

USE OF 3D FEM MODEL TO ASSESS THE IMPACT OF DEEP EXCAVATION ON EXISTING SYDNEY WATER TANK STREAM

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ABSTRACT

A residential-commercial development located in Alfred Street, Sydney (Circular Quay) was to be constructed adjacent to the heritage structure Tank Stream, currently owned by Sydney Water Corporation (Sydney Water), with a 6-level basement extending to approximately -17.3 m AHD (Australian Height Datum) resulting in an approximately 21 m deep excavation. The Tank Stream comprised a range of construction including brick oviform section, stone arch and twin concrete pipes employed to replace a damaged section. Due to the proximity of the proposed excavation to the Tank Stream, a geotechnical impact assessment was warranted. As part of the impact assessment work, a three-dimensional finite element numerical modelling (3D FEM) was carried out to assess potential impacts of the basement construction on the various components of the Tank Stream. The retention system was designed to satisfy a reasonably stringent criteria intended to keep oviform and stone arch components in compression. The paper discusses the development of the numerical model, the results of the analysis and the predicted ground movement arising from the construction and the measures taken to monitor and protect the Tank Stream. Inclinometer monitoring results are presented for comparison against the movements predicted from modelling.

Keywords: 3D FEM model, deep excavation, Tank Stream, geotechnical monitoring, ground movement

1 INTRODUCTION

The Tank Stream, currently owned by Sydney Water Corporation (Sydney Water), was the name given to a fresh water course which originally drained a catchment within the modern Sydney CBD, with the primary water course running northwards from the present-day Hyde Park to its termination in Sydney Harbour at the present-day Circular Quay. It was originally established in 1790 as Sydney's original water supply for the early European settlers of Sydney. With time, however, the watercourse became fouled with sewerage and rubbish, essentially converting it to an open sewer (Godden Mackay Logan Heritage Consultants, 2010). The natural channel was progressively enclosed with a stone and/or brick semi-circular drain from the 1840's through to the 1870's. Sections of the drain were redeveloped throughout the 1900's (and in 2000) with concrete/steel piping or boxes. The Tank Stream was listed on the NSW State Heritage Register in 1999. The heritage protection is associated with the operational portion of the Tank Stream. The Tank Stream curtilage is 3 m from all surfaces of the operational Tank Stream and developments within 10 m of the Tank Stream structure should be approved by a suitable qualified structural engineer (Casey and Lowe Pty Ltd Archaeology and Heritage, 2013). Activities that may impact the operational Tank Stream within a 3 m buffer zone which extends from the outer face of the fabric of the operational Tank Stream, requires approval under the Heritage Act 1977.

The development is located at 1 Alfred Street and bounded by Pitt Street to the east, which has an approximate footprint area of 4,000 m² as shown in Figure 1. The length of eastern boundary of the site is approximately 60 m. The Tank Stream approaches the south-eastern corner of the site at a slight angle before it continues, approximately parallel to the eastern boundary. The Tank Stream changes in structural form from brick oviform to upstream stone-arch followed by twin concrete pipes before it changes back to downstream stone-arch near the north-eastern corner of the site. These portions of Tank Stream are connected via rectangular-shaped concrete structures (i.e. transfer chambers).

The development comprises the demolition of the existing buildings and the construction of two towers with a common 6-level basement extending to approximately -17.3 m AHD. Due to the proximity of the proposed excavation to the Tank Stream, a geotechnical impact assessment was warranted. In regards of this, a three-dimensional finite element numerical modelling (3D FEM) was carried out to assess potential impacts of the basement construction on the various components of the Tank Stream.

