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14-Jul-19
Available Documents:

[1] North East Link Environment Effects Statement (EES) documents, Summary Report (Victorian Government, 1 Treasury Place, Melbourne);

[2] North East Link Environment Effects Statement (EES) documents, Chapter 6 Project development;

[3] North East Link Environment Effects Statement (EES) documents, Chapter 7 Urban design;


[8] North East Link Environment Effects Statement (EES) documents, Chapter 23 Contamination and soil;

[9] North East Link Environment Effects Statement (EES) documents, Chapter 24 Surface water;

[10] Inquiry and Advisory Committee North East Link Project, Preliminary Matters and Further Information Request (20 June 2019);

Appendix List:


[A2] BabEng Report on Options for Extension of the Underground Alignment, North-East Link Project, Banyule City Council, Victoria, dated 2 May 2019


[A4] CV Lars Babendererde
A STATEMENT DETAILS

Name:
Lars Babendererde

Address:
BabEng GMBH
Einsiedelstr. 28
235554 Lübeck
Germany
Phone 0011 49 451 286 678 0
Email: LB@babeng.com

Qualifications, experience and area of expertise:
- Dipl.-Ing (FH) in Mechanical Engineering in 1991
- Since then working as engineer in the field of mechanised tunnelling.
- Since 1996 Managing Partner of BabEng GmbH (formerly with different names), operating worldwide.
- Active in various organisations as ITA, DAUB, NAT, TAC

Contributors to the statement:
The statement has been prepared by me. Identifying relevant documents of the EES package by employed engineer Mrs. Linquin Lyu. I have not relied on other contributors.

Instructions:
I was initially instructed by Banyule City Council to assess the prospect of extending the proposed tunnel for the North East Link further to the north of the reference design northern portal. These instructions were by letter dated 7 January 2019.
I was subsequently instructed by letter dated 28 June 2019 from Maddocks Lawyers to prepare a witness statement addressing specific issues set out in the letter. A copy of this letter of instruction is provided as Appendix to this statement.

Tests or experiments:
No tests or experiments have been carried out for the purposes of this statement.

Prior report:
BabEng Report on Options for Extension of the Underground Alignment, North-East Link Project, Banyule City Council, Victoria, 2 May 2019
B  INTRODUCTION

The North East Link Project (NELP) is developing its design of the North East Link (NEL) based on the State Government decision to adopt corridor Option A, which is a new freeway connection between the M80 Ring Road and the Eastern Freeway, and passes in part through Banyule municipality.

The North East Link reference design for Option A indicates that the new freeway will be in tunnel from north of the Eastern Freeway (southern portal) to just north of Lower Plenty Road (northern portal). The section between northern portal and M80 Ring Road will be constructed in trench and at grade.

Banyule City Council (BCC) has identified a number of issues such as impacts to local businesses, local access and local environment, due to the extensive surface works proposed between northern portal and M80 Ring Road. Extending the NEL tunnel to the north has been proposed as an option to reduce these impacts on the Banyule community. Prior to the public release of the EES, BCC engaged BabEng to consider alternative tunnelling options. BabEng reported on the options in the Report on Options for Extension of the Underground Alignment, 2 May 2019. This Report is provided as Appendix A2 and a summary of this report is set out below.

Maddocks, lawyers representing BCC as well as Boroondara City Council and Whitehorse City Council during the EES phase, has asked that I prepare this expert witness statement to address specific tunnelling issues.

This statement makes use of the findings of the earlier report, where appropriate.
C PREVIOUS REPORT ON TUNNEL OPTIONS

Banyule City Council retained BabEng to:

- Explore options for extending the tunnelled section of NEL;
- Assess the costs of any viable option; and
- Evaluate the viability of a longer tunnel option suggested by Banyule community stakeholders.

I was the principal author of the report. I was assisted by Dipl.-Ing. Christiane Kitscha, and Dr.-Ing. Rohola Hasanzpour, supporting in the design and cost assessments.

In the report, BabEng considered four options for extending the tunnelled section of the NEL. Of the options, option A2 extended the tunnelled section approximately 2.5 km north of the northern portal in the reference design to a point south of Grimshaw Street. This option met the alignment constraint of maintaining a functional interchange at Grimshaw Street, while providing the maximum length of tunnel.

We assessed the time that the additional tunnelling, and associated works, would take between 29 and 37 months, depending on variations to construction approaches.

We assessed the tunnelling costs of the reference design and option A2. The cost increases from about $168 million to about $255.4 million. (The estimates were approximations only, carried out for comparison purposes. The estimates only cover the tunnel-related costs, and do not address costs for temporary structures, machinery and equipment, road construction, the costs of the interchange and related costs. Risks and uncertainties are not allowed for.)

In the absence of costing data, we carried out a comparison of the changes in volume in different structures and options. Potential savings were considered by comparing the construction volume. These comparisons are set out at tables 5 and 6 of the report. With option A2:

- The extent of mined tunnel increases in volume by 88% with a cost increase of 53%, the extent of cut and cover remains the same, the volume of open cut trenches reduces by 70% and the extent of surface roads reduces by 40%.
- There is no need for land bridges; and, within the area of the extended tunnel section from Lower Plenty Road to Doris Street, land and buildings remain intact.

The report sets out key assumptions. I note:

- We had to rely on information gathered from the internet, especially Google Maps, as well as assessments derived from our own photos. Consequently, the findings of the report would need to be verified in future design phases.
- Information on the geological situation north of Greensborough Road was not available and would need to be confirmed.
The rail line tunnel crosses the tunnel alignment with a shortest separation distance of 7 m at the southbound tunnel (see figure 13 of the report). This small distance might require additional protection measures for the rail line, like compensation grouting. This would need to be further investigated.
D STATEMENT

In this part of the statement, I address the questions put to me by Maddocks in their letter of 28 June 2019 as relevant to the field of tunnelling and tunnel design.

1. Does the EES contain sufficient information about the geotechnical and hydrogeological conditions of the project area to form a proper basis for understanding the effects of tunnel construction,

1.1. as proposed by the Project described in the EES

The elaborated corridor A of the alignment options is well documented. Descriptions and various graphics explain the effects the tunnel structures will have on the hydrogeology and on the surface structures. Further explanations are given about the expected ground in general terms and any effects of tunnelling through contaminated ground.

With some technical background the scope of the planned works is comprehensible.

1.2. or any modifications to the alignment, position or length of the tunnel as described in the EES.

For the purpose of developing BabEng’s own tunnelling alternatives, the content of the EES documents needs further enhancement.

The available documents list only the general rock or soil type. No geotechnical or hydrogeological conditions or parameters have been found within the EES documents.

The following Table 1 gives an example of the geological description.

