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Spoil Reconciliation in Slurry TBM Tunnelling: A literature review and framework designed for application on Melbourne's Suburban Rail Loop East – Tunnels South

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ABSTRACT: Accurate muck reconciliation is critical for efficient slurry TBM operations, ensuring alignment between theoretical and actual excavation volumes. This paper reviews methodologies for TBM dry mass calculation, volume measurement, and slurry treatment plant (STP) reconciliation, analysing challenges including sensor inaccuracies and geological variability. A novel risk-aware framework is developed to guide method integration, demonstrating how hybrid approaches reduce errors. The framework will be applied on Melbourne's Suburban Rail Loop (SRL) East – Tunnels South (delivered by Suburban Connect JV: CPB Contractors, Acciona and Ghella) to support reconciliation in mixed-ground conditions.

1 INTRODUCTION

The slurry shield, pioneered in the UK during the 1970s, addressed excavation control in challenging ground, initially targeting submerged sand/gravel without face instability. Recent decades have seen global adoption for long-distance tunnelling in complex geology due to technical feasibility and automation. Projects like the Channel Tunnel Rail Link (UK), Shanghai Yangtze River Tunnel (China), and Singapore's Deep Tunnel Sewerage System (DTSS) exemplify its application in variable strata under high water pressures (Shirlaw et al., 2003; Thewes & Hollmann, 2016). Similar methodologies are implemented in Sydney's Eastern Tunnelling Package (ETP).

1.1 *Slurry System*

Face support is provided by bentonite/polymer-water slurry counterpressure, forming a filter cake or impregnated zone to transfer pressure and mitigate collapse risks (Maidl et al., 2012; Hochart et al., 2021). Excavated material is transported to surface STPs for separation and bentonite recycling (Herrenknecht, 2020). Advanced software standardises dry mass/volume calculations for real-time efficiency monitoring (EFNARC, 2005; Peila & Picchio, 2020).

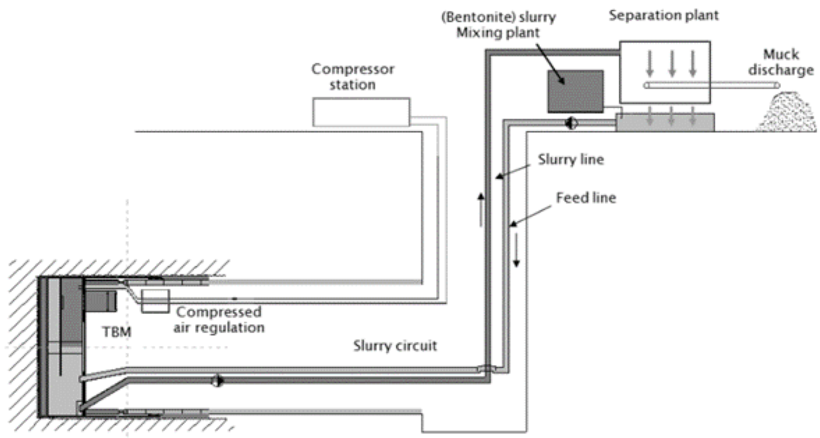

Figure 1 - Slurry circuit (Duhme et al., 2016)

1.2 *Need for three distinct reconciliation approaches*

Three distinct reconciliation approaches - TBM dry mass calculation, TBM volume measurement, and slurry treatment plant (STP) muck reconciliation - are critical to address uncertainties in excavation management, particularly in scenarios involving over-excavation (Tang et al., 2021).

The need for distinct approaches has been also extensively discussed in recent literature, emphasising the accuracy of mass and volume-based reconciliation techniques (Gravemeijer & Peila, 2022)

1.2.1 *Scenario 1: Over-Excavation with Unfilled Void:*

When over-excavation occurs, and the resulting void remains unfilled, excess soil volume is transported through the discharge line. This leads to a measurable discrepancy between the theoretical and actual volumes, directly indicating the over-excavation volume. Volume-based measurements alone, however, may fail to detect localised ground loss or slurry infiltration into adjacent strata, necessitating complementary mass-based calculations (Connors, 2017).