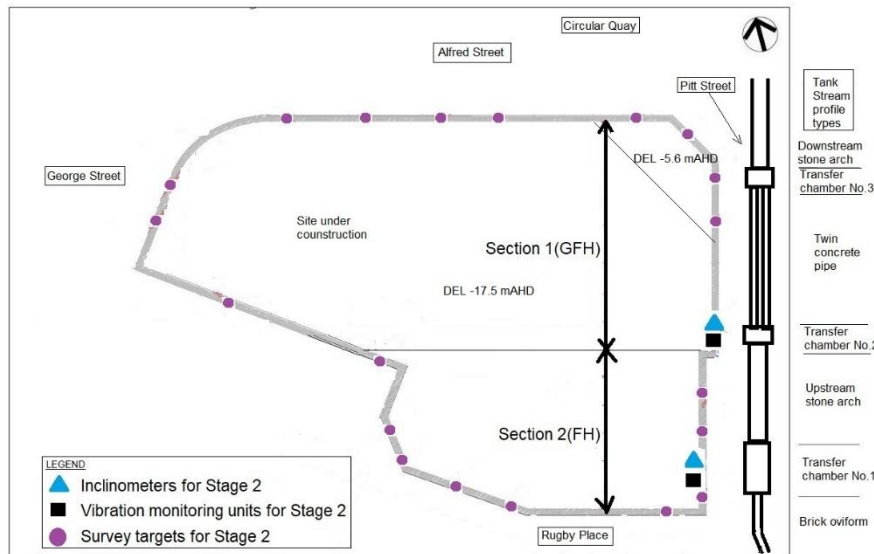


Figure 1: Plan showing the site, monitoring locations and outline of Tank Stream near eastern boundary (data sourced from Pile Design Solutions, 2019)

2 PROPOSED DEVELOPMENT

The existing buildings on site comprised of Gold Fields House (GFH) at 1 Alfred Street with 28 levels and two to three levels of basement, Fairfax House (FH) at 19-31 Pitt Street with 16 levels and one basement level and the Rugby Club (RC) off 31 Pitt Street with 6 levels and no basement. The existing GFH and FH basement perimeter retaining walls were to be left in place and re-used as permanent retention for the new basement construction, where applicable. The existing walls were expected to provide cut-off against the groundwater seepage. Construction of a secant pile wall was proposed to provide groundwater cut-off where the existing wall does not extend to the bedrock.

As shown in Figure 1, the existing basement wall along the eastern site boundary was categorized as Section 1 (GFH) which extends vertically down to about -5.1 m AHD and the outer edge of the wall is approximately 1.5 m away from the outer edge of the nearest portion of the Tank Stream and Section 2 (FH) which extends vertically down to approximately -0.5 m AHD.

The constructed shoring system along the eastern boundary and its main features are as follows:

- Along Section 1, a new concrete wall was cast in front of the existing shoring wall providing support for excavation down to -5.6 m AHD. Vertical props and rock anchors were designed to provide temporary lateral restraint to the system.
- Along Section 2, a new secant piled wall at a short distance in front of the existing basement wall was constructed with 'hard' piles socketed to a minimum depth of 1 m into Class III Sandstone (approximately -5.6 m AHD) or toe level of -6 m AHD, whichever is deeper and the 'soft' piles terminated to a depth of 0.5 m into the top of the bedrock. Horizontal props, rock anchors and walers were designed to provide temporary lateral restraint to the shoring system.
- For both of the above sections the design required rock bolts were to be installed during the basement excavation phase below -5.6 m AHD.

Within the majority of Section 1 and the whole Section 2, the bulk excavation is to be carried out to -17.6 m AHD. In the vicinity of north-eastern corner of Section 1, the bulk excavation is to be undertaken to -5.6 m AHD.

3 DEVELOPMENT OF 3D FEM MODEL

The assessment was undertaken using three-dimensional Finite Element Method (3D-FEM) within a commercially available program PLAXIS 3D. About half of the site along Pitt Street was modelled and the adopted 3D FEM model is shown in Figure 2. Soil layers were modelled using a hardening soil model and rock layers Mohr Coulomb criteria by taking into account appropriate in-situ stresses. The majority of structural elements including Tank Stream have been represented by volumetric elements in the model.

The adjacent nearby development of Lendlease Circular Quay (LL-CQT) is located to the south/southeast of the site and is being constructed by Lendlease Building Pty Ltd (Lendlease). It is understood that LL-CQT development comprises varying basement levels with two basement levels along Pitt Street end of the site, south

of Rugby Place. An interaction between two project sites has been analysed previously and presented in Coffey Services Australia, Pty Ltd (2018a). A simplified adjacent LL-CQT construction has been included in this paper.