<table>
<thead>
<tr>
<th>Location</th>
<th>Volume loss – $V_L$</th>
<th>Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Plenty Road to Leura Avenue (TBM)</td>
<td>0.8</td>
<td>Faulted zones have been detected near the temporary portal in the vicinity of Lower Plenty Rd. Reduced ground cover above the tunnel, with some superficial soil.</td>
</tr>
<tr>
<td>Leura Avenue to Banyule Flats (TBM)</td>
<td>0.2</td>
<td>Greater than one-tunnel diameter of cover above the tunnel crown and ground is believed to be mainly competent siltstone.</td>
</tr>
<tr>
<td>Banyule flats northern valley interface (TBM)</td>
<td>0.8</td>
<td>Reduced ground cover above the tunnel crown beneath the Yarra Valley. The ground cover consists of a thick layer of geologically ‘recent’ alluvial soils and highly fractured rock; potential ‘mixed ground’ conditions in TBM face.</td>
</tr>
<tr>
<td>Banyule flats (TBM)</td>
<td>0.4</td>
<td>Ground cover above tunnel crown increases as the alignment continues under the Yarra Valley.</td>
</tr>
</tbody>
</table>
### Location Volume loss – VL% Reasoning

<table>
<thead>
<tr>
<th>Location</th>
<th>VL%</th>
<th>Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siltstone in this location is of lower GSI as rock fracturing is more prominent and fault zones are possible.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Banyule flats southern valley interface (TBM)</td>
<td>0.8</td>
<td>Ground cover of material above tunnel crown decreases as the alignment rises to meet the Manningham Road interchange box.</td>
</tr>
<tr>
<td>Surface material comprises weathered siltstone with some fault zones expected. Mixed face conditions comprising rock and alluvium anticipated.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mined (SEM) tunnels</td>
<td>0.3</td>
<td>Moderately weathered, moderate strength fractured rock is anticipated in this section of the alignment.</td>
</tr>
</tbody>
</table>

Table 1: Table 5.4 from NELP-EES-Technical-Report-M-Ground-Movement.pdf

There is only a general description of the present geology, like “mainly competent siltstone”. The provision of relevant parameters, e.g. dry unit weight, saturated unit weight, cohesion and the friction angle, would permit more reliable calculations and assessments for tunnelling options. Combined with data from the ground water table, it would have been possible to carry out the necessary face support calculations with project data, in order to determine the possible vertical alignments of tunnels.

In the absence of those geotechnical and hydrogeological data, typical values were taken in our earlier report [A1] from literature. Ground water levels were taken from overview drawings. This automatically increases uncertainty within the calculations.

In consequence, the available information in the EES alone did not permit us to develop the alternative tunnel options with precision. The proposed alternatives are subject to further studies or information.

For assessing the effects of tunnel construction only, the expected volume loss (VL%) is a good indicator. It is the base indicator for the later assessment of surface deformation caused by the tunnelling. The higher the value, the larger is the influence on the surface structures.

The expected volume loss is a calculated value, following a prediction model. Depending on the model, different parameters are applied in formulas. The EES documents (Technical Report M, Ground movement) refer for the Ground Loss prediction to a model of Peck, published in 1969. Though being quite old, this model is still broadly used. Compared to current tunnelling, it delivers reliable values on the conservative side.

One reason is that TBMs with active face support (Slurry-TBMs or EPB-TBMs) have been introduced into the market only in the 1970’s. The improvements in ground control by applying continuously active face support during tunnelling, could not
have been considered by Peck in 1969. Current ground loss values are typically less than 0.5 %. The listed 0.8 % (Table 1) are to our understanding overly conservative. No data are disclosed to allow a more detailed review and to make our own assessment for our tunnel alternatives.

For example, in 2000, PhD Student N. Loganathan, et al., took the chance of the Sydney Airport Link to compare his own theoretical ground loss model with the later achieved settlement values excavated by a Slurry-TBM. From the publication [A3, page 5, Table 3] it can be derived that, that even his predicted ground loss values have been conservative with a range of 0.29 % to 0.56 %. The related settlements have always been less than predicted by the model. Taking these positive results into consideration at the NEL, the tunnels would have more options regarding length and vertical alignment.

2. From your review of the EES, is there any geotechnical, hydrogeological or engineering reason why the tunnel as proposed could not be extended north towards Grimshaw Street, and/or south towards the Eastern Freeway?

North:
The reviewed documents do not disclose why the tunnel could not be extended to the south of Grimshaw Street, as has been proposed in our report for Banyule Council.

One possible reason, though not mentioned, would be the distance between the existing railway tunnel and the new tunnel. Since the ground conditions in this area are presumably rather favourable, we expect the risks are acceptable after mitigation.

South:
We conducted, for the connection to/from the Eastern Freeway, a preliminary study of the ground description and the proposed structures in this area. Just by the geology, tunnelling with a soft-ground TBM should be feasible.

3. If the tunnel were to be extended, either north or south, what would be the implications for tunnel design at the interchanges?

North:
In our report, it was demonstrated that the tunnel could be elevated in such a way that there is enough space for the merging lanes and ramps before the intersection with Grimshaw Street.

For the tunnel design itself, I do not see any adverse implication, based on the available information.

South:
Without having a vertical profile of the alignments in the south it is difficult to make a judgement on the feasibility. Looking onto the layout plans of the Option B, the TBM tunnel length, especially the tunnel connecting the Great Eastern Highway EB to the
road parallel to Thompson Road seems rather short and might be better excavate either as Cut & Cover or Mined Tunnel, if possible. Both curved tunnels connecting the NEL in direction east to the Great Eastern Highway seem to have feasible radii. Again, the judgement is based on this rather superficial information.

4. Are there any recommendations that you would make as to specific measures which you consider necessary and/or appropriate to improve the design of the tunnel or to prevent, mitigate and/or offset adverse environmental effects? In answering these questions please explain your reasoning in detail.

The NEL, in its reference design, already involves, aside of the open trenches, extensive tunnelling. The central part of the alignment will be excavated by two tunnel boring machines (TBMs).

The International Tunnelling Association (ITA) has many documents describing the advantages in maximising use of the underground space through tunnelling to the benefit of the public and the environment on the surface. The NEL has special conditions which could facilitate this approach. Since the TBMs, being the major equipment on site, are already engaged, it is not problematic to extend their operation to the north as much as possible.

The environmental advantages compared to open trenches for the northern part do not need to be stressed. The only disturbance at surface is around the shafts and other structural elements like ventilation buildings, if required. There might be even the possibility to recover free space on surface, since the double lane roads might not be required anymore, once the tunnel is in operation.

The financial impacts on maximising the TBM operations are minimised, since the TBMs are being used by the project anyway.

5. To the extent that it is within your expertise to comment upon the feasibility of either extending the tunnel or any of your other recommendations, please state whether or not any recommendations are feasible, explaining your reasoning.

With my current knowledge, the extension to the north is feasible. The ground conditions appear favourable. The selected distance between the south bound tube and the railway tunnel is for a short stretch about half a diameter of the road tunnel. The increased risks arising from this separation can be mitigated by the help of compensation grouting while the TBM is under the tunnel. Our report explains as well that the space for TBM retrieval is sufficient.
I have made all the inquiries that I believe are desirable and appropriate and no matters of significance which I regard as relevant have to my knowledge been withheld from the Panel.

Lübeck, 14 July 2019

Lars Babendererde
E  APPENDIX

[A2]  BabEng Report on Options for Extension of the Underground Alignment, North-East Link Project, Banyule City Council, Victoria, dated 2 May 2019
[A4]  CV Lars Babendererde
North East Link Inquiry and Advisory Committee

Dear Lars

We continue to act for Banyule City Council (Banyule), City of Boroondara (Boroondara) and City of Whitehorse (Whitehorse) (collectively, the Councils) in relation to the Joint Inquiry and Advisory Committee (IAC) for the North East Link (Project).

We are instructed to engage you to provide expert evidence in the area of tunnelling.

The IAC has been appointed:

- to hold an inquiry into the environmental effects of the Project under section 9(1) of the Environmental Effects Act 1978; and
- to review the draft planning scheme amendment prepared to facilitate the Project under section 151 of the Planning and Environment Act 1987.

Further details regarding the role of the IAC is set out in paragraphs 1 and 2 of the Terms of Reference. The biography for each committee member of the IAC is available here.

The IAC will hold a public hearing commencing on 25 July 2019.

