POLITECNICO DI TORINO
Repository ISTITUZIONALE

In-line foam quality control for EPB-TBM: A conductivity-based FER monitoring system.

Original
In-line foam quality control for EPB-TBM: A conductivity-based FER monitoring system / Carigi, A., Todaro, C., Berariu, R., Di Giovanni, A., Saltarin, S., Peila, D.. - (2026), pp. 1484-1491. (ITA World Tunnel Congress 2026 Montreal (Can) 15-21 May 2026) [10.1201/9781042001064-186].

Availability:
This version is available at: 11583/3016354 since: 2026-10-06T09:59:10Z

Publisher:
CRC Press

Published
DOI:10.1201/9781042001064-186

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)

15 November 2026

Connecting Communities Through Underground Infrastructure – Eberhardt et al. (Eds)
© 2026 The Author(s), ISBN: 978-1-041-35997-5

In-line foam quality control for EPB-TBM: A conductivity-based FER monitoring system

A. Carigi, C. Todaro, R. Berariu, A. Di Giovanni, S. Saltarin and D. Peila
Department of Environment, Land, and Infrastructure Engineering (DIATI), Politecnico di Torino, Turin, Italy

ABSTRACT: Earth Pressure Balance Tunnel Boring Machines (EPB-TBMs) rely on foam conditioning to maintain excavation chamber pressure and ensure ground stability. The Foam Expansion Ratio (FER) – defined as the ratio between foam volume and foaming liquid volume – is one of the primary parameters governing conditioning effectiveness. Current practice relies of FER measurement on machine PLCs calculating FER based on measured volumes of foaming agent and compressed air, assuming ideal mixing conditions, but this approach cannot detect phase segregation within injection lines, when foaming agent and compressed air flow separately, with liquid gravitating toward the bottom and gas rising to the top, no actual foam formation occurs, despite correct volumetric proportions. This segregation creates air pockets in the excavation chamber that may compromise pressure distribution and potentially trigger face instability and surface settlements. This research proposes a novel real-time monitoring system for direct FER measurement based on electrical conductivity principles. As air content increases, the conductive liquid fraction decreases proportionally, reducing overall foam conductivity. The system employs sensors positioned at upper and lower injection line sections, enabling simultaneous foam quality detection and phase segregation identification through comparative analysis. Preliminary laboratory investigations demonstrate promising correlations between electrical conductivity measurements and independently verified FER values. The system will provide robust information to the EPB-TBM operators with continuous, real-time feedback on actual foam quality at injection points for immediate corrective interventions when segregation occurs, defining a paradigm shift toward predictive maintenance and operational optimization in mechanized tunnelling.

1 INTRODUCTION

1.1 *Growth of EPB in tunnelling use*

In recent decades, the global tunnelling industry has experienced continuous expansion, driven by the growing demand for underground transport systems and underground infrastructure. It is estimated that the total length of tunnels excavated worldwide increases by roughly 7% every year, reaching about 4700 km of new tunnels annually (Schneider et al. 2019). This development is reflected in multiple regions, with significant growth in several countries (Gruber & Östrand 2019, Kaise et al. 2019). The expansion of underground networks is also evident from the rising number of cities investing in metro and subway systems (Chen et al. 2018). As tunnelling activities intensify worldwide, the choice of full-face mechanized excavation technology plays a crucial role in achieving both safety and efficiency. The progressive shift toward mechanized excavation methods has made Earth Pressure Balance shields one of the most commonly employed tunnelling technologies. In the EPB-TBM, as well known, the key factor is the soil

DOI: 10.1201/9781042001064-186
This chapter has been made available under a CC BY-NC-ND license

conditioning, whose primary objective is to transform the excavated material into a plastic, flowable paste that can be safely and efficiently transported through the EPB machine. This topic has been discussed by many authors such as Peila et al. (2019), Thewes & Budach (2010). To achieve these purposes, the quality of foam delivered to the excavation chamber is critical for proper soil conditioning. When foam is not fully homogeneous due to imperfect mixing or lamination along the delivery pipeline, the foam performance in conditioning can be compromised. Lamination occurs when the liquid phase settles in the lower section of the pipe while air migrates to the upper section, producing a stratified foam structure. As a result, air pockets may form in the upper part of the excavation chamber, disrupting the pressure equilibrium at the tunnel face, which can lead to operational instability and, in severe cases, surface settlements or sinkholes above the tunnel alignment.

