

MANAGEMENT OF COMPLEX GEOLOGICAL STRUCTURES USING ENGINEERING GEOLOGICAL MODELS DURING TUNNEL CONSTRUCTION: THE LUNA PARK FAULT ZONE, SYDNEY

Richard Brehaut, Beatriz Estrada¹

*Stuart Simmonds*²

¹*PSM*

²*John Holland*

ABSTRACT

This paper describes the evolution of an engineering geological model developed as part of Construction Phase Services for the Sydney Metro City & Southwest Tunnel and Station Excavation project.

Barangaroo Station, located on the southern side of Sydney Harbour, comprises a 34 m deep temporary construction shaft, 35 m long crosscut adit and 230 m long crossover cavern adjacent to the north of the 28 m deep station box excavation. The site is founded within the Permian - Triassic Hawkesbury Sandstone and transected by the Northeast – Southwest trending Luna Park Fault Zone (LPFZ).

The LPFZ was anticipated to occur at the Barangaroo Cavern. During construction, the primary LPFZ plane was initially identified in probe holes before daylighting in the temporary shaft and crosscut adit. In total, the fault zone was exposed for approximately 70 m along the strike and encountered in each of the three respective underground excavations. The total zone of structural deformation was excavated over a width 50 m along the wall of the crossover cavern, equating to a true thickness of 30 m. The structure included packages of normal and strike-slip dominated displacements which combined with high angle reverse faults, Riedal shears and orthogonal transfer faults.

A three-dimensional engineering geological model was developed within a construction environment and offered rapid reproduction of encountered conditions in a format suitable for design verification during Permit to Tunnel meetings. Geotechnical borehole and field mapping records offer detailed insights into ground conditions. However, they can be difficult to visualise in two dimensions. Understanding the details of a ground model is essential in reviewing support systems that can be readily applied (and constructed) to the variable conditions encountered within a complex structural environment. The resultant model offered high-resolution imagery and interactive three-dimensional elements that could be queried and interrogated, offering increased value to numerous stakeholders.

Beyond documenting the engineering model development during construction, this paper also intends to share our observations and contribute to existing publications and the current understanding of the LPFZ within the engineering industry.

1 INTRODUCTION

The Luna Park Fault Zone (LPFZ) is considered one of the primary subvertical structural features traversing the Sydney CBD. Originally observed during the Luna Park redevelopment (Och et al., 2004), the LPFZ had only been exposed in limited locations following surficial development along the interpreted location of the fault.

The character of the LPFZ varies at each exposed location in terms of fault thickness, extent of the damage of the surrounding rock, and general rock mass condition. Accordingly, the impact of the LPFZ for urban development is also highly variable along its length.

The excavation of the Barangaroo crossover cavern exposed the LPFZ from multiple angles. This allowed for a detailed assessment of the fault zone's characteristics. This paper presents these observations and details how the engineering geological model developed in the design phase was verified during construction and communicated to designers and contractors allowing them to adapt to the encountered conditions while maintaining and optimising excavation progress.

1.1 PROJECT DESCRIPTION

The Sydney Metro City & Southwest project creates a connection from Chatswood to Bankstown via Sydney’s central business district (CBD), extending the existing Sydney Metro Northwest Line by approximately 30km. The project involved the construction of:

- 15.5 kilometres of twin railway tunnels including the city’s second passage under Sydney Harbour constructed using four hard rock and one slurry Tunnel Boring Machines,
- Excavation and construction of six new metro stations at Crows Nest, Victoria Cross, Barangaroo, Martin Place, Gadigal (Pitt Street) and Waterloo
- Tunnel dive structures at Chatswood and Marrickville
- Three temporary construction and service shafts at Artarmon, Blues Point and Barangaroo
- 57 cross passages providing emergency access and egress between running tunnels
- A crossover cavern located at the northern end of Barangaroo Station to permit trains to change tracks within the running alignment.

1.1.1 BARANGAROO STATION AND CROSSOVER CAVERN

Barangaroo is a waterfront precinct located on the southern side of Port Jackson (Sydney Harbour), situated to the south of Walsh Bay and extends along the shoreline past Nawi Cove towards Darling Harbour. Barangaroo occupies a reclaimed industrial site that was formerly part of Sydney’s maritime infrastructure, transitioning from a docklands area into a thriving, modern commercial and recreational precinct.

The Barangaroo metro station is positioned to service the rapidly evolving western fringe of the CBD while creating the harbourside connection to the lower north shore. The following elements were included in the Tunnels and Station Excavation (TSE) contract at Barangaroo:

- Station box excavation – 215 m x 25 m, 28 m (d)
- Crossover cavern – 230 m x 22 m x 16 m (h)
- Hickson Road access shaft (temporary) – 17 m x 10 m x 30 m (d)
- Crosscut adit (temporary) – ~13 m (h) x 12 m (w) arched

Individual elements are presented in plan on Figure 1, as well as the inferred extents of the Luna Park Fault Zone, as interpreted prior to construction.