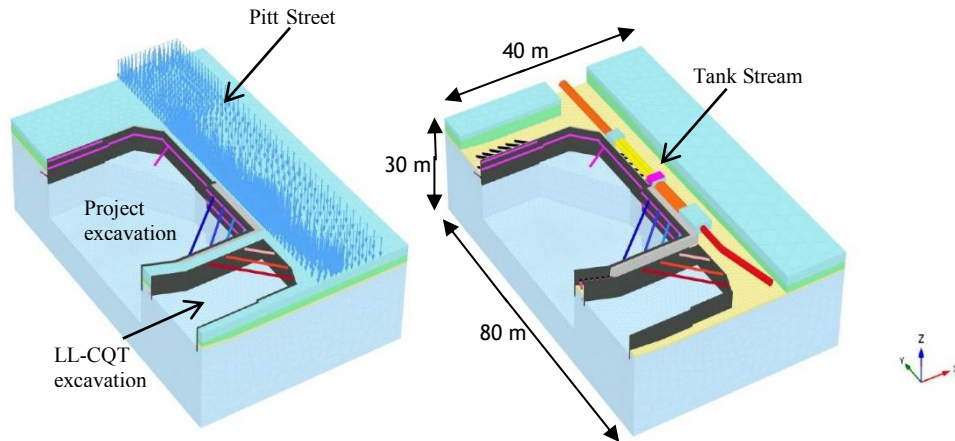


Figure 2: 3D FEM model showing surface view at the end of bulk excavation (left) and with some soil layers hidden to display Tank Stream (right)

3.1 TANK STREAM MODEL

In vicinity of the eastern site boundary the Tank Stream comprises brick oviform, upstream stone arch, twin concrete pipes and downstream stone arch. These components were separated by transfer chambers. Figure 3 presents a rendered image of Tank Stream and the modelled various sections. The dimensions of various components of the Tank Stream and adopted model properties for these components are tabulated in Table 1.

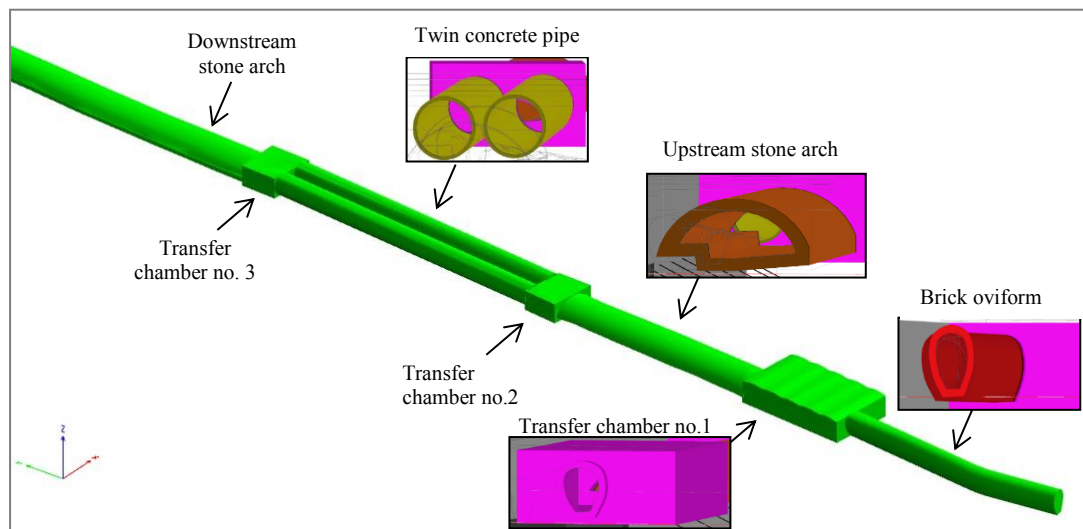


Figure 3: Alignment of rendered Tank Stream and modelled components

Table 1: Adopted dimensions of Tank Stream components and model properties (Coffey Services Australia Pty Ltd., 2018b)

Components	Length (m)	Internal height/width (m)	Thickness (m)	Unit weight (kN/m ³)	Young's modulus (GPa)	Poisson's ratio (ν)
Brick oviform	4.0	1.68/1.14	0.23	24	4.9	0.15
Transfer chamber no.1	7.5	2.00/4.00	0.30	24	21.9	0.15
Up/Downstream stone arch	15.0	1.32/3.08	0.37	24	10.1	0.15
Transfer chamber no.2	2.5	2.00/3.00	0.30	24	21.9	0.15
Twin concrete pipes	20.5	1.37	0.08	24	21.9	0.15
Transfer chamber no.3	2.5	2.00/2.80	0.30	24	21.9	0.15

3.2 GEOTECHNICAL MODEL

The subsurface profile adopted in this assessment was based on the geotechnical investigation report for the proposed site (Coffey Services Australia, Pty Ltd, 2015) and Coffey's experience in the neighbouring sites in Circular Quay. The adopted subsurface foundation profile and design parameters are listed in Table 2.