Moreover, among the operational consequences of lamination, there are also increased energy consumption, higher surfactant usage, and elevated operational costs. At present, lamination can only be detected indirectly through its effects on excavation performance, since no method allows real-time monitoring of foam stratification inside pressurized delivery pipelines.

The proposed technology introduces a novel approach for assessing Foam Expansion Ratio (FER) and detecting foam stratification under pressurized conditions. The method is based on measuring the electrical resistance of the foam as it flows through the designed prototype, which is to be installed in-line with the foam generator. Since electrical resistance is directly linked to the conductivity of the liquid phase and its volumetric predominance, it serves as an indirect indicator of foam composition and monitors in real-time the correct composition of the foam in-line.

2 MATERIALS & METHODS

In EPB tunnelling, as well as in every laboratory setup that aims to replicate the functioning of an EPB, foam is produced by combining compressed air, water, and a surfactant agent, forming a stable mixture used to condition the excavated soil (Thewes & Budach 2010). The generated foam is then used as a conditioning medium, modifying the natural properties of the soil to improve its plasticity, compressibility, and flow behaviour inside the excavation chamber and screw conveyor.

Once produced through the turbulent mixing of the foaming agent and air in the "foam guns", the foam is injected into the excavation chamber through dedicated nozzles positioned on the bulkhead and cutterhead, ensuring homogeneous distribution within the conditioned soil. Additional foam can also be introduced along the screw conveyor to maintain uniformity during material discharge.

The proportion between the volume of injected foam and the volume of excavated soil is described by the Foam Injection Ratio (FIR). The foam flow rate, which depends on both the machine advance rate and the tunnel face area, is defined as sum of each foam component, air, water, and surfactant.

The efficiency of EPB tunnelling strongly depends on the quality of the foam which is commonly expressed through the Foam Expansion Ratio (FER), defined as the ratio between the volume of foam produced and the volume of liquid used for its generation, Equation 1:

$$FER = \frac{V_{foam}}{V_{generated\ liquid}} = \frac{\frac{Q_{foam}}{\Delta t}}{\frac{Q_{generated\ liquid}}{\Delta t}} \tag{1}$$

where V_{foam} = volume of the produced foam; $V_{generated\ liquid}$ = volume of the generated liquid; Q_{foam} = volumetric flow rate of foam; $Q_{generated\ liquid}$ = volumetric flow rate of generated liquid; Δt = time interval.

Typical FER values in EPB operations range from 8 to 25, depending on soil type and excavation conditions.

While the theoretical formulation provides an estimation of the FER based on the air and liquid flow rates measured by the machine sensors, it does not account for the actual mixing

efficiency or the effects of pressure within the pressurized delivery pipeline. Although volumetric flow measurements can provide reliable FER determinations under ideal conditions, they are unable to detect heterogeneous mixing or partial phase separation within the foam.

Alternative methods, such as visual inspection through transparent pipe sections or foam sampling, present limitations. Optical systems are hindered by the opacity of foam and can only identify extreme cases of separation. Batch sampling, on the other hand, disrupts the foam due to rapid depressurization, causing expansion and gas loss, thus invalidating the original FER value. Consequently, none of these methods provide a reliable or continuous method of assessing FER in pressurized conditions representative of EPB operations.