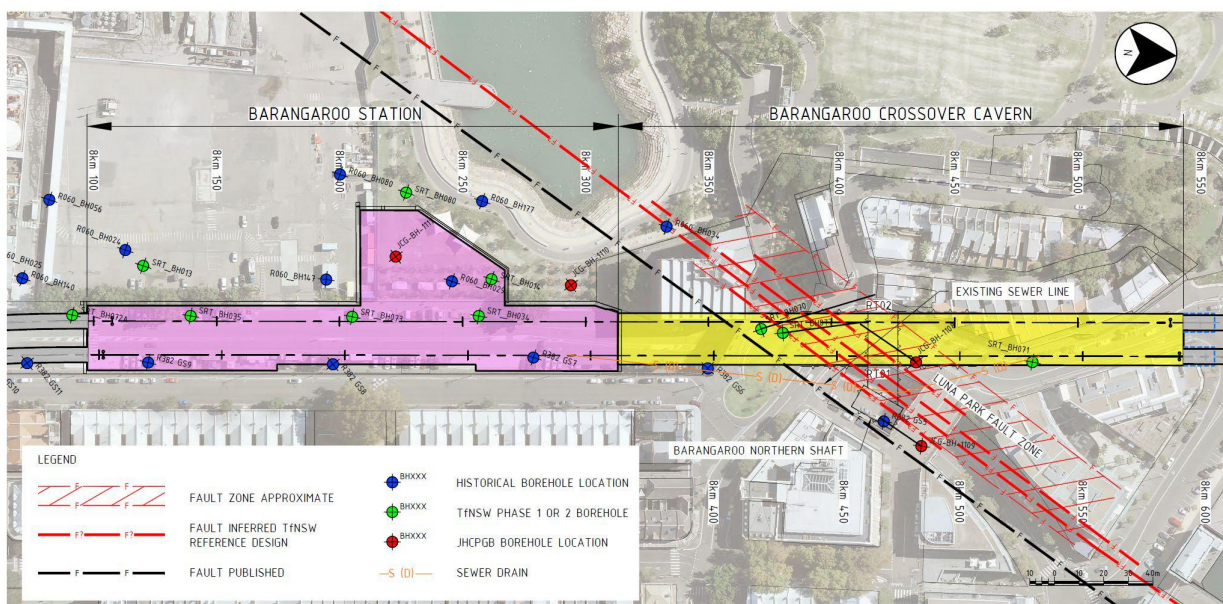


Figure 1: Barangaroo Station site plan - Station box (purple), crossover cavern (yellow). Northern access shaft and crosscut adit (dashed lines to the east of the crossover cavern) relative to the inferred extents of the Luna Park Fault Zone.

2. GEOLOGICAL SETTING

2.1 PROJECT GEOLOGY

The project is situated centrally within the Sydney Basin, which is a thick sedimentary sequence of Permian-Triassic aged rocks (290 Ma – 200 Ma). Within the project area, flat lying Lower Triassic rocks of the Hawkesbury Sandstone and Wianamatta Group dominate.

The Hawkesbury Sandstone was deposited in a fluvial paleo-environment, probably a braided river setting. Hawkesbury Sandstone is described as a medium to coarse grained, quartzose sandstone deposited in generally 1 to 3 m thick layers. These layers form primary bedding planes that range in thickness from less than 0.5 m to greater than 5 m but generally occur between 1 m to 3 m. Layers of shale breccia or clasts comprising fragments of siltstone between 50 and 4000 mm wide occur within the Hawkesbury Sandstone. They commonly occur as layers and often accumulate along primary bedding planes (Branagan et al, 1976, Pells, 2004).

Sandstone between the primary beds is described as either massive or cross bedded, the latter being referred to as ‘sheet facies’.

Siltstone interbeds termed ‘laminites’, or ‘mudstone facies’, form a minor part of the unit (around 5%). Laminites typically range in thickness from 0.5 to 3 m but generally occur less than 1 m and rarely up to around 12 m. The lateral extent of these units is highly variable and can occur laterally from tens of meters to hundreds of meters (Pells, 1994). These laminate beds may be associated with increased occurring of shearing of bedding.

2.2 GEOLOGICAL STRUCTURE

The typically sub-horizontal bedded rocks of the Sydney Basin (and the cross bedded facies of the Hawkesbury Sandstone) are occasionally disrupted by regional folding and faulting. Various types of faults (normal, reverse and strike-slip) are common in the Sydney Basin (Och et al., 2009).

Concentrations or clusters of faulting and jointing are known to occur. However, the geomorphological expression of faults on the surface is limited due to extensive urban development. Therefore, the opportunity for identification of faults from surface expression is limited.

Zones of concentrated faulting and jointing have been previously identified along the Sydney Metro alignment. These zones are referred to as the LPFZ, GPO Fault Zone, the Martin Place Joint Swarm and the Woolloomooloo Fault Zone (Pells et al., 2004; Och et al, 2009). Other geological structures such as jointing and low angle thrust faulting also occur but with larger spacing and lower persistence.

2.2.1 LUNA PARK FAULT ZONE – PUBLISHED RECORDS AND DESIGN INTERPRETATION

The character and extent of the LPFZ can vary significantly at relatively short distances. Existing exposures of the fault zones in published records are described as follows:

- Miller Street rail cutting (North Sydney) - Three sub-vertical faults are documented by Longworth & McKenzie (1984) to occur within a 110 m zone. The faults strike 045 to 048° and have a fault thickness between 0.5 to 0.8 m wide comprising angular sandstone fragments within a re-cemented “rock flour”. Adjacent thrust faulting was later noted by Branagan (1991).
- Luna Park (Milsons Point) - The fault zone was described as comprising two separated faults (Och et al., 2009). The eastern extent has 100 mm fault gouge with brecciated sandstone. The western extent has up to 1 m zone of observed jointing and shearing where the rock appears to be relatively intact. At the Luna Park Car Park, the character of the fault is different at the intersected walls. In the northern wall it is described as a 2 m zone of cataclastic/brecciated sandstone thinning to 1 m zone in fresher rock. In the southern wall, the LPFZ is observed as a discrete plane.
- Start City Casino Excavation (Pyrmont) - The fault zone is described (Speechley et al., 2004) as a shear zone up to 8 m wide zone comprising extremely low to very low ‘sugary’ sandstone with some pockets of intact medium to high strength indurated sandstone. The contact between the shear zone and the hosting sandstone is described as gradational with few defects occurring within 8 m of the edge of the observed shear zone. Steep jointing (75 - 90°) was observed adjacent to the shear zone together with brecciated shale beds dipping 10 to 15° to the west.

