Excavation Management of Slurry TBMs – Long Term Operational Accuracy Evaluation

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ABSTRACT: Singapore's tunnel construction industry has collected a significant amount of experience in the usage of slurry TBMs in difficult ground conditions. Throughout the years, TBM suppliers, contractors, owners and consultants have grown their know how on excavation management systems. Today the industry is able to provide sensor systems that give a clear insight into the TBMs operation. Their accuracy is a constant topic of discussion, as much as expected alarm thresholds. In order to provide a wider knowledge on the accuracy of the associated sensors in a practical jobsite environment the authors have performed a study across a number of projects to evaluate the long-term accuracy and precision of measurement results from flow meters and density meters.

1 INTRODUCTION

The precise measurement of the excavated amount of material in Mixshield TBMs poses great challenges for all involved parties and has been subject to a number of misconceptions with regards to accuracy and interpretation of measurement results. The deployed software systems have been significantly refined in recent years and the general standard of practice in terms of sensor calibration, prevention of errors and interpretation of results has strongly improved.

However, Singapore's project challenges and strict supervisory guidelines require a more detailed understanding of the deployed sensor systems and the data they provide. While the technical and mathematical foundations have been investigated in detail (Duhme et al. 2015), there is little systematic evaluation of the accuracy that can be achieved on site (Rysdahl, 2015), (Rysdahl et al., 2015). The suppliers of flow- and density meters provide the users with the accuracy of their products (Berthold Technologies, 2015), (Endress + Hauser, 2007). However, these values are valid for individual measurements under laboratory conditions. They do not take into account the actual operating conditions of the slurry circuit and sensors on site and the influence of data transfer and processing.

The presented study analyzes the long-term accuracy of density and flowmeters by investigating fluctuations or drifts in their calibration points. This allows answering a number of highly relevant questions for the operation and supervision of slurry TBMs in challenging conditions:

- What are the practical limitations of accuracy that can be expected under stable site conditions with adequate care given to calibration and operation?
- How can the state of "correct calibration" be defined and determined under site conditions?
- What lessons and guidelines for operators can be drawn from past data to improve future working procedures regarding the on-site calibration of slurry circuit sensors?
- Which observations can be made regarding macroscopic trends regarding the loss of "correct calibration" to determine the reasonable frequency for recalibration?

2 MEASURING ENVIRONMENT

To understand the influence of sensor calibration onto the excavation management systems results, one must investigate the structure of the slurry circuit first. Figure 1 shows an overview of the slurry circuit.

The slurry circuit is fed from the driving tank (1) at the separation plant (2). Via the feed line (3), the bentonite is pumped to the TBM's excavation chamber (4). After mixing with the excavated soil, the bentonite is pumped back to the separation plant (2) via the slurry line (5). The slurry circuit is powered by one or more feed pumps (6) in the feed line (3) and one or more discharge pumps (7) in the slurry line (5). A bypass line (8) allows operating the circuit in a bypass mode, where the bentonite from the feed line (3) is directly going back to the slurry line (5) while bypassing the excavation chamber (4). The bypass mode is controlled by a set of valves. The feed line valve (8) controls entrance into the excavation chamber (4). The discharge valve (9) exit from it. The bypass valve (10) controls the bypass line (8). During advancing, the bypass valve (10) is closed, the two others open. During bypass mode, the feed line valve (8) and discharge valve (9) are closed, while the bypass valve (10) is open. The aforementioned components are equipped with sensors to determine their operating status. A feed line density sensor (11) and corresponding slurry line density (13) sensor inform the operator on the transported material. A feed line flowmeter (12) and slurry line flowmeter (14) produce the current flow rates.