2.1 *Foam generator system and foam production*

For this research study, a foam generator according to the scheme in Figure 1 was employed. Its operating principle is similar to the foam generators commonly integrated into EPB tunnelling machines.

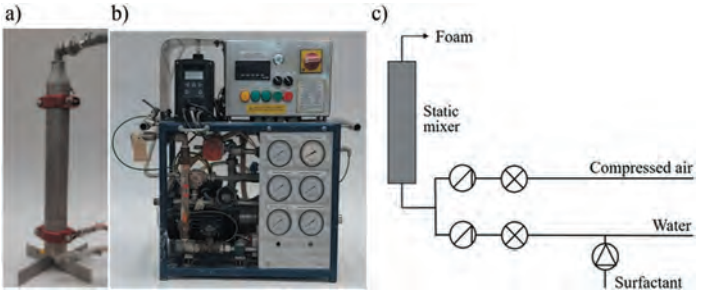


Figure 1. Static mixer (a), foam generator used (b), scheme of the foam generator (c).

The main technical specifications of the used foam generator are:

- maximum flow rate of the foaming agent: 11.9 L/min;
- maximum air pressure: 4 bar;
- independent and precise control of both component volumes through needle valves;
- the static mixer with a diameter of 78 mm and the length of 450 mm, which is filled with glass fragments (mean diameter ≈ 5 mm) to enhance dispersion efficiency;
- a volumetric pump for surfactant with an integrated mixing chamber to guarantee homogeneous mixing of water and surfactant.

The foam was produced using a commercial foaming agent at a concentration of 1.5%, characterized by the following composition (Carigi & Todaro 2025):

- alcohols, C12–14, ethoxylated, sulfates, sodium salts (concentration >10% and <20%), CAS No. 68891–38 – 3;
- 5 – Chloro – 2 – methyl – 2H – isothiazol – 3 – one and 2 – methyl – 2H – isothiazol – 3 – one (concentration >0.0002% and <0.0015%), CAS No. 55965–84 – 9.

2.2 *Developed prototype*

2.2.1 *Measuring device*

A custom 3D-printed device has been developed as part of the prototype, to host the electrodes and the temperature sensor needed to monitor the FER in laboratory setting. The device was designed to be integrated into and connected to the foam generator described in paragraph 2.1, and it consists of the following components, as illustrated in Figure 2:

- main body: a cylindrical pipe with an internal diameter of 14.50 mm, an external diameter of 20.00 mm, and a total length of 120 mm. The pipe includes threaded sections of 10 mm at each end to allow connection with the adapters;

- two adaptors: these components connect the main body to the existing pipeline of the foam generator. One of the adapters houses the temperature sensor, enabling real-time monitoring of foam temperature for electrical conductivity correction;
- external shell: this component completes the prototype assembly and provides an additional protective layer for the cables.

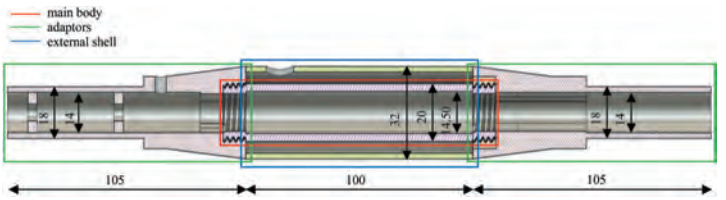


Figure 2. Section view of the prototype showing the main dimensions expressed in mm.

In the design of the prototype, the choice of material was based on the following requirements:

- being waterproof and airtight – due the presence of water and air in the foam;
- having adequate mechanical strength – to withstand the internal pressure generated during the foam production;
- being non-conductive – to prevent possible short circuits at the electrode interfaces.

Based on these criteria, PLA (polylactic acid) was selected as material to be used, since its insulating properties reduce the risk of electrical leakage during the measurements, which may affect the measurement accuracy, while its mechanical characteristics provide sufficient rigidity and dimensional stability. All prototype components (the main body, adapters and external shell) were 3D printed using the same material configuration to ensure uniform behavior and overall impermeability.