Scope of Instructions

You are instructed to:

1. review the Ministerial Guidelines for assessment of environmental effects under the Environmental Effects Act 1978 (2006);

2. review the exhibited North East Link Environment Effects Statement (EES) documents, relevant to your area of expertise, including, but not limited to, section 6.4.1 of Chapter 6 of the EES regarding tunnelling;

3. review:
   (a) the Councils submission on the EES, dated 7 June 2019;
(b) the IAC report on Preliminary Matters and Further Information Request; and

(c) any other submissions or documents we subsequently refer to you;

4. prepare an expert witness report that contains your opinion on the following matters, as relevant to your area of expertise:

4.1.1 does the EES contain sufficient information about the geotechnical and hydrogeological condition of the Project area to form a proper basis for understanding the effects of tunnel construction:

(a) as proposed by the Project described in the EES; and/or

(b) any modifications to the alignment, position or length of the tunnel as described in the EES.

4.1.2 from your review of the EES, is there any geotechnical, hydrogeological or engineering reason why the tunnel as proposed could not be extended north towards Grimshaw Street, and/or south towards the Eastern Freeway?

4.1.3 if the tunnel were to be extended, either north or south, what would be the implications for tunnel design at the interchanges?

4.1.4 are there any recommendations that you would make as to specific measures which you consider necessary and/or appropriate to improve the design of the tunnel or to prevent, mitigate and/or offset adverse environmental effects? In answering these questions please explain your reasoning in detail.

4.1.5 to the extent that it is within your expertise to comment upon the feasibility of either extending the tunnel or any of your other recommendations, please state whether or not any recommendations are feasible, explaining your reasoning.

4.2 in due course, review and comment on other parties’ expert evidence in relation to your area of expertise.

5. participate in any expert conclave requested by the IAC; and

6. present your evidence at the IAC Hearing. You should anticipate preparing a short (no more than 30 minutes) presentation to facilitate the delivery of your evidence. The presentation is to be drawn from your expert witness report and may respond to other expert reports (as relevant).

Please ensure you are familiar with the requirements of the Planning Panels Guide to expert evidence (DOCX, 81.8 KB), April 2019 and the IAC Directions and ensure that your evidence is prepared in accordance with the requirements set out in both of these documents.

Relevant documents

The exhibited EES documents can be accessed at:

Please also consider any relevant “information updates” contained on the NELP website:

Key Dates

The IAC Directions are available online here. These directions address a number of important matters including:
• Expert witness reports: directions 8 to 13;
• Expert witness conclaves (meeting of expert witnesses): directions 14 to 30;
• Informal meetings between NELP experts and other experts before circulation of expert evidence: directions 4 to 7;
• Cross-examination of experts: directions 31 to 34;
• The IAC’s independent experts: directions 35 to 3;
• Further information to be supplied by NELP: directions 40 to 45.

Please ensure you carefully read all of the IAC’s directions and note the following key dates below.

▪ Your expert witness statement will need to be circulated by **9:00am on Monday 15 July**. We kindly ask that you provide us with a copy of the report no later than **5:00pm on Tuesday 9 July**.

▪ NELP has offered for its experts to meet with other experts (outside the formal expert conclave process) prior to **5pm Friday 12 July 2019** to discuss issues, view models etc. The IAC has encouraged parties to take-up this offer in the IAC Directions (orders 4-7). If you would like to take up this offer and meet with a NELP expert before you finalise your expert evidence, please let us know as soon as possible and we will arrange for this to occur.

▪ Presentation of the proponent’s case is scheduled to commence on **Thursday 25 July**; and

▪ Presentation of the Councils’ case is likely to be scheduled to commence in mid-August. We will confirm this as soon as possible.

**Key Contacts**

Council’s representative for this engagement will be Terry Montebello, Partner, Maddocks

Terry.Montebello@maddocks.com.au and Phone: 03 9258 3698.

Terry is being assisted by Sophie Jacobs, Senior Associate, Maddocks Phone: 03 9258 3546
Email: Sophie.Jacobs@maddocks.com.au

Please contact **Sophie Jacobs** on 03 9258 3546 if you have any queries or wish to discuss any aspect of these instructions with us.

Yours faithfully

Terry Montebello
Partner
NORTH-EAST LINK PROJECT
BANYULE CITY COUNCIL, VICTORIA

Options for Extension of the Underground Alignment
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[B] Vertical alignment of Option B
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[E] Time schedule North East Link Variations of Option B
EXECUTIVE SUMMARY

Banyule County asked BabEng to elaborate on the following questions in connection with the North-East Link Project, as designed and presented by the State of Victoria:

- Explore technical options for extending the underground portion of the proposed alignment,
- Assess the costs of any viable option, and
- Evaluate the alignment proposal from a resident architect.

Taken in account mentioned constraints like existing railway lines, bridges, underground main gas line, limits in permissible road inclination, and maintaining existing interchanges, one of four theoretical options appeared to be the most viable alternative.

Option B consists of the replacement of the open trench section by continuing the TBM excavations for another 2,500 m of twin tunnels. This option would stand for the following characteristics:

- Reduction of surface roads by approx. 40%
- Replacing the open trench by a fully covered structure
- All through traffic below surface for the major part of the alignment
- Maintaining all major connections and intersections

Further, BabEng was asked to give a cost assessment. A detailed cost estimate would have been beyond the possibilities of this study in the set time frame and budget. Instead, the construction volumes of the different main structures, for example “open trench” or “bridges”, were compared between the reference design and Option B.

Option B shows a substantial reduction of all works on surface, while the further utilisation of the TBMs from the southern alignment section permits the continuation of TBM tunnelling at comparably reduced costs. Classifying all TBM tunnelling related machinery costs as “anyway-costs” for the project, the Option B should be on a comparable level cost-wise with the reference design.

Mr. Fred Buono, a resident architect, submitted an own proposal for the extension of the underground section. BabEng was asked to evaluate the technical underground part of the document and found concordance in regard to the Northern tunnel portal position. Option B used the surface lay-out, as proposed by Fred Buono.
A INTRODUCTION

The Australian State of Victoria plans to improve the road connections in the greater Melbourne area. One of the projects is the North-East Link. It shall enhance the road capacity between the Eastern end of M80 at Watsonia North and the M3 near Bulleen Park in the Southern direction.

The major part of the future alignment North-East Link passes through Banyule City Council. The current reference design incorporates a large underground section in the Southern half of the future road, while the Northern part consists mainly of open trenched or at-surface alignment. In this part the design shows up to 5 lanes in each direction.

Banyule City Council contacted BabEng late 2018 to:

- explore options for extending the underground portion of the alignment,
- assess the costs of any viable option, and
- evaluate the alignment proposal from an architect citizen of the municipality.

For this purpose, BabEng received publicly available documents as listed under “Available Documents”. To further support the study, BabEng had to rely mainly on information gathered from the internet, here especially Google Maps, as well as assessments derived from own photos. Consequently, the findings in this report need to be verified in future design phases.

This study focuses on optimizing the extension of the underground alignment while maintaining the interchanges.

B REFERENCE DESIGN

The current North-East Link Project alignment has been divided into the three project elements, which are 1) connection of the M80 / Road 46 to the Northern tunnel portal, 2) Northern tunnel portal to Southern tunnel portal, and 3) connection structures to the M3 Eastern Freeway.

The second element expands approximately 5.2 km of twin three-lane tunnels. Both parallel tunnels expand from Lower Plenty Road in the North to the proximity of the Veneto Club in Bulleen in the South.

According to the available documents, the tunnels would be constructed using three different tunnelling methods: Cut & Cover, conventionally mined tunnels, and utilising tunnel boring machines (TBMs) (see Figure 1).

The baseline design incorporates about 3.1 km bored tunnels, excavated in parallel by two TBMs. The excavation diameter of 15.6 m would allow for three traffic lanes in the tunnels. The maximum overburden above tunnel alignment is found to be 40 m. Cross Passages (XPs) between the tunnels for safety purposes are planned to be excavated every 120 m.
Cut & Cover

The standard earth moving equipment are implemented for opening a space for construction of the tunnel structure using C&C method. After building of the main structural elements, the tunnel can be covered again with the excavated material, then the created space on surface is available for reusage. It is comparable to the construction of basements. This technique especially applies for shallow alignments above the ground water table. With water drainage, this technology can be applied as well below the ground water table. This technology does not require any overburden and permits flexibility in the tunnel profile. Figure 2 shows an open trench excavated below the ground water table just before construction of the main structural elements of the tunnel.