Table 2: Subsurface foundation profile and design parameters (Coffey Services Australia, Pty Ltd, 2015)

Units and descriptions	RL at top of unit (m AHD)	Weight (kN/m ³)	Strength Parameters		Stiffness Parameters			At-rest earth pressure coefficient K_0^*
			Effective cohesion c' (kPa)	Effective friction angle ($^\circ$)	Elastic modulus E_v (MPa)	Un/reloading modulus E_{ur} (MPa)	Poisson's ratio, ν	
2-Alluvium	-0.7	18	0	28	8	24	0.3	0.53
3a-Sandstone**	-2.1 to -3.1	22	30	35	300	N/A	0.25	
3b-Sandstone***	-2.8 to 3.8	23	1000	40	2000	N/A	0.25	

Note: * In-situ stresses for Units 3a and 3b were assessed as part of the initialisation phase of 3D FEM to obtain the stress regime described in Pells (2002); ** Extremely to moderately weathered sandstone; *** Slightly weathered to fresh sandstone

The original groundwater level at -0.5 m AHD has been adopted in the model. The general groundwater flow was assessed to generally move inland within the Circular Quay area. This was possibly influenced by the recently completed and ongoing developments within the area where temporary dewatering and permanent water take have been undertaken.

3.3 LOADING AND BOUNDARY CONDITIONS

Surcharge load of 20 kPa has been applied starting from 0.5 m offset from the outer edge of the existing wall. This load represents traffic load on the footpath and adjacent Pitt Street, which runs parallel to the eastern boundary of the site. It was assumed that this load has been in place for a considerable amount of time in the past. Four displacement boundaries were applied on the rock layers to compress the rock body during initialisation of stresses. The top and bottom boundaries were set to roller boundaries. Displacement boundaries were applied for major (north-south) and minor (east-west) directions followed by removal of top boundary and bottom boundary being changed to "fixed" boundary.

3.4 ANALYSIS METHODOLOGY

In order to incorporate the in-situ stresses within Hawkesbury Sandstone, proper at-rest earth pressure coefficient K_0 values were adopted using equations (1-3) by Pells (2002):

$$\sigma_1 = \sigma_{(N-S)} = 1.5 + 1.2\sigma_v \text{ to } 2.0\sigma_v \text{ MPa} \quad (1)$$

$$\sigma_2 = \sigma_{(E-W)} = 0.5\sigma_1 \text{ to } 0.7\sigma_1 \text{ MPa} \quad (2)$$

$$\sigma_3 = \sigma_v = 0.024H \text{ MPa} \quad (3)$$

where, σ_v is the vertical stress, $\sigma_{(N-S)}$ the horizontal stress oriented approximately 20° East of the true north, $\sigma_{(E-W)}$ the orthogonal to $\sigma_{(N-S)}$.

The adopted construction sequencing in the 3D FEM model is presented in Table 3.

Table 3: Adopted numerical simulation construction phases in 3D FEM model

Phase	Description	Construction stage
1	Initialisation of stresses	Existing condition
2	Application of in-situ stresses for rock layers (Units 3a and 3b)	
3	To reset displacement to zero and active basements for Section 1 (GFH) and Section 2(FH)	
4	To reset displacement to zero and backfill the existing basement within Section 2 and remove ground floor slab	Stage 1
5	Install and prestress upper level of anchors within Section 1	
6	<ul style="list-style-type: none"> Install diagonal bracings within LL-CQT site Excavate to bulk excavation level within LL-CQT site 	
7	<ul style="list-style-type: none"> Install new reinforced concrete wall within Section 1 Install shoring system (secant piled wall) within Section 2 	
8	Excavate to 0.5 m below the diagonal bracings level within Section 2. The backfill materials located in between the existing wall and new wall was left in place	Stage 2
9	Install diagonal bracings within Section 2 and walers	
10	<ul style="list-style-type: none"> Excavate to the lower level of anchors within Sections 1 and 2 Remove basement slab within Section 2 	
11	Install and prestress lower level and anchors	
12	<ul style="list-style-type: none"> Demolishing remaining slabs Demolish remaining separation wall between Section 1 and Section 2 Excavate to -5.6 m AHD 	
13	<ul style="list-style-type: none"> Install and prestress rock bolts Install raker prop 	
14	Excavate to -11.5 m AHD	
15	Excavate to -17.6 m AHD (bulk excavation level)	

At any given phase where excavation was carried out below the groundwater level, the dewatering is carried out within the excavation up to 0.5 m deep below the achieved base of excavation.