After the printing phase, three pairs of electrodes were installed to provide measurement redundancy. Each electrode is 10 mm long to ensure that the presence of larger, individual bubbles of foam would not produce spikes in the measurement due to the absence of contact between liquid phase and the electrode (Figure 3). The holes along the main body precisely accommodate the electrode pairs. Each electrode was fixed in place using a small amount of adhesive, carefully ensuring that the metallic surface of the electrode remained completely free of glue to avoid interference with the electrical measurements.

2.2.2 *Data acquisition system*

The data acquisition system was developed as an open-source, customizable platform based on Arduino, designed and assembled from individual components to ensure flexibility, accessibility, and adaptability for research and prototyping activities.

As shown in Figure 4, the hardware configuration includes the following components: one Arduino A2 Delivery board, a USB power cable, a breadboard, a 20×4 LCD module with an I2C interface, an NTC temperature sensor, three 1 kΩ resistors, one 10 kΩ resistor, and standard jumper wires.

The Arduino board represents the core of the system, receiving analog input signals corresponding to potential differences between the three pairs of electrodes. Each electrode pair was connected in a voltage divider configuration, where the unknown resistance, representing the reciprocal of the electrical conductivity of the foam between the electrodes of each pair, is coupled with a known resistor (1 kΩ). This setup enables precise resistance calculation through Arduino's built-in analog-to-digital converter (ADC). The breadboard assembly provided flexibility during circuit testing and adjustment; however, the system can be later transferred to a printed circuit board (PCB) layout for improved robustness and long-term stability.

A temperature monitoring function was integrated into the circuit through the negative temperature coefficient (NTC) sensor, which allowed real-time compensation of conductivity measurements. The LCD display was connected via the I2C interface to provide immediate

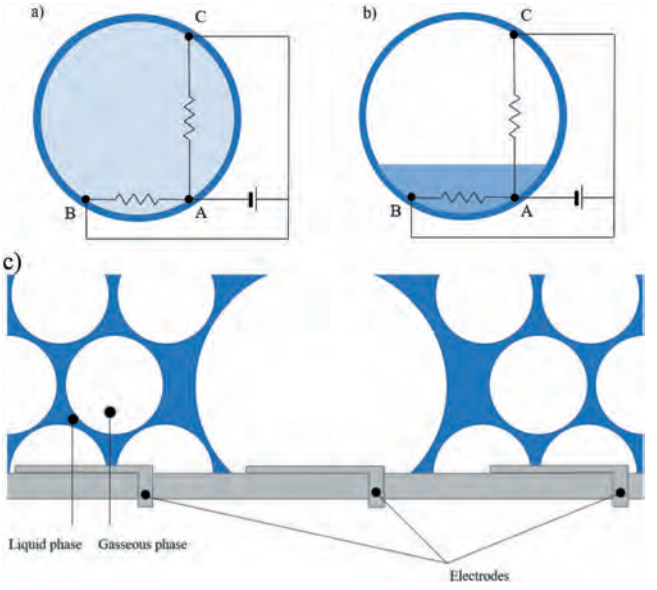


Figure 3. Position of the electrodes in the cross-section of the device. a) In homogeneous foam, both pairs of electrodes measure the same resistivity. b) In the presence of lamination, different resistivities are detected. c) Positioning of electrodes to avoid spikes in resistivity due to single bubbles.