Based on these published observations the LPFZ was anticipated to be encountered by the Barangaroo Cavern excavation. This became a key site investigation target to constrain both site specific extents and expected geotechnical conditions. Six cored boreholes (both vertical and inclined) were drilled within the projected LPFZ lineament corridor as part of the tender and later detailed design phases. Within the proposed excavation profile fresh, high strength sandstone was intersected with localised intervals of increased fracturing. The recovered core was largely unaltered and displayed relatively discrete zones of structural disturbance, Figure 2.



Figure 2: Examples of structurally deformed, fresh Hawkesbury Sandstone from within the published LPFZ as highlighted. Borehole SRT_BH070 completed as part of the projects tender phase site investigation program.

An additional eight cored boreholes were completed by the contractor as part of its design development and risk mitigation works during early excavation of the Hickson Road temporary shaft to further assess geotechnical and hydrogeological conditions within the fault zone. Using speciality drilling equipment, low angle (15 and 30°) cored and rotary boreholes were progressively drilled within the west and southwest shafts wall. This targeted investigation allowed the sub vertical structure to be intersected more obliquely than traditional surface drilling techniques. Rising head tests were also completed to assess inflow potential within the LPFZ noting the potential hydraulic connection along strike from both Nawi Cove and Walsh Bay. The boreholes identified more intense fault gouge and deformation than previously intersected from surface. The variable rock mass contained numerous clays seams, siltstone laminite lenses and closely spaced sub vertical joint clusters indicating a package of steep easterly/south easterly dipping shear zones were present.

3. GEOTECHNICAL VERIFICATION - CONSTRUCTION PHASE SERVICES

As part of the Construction Phase Services (CPS), the geotechnical site conditions interpreted during design were verified. The primary role as the Contractors CPS representative was to compare the encountered ground conditions during construction against the documented design assumptions and support selection criteria. If the encountered ground conditions are considered to be a departure from the design assumptions, a geological change notice was provided to the design team to formally capture the conditions and enable a timely review.

The configuration of the Hickson Road access shaft, crosscut adit and crossover cavern relative to the orientation of the LPFZ presented several geotechnical complexities. This necessitated development of a detailed three dimensional engineering geological model that could be readily updated with various data sources including boreholes, forward probe holes and geotechnical face mapping to inform both the design team and contractor throughout construction.

The following sections present selected CPS observations used to inform the LPFZ model develop during construction and aim to portray the encountered variability within the fault zone and how differently the ground conditions presented as approached from various orientations during tunnelling.

3.1.1 ACCESS SHAFT

Space constraints are commonly associated with large scale infrastructure projects in established cities. Barangaroo’s Hickson Road temporary access shaft was located immediately adjacent to a live road, between two heritage bridges and active sewer connection (both considered to be sensitive structures). To accommodate these constraints, the shaft footprint at surface was smaller than its base meaning there were overhanging walls on two sides of the shaft excavation.

To manage potential instabilities, excavation was completed using relatively small lift heights, between 1.25 and 2 m. In addition to routine geotechnical face mapping, endoscope inspections were completed within the north, west and southern shaft walls. These aimed to identify adversely orientated geological structures with the potential to form unstable kinematic sliding planes as the shaft progressed through the overhanging walls at depth.

As documented by Nash et al, (2017), using endoscope inspections, it is difficult to identify defect spacing, infill, and orientation. Furthermore, assessing rock mass conditions based on recognised Sydney classification systems (Pells et al., 2008, 2019 and Bertuzzi, 2014) is nearly impossible without a full tactile assessment. This is due to the inability to measure rock strength, defect spacing and seam thickness accurately.

With close reference to adjacent cored boreholes, defect occurrences were recorded and supplemented by observations relating to gouge/clay infill, hole integrity (wash outs) and visible changes in rock mass weathering. Findings were plotted in cross section (Figure 3) and projected three dimensionally following each excavation lift to interpret the distribution of shearing withing the rock mass. A series of steep, easterly dipping shears were identified and correlated between endoscope inspection and cored boreholes drilled from within the shaft confirming a viable failure mechanism. In response, cable anchors were proactively installed from upper levels to address the identified mechanism which subsequently daylighted within the lower southwest wall.