1.2.2 *Scenario 2: Over-Excavation with Void Filled by Slurry*

In this case, the void created by over-excavation is filled with slurry, masking the volume discrepancy. While the measured volume aligns with theoretical expectations, the dry mass of excavated material will exceed projections due to the additional soil removed. This highlights the necessity of integrating mass reconciliation to identify hidden over-excavation risks, as volume measurements alone become insufficient (Herrenknecht, 2020).

1.2.3 *Why Three Approaches Are Required*

1. TBM Dry Mass Calculation: Determines the actual excavated soil mass by accounting for slurry density, flow rates, and solids content. This method detects over-excavation even when voids are slurry-filled, as mass discrepancies persist despite normalized volumes (EFNARC, 2005).
2. TBM Volume Measurement: Monitors real-time slurry inflow/outflow volumes to identify unfilled voids. However, it cannot distinguish between soil displacement and slurry infiltration, requiring cross-verification with mass data (Tang et al., 2021).
3. STP Muck Reconciliation: Validates excavated material quantities post-separation at the slurry treatment plant. By comparing STP outputs with TBM data, this approach identifies systemic errors (e.g., sensor drift, slurry loss) and ensures alignment between theoretical and actual excavation (Underground Singapore, 2018).

The integration of these methods mitigates risks such as ground subsidence, face instability, and project cost overruns. For instance, STP reconciliation at Singapore's Thomson-East Coast line revealed inconsistencies in fine particle retention within the slurry circuit, which were undetectable via TBM sensors alone (Underground Singapore, 2018). Similarly, the Sutong GIL Chang Jiang Tunnel project demonstrated that traditional volume-based systems underestimated over-excavation by 12–18% in permeable sandy ground, necessitating improved mass-balance models (Tang et al., 2021).

An approach grounded in the same principles is also being applied on other major tunnelling projects delivered by the same joint venture partners. For example, the Eastern Tunnelling Package (ETP) in Sydney, is implementing a spoil reconciliation methodology aligned with slurry TBM operations frameworks.

2 BASIC CONCEPT OF SOIL AND ROCK COMPOSITION

To understand the theory of the excavation management system, it is necessary to refer to the basic soil structure (Figure 2), which consists of three primary phases: solid particles, water, and air (Terzaghi et al., 1996). In geotechnical engineering, soil behaviour under excavation depends on the interaction of these phases, particularly in saturated or partially saturated conditions. For

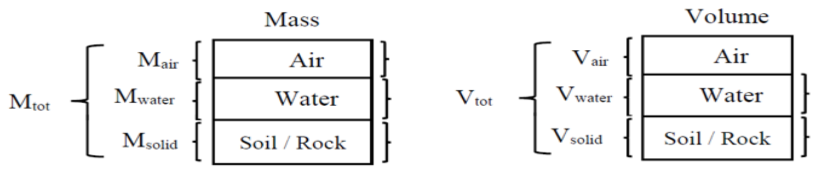

Figure 2 - Basic soil structure.

fully saturated in situ soil or rock, the mass and volume of air (M_{air}, V_{air}) are negligible and can be assumed as zero, as voids are entirely filled with water (Das & Sobhan, 2018).

2.1 *Soil/Rock Properties and Variables*

The following variables are essential for quantifying soil/rock behaviour and ensuring accurate excavation management:

1. M_{air}: Mass of air (equal to zero)
2. V_{air}: Volume of air (negligible in saturated conditions)
3. M_{water}: Mass of water
4. V_{water}: Volume of water, linked to porosity ($n = V_{water} / V_{tot}$).
5. M_{solid}: Mass of solid particles
6. V_{solid}: Volume of solid particles
7. M_{tot}: Total mass of soil or rock ($M_{solid} + M_{water}$)
8. V_{tot}: Total volume of soil or rock ($V_{solid} + V_{water} + V_{air}$)
9. ρ_{water}: Density of water (M_{water} / V_{water})
10. ρ_{solid}: Density of solid particles (M_{solid} / V_{solid})
11. μ: Moisture content (M_{water} / M_{solid})

These parameters underpin calculations for dry density ($\rho_{dry} = M_{solid} / V_{tot}$), void ratio ($e = V_{void} / V_{solid}$) and degree of saturation ($S = V_{water} / V_{void}$), which are pivotal in slurry shield TBM operations to balance excavation pressures and avoid ground collapse (Maidl et al., 2012).