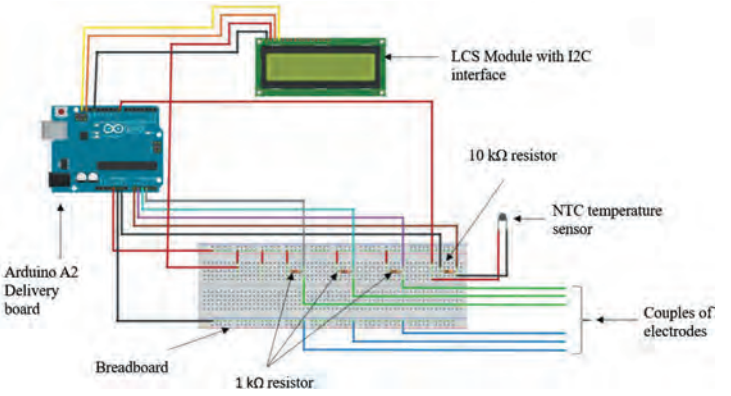


Figure 4. Wiring of the electrical circuit.

visualization of key parameters, including timer, temperature, and both raw and temperature-compensated electrical conductivity values for all three probes. All connections were carefully routed to minimize electrical interference and maintain stable operation during testing.

The embedded software was developed specifically for this application to perform real-time measurement and recording of temperature and electrical conductivity (EC) values from the three electrode pairs. After the initialization of the I2C communication and core Arduino libraries, the program configures the LCD display, the analogue inputs and the temperature probe.

The measurement of temperature is based on the Steinhart-Hart equation, see Equation 2:

$$\frac{1}{T} = A + B\ ln(R) + C[ln(R)]^3 \tag{2}$$

where T = temperature in Kelvin; R = thermistor resistance (Ω); A, B, C = Steinhart-Hart coefficients.

Then, the EC computation for each probe is performed using the voltage divider output, with conversion from resistance to conductivity using a predefined cell constant (K), and temperature compensation at 25 °C. Finally, the data are both shown on the LCD screen and saved in a . xlsx file. This configuration enabled stable, accurate, and continuous monitoring of the foam's electrical properties, ensuring reliable data collection for subsequent analysis and refinement.

2.2.3 *Testing method for FER-EC analysis*

In order to investigate the relationship between FER and the EC of the foam, two types of laboratory tests were performed:

a. Progressive variation of FER
   The test aimed to verify whether variations in FER were followed by corresponding variations in EC. It was carried out by starting from a low FER value, which was gradually increased and then gradually reduced back to the initial value. This procedure allowed the system's response to be evaluated during both the increasing and decreasing phases of foam expansion, covering the full range of FER values relevant to the intended industrial application.
b. Constant FER during the measurements
   In this test configuration, the FER was maintained at a constant level for approximately three minutes, during which four measurements were performed. Measurements were performed at different steady FER values in order to assess the consistency and stability of the system's response over time.

In both types of tests, the foam was generated until the target FER value was reached, then collected in three identical containers of know volume and immediately weighed. This process enables to determination of the corresponding FER value for each test according to the classical measurement method. During the period in which the foam was collected and weighed, the data measured by the proposed open-source device were continuously recorded and stored. The procedure was repeated for each target FER value.

3 RESULTS

The experimental results obtained using the developed prototype under controlled laboratory conditions are presented below.

The analysis focused on the relationship between FER and the corresponding electrical resistance, with the aim of validating the system's accuracy and consistency.

Table 1. Results of tests with progressive variation of FER.