3.5 ADOPTED ASSESSMENT CRITERIA FOR VARIOUS TANK STREAM COMPONENTS

There was no specific assessment criterion available for the Tank Stream stone arch, twin concrete pipes and transfer chambers. Based on indicative criteria provided by Sydney Water for the brick oviform and literature resources (Burland and Wroth 1974; Boscardin and Cording, 1989), the following impact assessment criterion for various components of Tank Stream at construction Stages 1 and 2 were adopted (Table 4).

Table 4: Summary of adopted criteria for impact assessment

Components	Criterion
Brick oviform	<ul style="list-style-type: none"> Net tensile strain of zero within oviform structure at the end of construction Max. incremental tensile strain of 0.01 % due to transverse displacement along the longitudinal alignment Max. incremental tensile strain of 0.01 % due to vertical displacement along the longitudinal alignment
Stone arch and twin concrete pipes	<ul style="list-style-type: none"> Ratio of horizontal strain to angular distortion of less than 0.44 Longitudinal tensile strain less than 0.05% Transverse tensile strain less than 0.0125% Deflection ratio (sagging ratio) less than approximately 1 in 600
Transfer chambers	<ul style="list-style-type: none"> Tensile strain less than 0.05%

4 ANALYSIS RESULTS AND DISCUSSION

4.1 EXCAVATION-INDUCED GROUND MOVEMENTS

Figure 4(a) presents the deformation of the ground for Section 2 where the proposed excavation level is deeper at -17.6 m AHD and the critical portions of the Tank Stream (i.e. brick oviform and upstream stone arch) are located in a close proximity. The deformed shape has been magnified to visually signify the differential movement and identify the point of maximum lateral movement. The assessed maximum movement occurs within Unit 3b (Class III or better Sandstone). These results were likely influenced by the relaxation of high magnitude of in-situ stresses which are typically present in Sydney basin. Figure 4(b) presents the assessed profiles of horizontal movements at various excavation stages within Section 2. The assessed horizontal movements during the excavation are predominantly influenced by the relief of rock in-situ stresses within Units 3a and 3b, the horizontal movements increase as the excavation depth increase. The assessed ground movements generally reduce towards the ground surface where the retention system (i.e. secant piled wall, new reinforced concrete wall and existing basement walls) along with the support features (anchors, rock bolts, diagonal bracing waler and prop) are installed. Trigger levels as 80% of the assessed horizontal movements were proposed for Section 2, which will allow a progressive monitoring and earlier identification and mitigation of any exceedance of assessed movement during the excavation.