2.2 *Application to Excavation Management*

In slurry shield tunnelling, deviations in moisture content (μ) or void ratio (e) directly impact the stability of the excavation face. For instance, fully saturated soils (S = 100%) require precise slurry pressure to counteract hydrostatic forces, while partially saturated soils (S < 100%) demand adjustments to account for air compressibility (Herrenknecht, 2020). Modern TBMs integrate sensors to monitor ρ_{solid}, μ, and V_{tot} in real time, enabling dynamic adjustments to slurry density and flow rates (EFNARC, 2005).

3 THEORETICAL EXCAVATION VOLUME

The theoretical excavation volume depends on the TBM cutting diameter and the theoretical length of advance, calculated as in equation 1 below:

$$V_{theo} = \frac{\pi {d_T}^2}{4} L_{advance} \tag{1}$$

where d_T is the cutting diameter of the TBM in meters and $L_{advance}$ is the length of advancement in meters.

This formula assumes a perfectly cylindrical excavation profile, which is critical for benchmarking against actual excavated volumes to detect over- or under-excavation (Maidl et al., 2012).

3.1 *Theoretical Dry Volume and Dry Mass*

The dry mass is derived from the equivalence of total mass and phase relationships:

$$M_{tot} = M_{solid} + M_{water} \tag{2}$$

which can be expressed as:

$$V_{tot}\rho_{in\,situ} = V_{solid}\rho_{solid} + V_{water}\rho_{water} \tag{3}$$

The volume of water is expressed as:

$$V_{water} = V_{tot} - V_{solid} - V_{air} \tag{4}$$

For the fully saturated soil the volume of air is equal to zero, therefore:

$$V_{water} = V_{tot} - V_{solid} \tag{5}$$

And substituting:

$$V_{tot}\rho_{in\,situ} = V_{solid}\rho_{solid} + (V_{tot} - V_{solid})\rho_{water} \tag{6}$$

Further elaborating the formula:

$$V_{tot}\rho_{in\,situ} = V_{solid}\rho_{solid} + V_{tot}\rho_{water} - V_{solidt}\rho_{water} \tag{7}$$

$$V_{tot}\rho_{in\,situ} - V_{tot}\rho_{water} = V_{solid}\rho_{solid} - V_{solidt}\rho_{water} \tag{8}$$

$$V_{tot}(\rho_{in\,situ} - \rho_{water}) = V_{solid}(\rho_{solid} - \rho_{water}) \quad (9)$$

The volume of solids is equivalent to the Dry Volume; therefore, the formula can be expressed as:

$$V_{dry} = V_{tot}\left(\frac{\rho_{in\,situ} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right) \quad (10)$$

The dry soil mass can be then calculated as:

$$M_{dry} = V_{tot}\left(\frac{\rho_{in\,situ} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right)\rho_{solid} \quad (11)$$

This derivation ensures accurate reconciliation between in situ soil properties and excavated material, particularly in saturated conditions where pore water pressure significantly impacts stability (Mitchell & Soga, 2005; Das & Sobhan, 2018).

3.2 *Practical Implications*

Over-Excavation Detection: Deviations between V_{theo} and actual volumes signal potential ground loss or slurry infiltration, necessitating adjustments in slurry pressure (Herrenknecht, 2020). Moisture Content Sensitivity: Errors in μ (moisture content) measurements can lead to overestimation of M_{dry}, affecting spoil disposal and slurry recycling efficiency (EFNARC, 2005).