ID	Weight (g)				R (Ω)				FER
	w_1	w_2	w_3	$w_{average}$	R_1	R_2	R_3	$R_{average}$	
1	107.09	105.09	110.13	107.44	82.10	87.90	101.07	89.68	8.38
2	111.20	109.94	103.68	108.27	76.18	81.01	92.93	82.80	8.31
3	89.21	86.22	90.50	88.64	82.26	86.25	94.64	87.42	10.15
4	74.54	76.39	77.20	76.04	90.46	94.79	101.73	95.44	11.84
5	61.50	62.82	62.56	62.29	98.54	101.77	108.07	102.64	14.45
6	48.28	48.33	45.86	47.49	112.14	114.12	117.54	114.56	18.95
7	35.24	34.54	36.48	35.42	124.45	122.93	121.56	122.97	25.41
8	32.98	36.53	34.99	34.83	124.51	123.47	122.98	123.65	25.84
9	44.13	39.90	40.09	41.37	120.16	121.07	123.28	121.49	21.75
10	45.91	47.82	50.13	47.95	114.34	117.38	121.00	117.51	18.77
11	56.95	52.37	55.58	54.97	109.04	112.38	118.18	113.08	16.37
12	64.34	64.68	62.77	63.93	102.05	106.44	112.72	106.89	14.08
13	73.60	72.84	74.91	73.78	89.18	92.56	99.60	93.58	12.20
14	92.65	91.54	91.41	91.87	83.09	87.49	97.07	88.84	9.80
15	113.00	108.55	107.61	109.72	78.42	83.86	96.25	85.55	8.20

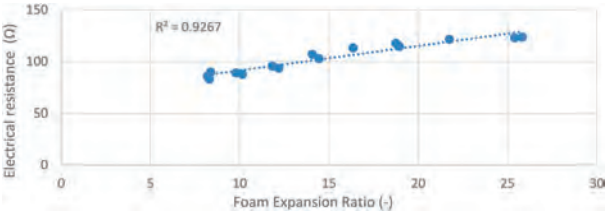


Figure 5. Results of tests with progressive variation of FER.

The results are expressed in terms of electrical resistance (R), a parameter directly proportional to the Foam Expansion Ratio, and inversely proportional to the electrical conductivity, enabling straightforward statistical evaluation through indicators such as the coefficient of determination (R^2).

The data presented in Table 1 indicate a linear relationship between FER and R, with R^2 equal to 0.9267 (Figure 5).

Meanwhile, the results reported in Table 2 demonstrate that maintaining FER at constant values produces stable and consistent resistance measurements. For these data, R^2 is equal to 0.9759 (Figure 6).

Table 2. Results of tests at constant FER.

ID	Weight (g)				R (Ω)				FER
	w_1	w_2	w_3	$w_{average}$	R_1	R_2	R_3	$R_{average}$	
1	105.87	109.86	109.65	108.46	61.30	63.97	79.46	67.37	8.30
2	110.44	115.05	113.49	112.99	60.78	63.31	78.82	66.76	7.97
3	110.18	111.52	110.28	110.66	60.65	63.04	78.66	66.57	8.13
4	107.43	110.65	113.85	110.64	60.74	63.19	79.14	66.78	8.13
5	80.55	77.81	79.48	79.28	71.49	72.13	84.13	75.49	11.35
6	81.21	79.24	82.15	80.87	71.46	72.12	83.83	75.40	11.13
7	79.57	83.94	81.46	81.66	70.32	70.76	81.80	73.93	11.02
8	81.17	81.06	80.55	80.93	70.42	70.84	81.83	74.01	11.12
9	44.13	43.36	47.16	44.88	86.70	86.28	90.03	87.64	20.05
10	45.89	43.13	46.03	45.02	87.97	87.26	90.96	88.70	19.99
11	48.68	47.79	46.72	47.73	89.29	88.99	92.38	90.19	18.86
12	43.14	46.65	45.77	45.19	90.15	89.38	92.98	90.81	19.92

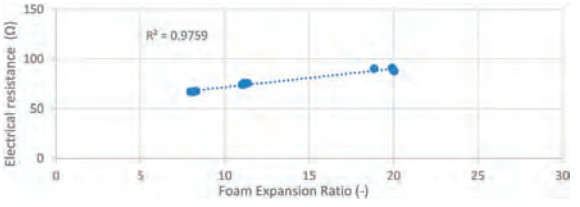


Figure 6. Results of tests at constant FER.