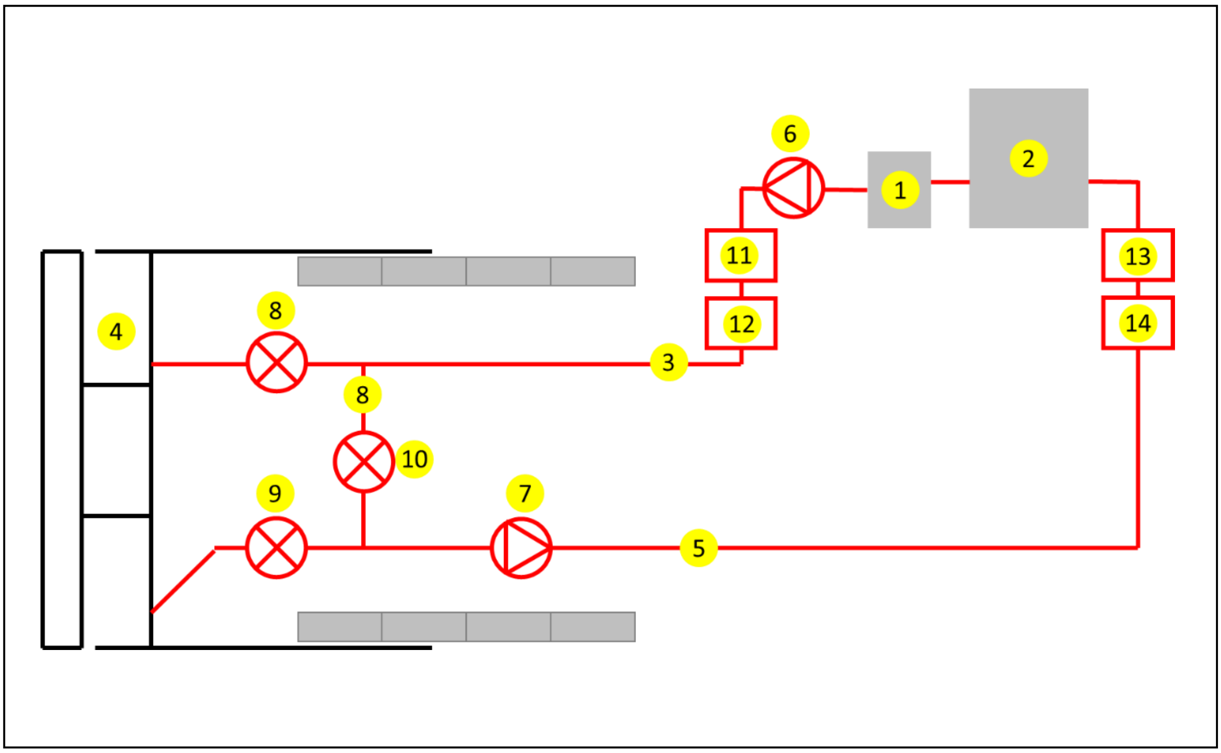

Figure 1. Layout of a slurry circuit with main components

2.1 Operating Conditions

The slurry circuit is operating in a typical pattern. At the beginning of each ring, the valves are switched from bypass mode to advance mode and the TBM starts excavating. During TBM advance , the feed line is delivering fresh bentonite and the slurry line transports bentonite and muck mixture back to the surface. Flow and density of the slurry line are higher than the feed line due to the additional material from the excavation. Due to the operational conditions and the inhomogeneity of the pumped material, the fluctuation of the measured flow and density values is considerable. The calculated results of excavation management systems rely on a large number of individual measurements and thus even on this fluctuation.

At the end of the advance stroke, the slurry circuit valves are switched to bypass mode. During a transition period, the remaining excavated material in the slurry line is flushed out and flow and density readings in both lines converge. Furthermore, flow and density readings become stable and fluctuate much less. If the sensors in any line are miscalibrated, an offset between feed line and slurry line readings becomes visible in bypass mode.

After flushing the pipelines completely, the slurry circuit is turned off during ring build to conserve energy. Upon completion of the ring it is turned back on to prepare the TBM for the start of the next stroke.

