C/o
121 Exhibition Street
Melbourne VIC 3000

PO Box 23061
Docklands VIC 8012
Australia

Memorandum

To	**Michelle Keen, Joshua Dellios**	From	**Anthony Bennett**
Copy		Reference	**Melbourne Metro Rail Project**
Date	**29 August 2016**	Pages (including this page)	**24**
Subject	**Memo Outlining Modelling Work in Response to Additional Geological Information**		

1 Introduction

In my expert witness statement dated 11 August 2016 at Sections 4.5 and 4.6, I referred to further numerical modelling and sensitivity modelling after review of the following updated information included in Technical Note 8 and Technical Note 23:

- Interpreted Geological Setting EES Summary Report – July 2016 Update (Part of Technical Note 23) which incorporates the revised geological long section discussed in Technical Note 8 (**Updated Geological Setting Report**); and
- Bore log data (Technical Note 8), which forms the basis for the updated Geological Long Section.

The objective of the further numerical modelling and sensitivity modelling was to assess:

- whether the effects of these revisions of the geological data create any potential differences from the magnitudes of the predicted ground movement as outlined in Appendix P - Ground Movement and Land Stability Impact Assessment (**Impact Assessment**) of the Environment Effects Statement (**EES**) for the Melbourne Metro Rail Project (**Project**); and
- whether any change is appropriate to the Environment Performance Requirements (**EPR**s), the Impact Assessment, or the Future Development Loading report (which is an appendix to Appendix E – Land Use and Planning Assessment of the EES).

In particular, I undertook:

- the numerical modelling[1] to consider any potential differences that the Updated Geological Setting Report might have on the impacts of the project as set out in the EES; and
- the sensitivity modelling[2] to inform my assessment of potential changes to Future Development Loading and, in particular, to the derivation of the extent of the Design and Development Overlay (**DDO**), that might result from the updated geological information. This modelling was also conducted to respond to questions on the appropriate ground parameters raised by the Peer Reviewer of the Impact Assessment which was exhibited with the EES.

The additional numerical modelling was prepared with the assistance of Roque Alea of AJMJV, who performed the analyses at the station caverns.

[1] This memorandum should be read in conjunction with Appendix P - Ground Movement and Land Stability Impact Assessment of the EES, where the general ground conditions and the original assessment analyses for ground movement are described.
[2] The Future Development Loading report, an appendix of Appendix E – Land Use and Planning Assessment, contains details of the modelling used for the derivation of the extent of the DDO.

2 Updated geological information

Through the CBD section, there are two main differences in the updated geological information from the ground model developed and exhibited as part 12 of the EES for the Concept Design that potentially affect the assessment of ground movement:

- The more weathered rock has been found to extend to greater depths than previously modelled. There is also more information on the extent of likely planes of weakness, mainly faults, through the rock. In combination, these mean that the strength and stiffness of the rock over the cavern stations is less than assumed in the EES assessment.
- The investigations have encountered a deeper channel filled with clay, between Flinders Lane and Flinders Street, where, previously, weathered rock was modelled.

3 Effects on Cavern Support Design

The updated geological information required further consideration of the ground support to be installed within the caverns and other underground structures as they are excavated. Potential changes to the ground support developed in response to the updated geological information have been described in Technical Note Number 24.

A sketch of one of the ground support system types incorporated into the additional ground movement analyses is shown in Figure 1. This system was used in the analyses at CH 99+320 (Figure 6) at CBD North and all the sections at CBD South (Figure 13, Figure 15, and Figure 17). Lighter support, using rock bolts, was used for the prediction of ground movement at the other two sections at CBD North (Figure 15Figure 4 and Figure 8). Technical Note 24 recommends that the heavier support be adopted for the full length of the CBD North cavern, which would lead to less settlement than predicted in this work.

The assessment proceeds on the basis that these ground support and excavation staging techniques would apply to the station caverns that form part of the Concept Design.

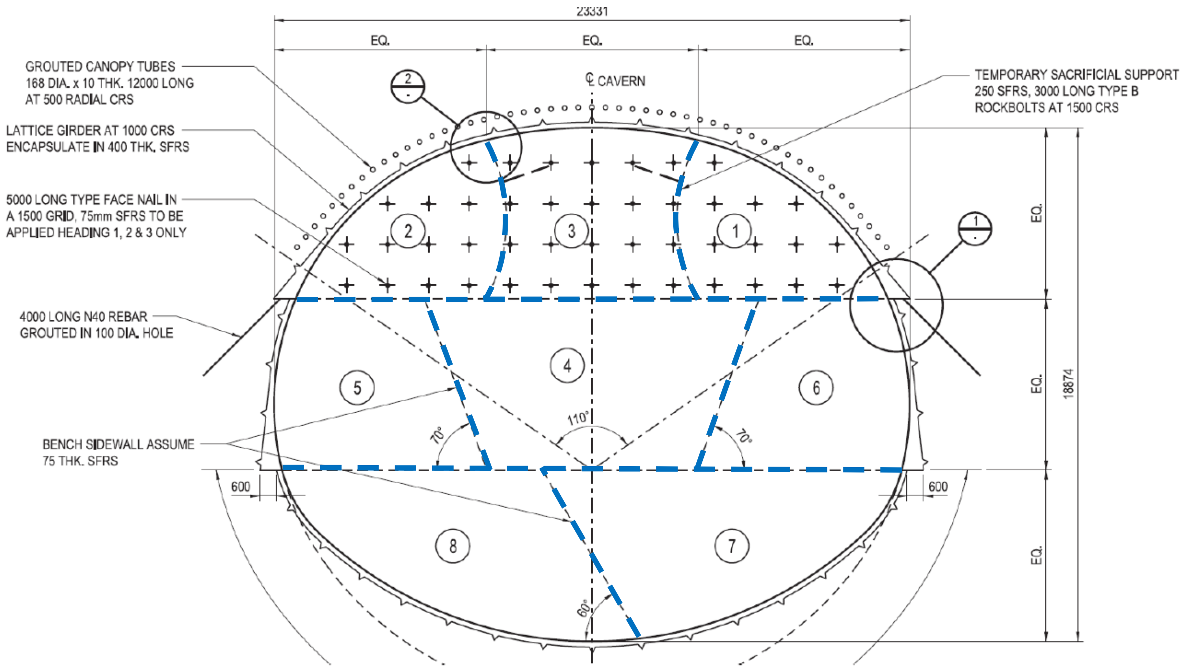

Figure 1 - Ground Support (indicative excavation staging boundaries indicated in blue)

4 Ground Movement Assessment

In order to assess the effects of weaker ground and stiffer support on my initial assessment of the Concept Design, I undertook additional numerical modelling. The geotechnical parameters to model a particular unit of the ground (e.g., the Melbourne Formation unit MF2) was not changed. Modelling of the caverns used the same depth as the EES assessments. The option to lower CBD South by 4 m that is also discussed in Technical Note Number 8 is addressed separately in Section 4.3 of this memorandum.

4.1 CBD North

The three sections modelled at CBD North Station cavern are at CH 99+250, CH 99+320 and CH 99+480 and are shown in plan in Figure 2 and on the revised section in Figure 3. The sections were selected on the basis of the thicknesses of the different layers of Melbourne Formation to test where the greatest effect would occur.

They do not coincide exactly with the section at CH 99+260 used for the assessments that were exhibited as part of the EES, and had been selected on the basis of the EES ground model.

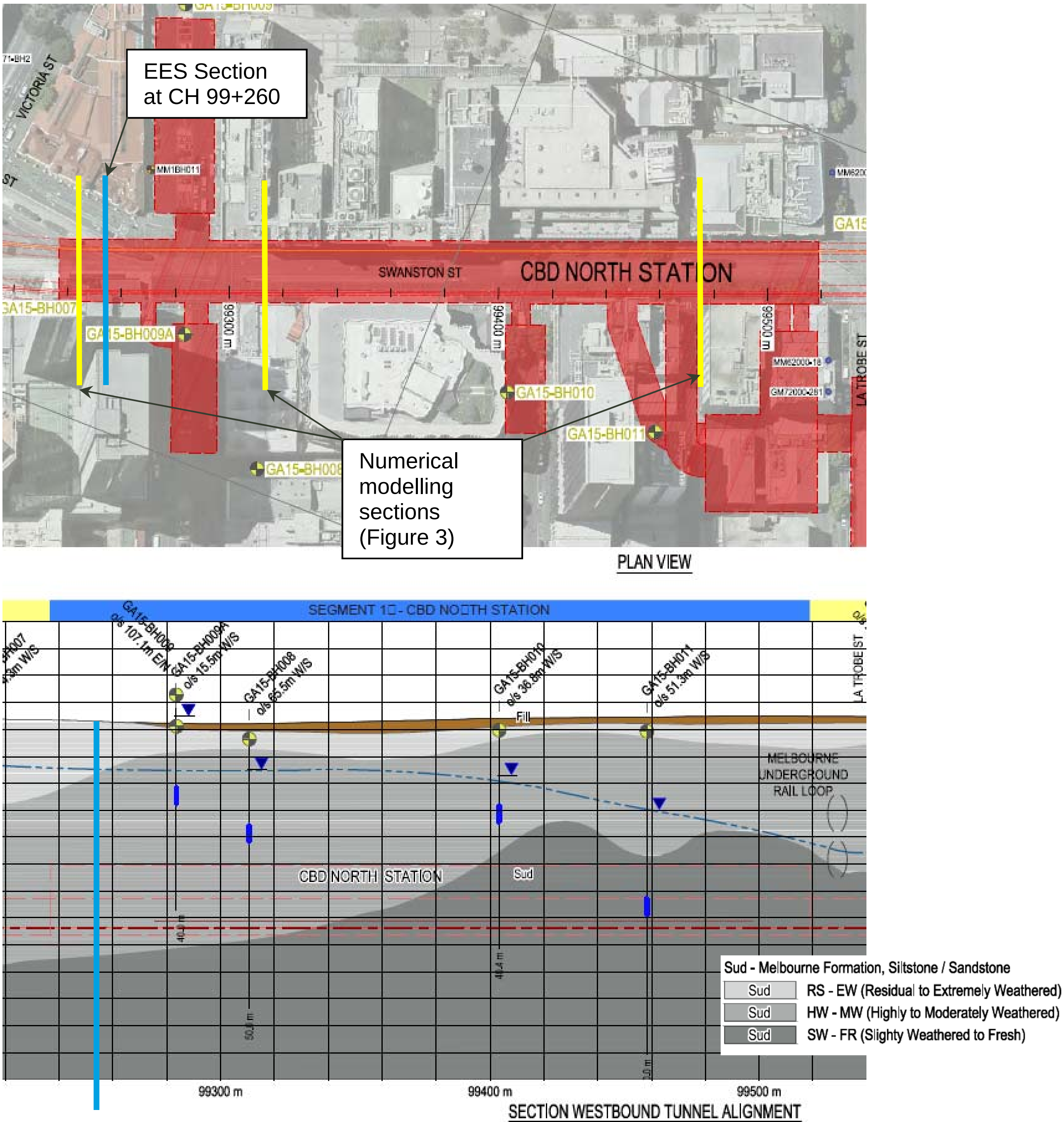

Figure 2 Plan at CBD North showing the sections (EES blue, modelling yellow), and the ground model section used for the assessments as exhibited as part of the EES (Extract from Interpreted Geological Setting EES Summary Report 20 April 2016)