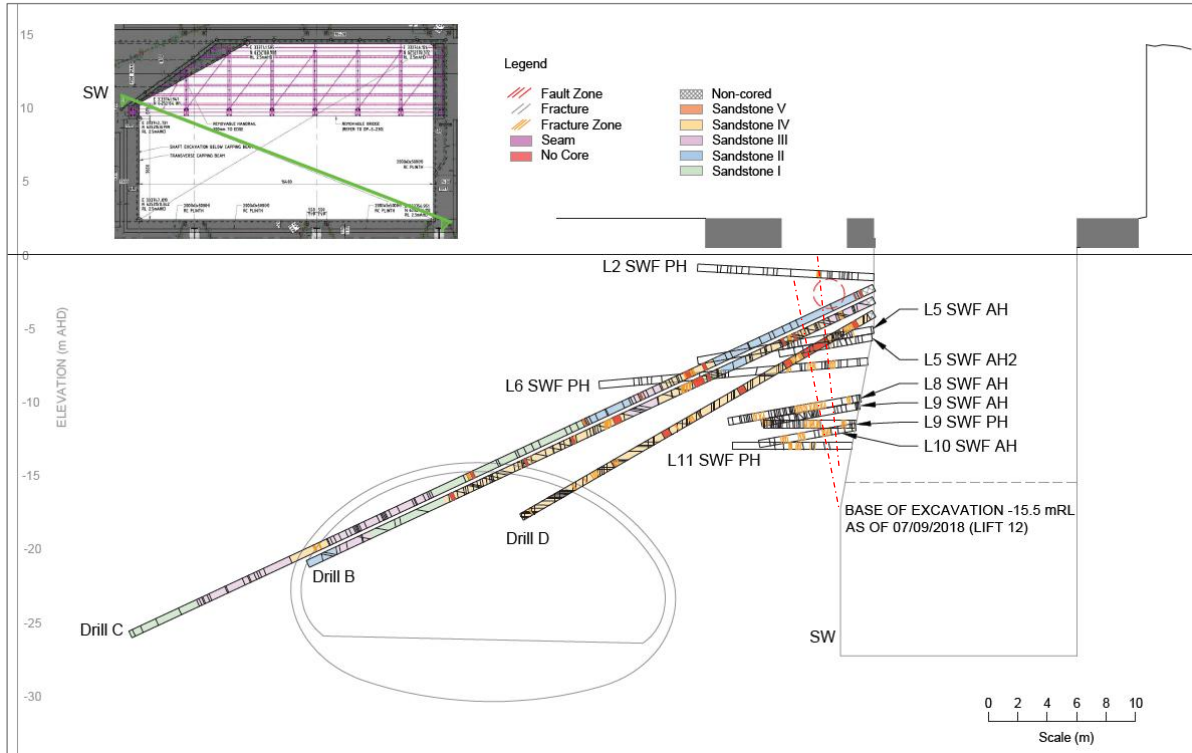


Figure 3: Cross section illustrating cored borehole and probe hole endoscope coverage within the southeast wall of the Hickson Road temporary access shaft. Adversely oriented kinematically sliding planes inferred to intersect at the base overhanging wall.

Localised instabilities were managed within subsequent excavation lifts beneath the crown level of the crosscut adit portal between -15 and -20 mRL where overbreak was observed up to 800 mm along daylighting shears, Figure 4 and Figure 5.



Figure 4: Subvertical shear daylighting in shaft wall at the crown level of the crosscut portal. Highly altered sandy clay breccia and gouge breaking away from the planar, slickensided subvertical shear at rear. Material was readily disaggregated by hand.



Figure 5: Subsequent excavation lift (approx. -20 mRL) where steeply dipping shears daylighted approximately 2.5 m vertically beneath initial plane. Note undulating defect surface and undercutting of wall along discrete sub horizontal joints

Forward probe holes were drilled and inspected with endoscopes from the base of the access shaft showing multiple zones of shearing and fault gouge material. This information was incorporated into the construction three-dimensional model to assess the forward extent and character of faulted ground prior to tunnelling. Pre-excavation support, including spiling bars, were installed. However, the bearing of the crosscut adit (260°) obliquely undercut the fault zone, which exhibited variable rock quality.

3.1.2 CROSSCUT ADIT AND CAVERN EXCAVATIONS

Geotechnical face mapping was undertaken by an experienced team of engineering geologists and geotechnical engineers using 4G enabled tablets. This hybrid digital mapping approach allowed highly detailed observations to be efficiently captured while summarising the following geotechnical attributes:

- Rock mass descriptions
 - Lithology
 - Weathering
 - Field estimated strength
 - Colour

- Defect spacing
- Rock class (as per Pells et al 2008, 2019)
- Defect characteristics
 - Defect type
 - Orientation
 - Shape and Roughness
 - Infill, thickness and spacing
- Design validation and nomination of additional support requirements.

An example of a CPS mapping records completed during verification of ground conditions within the crosscut adit is illustrated in Figure 6.

During excavation (late 2018), the use of photogrammetry or 3D colourised laser scanning surveys was not well established in heavy civil tunnel construction projects throughout Australia. While the technology was available, practical workflows that did not impede construction were still maturing.

At the time of construction, creation of full digital twins was not standard practice. Instead, face mapping records were georeferenced within the three-dimensional CPS engineering geological model for every advance within the LPFZ. Detailed mapping observations, combined with borehole and probe hole data, helped verify and refine the design geotechnical model, Figure 7.

Following completion of the crosscut adit's top heading, a full cross section of the LPFZ had been exposed. Both stages of excavation and primary support provided unique perspective as the fault zone was approached from different orientations. The CPS interpretation of geotechnical conditions was presented during daily Permit to Tunnel (PTT) meetings and provided a basis to confidently predict the expected conditions within the mainline cavern excavation, orientated to traverse obliquely along strike of the structure. The information informed both design team and the Contractor to forecast ground support requirements and production rates respectively.

Barracough et al, (2021) describes the application of the CPS engineering geological model in development of additional ground support types, including a hybrid detail, to cater to the encountered conditions. Due to the oblique orientation of the fault relative to the crossover cavern, the hybrid support type enabled the Contractor to maintain a heavy configuration in areas of faulted ground while permitting lighter ground support on side of the cavern with more favourable conditions. This collaborative team approach negated program delays, allowing assembly and launch of a slurry TBM required for the harbour crossing to the Blues Point Shaft on the north shore.

MATERIAL / MASS DESCRIPTION ⁽¹⁾

Mapped Unit	Lithology	Weathering	Est. Strength	Colour	Bedding Spacing (m)	Sub - Vertical Defect Spacing (m)	Joint Swarm (m)
A	-						
B	SANDSTONE	MW	M	PALE GREY	>0.6	>0.2	-
C	SANDSTONE	MW/HW	M/L	PALE TO MID GREY	>0.6	0.05 - 0.2m	-
D	FAULT GOUGE / INFILL	EW	VL	OFF WHITE / GREY	-	-	-

SEEPAGE RATING / DESCRIPTION
Seepage Rating 1 - Discontinuity is dry with no detectable seepage
Seepage Rating 2 - Discontinuity damp but no free water is present
Seepage Rating 3 - Discontinuity shows minor seepage, that is occasional drops of water
Seepage Rating 4 - Discontinuity shows continuous flow of water

Design drawing Nos: DP-T-08-SOS600	Face chainage and control line: Ch-13.0 to Ch-11.9
Draft copy of mapping inspection record	
Name: <u>JOE MADGWINS</u>	Sign: _____ Date: <u>11/10/18</u>
Final copy of mapping inspection record	
Name: <u>RICHARD BRIDGES</u>	Sign: _____ Date: <u>11/10/18</u>