2.2 Influence of Miscalibration

Two different error mechanisms govern technical sensing systems. Firstly stochastic errors. As they are usually evenly distributed around a mean value, their influence can be practically eliminated by using overall average results from a large number of individual measurements. The measuring parameter associated with the stochastic deviation of the sensors is often referred to as precision. As the measurement period (hours) is long in relation to the measurement interval (milliseconds), this criterion applies to TBM tunneling. The second error mechanism is miscalibration. The longer a measurement period lasts, the more will the effects of miscalibration grow. Thus, understanding miscalibration is crucial. The measuring parameter of the sensors associated with miscalibration is often referred to as accuracy. A sensitivity study regarding calibration errors in excavation management systems has been presented in (Duhme et al. 2015). Having 1% miscalibration of the feed density meter could potentially lead to a significant error in the evaluation of excavated dry mass as calculated in Equation 1 below:

$$m_{dry} = \int_{t_{ring\ start}}^{t_{ring\ end}} \left(\frac{\dot{Q}_{slurry} \times (\rho_{slurry} - 1) - \dot{Q}_{feed} \times (\rho_{feed} - 1)}{\rho_{particle} - 1} \times \rho_{particle} \right) \delta t \qquad (1)$$

In the calculation shall be assumed for the excavation to be 1 hour, the slurry flow Q_{slurry} to be $1240 m^3/h$, the feed flow Q_{feed} as $1200 m^3/h$, the feed density ρ_{feed} as $1.10 t/m^3$, the soil water content as 20%, its particle density $\rho_{particle}$ as $2.6 t/m^3$ and the slurry density ρ_{slurry} $1.148 t/m^3$. The excavated dry mass m_{dry} can then be calculated to 104 tons. If the discharge flow meter were miscalibrated by 1%, it would display 1.16 t/m^3 instead. Recalculating m_{dry} based on this value, would lead to a reading of 127 tons. On the basis of knowing the strong effects of miscalibration on the results, the incentives for understanding this topic and improving the interpretation of measurements seems significant. Due to the nature of construction site conditions, it is not possible to always maintain perfectly calibrated systems. While this study primarily aims at improving this situation, it also helps to distinguish false alarms from potentially dangerous situations.

3 ANALYSIS METHODOLOGY

Recapitulating the research targets formulated in the introduction, we can state explicit interest in the long-term behavior of the offset between the flowmeter and density sensor readings in the feed line and slurry line. In this paper, the offset is often referred to as “delta” and generally refers to discharge line value minus feed line value. However, the raw data that can be obtained from the TBMs shows many distortions from operational influences that prohibit using the data for measurement of sensor accuracy. Thus, a large part of the study has been devoted to preparatory work such as automated identification of relevant measurement values, data processing and filtering as well as the statistical evaluation of the raw data. The workflow has generally been carried out along the following steps:

1. Identification of bypass data from the TBM operating data acquisition system and automated extraction from raw data files.
2. Atomization of an individual data series for each individual uninterrupted and stable bypass event.
3. Introduction of filters to eliminate all data that does not represent bypass events that took place under conditions that do allow evaluation of the calibration status.
4. Common analysis of all individual bypass events concerning the research questions formulated in the introduction.
5. Derivation of conclusions from the analysis results.

3.1 Data Foundation for Analysis

The presented study includes all recent Herrenknecht Mixshield TBMs in Singapore. The TBMs have been operating mostly in Bukit Timah Granite of different weathering stages. The projects include LTAs currently constructed Thomson Line (S-893, S-894, S-930, S-936, S-946 and S-963) as well as

the completed Cable Tunnel NS3 tunnels (S-822, S-823 and S-825). Table 1 provides an overview of the machines and the available datasets including the number of overall bypass events, the number of events after filtering out unsuitable ones and the corresponding durations bypass events.
A set of Python scripts for processing files from the TBM data acquisition system has been developed. In a first step, sensor data relevant to this analysis has been copied into new files. Further processing identifies individual bypass events and saves these events for evaluation.