Figure 1 North-East Link Project alignment – Northern portal to Southern portal [2]
The current project documents show the following cross-section for this method (See Figure 3):

![Figure 2: Construction of Cut & Cover tunnelling](image1)

![Figure 3: Tunnel cross-section of the Cut & Cover section [2]](image2)
Mined Tunnelling
Mining or Conventional Tunnelling is the excavation of cavities below ground with immediate support of the profile, e.g. by shotcrete. Typical machinery for excavation are excavators or roadheader, depending on the ground conditions. The technology requires a certain overburden above the tunnel. Applying temporary water drainage, it can be applied as well below the groundwater table. It offers as well, in certain boundaries, flexibility in the excavated profiles. The mobilisation time for an excavation is rather short due to standard equipment.

Figure 4 shows an excavator that is mining the tunnel face at the crown part of a tunnel profile. In the front of the excavator is the tunnel face consisting in this case of soft rock. The tunnel invert and the side walls are already stabilised by steel wire mesh, shotcrete and rock bolts.

The cross section for a mined road tunnel using an excavator or road header is depicted in Figure 5 and has an excavation area for this project of about 173 m².

![Excavator working at the tunnel face](image)

*Figure 4: Excavator working at the tunnel face*

![Tunnel cross-section of the mined tunnels. [2]](image)
**Bored Tunnelling by Tunnel Boring Machine (TBM)**

A TBM, simplified, is a steel can with a full-face cutterhead on the front side to excavate the ground at once. The steel can give initial support to the ground and protects the workers. In the rear of the can the final round concrete structure is built out of precast elements. With hydraulic jacks the TBM is pushing itself off from the last concrete ring and further excavating the space for the next ring. The TBM can be equipped to work in ground water and in different geologies. TBMs require as well certain ground overburden. Changes in the excavation profile are rather difficult. TBMs require long mobilisation time, but are faster in the tunnelling process, surpassing the other technologies.

Figure 6 shows a TBM ready to advance in an underground cavern. On the left-hand side, the rotating cutterhead. The steel casing gives immediate support to the ground. On the right-hand side would be the concrete lining.

![Figure 6: TBM in underground cavern](image)

Figure 7 shows the cross section for the bored tunnel using TBM. The calculated excavation area is 193 m², 20 m² larger than the tunnel area of a mined tunnel.

![Figure 7: Tunnel cross-section of the bored tunnels](image)
Geology
The geology in the project area mainly consists of folded and faulted Palaeozoic marine sedimentary rocks. The Silurian Anderson Creek Formation and the Melbourne Formation form the bedrock. These sedimentary rocks are mainly siltstones, mudstones and sandstones. According to the “Groundwater Technical Report”, the massive siltstones layers are described as fractured rock aquifers and underlie the entire study area. Therefore, the geological subsurface in the project area is characterized by weathered siltstone and alluvial deposits associated to Yarra River floodplain (See Figure 8 and Appendix [A]). Further information on the geological situation north of Greensborough Road have not been available.

Alignment Constraints
The vertical alignment of the tunnel route needs to fulfill certain constraints due to the infrastructure. The Hurstbridge rail line underpassing Greensborough Road is located north of Watsonia Station and is a limiting factor influencing the position of the tunnel portal. According to [4], the acute angle of the Hurtsbridge rail line causes the TBM to be under the rail line for at least 150 m.

The 450 mm transmission gas main crosses the alignment at Elder Street just opposite of Watsonia Station at a depth of approximately 8 m and drops to 12 m on the northbound Greensborough Road. Hence the gas main is another limiting factor influencing the tunnel length.

Another constraint is the maximum tunnel gradient of 4 %. The grades for entry and exit ramps at Grimshaw were adjusted to a maximum value of 6 % by the Banyule City Council in order to achieve constructability of the Grimshaw interchange. The southbound entry ramp of the interchange Grimshaw Street incorporates a “weave” section to cross over lanes. This specification relocates the start of the entry ramp 150 m south of Grimshaw Street. Further, the land acquisition should be optimised by reducing the usage of private and public land along the roads.

Summarising the above, the vertical alignment needs to take the rail line and the position of the gas main into account by maintaining a necessary vertical clearance for safe passage of
the TBMs. At the same time, the alignment shall retain the functionality of the current interchanges and not to exceed the maximum gradient.

C EXTENSION OPTIONS

BabEng investigated possible options that can be employed for extension objectives. At first stage, four options aside of the reference design (NELP alignment) were identified and described in Table 1 and Figure 9.

In order to draw the vertical alignment of these extensions, the elevation model was extended further north, generated from elevation data provided by Google Earth Pro. The vertical alignment shall retain the functionality of the existing interchanges.

Table 1: Selected options at the first stage

<table>
<thead>
<tr>
<th>Options</th>
<th>Total length [m]</th>
<th>Extension [m]</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>3,100</td>
<td>0</td>
<td>3.1 km twin tunnels with TBM</td>
</tr>
<tr>
<td>Option A</td>
<td>4,000</td>
<td>900</td>
<td>Approx. 900 m in addition excavated by roadheader</td>
</tr>
<tr>
<td>Option B</td>
<td>5,600</td>
<td>2,500</td>
<td>Approx. 2.5 km additional TBM excavation</td>
</tr>
<tr>
<td>Option C</td>
<td>5,800</td>
<td>2,700</td>
<td>Approx. 2.7 km of additional TBM excavation</td>
</tr>
<tr>
<td>Option D</td>
<td>6,500</td>
<td>3,400</td>
<td>Approx. 3.4 km of additional roadheader excavation</td>
</tr>
</tbody>
</table>

Figure 9: Preliminary options for extending the North East Link Tunnel.
An extension of the tunnel northwards is achieved in Option A by a 900 m long roadheader section. The tunnel portal is located near Yallambie Road. Option B extends the tunnel by 2,500 m TBM drive until north of Doris Street. The tunnel portal of the TBM drive of Option C is located northwards of Grimshaw Street near Kempston Street. In Option D a roadheader is used to extend the tunnel by 3,400 m, directly linking to the M80.

Since the geological conditions at this end of the alignment can be described as weak, with shallow overburden and at least partly below ground water table, the risk for unstable tunnel face conditions might be increased applying mined tunnelling options. For this reason and with the current information, BabEng suspends mined tunnelling as viable option for this section and Option A and D are dismissed.

Options B and C were selected for further investigations. The proposed extension options were selected in this report for cost estimations as shown in Table 3 and in Figure 10. These options could be described as follows.

**OPTION B**

Option B as mentioned in Table 3 considers the extension of tunnel for further 2,500 m from Lower Plenty Road to north of Watsonia Station by continuing the TBM operations from the southern alignment part. The northern tunnel portal and ramp lie within the 600 m long open cut trench section, that is extending from the rail line to just north of Grimshaw street (Station 7+950 m).

The maintained minimum clearance to the rail line was calculated to 15 m. The vertical alignment of Option B (see Figure 11 and Appendix [B]) shows the position of the tunnel portal and the gradient of tunnel route. The gradient does not exceed the limitation of 4 % and remains within a range of 1 to 1.7 %. Furthermore, both the interchange Grimshaw Street and the underpass Kempston Street could be maintained. Enhanced available space at Watsonia Station might be used for an intermediate ventilation and access shaft. Due to the increased tunnel length, additional ventilation shafts are necessary. The baseline concept suggests ventilation shafts at the vicinity of the southern...
portal and Lower Plenty Road. An additional ventilation shaft is required at the northern portal. Considering the smoke exhaust shafts, an additional shaft is required at the northern portal.