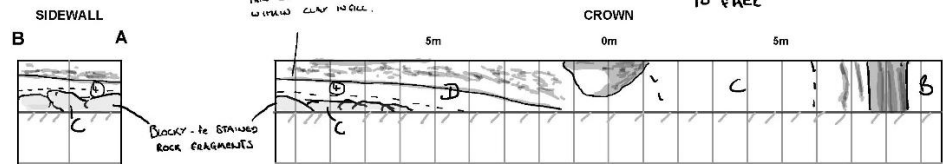
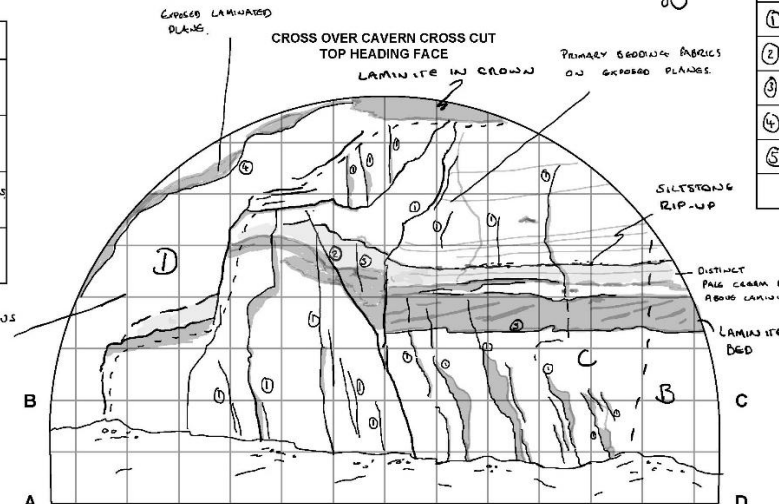
Chainage: Engineer Surveyor
 Other

MATERIAL / MASS DESCRIPTION Cont ⁽¹⁾

Mapped Unit	Rock Class	Other Observations
A	-	
B	SST III	MEDIUM TO COARSE GRAINED SANDSTONE SUB HORIZONTAL, PLANAR BEDDING FABRICS WITH SILTSTONE LAMINATIONS.
C	SST IV	MEDIUM TO COARSE GRAINED SANDSTONE WITH SUB - HORIZONTAL, PLANAR BEDDING FABRICS OCCASIONAL SECTIONS OF HIGH PE STAINING.
D	SST V*	FAULT GOUGE MATERIAL TYPICALLY COMPRISING CLAY WEILS AND OCCASIONAL FRAGMENTED ROCK. HAS NO PRIMARY SANDSTONE TEXTURES.

LEGEND	
	not excavated
	spoil
	overbreak
	seepage
	pattern bolt
	spot bolt
	shotcrete
	siltstone rip up clasts

Photos: ATTACHED
 Notes:
 * CLASSIFICATION BASED ON STRENGTH EQUIVALENT TO CLASS II



DEFECTS ⁽³⁾

ID	Type	Dip	Dip Dir. (grid)	Rns	Infill	Thickness (mm)	Spacing (m)	Shape	Persistence/Termination (m)	Seepage Rating
①	Jt	95°-90°	120/300 ± 5°	5m/8m	CLAY	≤ 2mm	0.1-0.2	PK	> 8m	2
②	Jt	35-60°	300° 10°	8m/16m	CLAY	4-10mm	-	UV	> 8m	2
③	Jt	85-90°	300° 10°	R0	CLAY	4-10mm	-	PK	> 8m	2
④	Jt	95-90°	290° 15°	5m/8m	CLAY	4-10mm	0.1-0.5	PK	> 8m	2
⑤	BP	± 5°	-	R0	CLAY	2-4mm	-	PK/UV	> 8m	2

VALIDATION OF DESIGN

- Are encountered ground conditions covered in support selection criteria?
NO WE UNDERSTAND THIS IS TO INCLUDED IN RFI-820
- Additional support recommended in this mapping interval (show on sketch)?
ADDITIONAL CABLES TO SATISFY SUPPORT TYPE 3 AS PER DESIGNER SKETCH DRG SOS325 REV 1 - DATED 11/10/18.

NOTES:

- Based on AS1726 (2017).
- Mapping changes post draft issue to be shown using clouds.
- Refer to explanation sheets for description of defect properties.
- All defects orientations are estimated unless noted otherwise.
- Crown grid has been reduced to approximately 67% laterally.

Figure 6: Example of detailed geotechnical face mapping records completed for individual tunnelling advances capturing the variable character of the LPFZ during construction.