Table 1. Overview of datasets and their properties

TBM	No. of analyzed rings [-]	No. of bypass events [-]	Mean duration [mm:ss]	No. of event > 5 min [-]	Duration evaluated [hh:mm:ss]
S-822	1705	10963	1:49	1025	183:45:37
S-823	1168	9665	1:13	491	96:00:01
S-825	1212	9678	2:48	1348	309:39:01
S-893	432	2458	2:52	359	78:55:09
S-893.1	477	2134	1:57	219	39:32:40
S-894	455	2074	2:25	266	54:00:39
S-930	419	3082	1:15	164	28:45:46
S-930.1	446	4703	0:44	86	11:44:07
S-936.2	504	4451	2:38	576	139:31:13
S-946	362	3888	3:43	728	188:08:10
S-946.1	349	2491	3:03	341	95:00:24
S-963	426	9681	1:32	626	145:00:40
S-963.2	553	9942	2:56	1508	328:42:18

A bypass event is defined by the conditions of the valves being in bypass mode, both line's flowrates being above a minimum of 75% of the design flow rate and feed pump P1.1 running at constant speed. This is evaluated by using the concept of mean average deviations to find sudden steps in flowrate which indicate a change of settings by the operator. If during a bypass event on site, the operator changes settings, this formal definition leads to the event being recorded as two separate ones. Thus, this formal definition may lead to a different number of shorter events than the intuitive counting on site.
The individual bypass events have been identified by evaluating the state of the valves and flow sensor readings. For those intervals that have been singled out as bypass events, selected sensor readings are extracted and saved. Figure 2 shows a screenshot of such a data sample. The extracted sensor readings firstly are the flow meter and density meter values, as well as the status of the main valves and pumps.

	SEC_1970	NO_RING	p11_rpm	p21_rpm	flow_feed	rho_feed	flow_slurry	rho_slurry	v030_closed	v031_open	v032_closed
0	1451243651	124	530.425	645.761	433.314	1.178	546.013	1.179	0	0	0
1	1451243652	124	530.425	645.761	433.314	1.178	546.013	1.179	0	0	0
2	1451243663	124	588.918	641.122	477.847	1.180	595.038	1.176	0	0	0
3	1451243673	124	632.667	623.322	503.629	1.178	533.903	1.178	0	0	0
4	1451243684	124	680.283	656.546	521.207	1.180	513.395	1.176	0	0	0

Figure 2. Screenshot of a data sample with the relevant sensor readings extracted

3.2 Data Filtering

After identifying all datasets that have been recorded during bypass state, they have been atomized into separate data series for each individual event of bypass. Thus, the individual events can be evaluated for their properties. Understanding the behavior of the slurry circuit is a relevant prerequisite for determining filtering conditions to single out those bypass events, which are influenced by external factors such as muck inside the slurry circuit, changes to the pumps and valves or refilling the STP driving tank with fresh bentonite. Additionally, influences that are unknown to the authors at the date of data analysis, must be assumed to be present in the data. In order to account for these influences, values with a mean average deviation (MAD) above 1.5 are removed. This eliminates areas of larger fluctuation in short periods from the data. Gradual changes are unaffected.

A second filter removes data from periods where there still is muck in the slurry pipes. By using the pipe diameter, tunnel length and the flow rates, data that originates from a certain interval after advancing is neglected. Figure 3 shows the remaining data in a common graph for the delta of flow meters and the delta of density meters from all remaining bypass events. One can observe a common behavior of a large number of bypasses, but also a number of outliers. Some of the volatile sections can be attributed to external influences from the STP operation.