4 MEASUREMENT OF ACTUAL EXCAVATION VOLUME

During tunnelling operations, excavated materials are conveyed into the slurry discharge line through the excavation chamber. This process increases the discharge flow rate (Q_{out}) proportionally to the material ingress rate, while the feed flow rate (Q_{in}) supplies fresh slurry to maintain face support (Herrenknecht, 2020) (Figure 3).

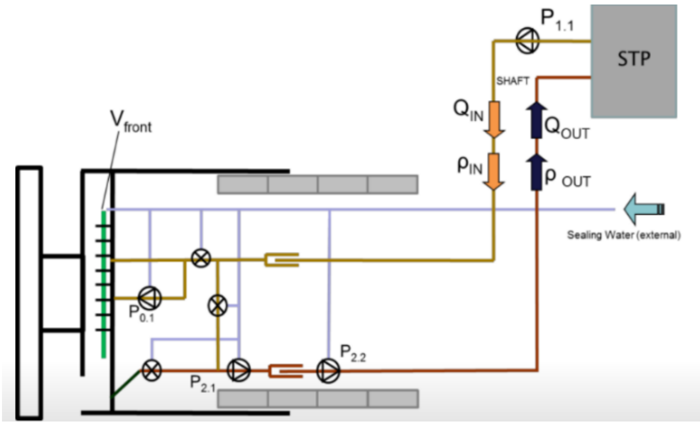

Figure 3 - Slurry flow schematic diagram.

4.1 *Schematic for Actual Excavation Volume Determination*

The actual excavation volume V_{tot} is calculated by integrating the discharge and feed flow rates over time, adjusted for changes in the excavation chamber volume $\triangle V_{chamber}$:

$$V_{tot} = \int Q_{out}\,d_t - \int Q_{in}\,d_t + \triangle V_{chamber} \quad (12)$$

Where:
- Q_{in}: Feed flow rate (m^3/hr), supplying slurry to the excavation chamber.
- Q_{out}: Discharge flow rate (m^3/hr), transporting excavated material to the surface.
- $\triangle V_{chamber}$: Net volume change in the excavation chamber from TBM advancement or slurry compression (Maidl et al., 2012), monitored in real-time via wire rope level sensors detecting slurry level variations in the chamber.

5 ACTUAL MEASUREMENT OF EXCAVATED SOLIDS (DRY MASS AND DRY VOLUME)

For fully saturated soil, the dry volume formula (Equation 13) is applied, assuming no air entrapment in feed/discharge pipelines (Mitchell & Soga, 2005):

$$V_{dry} = V_{tot}\left(\frac{\rho_{insitu} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right) \quad (13)$$

The total discharge dry volume can be calculated by considering the total volume of slurry passing through the discharge flow meter at the recorded density of ρ_{out}.

$$V_{tot(out)} = Q_{out} \triangle_t \quad (14)$$

$$V_{dry(out)} = Q_{out} \triangle_t \left(\frac{\rho_{out} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right) \quad (15)$$

The total feed Dry Volume can be calculated considering the total volume of slurry (Q_{feed} $\triangle$t) passing through the discharge flow meter at recorded density of ρ_{feed}.

$$V_{tot(in)} = Q_{in} \triangle_t \quad (16)$$

$$V_{dry(in)} = Q_{in} \triangle_t \left(\frac{\rho_{in} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right) \quad (17)$$

The total Dry Volume is the difference of dry volumes in the feed and discharge over time and can be therefore expressed as:

$$V_{dry(solid)} = \int Q_{out}\left(\frac{\rho_{out} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right) d_t - \int Q_{in}\left(\frac{\rho_{in} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right) d_t \quad (18)$$

The above can also be calculated as dry mass considering the equation:

$$M_{dry(soil)} = \int Q_{out}\left(\frac{\rho_{out} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right) \rho_{soild} d_t - \int Q_{in}\left(\frac{\rho_{in} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right) \rho_{soild} d_t \quad (19)$$

This method ensures real-time reconciliation of excavated solids, critical for detecting ground loss or slurry infiltration (Herrenknecht, 2020).