![Vertical alignment of Option B](image1.png)

**Figure 11: Vertical alignment of Option B**

**3D Model**

BabEng elaborated a 3D model of Option B to depict the complexity of the northern portal at Grimshaw Street. It includes google map information of the wider Grimshaw Street area and the traffic proposal from Mr. Buono, since these are well in line with the investigated portal position of Option B. The southbound merging lane from Grimshaw Street is the most critical lane, as the eastern tunnel tube is the closest to the Hurstbridge Rail line. Further the southbound entry ramp incorporates a “weave” section, that is considered in the design.

The 3D model depicts the different height levels for crucial points given by the alignment constraints. The cross section at the northern portal (see Figure 12) displays a 23 m difference in height between lanes and ground level. The space at the north ramp could be used for the ventilation and operation centre.

![Cross section of the northern tunnel portal displaying the different height levels](image2.png)

**Figure 12: Cross section of the northern tunnel portal displaying the different height levels**

With the vertical alignment of the tunnel route, the difference in height between lanes and Grimshaw Street bridge amounts to 10 m (see Figure 13).
The rail line tunnel crosses the tunnel alignment with a shortest distance of 7 m at the southbound tunnel (see Figure 14). This small distance might require additional protection measures for the rail line, like compensation grouting. This needs to be further investigated.

**OPTION C**

Option C, as mentioned in Table 3, considers the extension of tunnel for further 2,700 m from Lower Plenty Road to Grimshaw Street and using TBM. The tunnel portal would also be located between Watsonia station and Grimshaw Street, but 200 m further north. The tunnel portal has a length of 900 m (see Figure 15 and Appendix [C]). The minimum overburden was found to be 22 m below the rail line. The gradient of the tunnel route is
reduced to a maximum value of 1.6 %. Option C does not allow an interchange Grimshaw Street to the North East Link. In addition, the open cut trench cut offs Kempston Street.

**SUMMARY**

In consideration of the given alignment constraints, Option C does not meet the requirement of maintain the interchange Grimshaw Street. Further, Option C cut offs Kempston Street, which functions as a connection of the western and eastern areas separated by the North-East Link. Therefore, Option C is not an option to expand the North-East Link.

However, Option B does meet the requirements. All alignment constraints are fulfilled. Especially the interchange Grimshaw Street retains its functionality and the maximum-possible tunnel length is achieved. Further, the 3D model shows that a crossing of the rail line is possible. Hence, Option B is recommended as a concept of extending the North-East Link tunnel.

**DESIGN BY FRED BUONO**

In Addition, a design by the architect Fred Buono is provided by the Banyule City Council. This design shows a surface design for the interchanges Lower Plenty Road and Grimshaw Street with a potential tunnel portal near Doris Street. The design of the interchange Lower...
Plenty Road is adapted and the southern entry ramps towards the North-East Link are placed on the eastern and western side of the tunnel route. As described by Mr. Buono, the road design is straightened and simplified and generates safer and smoother traffic flows.

The comparison of the design by Fred Buono with Option B designed by BabEng, illustrates that the concept by Fred Buono correlates well with the vertical alignment of Option B. As seen in Figure 16, the tunnel portal of Option B is located at Doris Street and the distance towards Grimshaw Street should be long enough to not exceed the maximum ramp gradient of the access routes Grimshaw Street – North-East Link.

D  TIME SCHEDULE

To display both the location and time-base dimension of extension options B and C, a time schedule was created covering the entire length of the North East Link. The time schedules can be found in Appendix [D].

The construction of the cut and cover sections located at the interchanges Eastern Freeway, Manningham Road and Lower Plenty Road will start successively. Further, they are needed as start shafts for the mining and TBM sections. The site mobilisation of the Cut & Cover section is assumed to take 45 days and 60 days at the main construction site, followed by the excavation of these sections. The work on the final structures of the sections Manningham Road and Eastern Freeway interchange are assessed to be completed after two years. Since the TBM must pass through the cut and cover section at Lower Plenty Road, the final structures are completed after 2,5 years.

The construction of the mining section south of Manningham Road starts after the excavation of the cut and cover section is finished. The mining takes approximately 213 days.

Roughly one-year delivery and assembly time is needed for the TBM section. The final performance of the tunnel excavation is achieved after five months, assuming a learning curve with a 10 % advance rate within the first month, 30 % within the second, 60 % within the third and a 90 % advance rate within the fourth month. The second TBM will follow eight weeks after the first one started. The time required for the TBMs to pass through the Cut & Cover section is presumed with 50 days. The TBMs will need approximately 167 days for the 2,500 m long extension of Option B. The construction of culverts starts with a 21-week time offset to the TBM start. The construction of the kerbs starts 10 weeks later.

The construction time of the cross passages is expected to take 8 weeks and could commence after the completion of TBM drive 1 and could be finished after 22 months. There is also the possibility to split the construction of the cross passages into a mining part, that can run parallel to the TBM drive, and a finishing part, that follows up TBM drive. The works on tunnel equipment and M & E can commence while installing culverts and kerbs.

In addition, BabEng investigated the temporal impact of varying the amount of TBMs and the location of the start shaft. These variations can be found in Appendix [E]. It should be noted, that the location of the main construction site is not constraint to the cut and cover.
section Manningham Road. Another possible location is Lower Plenty Road.

Table 2 lists the variations of Option B. The concept suggests a northwards tunnel driving direction. Therefore Version 1 of Option B, with two TBMs, needs in total 20 month for tunnelling. A change in direction and an unchanging amount of TBMs leads to an increase in time required for tunnelling. While the duration until completion is reduced by one month due to a more effective processing. Undoubtedly, more TBMs would reduce both the time required for tunnelling and for completion.

Table 2: Time required using different amount of TBMs and varying the start direction

<table>
<thead>
<tr>
<th></th>
<th>Option B V1</th>
<th>Option B V2</th>
<th>Option B-V3</th>
<th>Option B-V4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of TBMs</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Direction</td>
<td>North to south</td>
<td>Centre to shaft</td>
<td>Centre to shaft</td>
<td>Centre to shaft</td>
</tr>
<tr>
<td>Duration Tunnelling</td>
<td>20 months</td>
<td>12 months</td>
<td>21 months</td>
<td>16 months</td>
</tr>
<tr>
<td>Duration Completion</td>
<td>37 months</td>
<td>29 months</td>
<td>36 months</td>
<td>32 months</td>
</tr>
</tbody>
</table>

E COST ESTIMATION

The cost estimation of the extension option is influenced by the limited market expertise of BabEng in Australia. Due to that reason and unavailable cost information of the current North East Project design, the cost evaluation of Option B is compared relatively to the reference design. Hence absolute numbers are not provided in the context of this study. Further, the costs include direct tunnelling costs only. Costs of road construction and tunnel fit-out are not assessed in this study. Cost savings are only shown in relation to the reduction of the length.

The main tunnel and machine parameters which are used for preliminary estimation of costs for extension options are summarized in Table 3.