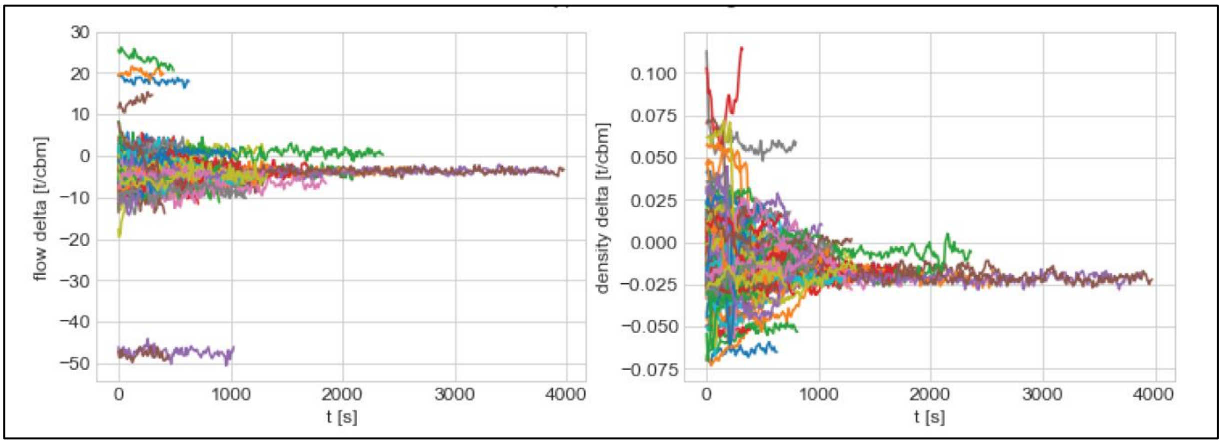

Figure 3. Typical behavior of density delta and flow delta readings during bypass from T206 (S-893)

4 ANALYSIS RESULTS

The analysis results have been determined firstly for each TBM separately to allow comparative studies between different projects. The first analysis point is the long-term observation of the calibration status by observing the delta between the two sensors. It is generally defined as the slurry line value minus corresponding feed line value. Subsequently, the precision and accuracy of the system are evaluated.

4.1 Trends in calibration status

To observe trends in calibration status, the flow and density deviation ("delta") between feed and discharge line is plotted over the course of the whole tunnel drive. For each bypass event, its mean flow delta and density delta are plotted. Additionally the range of their standard deviation during the event is shown. Figure 4 shows an example of this plot from S-946. The flow delta is shown in blue and the density delta in red. The standard deviation of each event is shown in grey for both.

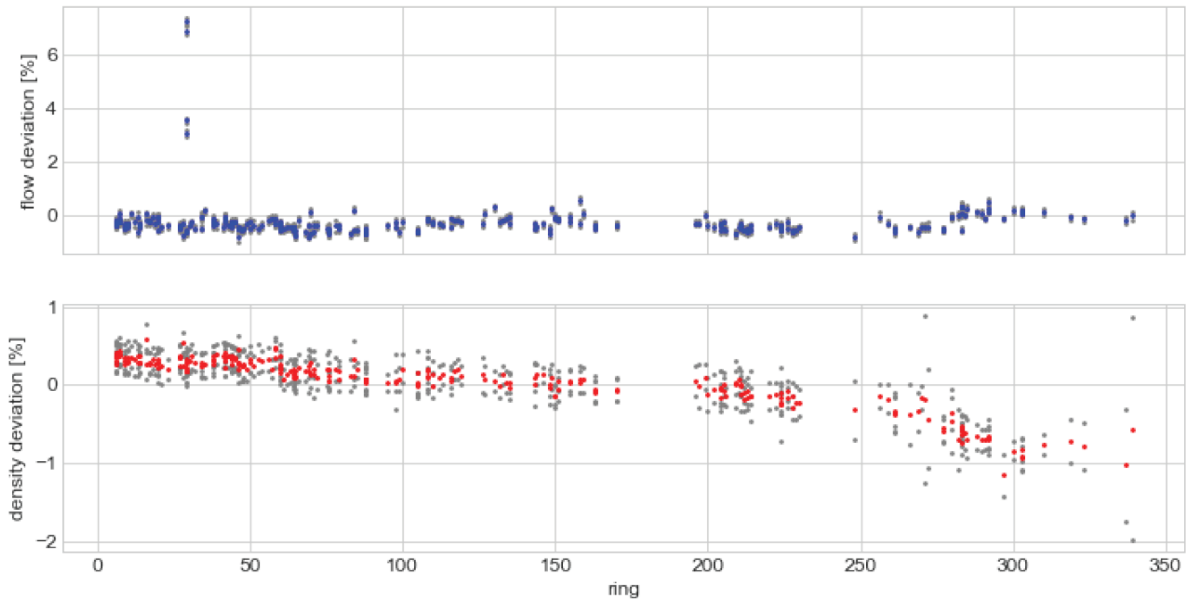

Figure 4. Development of flow and density delta throughout S-946 tunnel drive.