4 DISCUSSION

The developed and proposed prototype was tested across a wide range of FER values, under both progressive variation and constant FER. The results revealed a stable and repeatable response, with the recorded electrical resistance showing a linear correlation with the FER values

obtained in laboratory conditions. This consistency confirms that the system can effectively capture FER variations during foam production. Moreover, its ability to operate in real time and under controlled conditions highlights the potential of the proposed setup as a reliable tool for monitoring and analyzing foam performance in engineering applications.

5 CONCLUSIONS

The developed device has proven that, by applying a potential difference across electrodes positioned along the pipe section, the foam behaves analogously to an electrical circuit: current flow depends on the proportion and distribution of liquid and air phases. The strong correlation between the recorded electrical resistance and the conventionally measured FER values confirms the validity of the proposed approach. Continuous monitoring of resistance therefore allows for the estimation of the FER and, through proper electrode placing, the detection of any lamination phenomena.

Unlike conventional optical or sampling-based methods, this electrical approach operates inside the pipe and in real time, without interrupting the flow or altering pressure conditions. The system can effectively monitor the entire cross-section of the conduit, offering valuable insight into foam behaviour and supporting improved control of the EPB excavation process. This technique could be easily implemented in TBM systems, offering operators real-time insights into foam quality. Nevertheless, additional tests and refinements are necessary to further improve accuracy, durability, and integration within full-scale tunnelling environments. Future developments could include integrating the device within full-scale EPB systems and validating its performance in field conditions.

ACKNOWLEDGEMENTS

This research was carried out within the framework of the project *'In-line device for the continuous determination of the Foam Expansion Rate (FER) of foams used during tunnelling excavation'* (original title: *'Dispositivo in-line per la determinazione in continuo del Foam Expansion Rate (FER) di schiume utilizzate durante gli scavi di gallerie'*), financed by Compagnia di SanPaolo, conducted during the period 16 September 2024–15 September 2025 at Politecnico di Torino.

REFERENCES

Carigi, A. & Todaro, C. (2025). Reuse of EPB-tunnelling excavated soil: An approach of logistic constraints estimation through modified Proctor test. *Tunnelling and Underground Space Technology incorporating Trenchless Technology Research*. DOI:10.1016/j.tust.2024.106263.

Chen, Z.L., Chen, J.Y., Liu, H. & Zhang, Z.F. (2018). Present status and development trends of underground space in Chinese cities: Evaluation and analysis. *Tunnelling and Underground Space Technology*, 71, pp. 253–270. DOI:10.1016/j.tust.2017.08.027.

Gruber, B. L. & Östrand, P. (2019). Implementation of new methods for inspection of tunnels. *In Proceedings of WTC2019: Tunnels and Underground Cities. Engineering and Innovation Meet Archaeology, Architecture and Art*, pp. 2423–2431. CRC Press.

Kaise, S., Maegawa, K., Ito, T., Yagi, H., Shigeta, Y., Maeda, K. & Shinji, M. (2019). Study of the image photographing of the tunnel lining as an alternative method to proximity visual inspection. *In Proceedings of WTC2019: Tunnels and Underground Cities. Engineering and Innovation Meet Archaeology, Architecture and Art*, pp. 2325–2334. CRC Press.

Peila, D., Martinelli, D., Todaro, C. & Luciani, A. (2019). Soil conditioning in EPB shield tunnelling – An overview of laboratory tests. *Geomechanics and Tunnelling* 12 (2019), No. 5, pp.491–498, DOI:10.1002/geot.201900021

Schneider, O., Prokopová, A., Modetta, F., & Petschen, V. (2019). The use of artificial intelligence for a cost-effective tunnel maintenance. *In Proceedings of WTC2019: Tunnels and Underground Cities. Engineering and Innovation Meet Archaeology, Architecture and Art* (pp. 3050–3059). CRC Press.

Thewes, M. & Budach, C. (2010). Soil conditioning with foam during EPB tunnelling. *Geomechanics and Tunnelling* 3 (2010), No. 3, pp. 256–267, DOI:10.1002/geot.201000023.