Table 3: Main TBM and tunnel parameters used in the preliminary cost estimation

<table>
<thead>
<tr>
<th>TBM diameter [m]</th>
<th>Segmental ring internal diameter [m]</th>
<th>Segment thickness [m]</th>
<th>Overcut [m]</th>
<th>Boring diameter [m]</th>
<th>Ring length [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.30 m</td>
<td>14.40</td>
<td>0.50</td>
<td>0.20</td>
<td>15.70</td>
<td>2.00</td>
</tr>
</tbody>
</table>

For the assessment of the costs for the proposed options, both the construction of bored tunnels and Cross Passages are taken into considerations. The following items are considered in order to perform a cost estimation for construction of the bored tunnels:

- Cost of TBMs: Two EPB TBMs with diameter of 15.7 m are considered according to the bored tunnel diameter and geological conditions. Special installations such as the air locks (person and material) are assumed inclusive in TBM. The cost for the medical locks, oxygen, tunnel ventilation and compressed air plant are taken into consideration under this section.
- Precast concrete segment: cost of precast concrete segments inclusive reinforcement bars and the accessories like sealing gaskets, dowels etc. is estimated. The production cost is included.
- Tail void grout and plants: the material cost for the grout volume required to fill the ring gap and the cost of grout mixing plant and silos.
- Personnel: the numbers of working staffs are taken as per the specified task like operation of TBM, erectors, locomotives, cranes etc. The amount to be allocated is then assessed as per the number of working shifts and tunnel construction period with mobilization and demobilization period. It also comprises the cost for the management staffs.
- Tunnel transportation system: the transportation system for tunnel muck disposal within the job site, supply of segments, grout etc. Cranes, conveyer belt, track and walkway locomotives with segment cars, muck cars, person transport, flat bed cars etc. are assessed.
- Pipelines: cost of pipelines to supply industrial water, industrial air, cooling water, tunnel drainage is estimated.
- Consumables: cost of consumables like conditioning agent, electricity, diesel, hydraulic oil, tail skin grease etc. are estimated.
- Muck disposal: cost of tunnel muck disposal from the job site is estimated assuming a fixed price per cubic meter of tunnel muck.
- Site set up: as a parts of site installation fixed cost are adopted for driveways, site offices, workshop etc.
- Rescue tunnels: the lump sum price was considered in the cost estimation. The tunnels are assumed with diameter of 10 m.

The summary of the conducted cost assessments is presented in Table 4. An extended tunnel option reduces the cost per meter of bored tunnel by approx. 16%. Further, these cost savings are also related to the original tunnel length, since the costs for the TBMs are evenly distributed over the entire tunnel length. Material and personnel are time-dependent costs and do not affect the costs per tunnel meter.

It should be noted that the estimated costs here are an approximate estimation and for comparison purpose only. Furthermore, the estimated costs are covering the primary lining structure and are only tunnel related cost. Costs for temporary structures, road construction, M&E and other items are not considered. Further, costs affecting the interchanges and all related cost are not considered. Additionally, the risks and uncertainties associated with an estimate are not calculated within the cost estimations.
Table 4: Summary of estimated costs for baseline option and proposed extension option

<table>
<thead>
<tr>
<th>Options</th>
<th>Total length</th>
<th>Item Description</th>
<th>Reference 3,100 m Budget (AUD)</th>
<th>Option B 5,600 m Budget (AUD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel Boring Machine</td>
<td>3,100 m</td>
<td>TBM with back-up system and Transport</td>
<td>46,695,000</td>
<td>46,695,000</td>
</tr>
<tr>
<td>Personnel</td>
<td>5,600 m</td>
<td>For operation of TBM, Tunnel transportation, Segment erection, Management staffs</td>
<td>8,698,000</td>
<td>12,628,000</td>
</tr>
<tr>
<td>Materials</td>
<td></td>
<td>Installations, Supply of Segments, Grouting, Plants, Tunnel Transportation System, Pipelines, Consumables, Muck Disposal, Site set up, Rescue Tunnels and Launching Thrust</td>
<td>112,966,000</td>
<td>196,087,000</td>
</tr>
</tbody>
</table>

| Total Estimated Cost | 168,359,000 | 255,410,000 |
| Estimated Cost per Meter of Bored Tunnel | 54,400 | 45,700 |

In lack of resilient costing data, BabEng prefer to compare changes in volume of the different structures and options and potential savings are considered relatively by comparing the construction volume. Table 5 summarizes the construction volume estimation for Option B in comparison to the current North East Link Project design. Only for the TBM operation, costs have been assessed. The other tunnelling methods and surface works are compared by using the changes in volume. The TBM-Operation shows that an increase in volume of about 80% (2,500 m extension of the bored tunnels) does generate a cost increase of only 53%. This is mainly due to the already available TBMs on site. Of course, this does not apply to the final structures, road works, M&E, etc. and which are listed under “Mined Tunnel”. The construction volume for Cut & Cover tunnelling is not affected by an extended tunnel on the grounds that the amount and length of the Cut & Cover sections remain unchanged. The volume of Open cut trenches is reduced by 70%, if the Grimshaw Street Interchange is included in the consideration. The amount of surface roads is reduced by 40%

Table 5 Evaluation of volume estimation for Option B

<table>
<thead>
<tr>
<th>Construction work</th>
<th>North East Project Alignment</th>
<th>Option B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mined Tunnel</td>
<td>100 %</td>
<td>188 %</td>
</tr>
<tr>
<td>Cut &amp; Cover Tunnel</td>
<td>100 %</td>
<td>100 %</td>
</tr>
<tr>
<td>Surface Roads</td>
<td>100 %</td>
<td>60 %</td>
</tr>
<tr>
<td>Open Cut Trench</td>
<td>100 %</td>
<td>30 %</td>
</tr>
<tr>
<td>TBM Operation</td>
<td>100 %</td>
<td>153 %</td>
</tr>
</tbody>
</table>

By selecting the Option B, the cost for trenching and the surface use for the project would be reduced considerably. Further, the construction volume of trenches and bridges and the land use decrease (see Table 6). The construction volume of the concrete retaining walls was calculated by assuming a bored pile wall with 1,20 m of diameter and 0,3 m overlap and a
0.5 m thick concrete wall. It includes both the trench section and the Grimshaw Street interchange and is reduced by 66%. The point “trench” considers the trench section area between Lower Plenty Road and Watsonia Station and neglects the trenched Grimshaw Street interchange, resulting in a 100% decrease. With the extended tunnel option the area used for bridges is reduced by 82%. In order to provide public open space and a connection of the trenched area, the North East Project Alignment encompasses land bridges between Lower Plenty Road and Watsonia Station. The extended tunnel option B does not require land bridges. The land use was approximated by using the section and interchange length. The extended tunnel option B causes a decrease of land use by 73%.

Table 6 Evaluation of construction volumes

<table>
<thead>
<tr>
<th>Construction volume</th>
<th>North East Project Alignment</th>
<th>Option B</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trench</td>
<td>57,000 m²</td>
<td>0 m²</td>
<td>100 %</td>
</tr>
<tr>
<td>Concrete retaining wall</td>
<td>172,200 m³</td>
<td>58,000 m³</td>
<td>66 %</td>
</tr>
<tr>
<td>Bridges</td>
<td>11,735 m²</td>
<td>2,135 m²</td>
<td>82 %</td>
</tr>
<tr>
<td>Land use</td>
<td>80,310 m²</td>
<td>21,900 m²</td>
<td>73 %</td>
</tr>
</tbody>
</table>

The surface utilization of the extended tunnel Option B (see Figure 17) is reduced due to the tunnel section between the Lower Plenty Road and the northern portal at Doris Street. Within this area land and buildings remain intact.

Figure 17: Land utilization of the extended tunnel alignment
F  CONCLUSION

Considering the geological and groundwater conditions through the tunnel alignment within the project area from the southern portal to Greensborough Road, two extension Options B and C were selected by BabEng to creating a vertical alignment that fulfils the given alignment constraints. Option C does not comply with the constraints since the connection to Grimshaw Street would not be possible. However, in combination with the proposal by Mr. Fred Buono, it seems that the Option B is the best choice for extending the North-East Link Project using bored tunnelling. The extended tunnel Option B fulfils all alignment constraints. A cost estimation was performed for Option B, keeping in mind the limited market expertise of BabEng in Australia and unavailable cost information of the current North East Project. The cost per tunnel meter are reduced by approx. 16 %. This cost reduction is not limited to the extended tunnel but includes the already planned tunnel section. In lack of resilient costing data, BabEng compared changes in volume of the different structures and options. The trench section is reduced by 100 %, resulting in a decrease of land use by 73 % and less bridges. These evaluations were made by comparing volumes and areas of the current North East Project alignment with the extended tunnel Option B. The values were derived from the available documents. BabEng had to rely mainly on information gathered from the internet, here especially Google Maps, as well as assessments derived from own photos. Consequently, the findings in this report need to be verified in the next design phases.