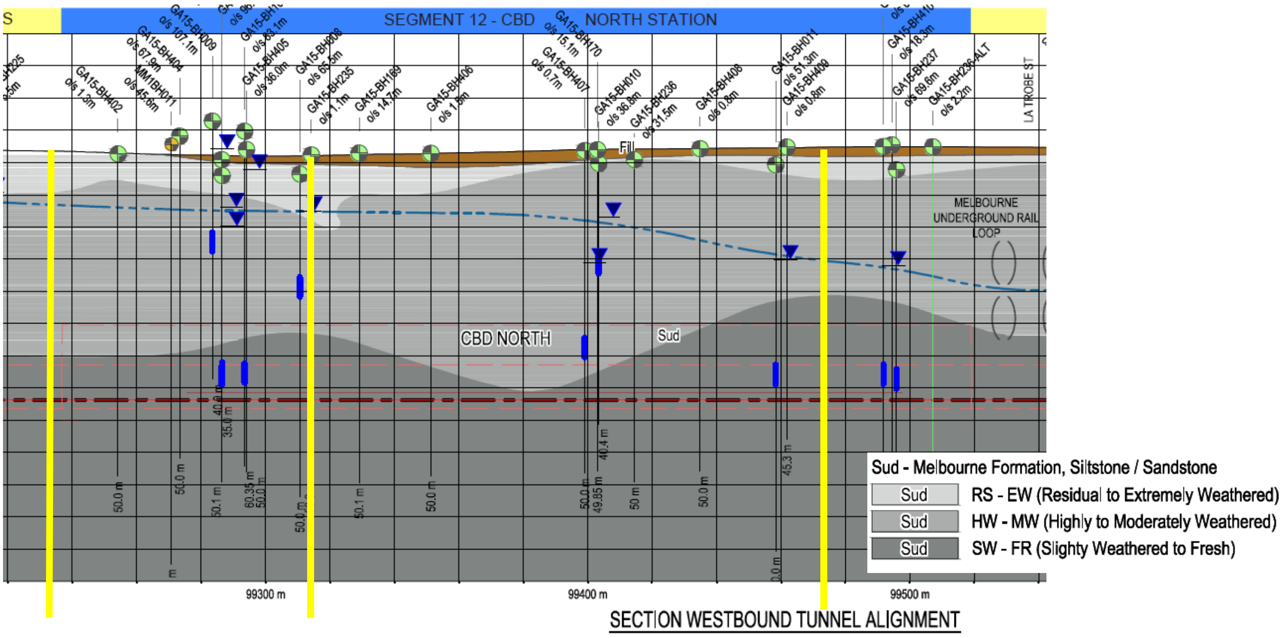

Figure 3 Updated section at CBD North with sections used for assessment modelling (this memo) in yellow. Extract from Interpreted Geological Setting EES Summary Report – July 2016 Update

In the modelling, the following parameters and assumptions were adopted:

- The permanent lining is 400 mm thick cast in-situ concrete.
- The ratio of lateral to vertical stress in the ground before tunnelling (Ko) is 1.5.
- For the staged excavation, the ground is assumed to relax up to 50% prior to lining installation.
- The temporary lining stiffness varies after installation and subsequent stages. This is to account for the strength gain of the primary lining.

Modelling Sequence:

1. Initial stress generation (modelling conditions before CBD North is constructed)
2. Activation of surface surcharge of 20 kPa
3. Excavation of CBD North Station heading – 3 stages (reset displacement to zero).
4. Excavation of CBD North Station bench (3 stage)
5. Excavation CBD North Station (2 stages)
6. Installation of final lining

