projects. Operations.

www.poyry.com