6 INFLUENCE OF EXTERNAL FACTORS ON THEORETICAL AND ACTUAL MEASUREMENTS

6.1 *Key Factors Affecting Accuracy*

Mis-calibration: Sensor drift in flowmeters or densitometers skews Q_{in}, Q_{out}, and ρ_{out} values (Connors, 2017).

Sealing Water: Injected sealing water from rotary pumps increases V_{tot} but does not alter M_{dry} and V_{dry}.

Time Influence: Prolonged excavation cycles cause particle settling in slurry pipelines, skewing density readings. Time-lagged sensor responses may also distort real-time Q_{out} integration (Herrenknecht, 2020).

Leakages: Slurry leakage from fractured pipelines or faulty joints reduces Q_{out} which can falsely indicate under-excavation. Conversely, groundwater ingress inflates Q_{in}, masking over-excavation (Shirlaw et al., 2020).

Interventions: Manual interventions (e.g., cutterhead inspections) halt slurry circulation, allowing solids to settle. Post-intervention restarts require purging to avoid biased ρ_{out} measurements (Maidl et al., 2012).

Pipe Extension: Adding segments to the discharge pipeline introduces air pockets, temporarily disrupting Q_{out} stability (Tang et al., 2021).

Slurry Travel Time: For long tunnels, transit delays between TBM and STP sensors complicate data reconciliation. Installing intermediate density/flow meters along the pipeline mitigates synchronization errors by enabling sectional monitoring.

Bubble Chamber Variations (Mix Shield TBMs): For double-chamber TBMs equipped with a bubble chamber, it is essential to account for variations in slurry volume and mass within the bubble chamber. The slurry level in the chamber, measurable via sensors, is then correlated to the corresponding volume variation.

While the variation in volume in the chamber is straight forward, the variation in solids particles should be calculated as a dry volume or dry mass:

$$Chamber_{dry\,soil} = \triangle V_{chamber}\left(\frac{\rho_{out} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right) \quad (20)$$

The measured dry mass formula considering variation in bubble chamber would then be:

$$M_{dry(soil)} = \int Q_{out}\left(\frac{\rho_{out} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right) \rho_{soild} d_t - \int Q_{in}\left(\frac{\rho_{in} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right) \rho_{soild} d_t + \triangle V_{chamber} \quad (21)$$

Sensor-based slurry level monitoring in the bubble chamber is essential to track $\triangle V_{chamber}$ (Maidl et al., 2012).

In-Situ Density Variability: Fluctuations in $\rho_{in\ situ}$ (e.g., due to heterogeneous strata) directly impact both theoretical and measured dry mass, requiring probabilistic models for error margins (Tang et al., 2021).

7 SECONDARY MEASUREMENT AT THE SLURRY TREATMENT PLANT AND MUCK PIT

Secondary reconciliation measurements at the STP rely on belt weighers installed between the STP and muck pit. However, these systems capture only coarse particles (gravel/sand) separated by sieves and cyclones, excluding fines below the STP's separation threshold. The total excavated dry mass is derived by combining measured coarse solids with estimated fines.

7.1 *Fines Calculation in Slurry Systems*

7.1.1 *Initial Fines Mass (Pre-Excavation):*

Measured before mining starts: Slurry density ρ_{slurry} is measured using density meters in the regulating tank.

$$M_{dry\ fines,\ before} = (V_a + V_b + V_c)\left(\frac{\rho_{slurry} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right)\rho_{solid} \quad (22)$$

Where:
- V_a = Volume of active tank (tank placed on the surface in line with the circuit)
- V_b = Volume of slurry pipes
- V_c = Volume of excavation chamber

7.1.2 *Final Fines Mass (Post-Excavation):*

Measured after mining completes: Slurry density is rechecked at the same locations, typically showing increased values due to fines accumulation during excavation.