Since the filters which have been discussed above are eliminating most datasets which are subject to external influences, these long term observations allow to judge changes in the calibration points over time. Such changes can be caused by wear in the sensors or other influences in the system. Some are obviously due to technical modifications. Since the analyzed projects have an additional software calibration method, this analysis does not allow judgement of how well the operator has made the settings or how well the final results of the excavation management system has been. This study only includes the hardware calibration point.

The data shown in Figure 4 above is quite representative for the observations which can be made. Both, the flow delta and the density delta readings increase in terms of their scattering within the bypass events. This is visible in the growing standard deviation of measurements in each event as shown by the grey dots in Figure 4. Another trend for both sensors is the increasing variation between bypass events. Both phenomena can be attributed to wear of components within the slurry circuit and sensors.

Another decisive phenomenon which can be observed in all projects is a gradual shift in the density meter's calibration point. The delta between the sensors can be seen shifting slowly with a rate of -0.8% to -1.5% over 500 rings. This can be seen on all projects and is most probably attributed to wear as well. Due to the more abrasive material in the discharge line, the discharge pipe is worn more than the feed line and the sensors gamma rays are less weakened. This range also provides a guideline for how often the need for recalibration is reasonable to be expected.

4.2 Operational accuracy of sensors

The operational accuracy of flow meters and density meters is regular subject of discussion. When calculating theoretical volume losses from the observed settlements, modern TBMs can reach the range of 0.2% to 0.5%. Thus, there is the desire by owners and authorities to verify and measure these volume losses from the slurry circuit sensors. For the existing projects, the bypass data has been evaluated statistically to evaluate if this target is achievable with the existing sensors.

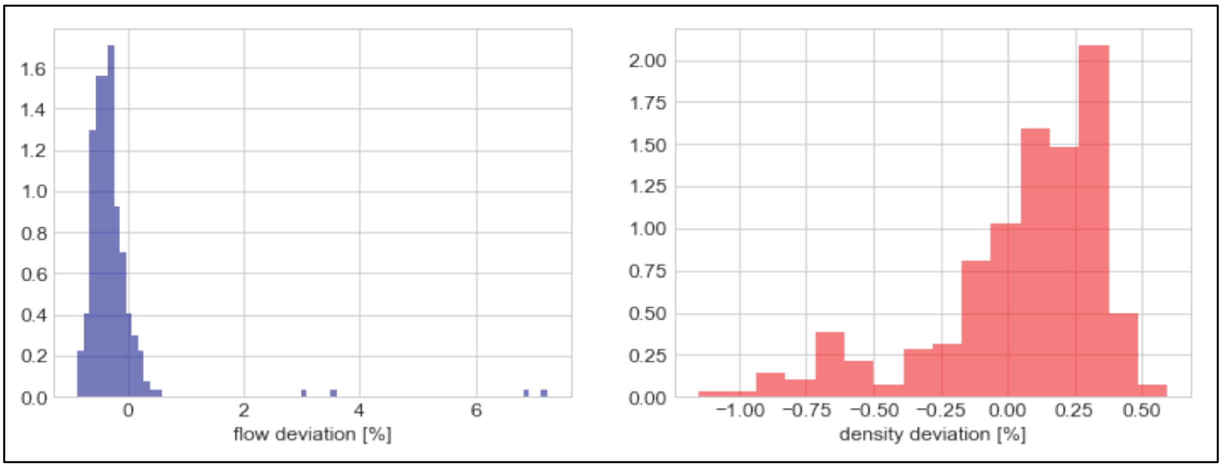

Figure 5. Histograms of flow delta and density delta measurements of S-946

When evaluating the deviations, one can derive the achievable accuracy and precision for calibration. The presented values have been derived after filtering the data from those with high fluctuation. Thus, the presented data represents the upper range which can be reached. In (Rysdahl, 2015) a comparable study has been performed for the New York Queens tunnels. However, in this study the filtering process has been less strict to still allow higher fluctuating datasets to be used. This is due to the slightly different focus. While the study presented in this paper is aiming at the achievable calibration accuracy, the study at Queens tunnel was targeting the correction of measuring results for a post project evaluation. Table 2 presents an overview of all measuring results from the Singapore study as well as the New York Queens tunnels in comparison. The table lists two main results for the density meters and flow meters each. Firstly the mean of means. This is the mean deviation of the flow and density delta over all filtered bypass events. This gives an indication for how close to the relative zero point the sensors in each project have been calibrated. Secondly, the sigma of means is given. This value represents the typical fluctuation level of the sensor readings between bypass events. It therefore equally represents the amount of fluctuation to expect between the time when a sensor is calibrated and when it is used to perform a measurement.