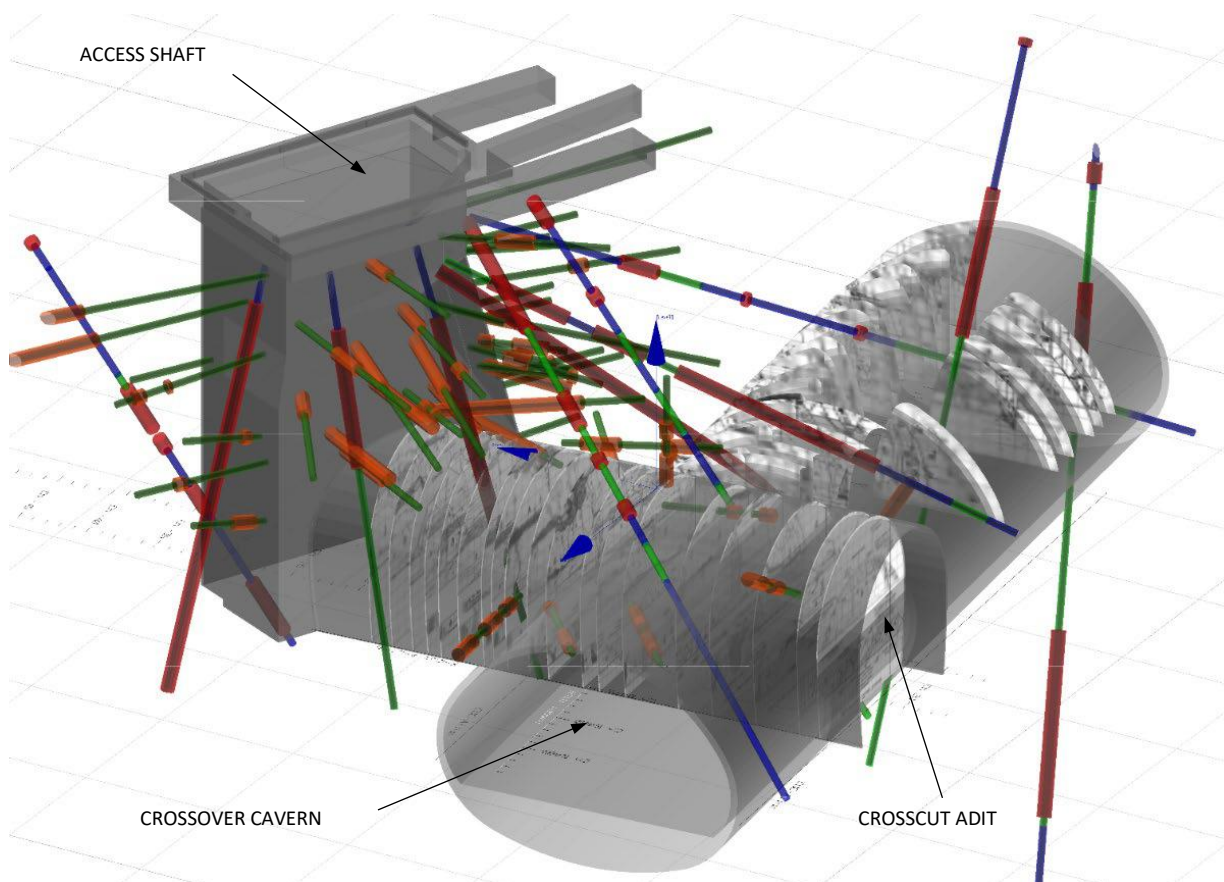


Figure 7: Oblique view showing data density of CPS face mapping, borehole and probe hole inspection records within the LPFZ portion of the Barangaroo crossover cavern looking south east. Boreholes (inclined) are displaying relative to the Pells classification - Blue Class I/II, Green Class III, Red Class IV/V. Probe holes (sub horizontal) presented using project specific classification for faulting - Green – Not fault affected, Orange – Fault affected.

4. SUMMARY OF ENCOUNTERED CONDITIONS WITHIN THE LPFZ

The sub vertical LPFZ, striking northeast (020 to 040°), was encountered for a length of approximately 50 m along the Barangaroo crossover cavern and temporary access excavations. The total exposure equated to a true thickness of approximately 30 m. The delineated extents of the LPFZ as included in the project geotechnical interpretive report and published literature were shown to be well aligned. The fundamental refinement in our understanding of the ground conditions was to characterise the nature and variability of ground conditions. Having the opportunity to excavate the fault zone from numerous orientations and over extended distances permitted a level of interpretation not achievable through the review of boreholes and limited surface exposures.

As encountered at Barangaroo, the LPFZ comprises a series of distinct structural deformation intervals. Individual aspects of the broader fault zone are summarised below with selected face mapping intervals included for reference in Figure 8 and Figure 9. The fault extents are also presented in plan as projected within the three-dimensional CPS engineering geological model in Figure 10.

- **Fault Core** - Three primary shear planes were observed within the central fault core of the LPFZ, orientated 75-85°/125-135° and 65-70°/090-100° (Dip/DipDirection) respectively and diverging with depth. These structures were infilled by up to 300 mm (true thickness) highly altered, soft mottled white and grey, highly plastic, sandy CLAY breccia. A magnesium coating was observed on the bounding slickensided shear surfaces, Figure 4 to Figure 6.

- **Fault Disturbed** – The rock mass located immediately west of the “fault core”, is described as typically low strength highly fractured sandstone with persistent defects spacing less than 200 mm. Fault breccia’s are observed to anastomose along strike resulting in changes to local scale shape and infill, Figure 8.
- **Fault Margins** - Two fault “margin” zones were encountered further west of the “fault disturbed” zone, summarised as corridors comprising discrete structures with minimal clay infill and associated sympathetic jointing with a true thickness of approximately four to five metres, Figure 9.