$$M_{dryfines,after} = (V_a + V_b + V_c)\left(\frac{\rho_{slurry} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right)\rho_{solid} \quad (23)$$

7.1.3 *Net Fines Retained:*

Represents fines excavated during mining**, calculated from the density-driven mass difference.

$$M_{dry,fines} = M_{fines,after} - M_{fines,before} \quad (24)$$

7.1.4 *Adjustments for Slurry Disposal/Addition*

Slurry Disposal:

In the event that slurry is disposed of from the active tank during mining operations, the mass of fines (M_{fines}) for the disposed slurry must be accounted for and added to the calculations. For disposal of slurry during the mining, the corresponding dry mass of fines is calculated as follows:

$$M_{dryslurry\ disposed} = V_{slurry\ disposed}\left(\frac{\rho_{slurry\ disposed} - \rho_{water}}{\rho_{solid} - \rho_{water}}\right)\rho_{solid} \quad (25)$$

Bentonite Addition:

Dry mass of bentonite powder could be taken directly from record of fresh bentonite or calculated using fresh bentonite density as:

$$M_{dryslurry\ added} = V_{slurry\ added}\left(\frac{\rho_{fresh\ bentonite} - \rho_{water}}{\rho_{bentonite} - \rho_{water}}\right)\rho_{bentonite} \quad (26)$$

Revised Fines Mass:

To account for the fines in the system, it is required to add back the solids being disposed and subtract the slurry being added:

$$M_{dry,fines} = (M_{fines,after} - M_{fines,before}) + (M_{dry\ slurry\ disp.} - M_{dry\ slurry\ added}) \quad (27)$$

7.2 *Dry Mass Calculation Methods at STP*

7.2.1 *Method 1: Moisture Content-Based*

Starting from the total mass composition formula:

$$M_{tot} = M_{solid} + M_{water} \quad (28)$$

On both side of equation, we divide by M_{solid}:

$$\frac{M_{tot}}{M_{solid}} = 1 + \frac{M_{water}}{M_{solid}} = 1 + \mu \quad (29)$$

Isolating the solid mass we obtain:

$$M_{solid} = \frac{M_{tot}}{1 + \mu} \quad (30)$$

Weight shown by the belt weight measurement from pre-screen equates to the total weight of gravel: $M_{tot\ gravel}$.

$$Dry\ mass\ of\ gravel\ M_{gravel\ dry} = \frac{M_{tot\ gravel}}{(1 + \mu_{gravel})} \quad (31)$$

Weight shown by the belt weight measurement from cyclones equates to the total weight of soil: $M_{tot\ soil}$.

$$Dry\ mass\ of\ Soil\ M_{soil\ dry} = \frac{M_{tot\ soil}}{(1 + \mu_{soil})} \quad (32)$$

Total fines remaining in the system is the dry mass of fines $M_{fines\ dry} = M_{fines\ after\ mining} - M_{fines\ before\ mining}$.

$$M_{fines\ dry} = V_{tot}\left(\frac{\rho_{in\ situ} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right)\rho_{solid} \quad (33)$$

$$\textbf{Total Dry Mass from STP} = M_{gravel\ dry} + M_{soil\ dry} + M_{fines\ dry} \quad (34)$$

7.2.2 *Method 2: Density-Based*

$$M_{dry} = V_{tot}\left(\frac{\rho_{in\ situ} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right)\rho_{solid} \quad (35)$$

Divide both sides of the equation by $\rho_{in\ situ}$:

$$\frac{M_{dry}}{\rho_{in\ situ}} = V_{tot}\left(\frac{\rho_{in\ situ} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right)\frac{\rho_{solid}}{\rho_{in\ situ}} \quad (36)$$