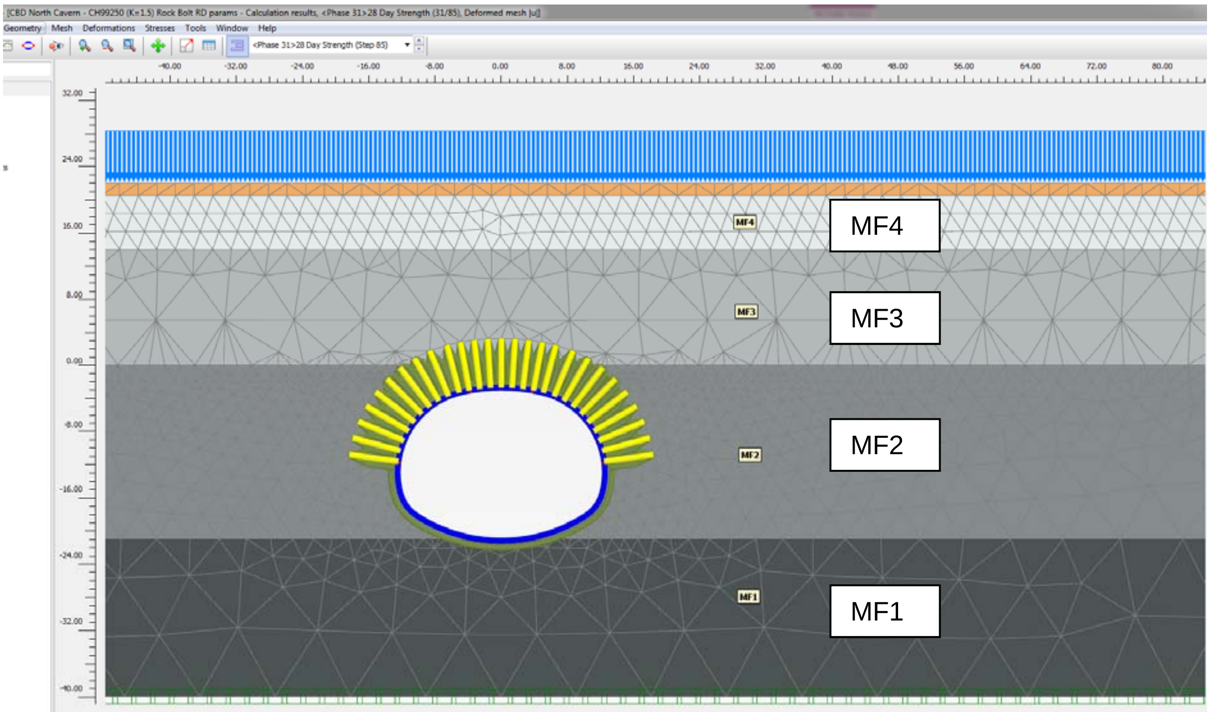

Figure 4 - Ground model CH 99+250

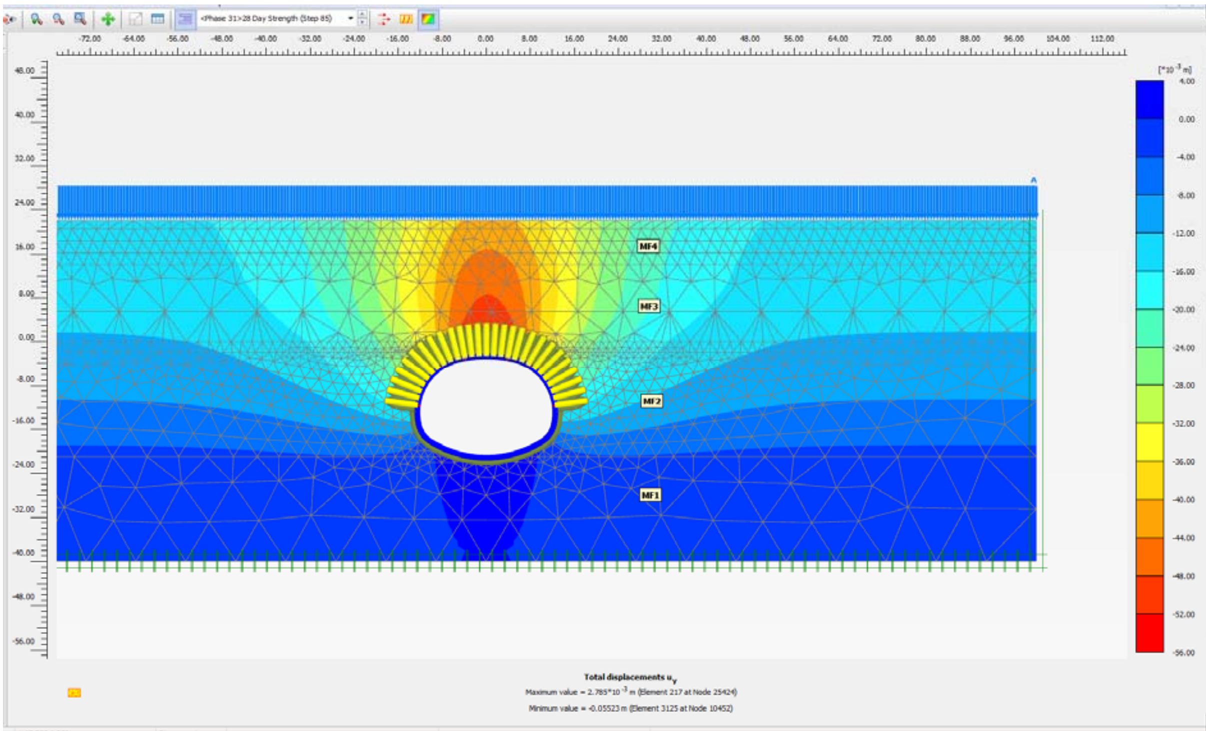

Figure 5 - Displacement plots at CH 99+250

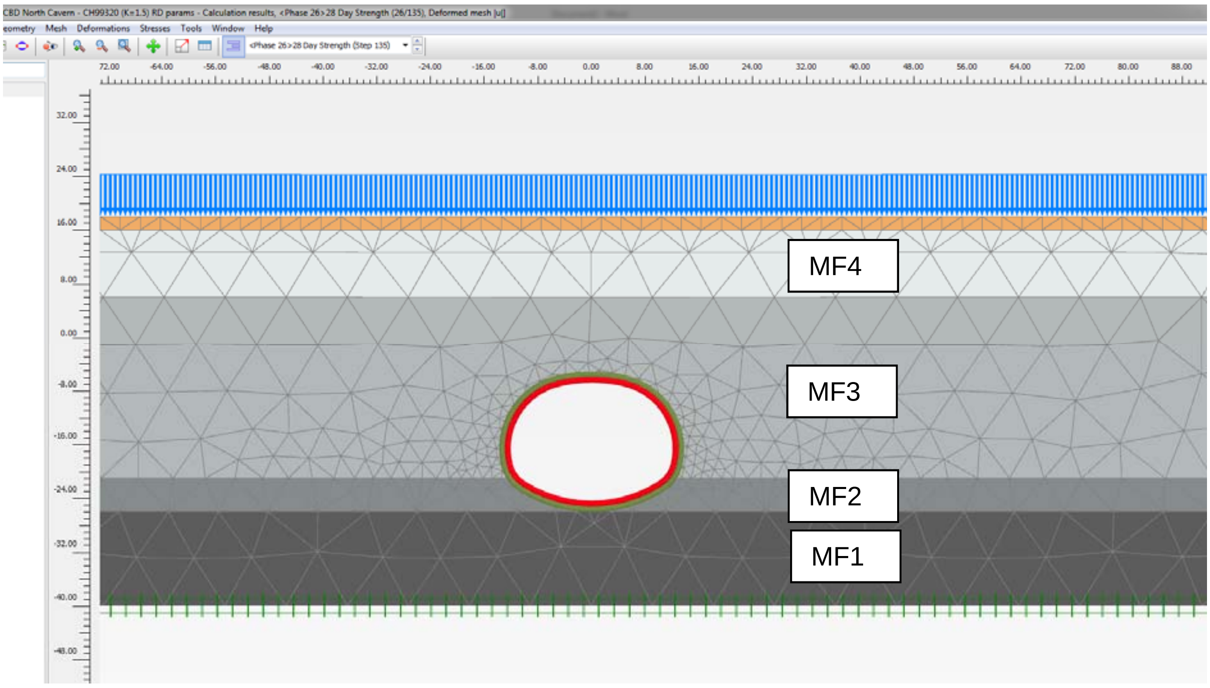

Figure 6 - Ground model at CH 99+320

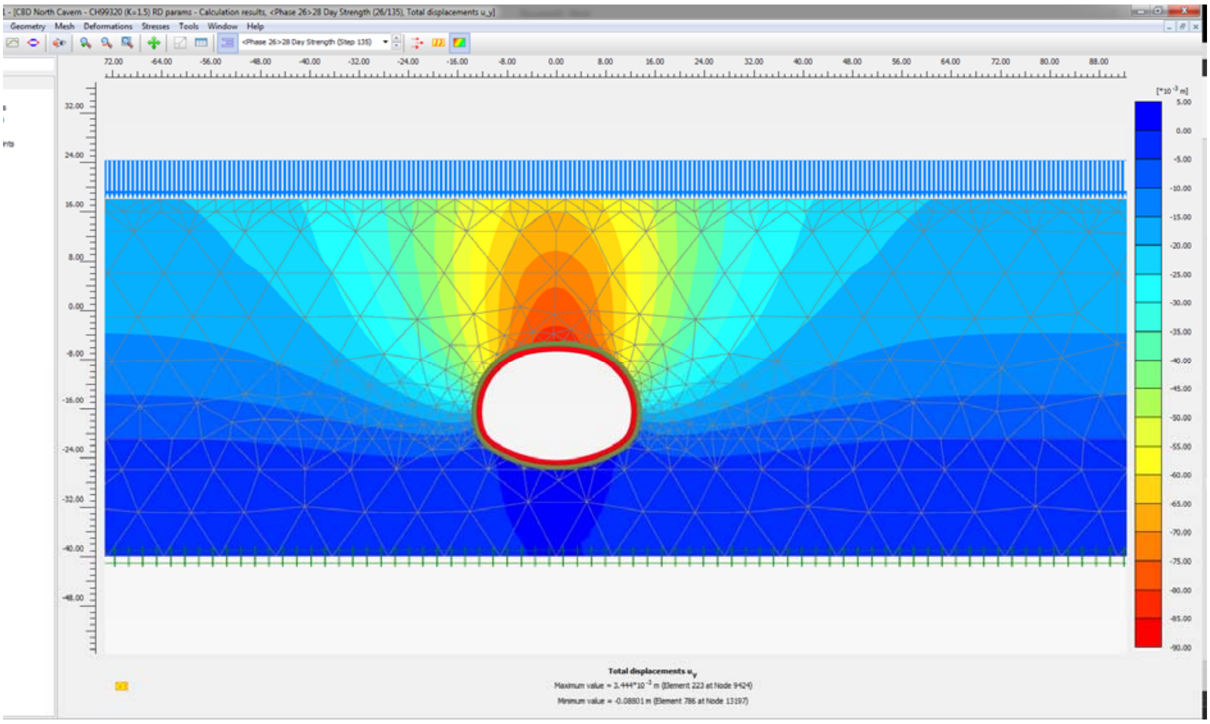

Figure 7 Plot of displacements at CH 99+320

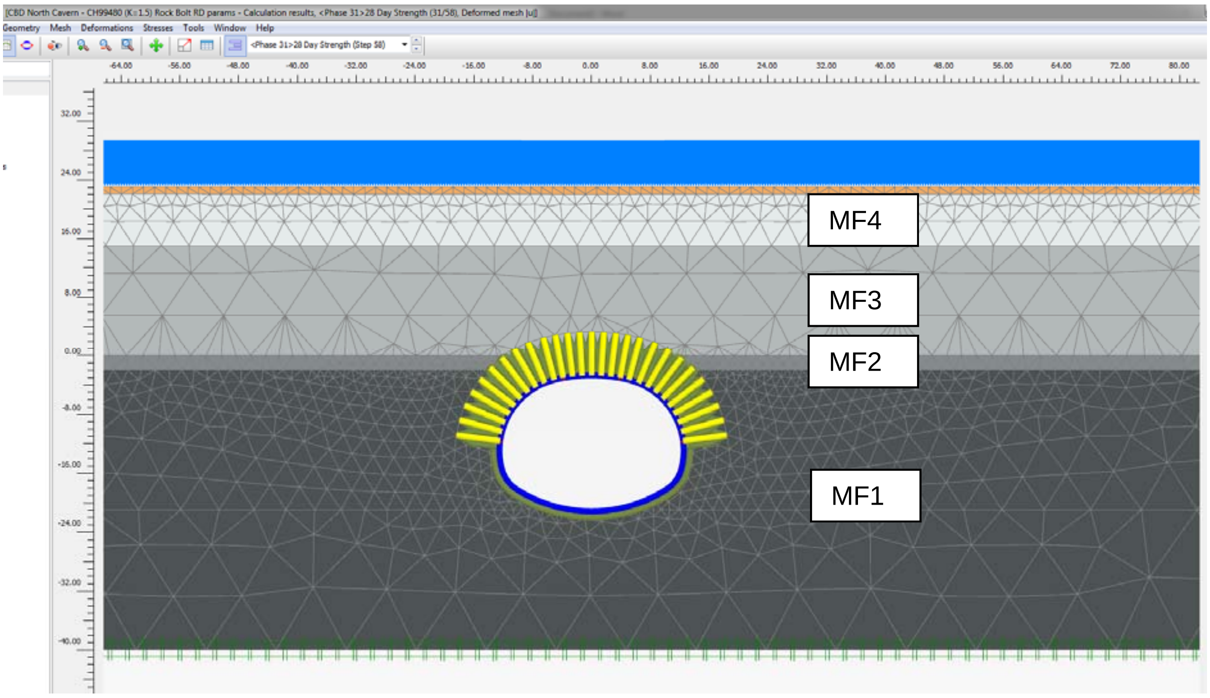

Figure 8 Ground model at CH 99+480

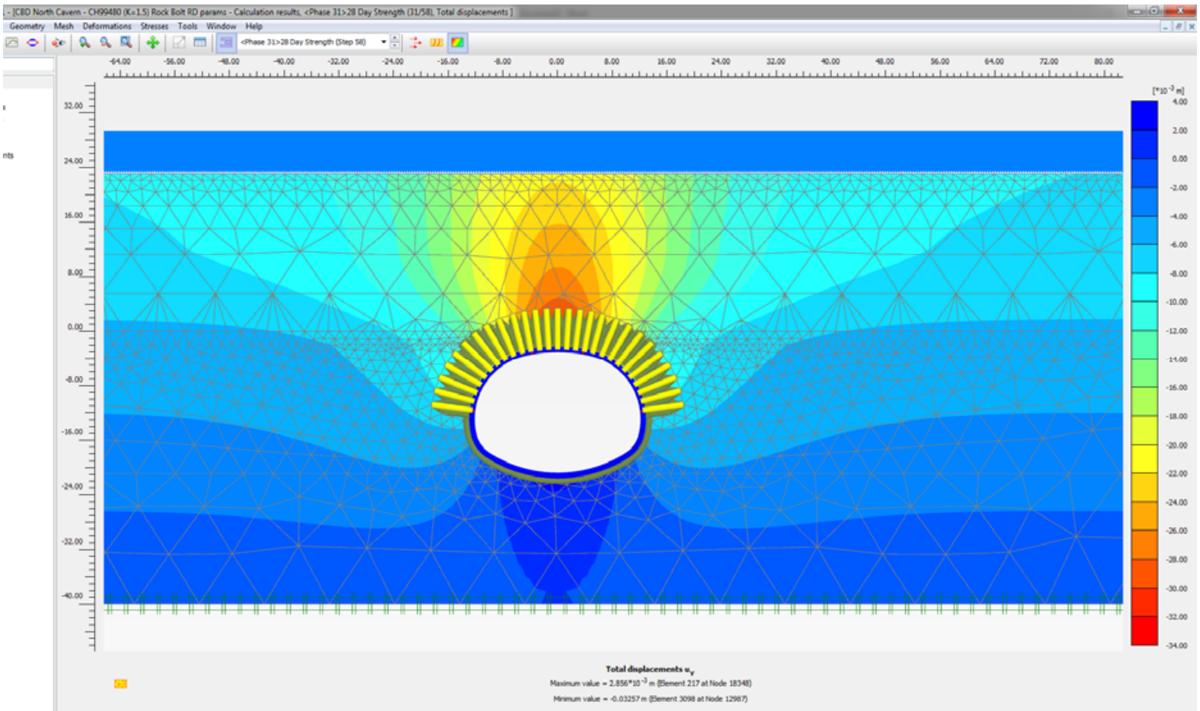

Figure 9 Plot of displacements at CH 99+480

The results of the analyses at the three sections[3] were then compared in Figure 10, with the settlement profile used for the EES assessment. For the EES assessments, settlements from the most affected section were adopted to represent the ground movements induced by the excavation of the cavern for its full length.

The further analyses, reflecting the revised geological information, predict an increase of 10 mm in maximum settlement for CBD North at the most-affected section (CH 99+320). This is associated with a wider trough than was derived for the EES assessment. The change in width for the deepest trough is less than 10 m when considering settlements greater than 5 mm (refer to Figure 10).