It is immediately obvious when comparing the mean of means that the deviations derived from the Singapore projects are smaller than those reported from the New York project. This can be attributed to the increased attention for calibration which is common on Singapore jobsites. The sigma of means however behaves the same as the natural fluctuations in the process are the same and lead to similar deviations in measuring results. While the mean of means value can be interpreted as the best achievable accuracy of relative calibration between the sensors, the sigma of means can be interpreted as the expected deviation of an individual measuring series from the calibration point. Together, they define the envelope for the achievable measuring accuracy and precision.

Table 2. Overview of evaluation results

Drive	flow deviation mean of means	flow deviation sigma of means	density deviation mean of means	density deviation sigma of means
S-822	-0.53%	0.71%	-0.38%	0.89%
S-823	-0.55%	0.82%	0.43%	1.43%
S-825	-0.29%	0.69%	0.05%	0.73%
S-893	-0.15%	0.56%	-0.35%	0.63%
S-893.1	-0.77%	0.88%	-0.97%	1.47%
S-894	-0.38%	0.45%	-0.11%	1.25%
S-930	0.02%	0.39%	-0.56%	0.51%
S-930.1	-0.03%	0.61%	-0.66%	0.85%
S-936.2	0.50%	0.61%	-0.78%	0.60%
S-946	-0.26%	0.76%	-0.05%	0.33%

S-946.1	-0.47%	0.24%	-0.16%	0.28%
S-963	0.27%	0.50%	-0.15%	0.40%
S-963.2	2.19%	0.61%	-0.94%	0.32%
Queens-YL	0.03%	0.69%	0.74%	0.43%
Queens-A	1.39%	0.84%	1.48%	0.37%
Queens-D	1.23%	0.69%	0.16%	0.69%
Queens-BC	-0.31%	0.64%	1.77%	0.33%
Average	**0.55%**	**0.63%**	**0.57%**	**0.68%**

5 CONCLUSIONS

The presented study has evaluated the actual calibration status of the flow and density meters in slurry shield projects in Singapore. The findings are of practical relevance for the industry practices on site. Firstly, a tendency for slow drift in calibration point of densitymeters due to pipe wear could be verified. This is in a range of -0.8% to -1.5% over 500 rings. This sets the order of magnitude for a reasonable interval for sensor recalibration. Secondly, the actual achievable measuring accuracies and measuring precisions of individual sensors could be quantified. They lie in a range of up to around 1% for most projects. In average at 0.55% for the flow meters and 0.57% for the density meters. Thirdly, the deviation of measurements from this calibration point can be estimated by the sigma of means. It typically lies in a range between 0.3% and 1%. In average the measured standard deviation between measuring points has been 0.63% for the flow meters and 0.68 for the density meters.
These values set the envelope for the expected measuring results of excavation management systems. It immediately becomes obvious, that the theoretical volume losses of 0.2% to 0.5% which the industry sees today cannot be verified from the slurry circuit sensors with the deviations we can observe. However, we can also observe, that the actual results in terms of measuring precision and accuracy are very good on an absolute scale.
Another point that is of immense practical relevance is the origin of sinkholes in unstable operating conditions such as flushing the excavation chamber or interventions. The results in this study are evaluating the quality of the calibration that can be achieved under jobsite conditions. However, the offset of the calibration points are a different issue than the measuring behavior during unstable operation conditions. Thus, the accuracies which have been measured for the calibration point cannot be transferred directly as accuracy of the overall excavation measurement system in all conditions. They form a guideline for interpretation of measuring results.
The results show, that with given care for the calibration of the sensors, high individual accuracies can be reached. This lies the foundation for stable and reliable measuring results as they have been achieved by the Singapore tunneling industry in recent years.

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