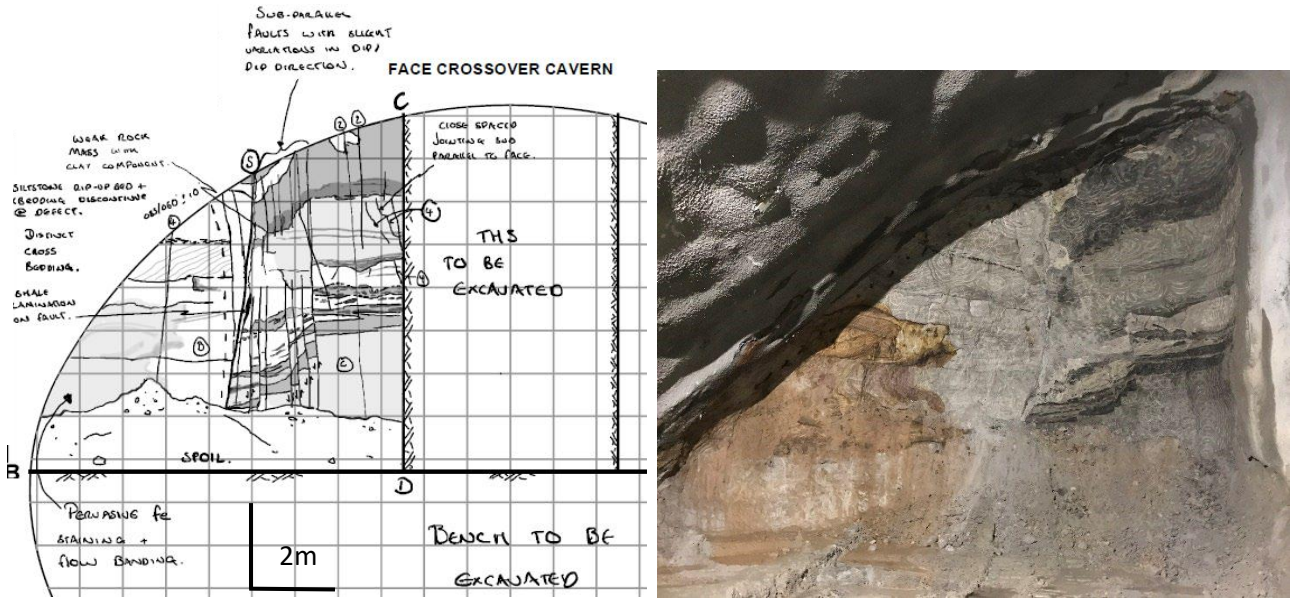


Figure 8: CPS face mapping excerpt of the Fault Core/Fault Disturbed Zones from the south left side, southbound heading. Laminite beds provided marker horizons to assess displacement between individual fault planes. Localised zones of moderately weathered sandstone were also observed on multiple occasions owing to preferential water flow along the fault.

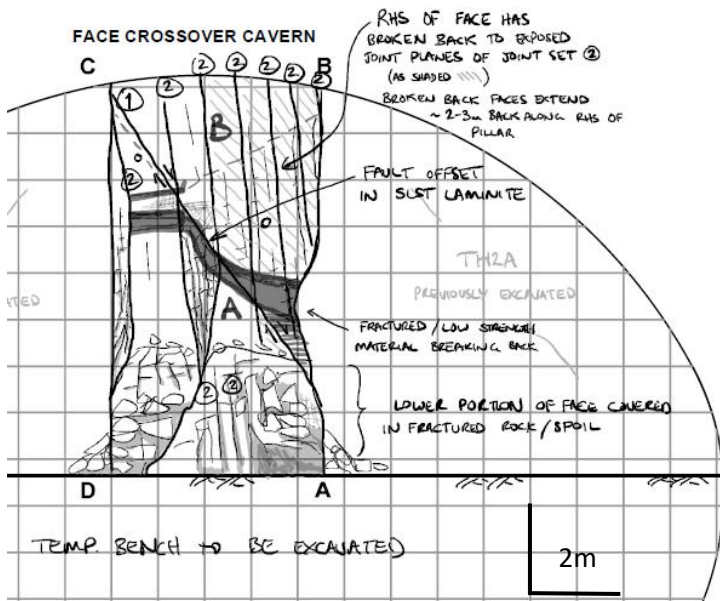


Figure 9: CPS face mapping excerpt of the Fault Margin Zone from the central cavern pillar (CH8476.6m) being excavated as part of a three stage, top heading advance. Image looking toward 350°.

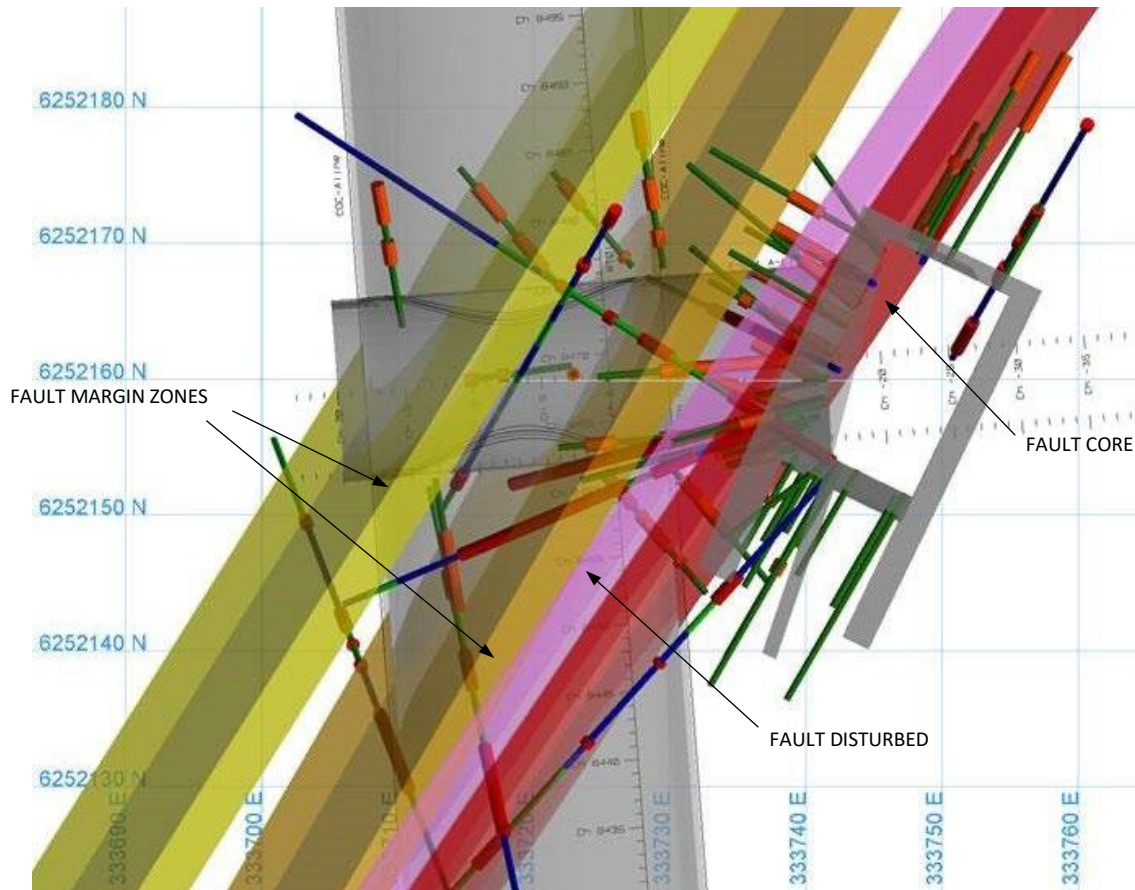


Figure 10: Plan view summary of the CPS model illustrating exposed extents of the LPFZ with the Barangaroo crossover cavern. Interpreted zones delineated as follows: Fault core – red, Fault disturbed – magenta, Fault margin zone – orange and yellow.