The shapes of the settlement profiles are similar, as are the maximum slopes. This indicates that, while a building might settle more overall, the distortion of the building, the action leading to tensions and cracking, would not increase significantly, and the assessed potential damage would remain in the same category. For the two profiles that are shallower than the EES assessments, the potential damage is expected to be less, and could be either in the same category or a lower category depending upon where it is within the bands of predicted strains.

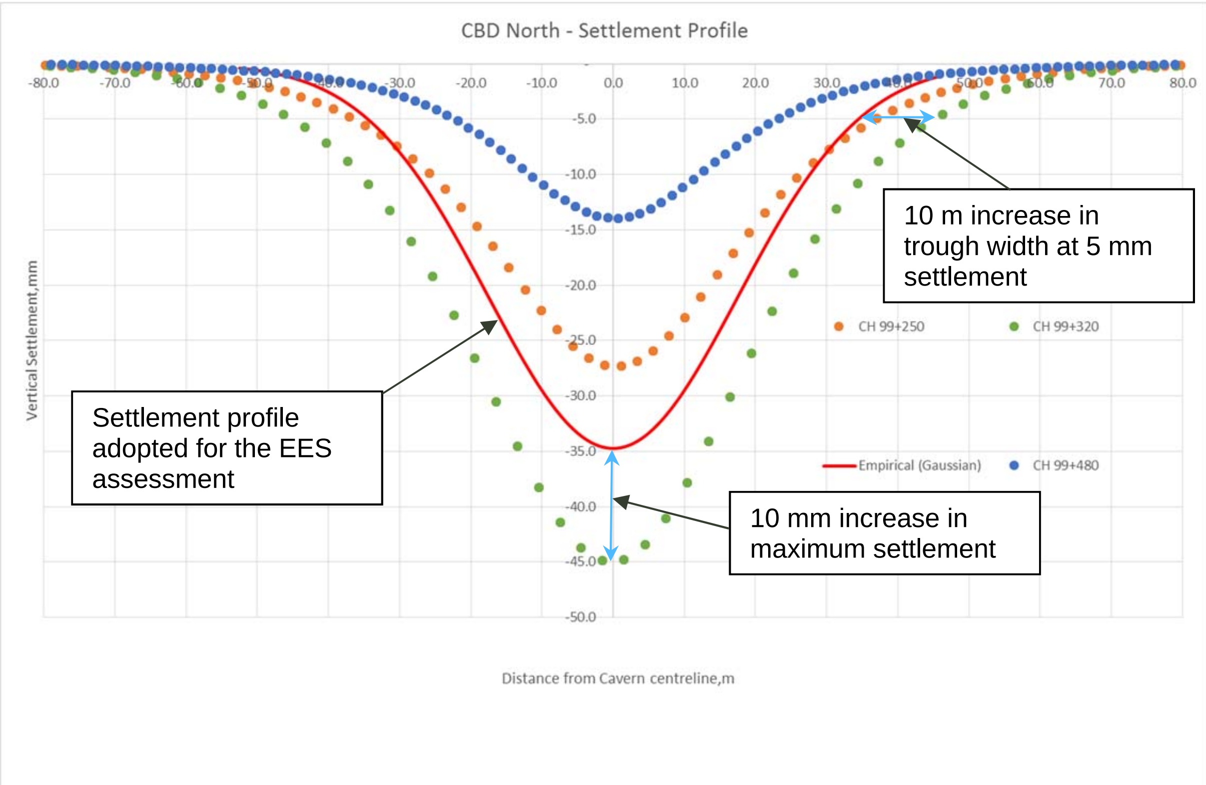

Figure 10 CBD North - comparison of surface displacement (updated geology) with EES assessment (solid line)

[3] For the purposes of the comparisons at CBD North, the settlement profiles for the updated geological conditions have been estimated based on excavation of the cavern sections only, excluding any contribution from cross connections between the cavern and shafts. This allowed the use of two dimensional analyses to arrive at an estimate of the influence of the changed ground conditions. It should be noted that the magnitude of settlement would be greater at intersections. However, assuming that the settlements over the intersections increase in the same proportion as elsewhere along the cavern, the settlements are expected to have a similar impact on buildings as those predicted in the EES, but possibly to affect buildings further from the station.

Two dimensional analyses, and three dimensional analyses where required, would be conducted during the detailed design stage to confirm the settlement predictions using the construction methodology selected by the contractor (this process is reflected in EPRs GM1-3 and GM5). The additional modelling and revised assumptions continue to support the feasibility of the Concept Design. It also supports my assessment that the impacts on buildings would remain acceptable, with only minor changes in the detail of the design or construction expected to remedy any locally higher movement that might be predicted by the full suite of analyses.

(Table 2 describing the various categories of building damage is included in Section 5 of this memorandum.)

4.2 CBD South

The three sections modelled at CBD South Station cavern are at CH 100+200, CH 100+395 and CH 100+445 and are shown in plan in Figure 11 and on the revised section in Figure 12. The sections were selected on the basis of the thicknesses of the different layers of Melbourne Formation to test where the greatest effect would occur.

They do not coincide exactly with the section at CH 100+420 used for the assessments that were exhibited as part of the EES, which had been selected on the basis of the EES ground model.

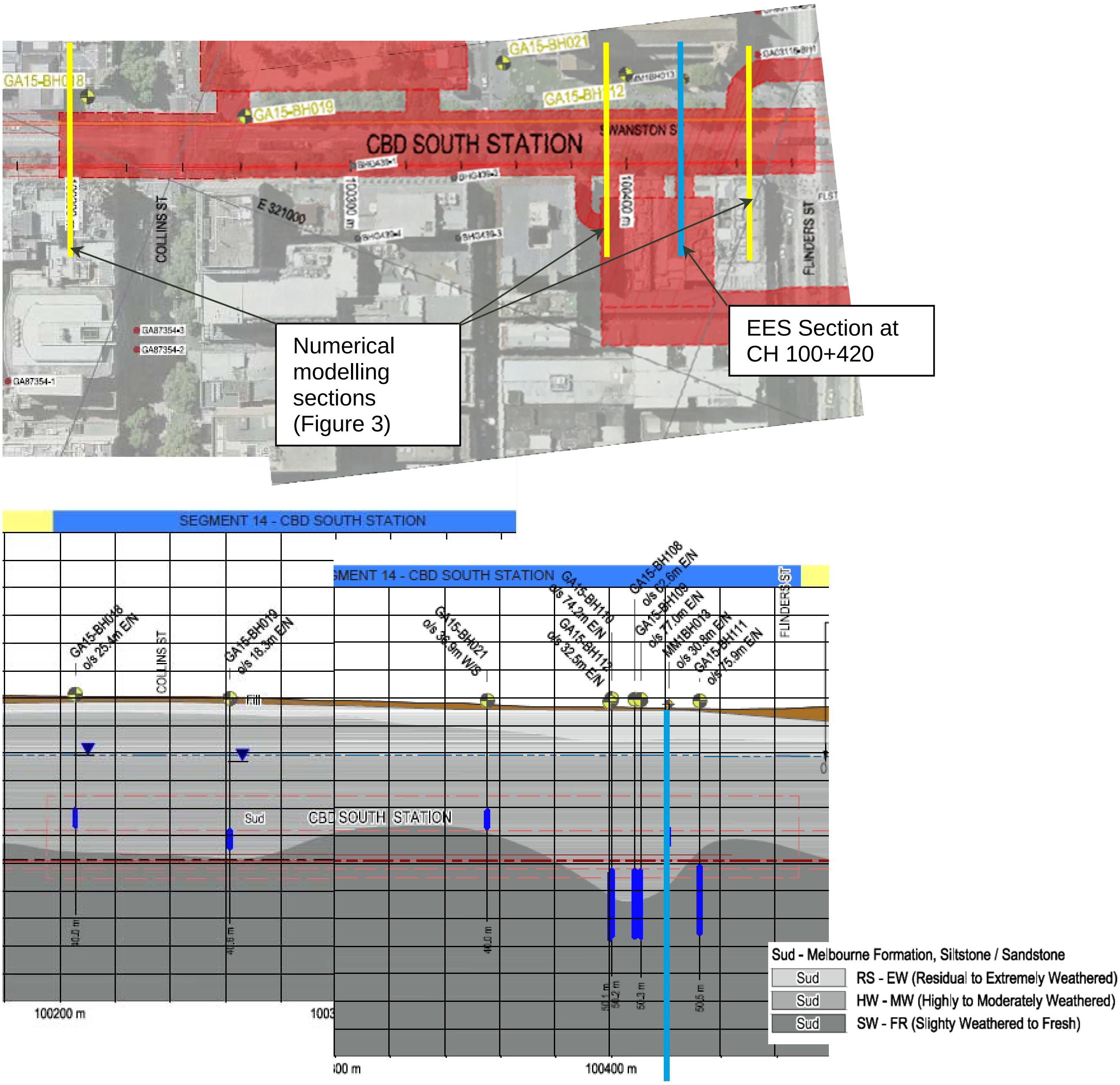

Figure 11 Plan at CBD South showing the sections (EES blue, modelling yellow) and the ground model section used for the assessments as exhibited as part of the EES (Extract from Interpreted Geological Setting EES Summary Report 20 April 2016)

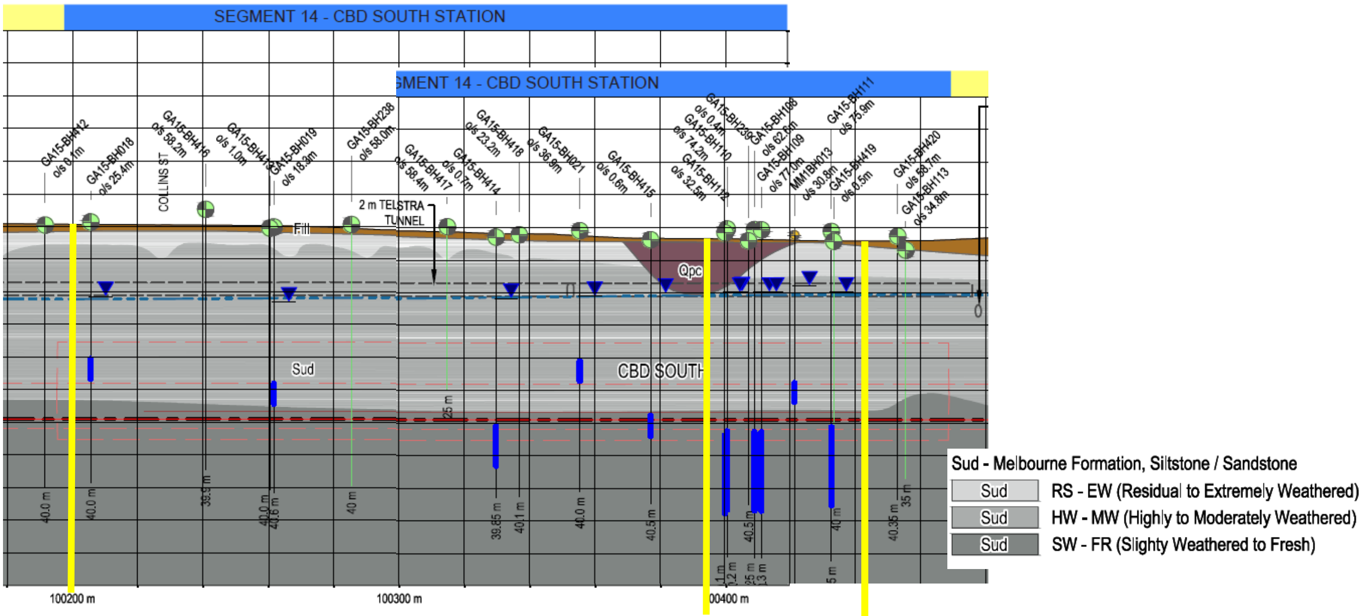

Figure 12 Updated section at CBD South with sections used for assessment modelling (this memo) in yellow. Extract from Interpreted Geological Setting EES Summary Report – July 2016 Update