The whole BabEng team hopes that Banyule County find this report helpful in their considerations. We would be pleased to answer any questions which may arise.

Lübeck, April 2019

Lars Babendererde
G  TBM DISASSEMBLY

In an addendum BabEng was asked to give opinion on the required space for a TBM disassembly at the northern end of the tunnel drive.

Figure 18 indicates a possible scenario to disassemble the TBMs within the ramp area of the future road alignment. The largest part of the TBM is the cutterhead which is typically lift off the TBM in one piece. The size and weight of it does not allow for transport in one piece. A 1,200 t crawler crane with additional counterweight will lift the cutterhead, rotate 180° and place it on the ramp utilizing a second crane for assistance. Once lying flat on the ramp, the cutterhead will be cut into segments and lifted by the assistance crane on trucks for transport off-site.

The main drive unit of the TBM is typically the heaviest single part of the TBM. The same crawler crane will lift the piece out of the TBM and will place it on special brackets for transport. This unit goes onto oversize trucks. Once these parts are off site, the crawler crane leaves the project and is replaced by standard mobile cranes for the remaining machineries.

The approximate duration for this work is about 2 months per TBM. Figure 19 shows an example of a TBM disassembly in a more congested situation. For the disassembly in Melbourne a width of twice the TBM diameter plus half the TBM diameter is suggested.

Figure 18: Construction site plan TBM dismantling.
During construction and dismantling, the new Greensborough Road can be used as the southbound temporary diversion road with three lanes. While, the three-lane northbound diversion road will be located on the western side of North East Link, minimizing the impact on the North Primary School and the AK Lines Reserve (see Figure 20).

![Figure 19: Example of a TBM disassembly in a congested situation](image)

![Figure 20: Possible temporary diversion road at the northern portal](image)
ESTIMATION OF GROUND LOSS DURING TUNNEL EXCAVATION

N. Loganathan¹, H G Poulos² and A Bustos-Ramirez³

ABSTRACT

Excavation of a tunnel provides an opening into which the soil can deform and gives rise to "ground loss". The ground loss is generally defined as the volume of soil that has been excavated in excess of the theoretical design volume of tunnel excavation. In practice, the ground loss values are estimated from empirical correlations based on past experiences. Rowe et al (1992) presented a theoretically-based method for the estimation of ground loss from first principles. This method considers the parameters related to tunnel boring method and soil conditions.

In this paper, design charts are presented to estimate ground loss by performing a detailed parametric study via the theoretical method presented by Rowe et al (1993). These design charts include; (i) a stability parameter which considers tunnel depth from the ground surface, tunnel diameter, earth pressure coefficient, vertical effective stress at the tunnel springline, tunnel face supporting pressure and pore pressure at the tunnel springline, (ii) average soil strength above the tunnel, and (iii) physical gap parameters involved with the tunnel boring machine, including the effects of thickness of tail piece, clearance for the erection of lining, length of shield, maximum allowable excess pitch and thickness of the cutter bead.

The design charts have then used to estimate the ground loss values in the soft ground tunnelling operations for the new Sydney airport link tunnel. These ground loss values have then been used to estimate the surface settlement troughs, and to compare the estimated settlements with those measured. In total, six sections in soft soil have been analysed, and the agreement between theoretical estimates and the measurements has been found to be encouraging.

INTRODUCTION

Rapid growth in urban development has resulted in increased demand for the construction of transportation systems, water supply, and sewage disposal systems. Tunnels are an essential component of these schemes and constitute one of the major portions of project expenditure. Recent advances in tunnelling technology reduce construction time with consequent decreases in cost. However, even with modern equipment, experience has shown that tunnelling-induced ground deformation inevitably occurs in areas above and adjacent to tunnels passing through soft soil deposits. Ground loss that occurs during tunnel excavation induces deformation around the tunnel. In practice, the ground loss values are estimated from empirical correlations based on past experiences. Empirical ground loss values have generally been established without the consideration of the tunnelling methods.

The main objectives of this paper are two-fold: first, to develop theoretically-based design charts to estimate the tunnelling-induced ground loss values considering tunnel boring methods and tunnel boring machine configurations, soil strength parameters, and tunnel configurations such as tunnel depth and diameter; second, to examine the applicability of this design charts by estimating the ground loss values in the soft ground tunnelling operations for the new Sydney airport link tunnel and to compare the measured ground settlement values with the predicted settlements.

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³Design Manager, Airport Link, Transfield Bouygues JV, 42 Church Avenue, Mascot, NSW 2020, Australia.
GROUND LOSS MECHANISM

The estimated ground deformation pattern is greatly influenced by the Ground Loss parameter. The ground loss occurs in 2 stages; (i) undrained, and (ii) consolidation and creep. Rowe et al (1992) proposed a procedure to estimate the ground loss parameter for undrained conditions. The undrained ground loss occurs in 3 stages; (i) ahead of the face, (ii) over the shield, and (iii) upon the errection of the lining. The components of loss of ground induced by tunnelling in cohesive soils are represented quantitatively by the so called gap parameters. The gap is the sum of the 3D elasto-plastic deformation at the tunnel face, over-excavation of soil around the periphery of the tunnel shield due to poor workmanship, and the physical gap that is related to the machine, shield, and lining geometry. The physical gap is determinable once the machine support system is chosen.

**Ground Loss Formulation**

This gap parameter, \( g \), can be used to estimate the case specific ground loss parameter. The undrained gap is estimated as shown in equation (1):

\[
g = G_p + U^*_{3D} + \omega
\]  

\( U^*_{3D} \) is equivalent 3D elasto-plastic deformation at the tunnel face. The volume of soil that intrudes into the tunnel face owing to pressure release at the face will eventually be excavated. There is a volume of lost ground equal to the amount of over-excavated material at the face called the face loss, \( V_f \). \( G_p \) is the physical gap of the tunnel system, given by \( G_p = 2\Delta + \delta \), where \( \Delta \) is the thickness of tailpiece and \( \delta \) is the clearance for erection of lining. \( \omega \) takes into account the quality of workmanship. This component includes the radial ground loss due to the over cutting bead.

Loganathan and Poulos (1998) redefined the method of estimating ground loss based on the gap parameter, \( g \), and developed the “equivalent undrained ground loss, \( \varepsilon_0 \), shown in equation (2):

\[
\varepsilon_0 = \frac{4gR + \frac{g^2}{4R^2}}{R} \times 100\%
\]  

where \( R = \) radius of the tunnel.

**Ground Loss Estimation Charts**

Based on the analytical results presented by Rowe et al (1992), and by combining equations 1 and 2, an attempt has been made to produce charts to estimate the ground loss values. A parametric study was carried out to assess the influence of each soil and tunnel configuration parameter. Basic factors considered are: tunnel depth/tunnel diameter ratio, soil strength, earth pressure coefficient, soil unit weight, Poisson’s ratio, internal air pressure applied during tunnelling, length of the shield, thickness of tail piece, clearance for erection of lining, maximum allowable excess pitch, bead thickness, and the grouting history.