Normal and strike-slip movements were interpreted along individual fault planes with the LPFZ. At a local scale within the excavation, other high angle reverse faults, Riedal shears and orthogonal transfer faults were observed to have taken up strain within the deformation zone. Absolute displacements were unable to be measured, particularly with respect to strike slip movements. The presence of laminate lenses provided clear marker horizons for assessing local scale vertical displacements within construction faces.

To the east of the immediate LPFZ boundary were a series joint clusters and discrete faults (100 to 300 mm offset and minimal infill) orientated subparallel to the main fault plan. Also associated with the eastern fault boundary was a localised zone of moderately weathered rock. These features may act a marker boundary should the structure be encountered in future developments.

The potential for groundwater connection to the adjacent harbour was identified as a risk during detailed design. However, the underground excavation experienced no notable groundwater inflow on either side of the fault during construction. The small inflows that did occur were consistent with rates estimated during rising head testing at the Hickson Road shaft and were equal to less than 1.0 L/s.

5. CONCLUSIONS

As part of the Sydney Metro City & Southwest Project the Barangaroo crossover cavern underground excavation provided a unique opportunity to observe and characterise the LPFZ. The integration of geotechnical data from boreholes, probe holes, and detailed geotechnical face mapping enabled the development of a comprehensive three-dimensional model that supported design verification and construction decision-making.

The LPFZ was observed to comprise distinct structural deformation zones, including a fault core with significant clay-rich shear planes, a fault-disturbed zone with high fracture intensity, and fault margin zones with discrete faulting and

joint clusters. The ability to assess the LPFZ from multiple excavation orientations greatly improved the broad understanding of fault variability and ground response to tunnelling. As echoed by Och et al (2012), it is hoped that these learnings can be applied to future projects that may encounter the structure, particularly in the interpretation of site investigation data and development of ground support designs.

The observations from this study contribute to the broader geological understanding of the LPFZ and highlight the importance of ongoing refinement of engineering geological modelling during construction.

6. ACKNOWLEDGEMENTS

The authors wish to acknowledge the commitment and dedication of our colleagues who contributed to the construction phase services delivery for the project. The quality of observation and resulting mapping detail has created an excellent record of the encountered conditions and are a credit to the individuals that created them.

Further appreciation is extended to the construction and management team from John Holland CPB Ghella Joint Venture for their collegial approach and valued contributions as we progressed through some of Sydney more structurally complex tunnelling conditions. A perspective of the completed northern half of the cavern excavation is included in Figure 11.



Figure 11: View of the final excavation profile of the Barangaroo crossover cavern.

7. REFERENCES

- Barraclough, P., Brierley, R., Amon, A. and Simmonds, S. (2021) Sydney Metro City & Southwest TSE – design and construction of the Barangaroo Cross Over Cavern through the Luna Park Fault Zone. *Proceedings of the Australasian Tunnelling Conference*, 235 - 254
- Branagan, D., Herbert, C. and Langford-Smith, T. (1976) An outline of the geology and geomorphology of the Sydney Basin, Science Press, Department of Geology and Geophysics, University of Sydney
- Branagan, D.F. (1991). Geology of the Pyrmont-Ultimo Area, Sydney. *Twenty Fifth Newcastle Symposium on Advances in the Study of the Sydney Basin*.
- Bertuzzi, R. (2014), Sydney sandstone and shale parameters for tunnel design, *Australian Geomechanics Journal*, 49(2), 95-104.

- Nash, T.R., Shen, B., and Bertuzzi, R. (2017). Geotechnical validation for Sydney Tunnels. *Proc., 16th Australasian Tunnelling Conference, Australasian Tunnelling Society, Engineers Australia.*
- Och, D.J. Offler, R., Zwingmann, H., Braybrooke, J., & Graham I.T. (2009). Timing of brittle faulting and thermal events, Sydney region: association with the early stages of extension of East Gondwana. *Australian Journal of Earth Sciences, 56*, 873-887.
- Och, D.J. Davies, S. Gilchrist, D. Kotze, G. Bowden, A and McNally, G (2012), Ground investigation in the Sydney CBD - A more sustainable model for the future. *Australian Geomechanics, 255-260.*
- Pells, P.J.N. (1994). Engineering geology of the Triassic rocks of the Sydney area. www.pellsconsulting.com
- Pells, P.J.N., Mostyn, G.R., and Walker, B.F. (1998). Foundations on sandstone and shale in the Sydney region, *Australian Geomechanics, 33(2)*, 17-29.
- Pells, P.J.N., Och, D.J., & Braybrooke, J.C. (2004). Map and selected details of near vertical structural features in the Sydney CBD. *Distributed at the Australian Geomechanics Society Sydney Chapter Mini-Symposium.*
- Pells, P.J.N., Mostyn, G., Bertuzzi, R., & Wong, P.K. (2019). Classification of sandstones and shales in the Sydney region: A forty-year review. *Australian Geomechanics, v.54: No. 2.*
- Speechley, L., Walker, B., & Scholey, G. (2004). Some examples of variability within Hawkesbury Sandstone. *Australian Geomechanics, 39(3)*, 23 - 30.