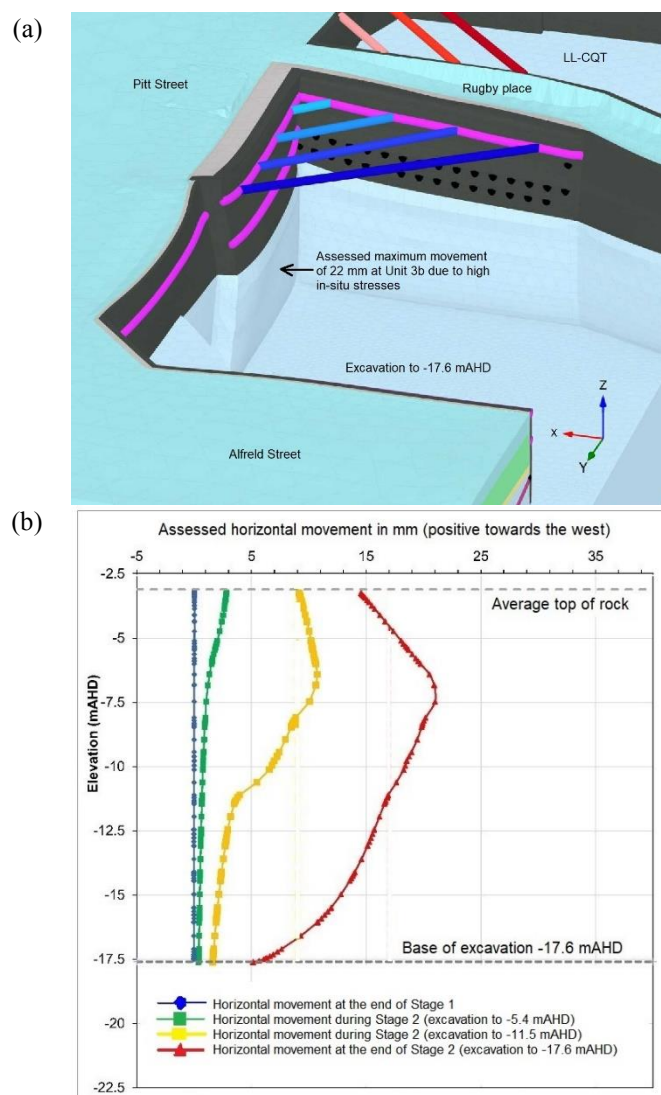


Figure 4: (a) Deformed shape of 3D FEM model (150 times exaggeration) induced by full excavation up to -17.6 m AHD (end of Stage 2) and (b) Assessed profiles of horizontal movements at various excavation stage within Section 2

4.2 IMPACT TO TANK STREAM DURING CONSTRUCTION

Analyses results for the construction stages (Stages 1 and 2) of the project are presented in Table 5 for the critical cross sections of the Tank Stream components. Results for the longitudinal sections are given in Table 6. Maximum net strain values were assessed by deducting the assessed strains for the construction stages from the strains assessed for the existing conditions. The existing condition considers the existing GFH and FH basements, Tank Stream and applied 20 kPa surcharge starting from 0.5 m offset from the outer edge of the existing wall, which was assumed to be in place for a considerable amount of time in the past.

Table 5: Analyses results for Tank Stream cross sections from the start of Stage 1 to the end of Stage 2

Component	Maximum differential deformation/shortest cord length	Maximum tensile strain (%)	Maximum net strain (%)
Brick oviform	<2 mm / 1 m	0.005	< -0.01
Transfer chamber no.1	<2 mm / 1 m	0.02	-0.03
Upstream stone arch	<2 mm / 1 m	0.005	<-0.01
Transfer chamber no.2	<2 mm / 1 m	0.04	-0.01
Twin concrete pipes	<2 mm / 1 m	0.02	0.003

Note: compression is negative and tension is positive

Table 6: Analyses results for Tank Stream longitudinal sections from the start of Stage 1 to the end of Stage 2

Component	Maximum differential horizontal movement/cord length	Maximum tensile strain (%)	Maximum net strain (%)	Horizontal strain/angular distortion
Brick oviform	1 mm/1.5 m	0.004	<-0.01	<0.44
Upstream stone arch	1.5 mm/2 m	0	<-0.025	<0.44
Twin concrete pipes	2.5mm/2.5 m	0.008	<-0.005	<0.44

The analyses show that the strain levels within various components of Tank Stream at the end of the construction works related to Stage 1 and Stage 2 would still likely be within compression state except for the twin concrete pipes. The response of all Tank Stream components were assessed to be within the proposed criteria outlined in Table 4 above.

5 MONITORING RESULTS

The ground movement monitoring was undertaken within the existing basement structures located near the Tank Stream during Stage 1 and Stage 2 utilising Inclinometers (INC 1 and INC 2). The locations of the inclinometers are shown in Figure 1.

The inclinometer readings undertaken up to 7 August 2020 when excavation had reached -17.4 m AHD at Section 1 and -3.5 m AHD at Section 2 indicate that the horizontal movement of the basement wall has occurred away from the tank stream by up to 9 mm which is within the proposed trigger levels as shown in Figure 5. The modelled results are larger than the indicated in the measurement this would likely be due to some relaxation in horizontal stress arising from earlier development at the site, which was not considered in the model.