In the modelling, the following parameters and assumptions were adopted:

- The permanent lining is 400 mm thick cast in-situ concrete.
- The ratio of lateral to vertical stress in the ground before tunnelling (Ko) is 1.5.
- For the staged excavation, the ground is assumed to relax to 50% prior to the permanent lining installation.
- The temporary lining stiffness varies after installation and subsequent stages. This to account for the strength gain of the primary lining.

Modelling Sequence:

1. Initial stress generation (modelling conditions before CBD South is constructed).
2. Activation of surface surcharge of 20 kPa.
3. Excavation of CBD South Station heading – 3 stages (reset displacement to zero).
4. Excavation of CBD South Station bench (3 stage).
5. Excavation CBD South Station (2 stages).
6. Installation of final lining.

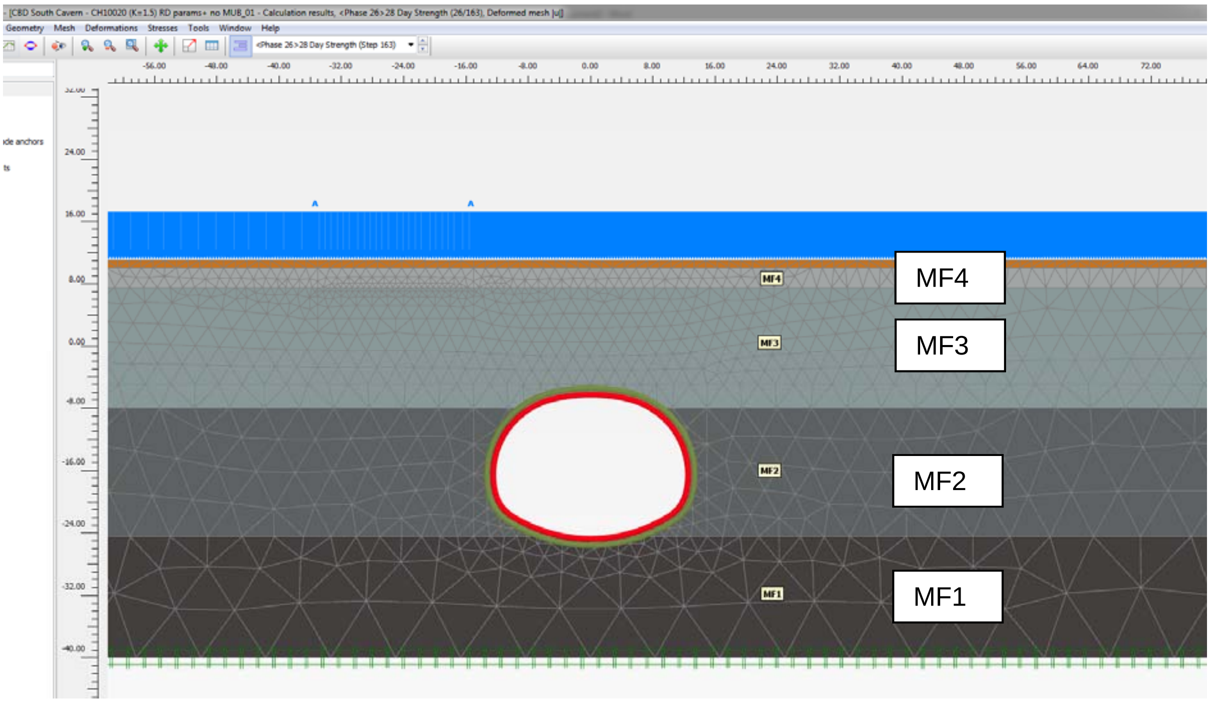

Figure 13 Ground model at CH 100+200

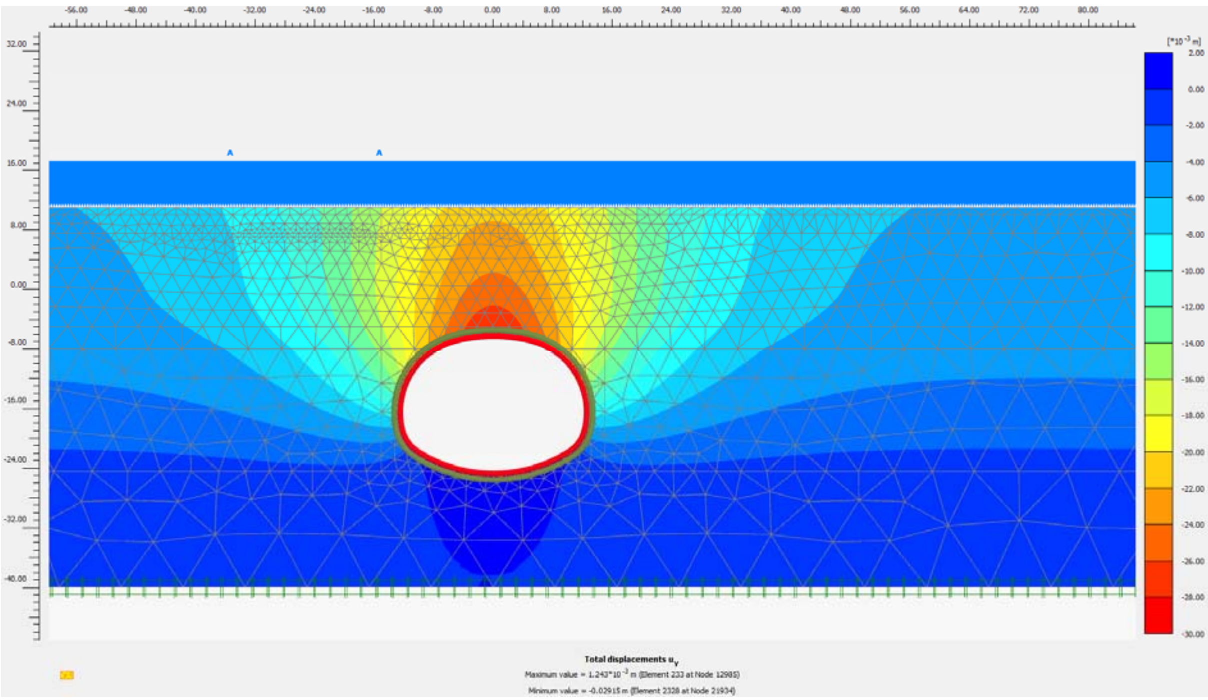

Figure 14 - Plot of displacements at CH 100+200

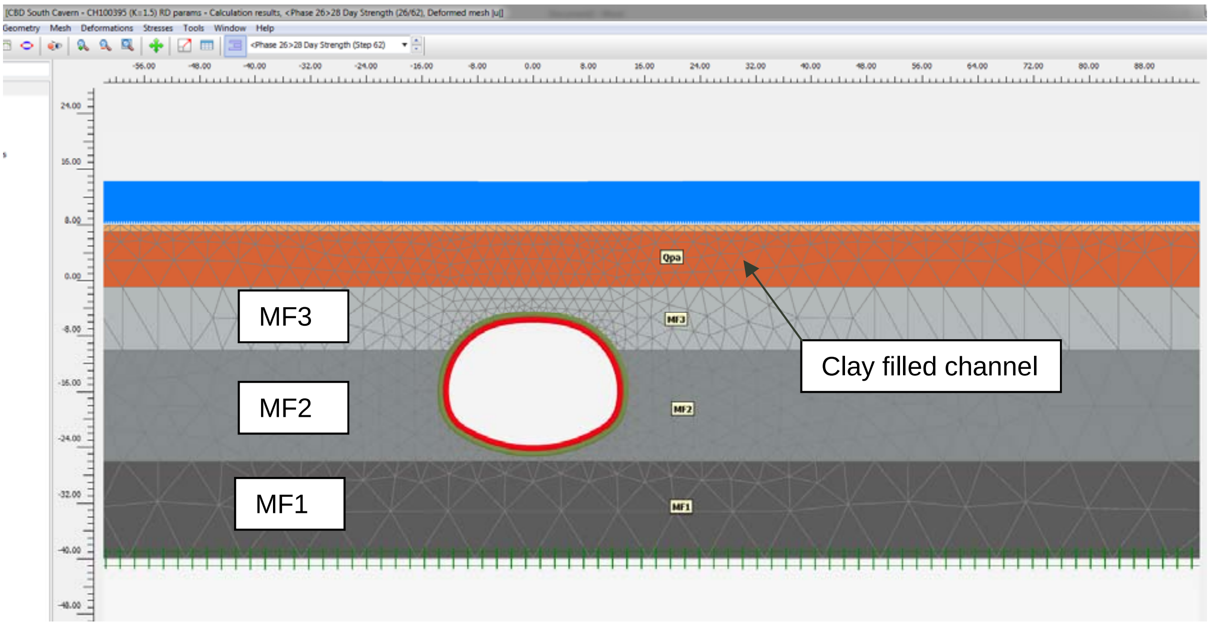

Figure 15 - Ground model at CH 100+395

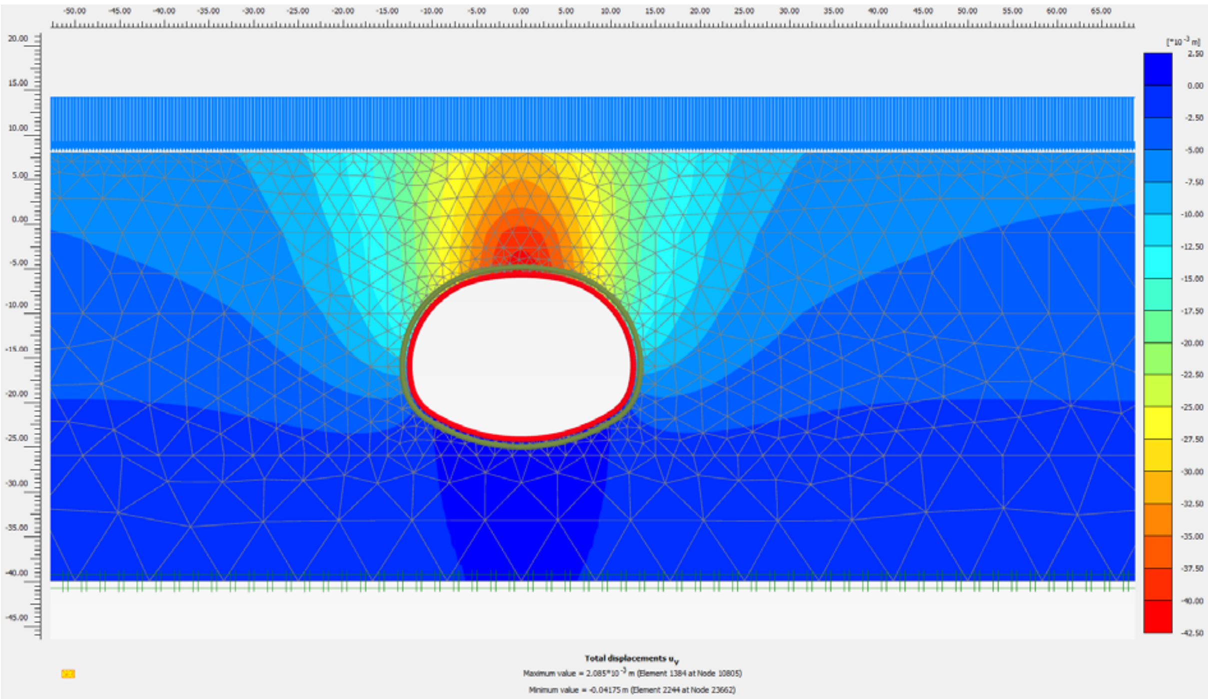