Further elaborating the formula:

$$M_{dry} = V_{tot}\rho_{in\ situ}\left(\frac{\rho_{in\ situ} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right)\frac{\rho_{solid}}{\rho_{in\ situ}} \quad (37)$$

$$M_{dry} = M_{tot}\left(\frac{\rho_{in\ situ} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right)\frac{\rho_{solid}}{\rho_{in\ situ}} \quad (38)$$

$$M_{dry\ gravel} = M_{tot\ gravel}\left(\frac{\rho_{in\ situ} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right)\frac{\rho_{solid}}{\rho_{in\ situ}} \quad (39)$$

$$M_{dry\ soil} = M_{tot\ soil}\left(\frac{\rho_{in\ situ} - \rho_{water}}{\rho_{soild} - \rho_{water}}\right)\frac{\rho_{solid}}{\rho_{in\ situ}} \quad (40)$$

8 COMPARISON OF DRY MASS BY DIFFERENT METHODS

All data for comparing TBM dry mass calculations were sourced from the Deep Tunnel Sewerage System 2 (DTSS2) Project, Contract T-09, in Singapore, executed by Leighton Contractors (Asia) Limited (Singapore Branch) and CPB Contractors Tunnelling Business Unit.

The graphs in Figure 4 compare:

- Theoretical Dry Mass: Derived from in situ soil properties and TBM advance metrics (Equation 10).
- Actual TBM Dry Mass: Calculated via the Automated Excavation Management (AEM) system using real-time slurry density and flow data.
- STP Dry Mass:
  - Method 1: Moisture content-adjusted calculations (Equations 31–32).
  - Method 2: Density-based reconciliation (Equations 39–40).

Notable sharp reductions in dry mass values occurred at:

- Ring 0: Incomplete sensor commissioning during initial TBM launch
- Ring 90: Chamber interventions (e.g., cutterhead inspections)
- Rings 950 & 1470: TBM recommissioning after crossing intermediate shafts

These deviations highlight how operational resets affect sensor calibration but do not invalidate the overall reconciliation methodology. The consistency across methods elsewhere provides a reliable cross-check when one approach shows discrepancies.

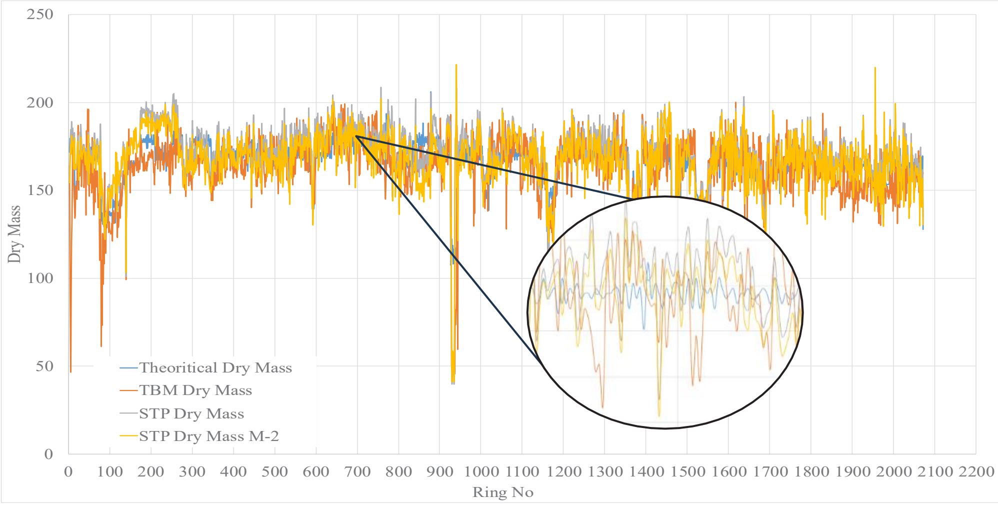

Figure 4 - Methods comparison graph.

9 CONCLUSION

The integrated framework—combining TBM dry mass, volume, and STP reconciliation—overcomes volumetric limitations in slurry-filled void scenarios. Field application on SRL East – Tunnels South (Suburban Connect JV, TBM launch 2026) will demonstrate real-time implementation in Melbourne's mixed-ground conditions, enhancing face stability control in urban environments.

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