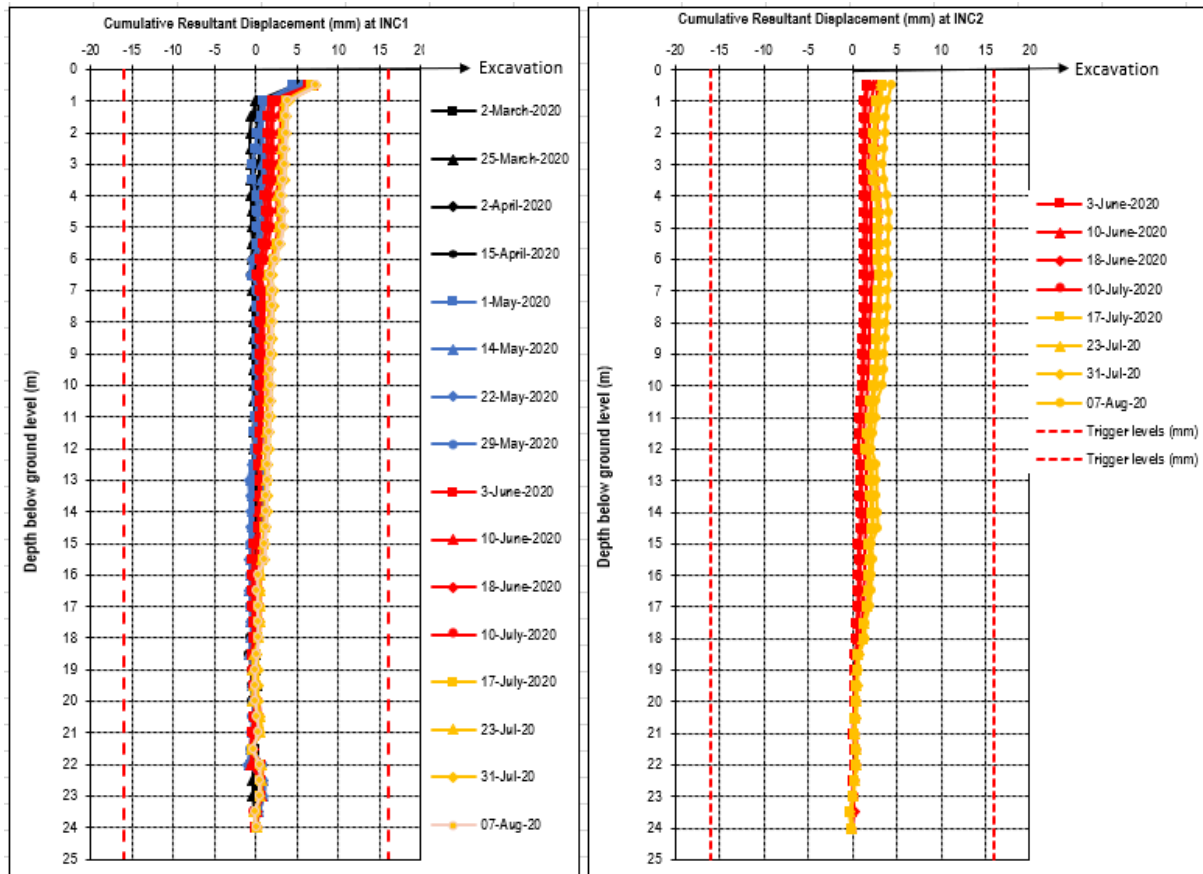


Figure 5: Cumulative resultant displacement (mm) from INC 1 and INC 2.

6 CONCLUSIONS

A 3D FEM model was established to predict the ground movement and investigate the impact of construction on the Tank Stream.

- Based on the inductive criteria by Sydney Water, assessment criteria including no net tensile strain in brick oviform was proposed. The numerical analysis indicated all Tank Stream components were assessed to be within the proposed criteria.
- The assessed maximum movement during excavation was 22 mm at sandstone layer, which is predominantly influenced by the relief of rock in-situ stresses. The horizontal movements increase as the excavation depth increase. In addition, movement trigger levels as 80% of the assessed horizontal movements were proposed for Section 2 (Fairfax House) allowing a progressive monitoring and early identification and mitigation in the event that observed movement exceeded expectations during the excavation.
- Inclinometer monitoring undertaken up to 17 July 2020 indicates favorable outcome where the basement walls moved towards the excavation by up to 6.5 mm which is within the proposed trigger levels.

7 ACKNOWLEDGEMENTS

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