Figure 16 - Plot of displacements at CH 100+395

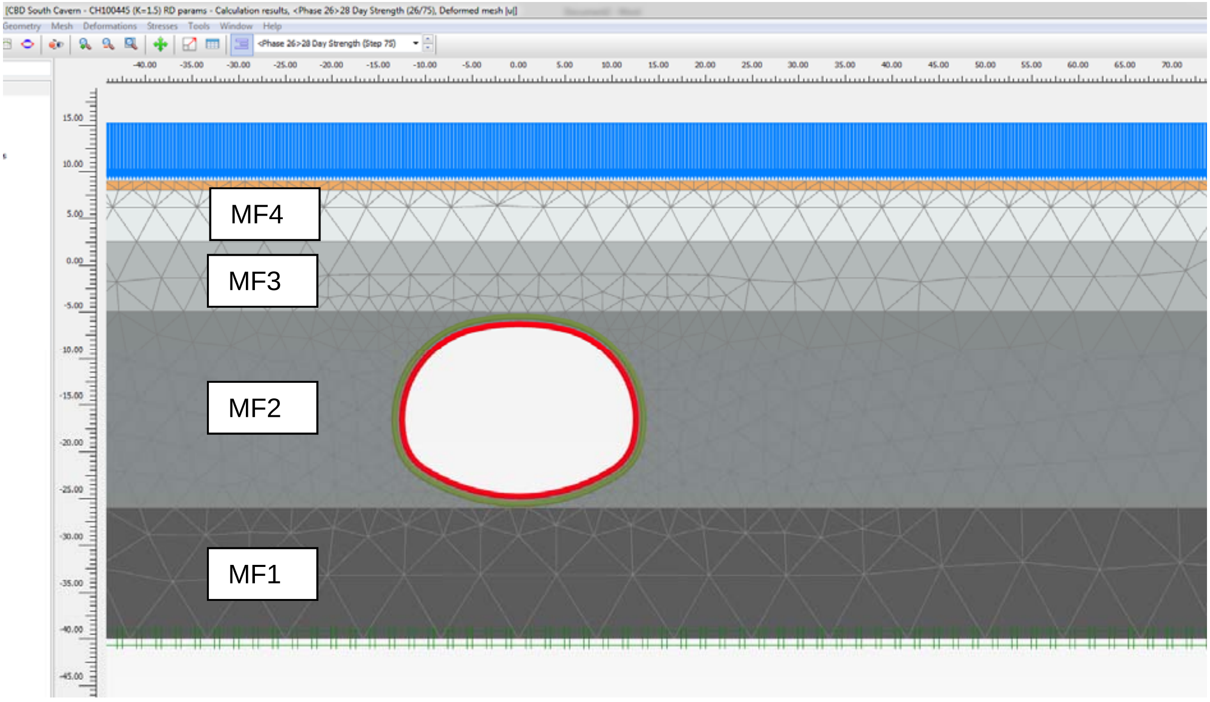

Figure 17 Ground model at CH 100+445

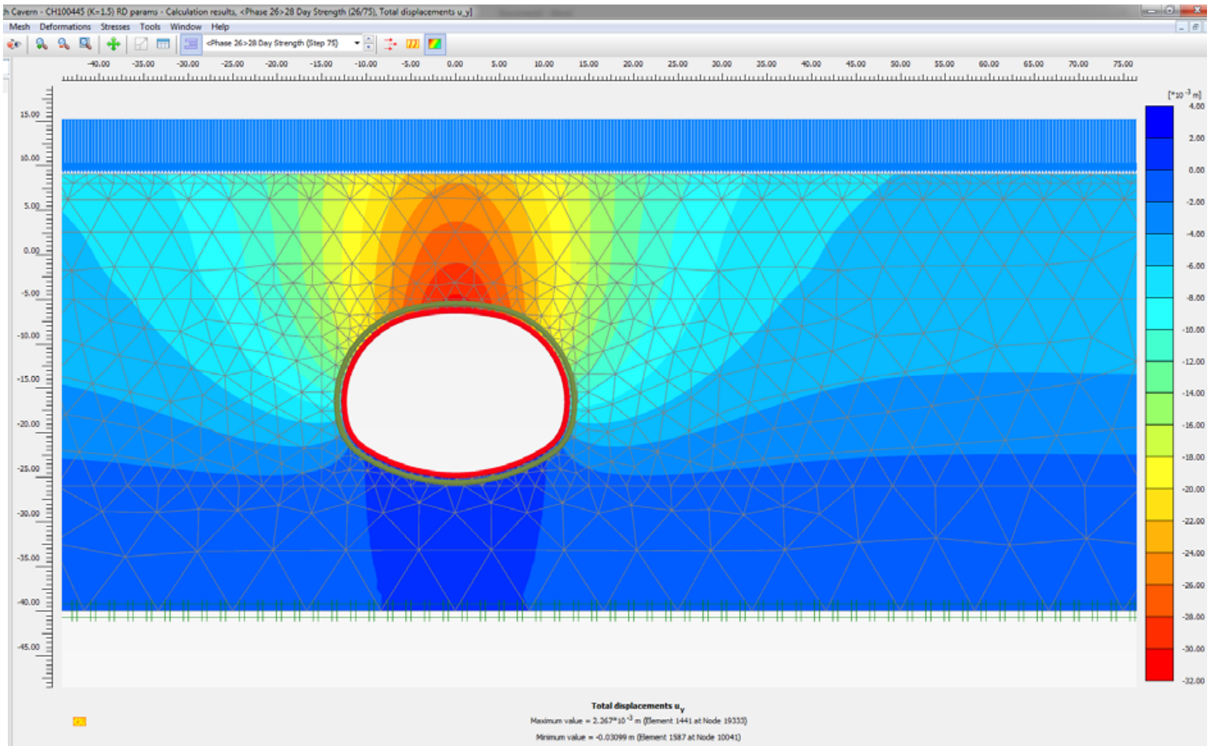

Figure 18 Plot of displacements at CH 100+445

The results of the analyses at the two more southern sections[4] are compared with the settlement profile used for the EES assessment in Figure 19.

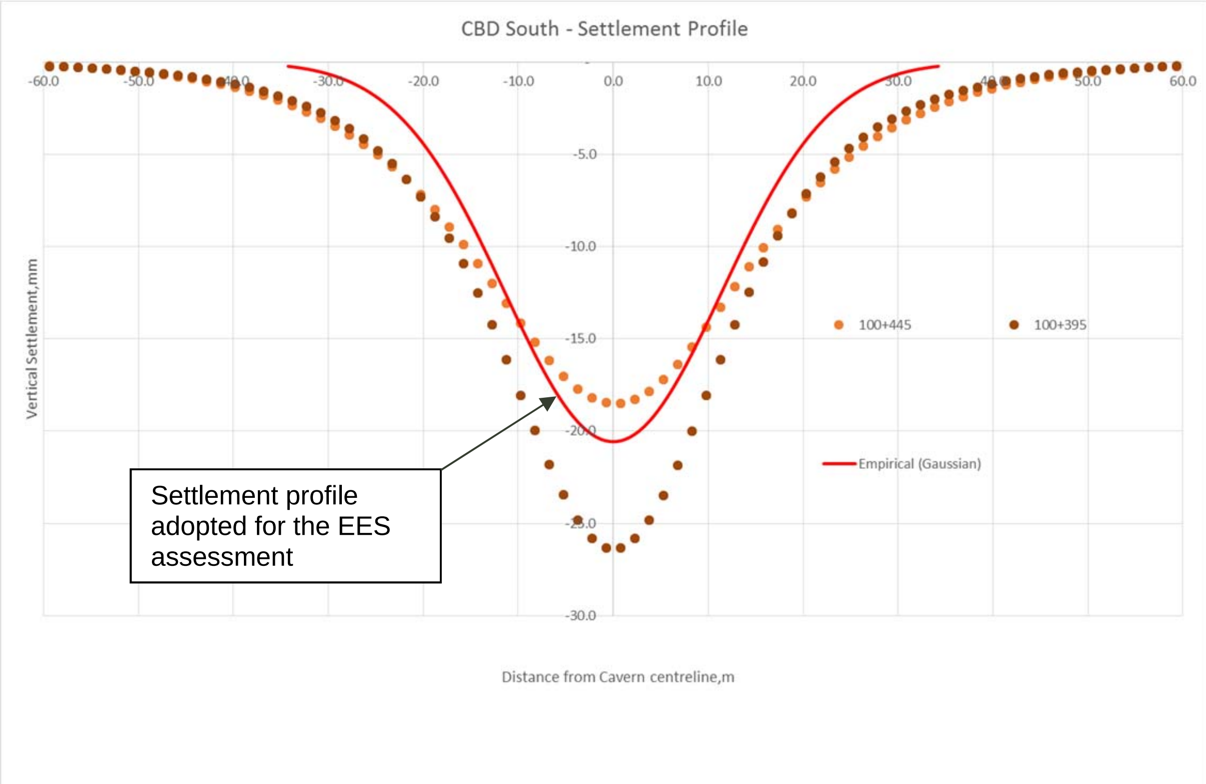

Figure 19 CBD South - comparison of surface displacement (updated geology) with EES assessment (solid line)

The further analyses, reflecting the revised geological information, predict an increase of 5 mm in the maximum settlement for CBD South at the most-affected section (CH 100+395), which coincides with the clay filled channel towards the southern end of the station. As was the case for CBD North, this is associated with a wider trough, and the shapes of the settlement profiles and the maximum slopes are similar. Again as discussed for the CBD North Station results, this indicates that the distortion of the building, and thus the predicted category of building damage, would not increase.

Two dimensional analyses, and three dimensional analyses where required, would be conducted during the detailed design stage to confirm the settlement predictions using the construction methodology selected by the contractor (this process is reflected in EPRs GM1-3 and GM5). The additional modelling and revised assumptions continue to support the feasibility of the Concept Design. It also supports my assessment that the impacts on buildings would remain acceptable, with only minor changes in the detail of the design or construction expected to remedy any locally higher movement that might be predicted by the full suite of analyses.

[4] As was the case at CBD North and discussed in Section 4.1, the assessments of the influence of the updated geology on the predicted ground movements have been conducted using two dimensional analyses, and thus do not include cross connections. In the case of CBD South, this is not strictly representative of the section at CH 100+395, where there will be service connections from near the base of the cavern to a shaft on the western side. For the purposes of this assessment, however, the two-dimensional analyses were considered adequate to provide a basis of comparison with the EES assessment.

(Table 2 describing the various categories of building damage is included in Section 5 of this memorandum.)

4.3 CBD South – Lowering by 4 m

I conducted a brief analysis to quantify the effects of lowering the alignment and the cavern itself at CBD South by 4 m, as discussed in Technical Note Number 8. This analysis is based upon the assessment for CH 100+445 presented in Section 4.2, and the assumption that the effectiveness of the excavation and support process are similar at the two depths.

The analysis was conducted by fitting the surface deflection profile shown in Figure 19 from the 2D modelling for CH 100+445 to the following equation, which is in the form of a Gaussian curve:

$$S(y,z) = \frac{V_f}{\sqrt{2 \cdot \pi} \cdot i} \cdot e^{-\frac{y^2}{2 \cdot i^2}}$$

Where:

- V_f is the face loss (assumed equal to the volume of the surface settlement trough),
- i is the trough width,
- y is the distance horizontally on the surface from the tunnel centreline, and
- S is the downwards settlement at the surface.

The effects of lowering the cavern were then assessed by modifying the trough width term to reflect a greater depth to the excavation. The results of my analysis are shown in Figure 20.

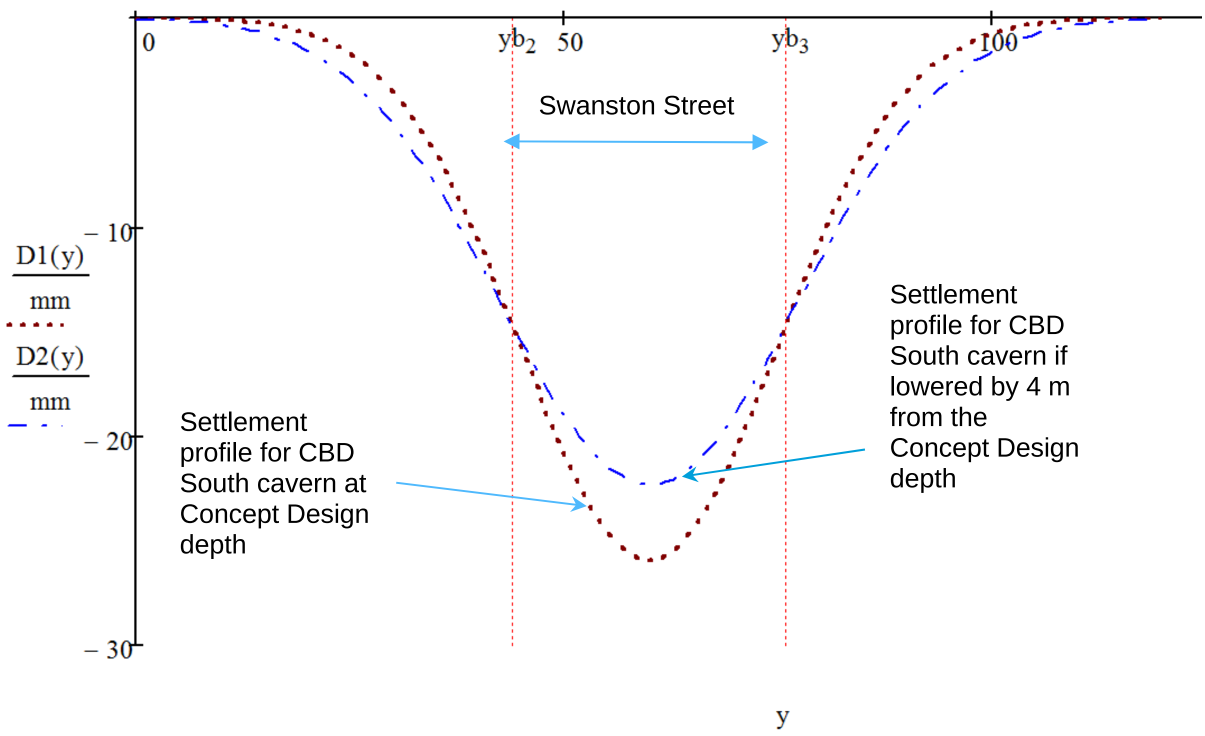

Figure 20 Comparison of settlement profiles for different depths of CBD South Station based on CH 100+395

Figure 20 shows that there is a small improvement in the maximum settlement, and the slopes of the trough. It also shows that the settlement trough becomes slightly wider at the smaller settlements towards the edges.

4.4 Sensitivity Analysis – Extent of DDO boundary as a function of ground stiffness

For the Future Development Loading Report, the Peer Reviewer raised a question regarding the appropriate value of elastic modulus to use in modelling the dispersion of surface loading. These analyses were used to determine the extent of the DDO. As the value depends upon how much the ground has moved, as measured by the strain in the ground, the query was around the choice of small strain rather than moderate strain.

Table 1 Elastic Properties for Small and Moderate Strain

Material	Elastic Modulus (E - MPa) Small strain	Elastic Modulus (E - MPa) Moderate strain	Poisson's ratio (ν) Both cases
Melbourne Formation MF4	100	80	0.3
Melbourne Formation MF3	500	300	0.25
Melbourne Formation MF2	1,000	500	0.2
Melbourne Formation MF1	4,000	2000	0.2

To respond to the queries, I reviewed both the most prevalent strains in the ground between the loading and the tunnels and also ran a sensitivity case.

For the modelling reported in the Future Development Loading Report, the parameters are small strain values.

The values reported in Ground Movement Assessment - EES Summary Report by Golder Associates dated 14 April 2016 (an appendix to Technical Appendix P of the EES), are focussed on ground movements in the immediate vicinity of the excavation of the tunnels, caverns and cut and cover structures, which are associated with moderate strain levels (and hence lower modulus values).

While the dispersion of the future development loads might be affected locally around the MMRP structures by the changes in the rock mass induced by the excavations, the majority of the load distribution will be through rock for which the small strain modulus values are appropriate.

In any case, as the dispersion of the loading is sensitive to relative rather than absolute values, the difference between the moduli values derived from small and moderate strains was tested in models using the two sets of elastic parameters. The set up the models is shown in Figure 21. The model runs showed that within the ranges being considered, the value of the elastic modulus has almost no effect on the results derived from this assessment, as can be seen below in the results from small strain values Figure 22 and moderate strain Figure 23.

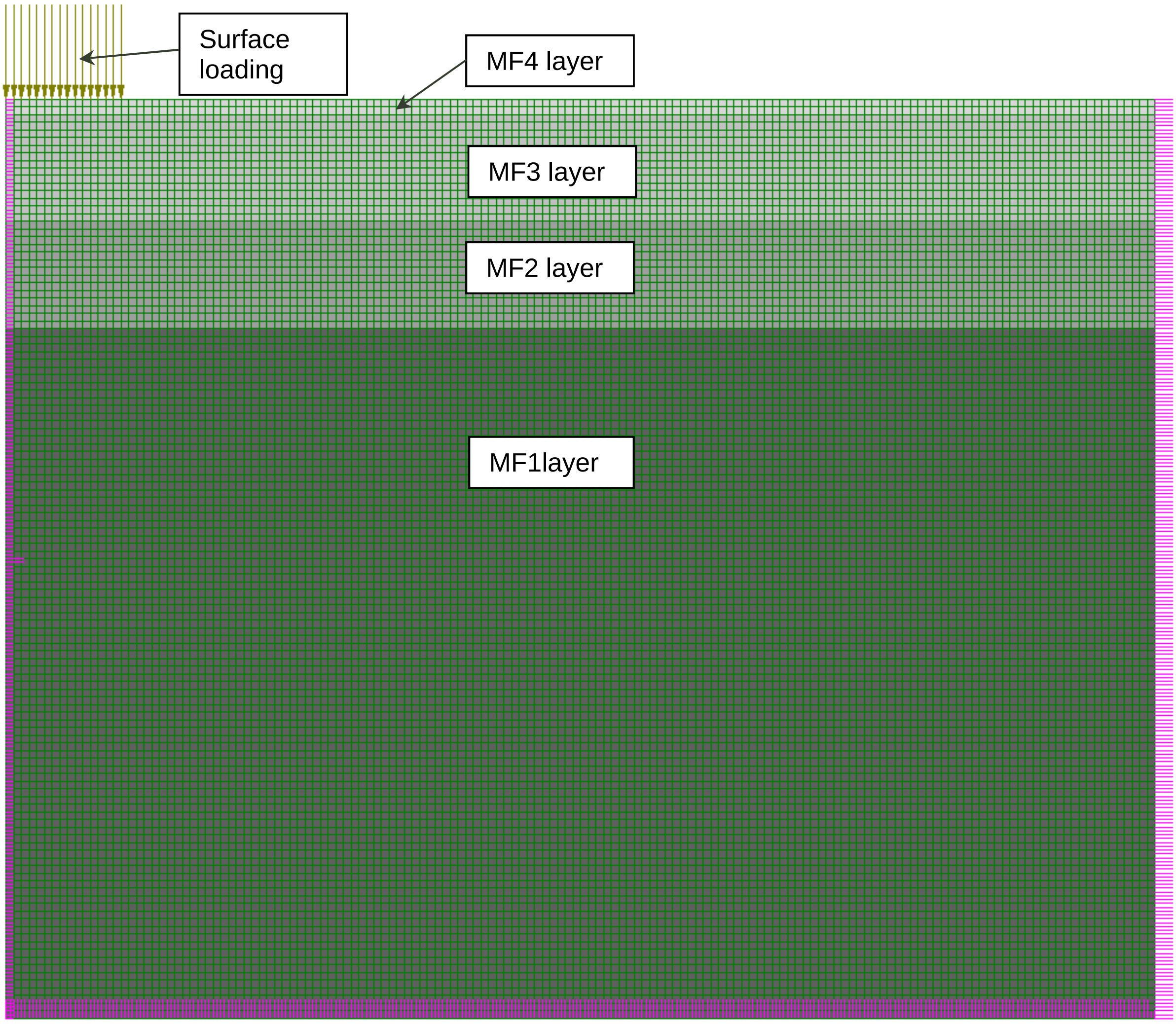

Figure 21 2D sensitivity model (120 m deep to avoid boundary effects)

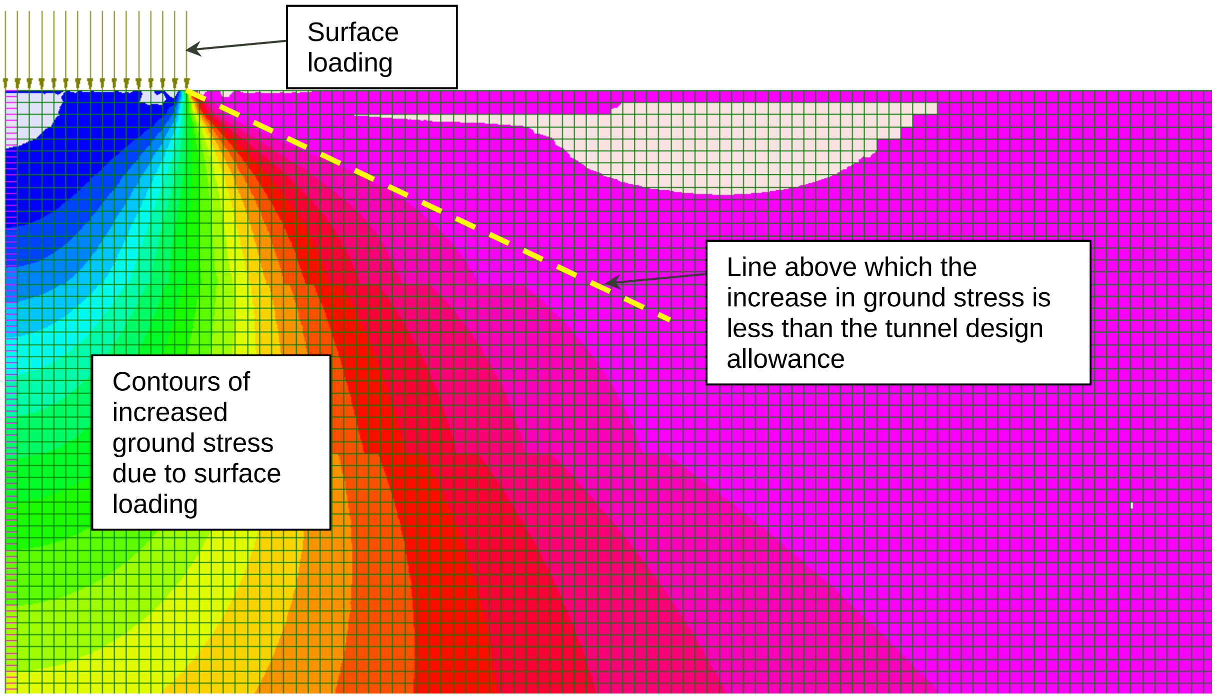

Figure 22 - Dispersion in 2D of 1000 kPa applied at the surface - small strain properties

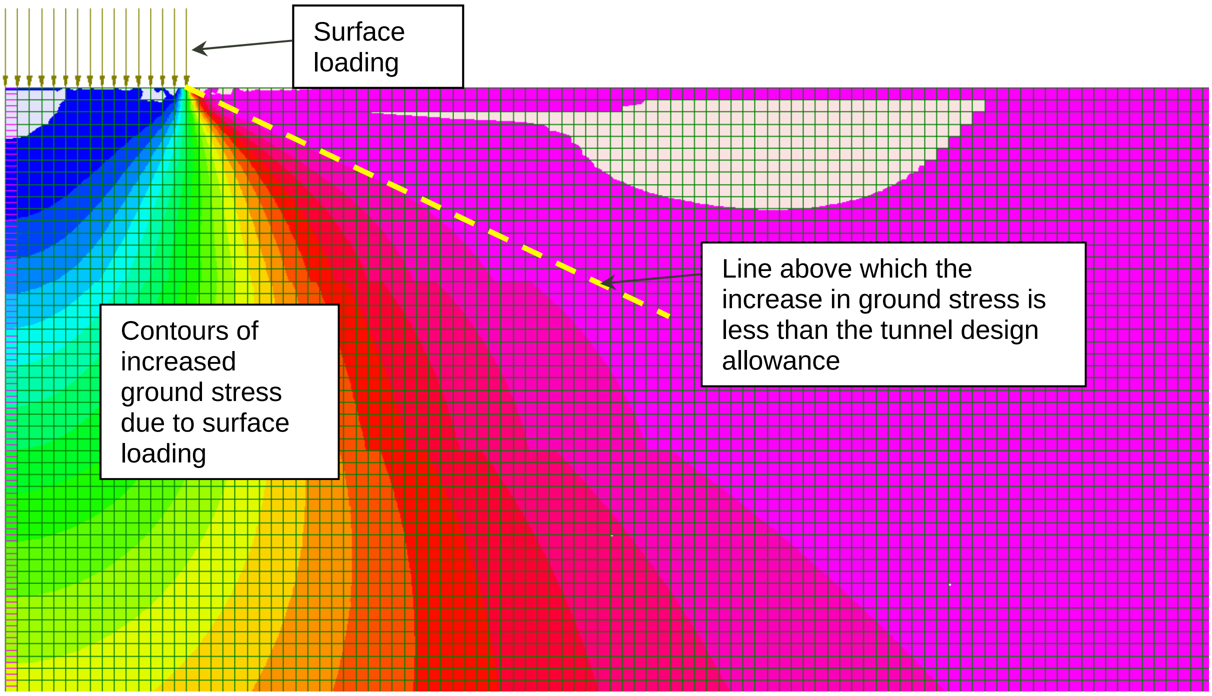

Figure 23 Dispersion in 2D of 1000 kPa applied at the surface - moderate strain properties

The outcome of these analyses was also used as the basis for concluding that the updated geological information would not affect the general approach described in the Future Development Report for protecting the Project's underground assets and would not affect the extent of the DDO.

5 Assessment of results and implications for EPRs

The revised assumptions and additional modelling based on the updated geological information continue to support the feasibility of the Concept Design. The results of the analyses show that:

- The ground movements are expected to increase but the predicted damage for affected buildings would generally remain within the same categories (as described in Table 2 which has been reproduced from Appendix P – Ground Movement and Land Stability of the EES)
- The zone of influence would be wider in some cases, potentially affecting additional buildings. The change in width for the deepest trough, which was one of the results of the analyses at CBD North, shown in Figure 10, is less than 10 m when considering settlements greater than 5 mm.

As a consequence of these findings, I make no recommendations to modify or add to the current EPRs related to ground movements, as they would adequately manage the updated conditions. I consider that the EPRs remain appropriate for design within the project boundary.

While no analyses were conducted specifically for the possible effects on the Future Development Loading, in particular the derivation of the extent of the DDO, work has already been conducted to respond to comments from the Peer Reviewer, and noted in my Expert Witness Statement. I regard these analyses as sufficient to indicate that the derived dispersion of future building loads from the surface was not very sensitive to the stiffness of the ground and therefore the derived DDO widths would not be affected by the updated interpretation of the geology.

The following table shows the categories used to describe the building damage predicted as a consequence of ground movement and has been reproduced from Appendix P – Ground Movement and Land Stability of the EES. The category is determined by deriving the tensile strain in a building resulting from ground movement. These strains are in ranges, which explains how the settlement estimates can change without modifying the predicted damage category.

Table 2 - Categories of Potential Building Damage

Potential Impact*	Category of damage and Normal degree of severity***	Description of typical damage**	Limiting tensile strain*** (%)	Broad category grouping
Negligible	0 - Negligible	Hairline cracks less than about 0.1 mm wide.	Less than 0.05	Aesthetic Damage
Minor	1 – Very Slight	Fine cracks that are easily treated during normal decoration. Damage generally restricted to internal wall finishes. Close inspection may reveal some cracks in external brickwork or masonry. Typical crack widths up to 1 mm.	0.05 to 0.075	Aesthetic Damage
Minor	2 – Slight	Cracks easily filled. Redecoration probably required. Recurrent cracks can be masked by suitable linings. Cracks may be visible externally and some repointing may be required to ensure weather-tightness. Doors and windows may stick slightly. Typical crack widths up to 5 mm.	0.075 to 0.15	Aesthetic Damage
Moderate	3 - Moderate	The cracks require some opening up and can be patched by a mason. Repointing of external brickwork and possibly a small amount of brickwork to be replaced. Doors and windows sticking. Service pipes may fracture. Weather-tightness often impaired. Typical crack widths are 5–15 mm or several >3 mm.	0.15 to 0.3	Serviceability Damage

Potential Impact*	Category of damage and Normal degree of severity***	Description of typical damage**	Limiting tensile strain*** (%)	Broad category grouping
Major	4 - Severe	Extensive repair work involving breaking out and replacing sections of walls, especially over doors and windows. Windows and door frames distorted, floor sloping noticeably. Walls leaning or bulging noticeably, some loss of bearing beams. Service pipes disrupted. Typical crack widths are 15–25 mm, but it also depends on the number of cracks.	Greater than 0.3	
Severe	5 – Very Severe	Irreversible, significant changes resulting in widespread risks to human health and/or the functioning of the building. This requires a major repair job involving partial or complete rebuilding. Beams lose bearing; walls lean badly and require shoring. Windows broken with distortion. Danger of instability. Typical crack widths are greater than 25 mm, but it also depends on the number of cracks	Greater than 0.3	Stability Damage

*The Potential Impact uses terms consistent with other uses with the Project's EES.

**Note: Crack width is only one factor in assessing category of building damage and is not used as a direct measure of damage. Ease of repair is the key factor in development of this table, based on a large number of other studies

***Relationship between Category of Damage and Limiting Tensile Strain for Buildings (After Burland (1995), and Mair et al (1996))