The following dimensionless parameters were considered in the parametric study:

1. **Stability Parameter, NP**

\[
NP = \frac{H \gamma - p_0}{c_u}
\]  

where \( H = \) depth of tunnel from the surface, \( \gamma = \) bulk unit weight if the soil, \( p_0 = \) total stress removed at the tunnel face, and \( c_u = \) undrained strength of the soil. The total stress removed, \( p_0 \), may be expressed as given in (4):

\[
p_0 = (k_0 p_v + p_w) - p_i
\]
where $k_0$ = effective co-efficient of earth pressure at rest, $p_v$ = vertical effective stress at the tunnel spring line, $p_w$ = pore pressure at springline prior to excavation, and $p_i$ = tunnel face supporting pressure.

2. Average soil strength, $c_u$ ($E_u = 400 \ c_u$)
3. Physical gap parameter, $PG$

$$PG = t + \Delta + L \theta + t_b$$

where $t$ = thickness of tail piece, $\Delta$ = clearance for the erection of lining, $L$ = length of shield, $\theta$ = maximum allowable excess pitch, and $t_b$ = thickness of cutter bead.

Since the stability parameter plays a major role (Mair et al, 1981) in the magnitude of the ground loss, the ground loss values are calculated for various NP values. The other parameters have then been varied and the influence of each factor estimated. The ground loss may be expressed as in equation (6):

$$\varepsilon_0 = \varepsilon_{NP} f_{cu} f_{PG}$$

The ground loss component attributed to the stability number may be obtained from Figure 1.

It is observed that the Poisson’s ratio $\nu$ does not have any significant influence in the estimation of the ground loss. The Young’s modulus of the ground is estimated using the approximate empirical relationship $400 \ c_u$. The ground loss components corresponding to various ground stiffness (in terms of soil strength) are calculated and the influence factor $f_{cu}$ is calculated as shown in equation (7):

$$f_{cu} = \frac{\varepsilon_{cu}}{\varepsilon_{NP}}$$

The ground loss influence $f_{cu}$ is plotted as a function of $c_u$ in Figure 2.

The ground loss influence factor for the physical gap parameter, $f_{PG}$, is shown in Figure 3.

Figure 1 : Ground loss component $\varepsilon_{NP}$ % Vs. Stability Parameter, NP

Figure 2 : Ground Loss influence Factor Vs. Soil Strength
CASE HISTORY: Airport Link, Sydney, Australia

The New Southern Railway (NSR) in Sydney, Australia, involves the excavation of approximately 10 km of single bore tunnel from Tempe Reserve, Tempe, to Princes Alfred Park (PAP). PAP is located just south of Central Railway Station in Sydney's Central Business District (CBD). From Tempe Reserve the alignment takes the tunnel under Sydney Airport including the main north/south runway. Sydney Airport is approximately 8 km south of CDB.

Approximately 6 km of the 10 km tunnel is in soft ground (clays and sands) and it has been excavated by a 10.7 m external diameter Herrenknecht slurry Tunnel Boring Machine (TBM). TBM parameters used in this study to estimate the ground loss are given in Table 1.

<table>
<thead>
<tr>
<th>Method</th>
<th>Slurry tunnel boring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of Shield, ( L )</td>
<td>10 m</td>
</tr>
<tr>
<td>Thickness of tail piece, ( t )</td>
<td>50 mm</td>
</tr>
<tr>
<td>Clearence for errection of lining, ( \Delta )</td>
<td>35 mm</td>
</tr>
<tr>
<td>Maximum allowable excess pitch, ( \theta )</td>
<td>0</td>
</tr>
<tr>
<td>Bead thickness, ( t_b )</td>
<td>20 mm (full circle)</td>
</tr>
<tr>
<td>Skin grouting</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 2: Soil Parameters, Section MP 7550

<table>
<thead>
<tr>
<th>Location</th>
<th>B5-Runway I6, MP 7550</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth, ( H )</td>
<td>30.2 m</td>
</tr>
<tr>
<td>Diameter, ( D )</td>
<td>10.7 m</td>
</tr>
<tr>
<td>Soil type</td>
<td>Alluvial Clay, A5</td>
</tr>
<tr>
<td>Poissons ratio, ( \nu )</td>
<td>0.5</td>
</tr>
<tr>
<td>Undrain Strength, ( c_u )</td>
<td>120 kPa</td>
</tr>
<tr>
<td>Earth pressure coefficient, ( K_0 )</td>
<td>0.6</td>
</tr>
<tr>
<td>Unit weight, ( \gamma )</td>
<td>20 kN/m³</td>
</tr>
<tr>
<td>Depth of water table (from surface)</td>
<td>1 m</td>
</tr>
<tr>
<td>Slurry pressure, ( p_i )</td>
<td>453 kPa</td>
</tr>
</tbody>
</table>

The ground loss value for a typical section (MP 7550) was estimated using the design charts presented in Figures 1, 2 and 3 and the soil parameters presented in Table 2 (Transfield Bouygues JV, 1995).

The ground loss, \( \varepsilon_{0b} \), estimated from the proposed design charts, was 0.4%. Comparisons of settlement predictions made using this ground loss value and the measured values are shown in Figure 4. The finite element predictions reported by Transfield Bouygues JV, Report: 14.TR.205, are also incorporated. It may be observed from Figure 4 that the measured settlements are smaller than the predictions using both the method proposed in this study and the FEM analysis.
The surface settlement trough shown in Figure 4 has been predicted by a closed-form solution presented by Loganathan and Poulos (1998), shown in equation (8):

\[
U_{z=0} = 
\varepsilon_0 R^2 \frac{4H(1-\nu)}{H^2 + x^2} \cdot \exp \left\{ -\frac{1.38x^2}{(H + R)^2} \right\}
\]

where \( U_{z=0} \) = ground surface settlement; \( R \) = tunnel radius; \( z \) = depth below ground surface; \( H \) = depth of tunnel axis level; \( \nu \) = Poisson’s ratio; \( \varepsilon_0 \) = ground loss ratio and \( x \) = lateral distance from tunnel centerline.

Figure 4: Measured and Predicted Surface Settlements, Airport Link, Sydney, Australia (Field measurements and FEM predictions based on Report: 14.TR.205, Transfield Bouygues JV, 1995)

Similar predictions were carried out for few other sections MP5530, MP6925, MP7750, MP8060 and MP8600. Only centerline settlements were measured for these sections and therefore it is not possible to make any comparisons with the settlement trough predicted using equation (8). Table 3 shows the estimated ground loss values using the proposed design charts, the maximum settlement predicted using equation (8), and the measured settlements measured at the surface above the centreline of the tunnel.

Table 3: Estimated Ground Loss Values and Comparisons of Settlement predicted and measured.

<table>
<thead>
<tr>
<th>Tunnel Section</th>
<th>Tunnel Depth (m)</th>
<th>Soil Profile</th>
<th>Estimated Ground Loss (%)</th>
<th>Measured Settlement (mm)</th>
<th>Predicted Settlement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MP5530</td>
<td>20</td>
<td>0 - 18m: Dune deposit 18 - 20m: Alluvial &amp; residual clay &gt; 20m: Sandstone</td>
<td>0.29</td>
<td>4.0</td>
<td>7.6</td>
</tr>
<tr>
<td>MP6925</td>
<td>16</td>
<td>0 - 14: Sandy soil 14 - 20: Alluvial clay &gt; 20: Sandstone</td>
<td>0.55</td>
<td>16.0</td>
<td>17.2</td>
</tr>
<tr>
<td>MP7750</td>
<td>25</td>
<td>0 - 7: Sandy soil 7 - 30: Alluvial clay &gt; 30: Sandstone</td>
<td>0.56</td>
<td>5.0</td>
<td>9.4</td>
</tr>
<tr>
<td>MP8060</td>
<td>20</td>
<td>0 - 8: Sandy soil 8 - 32: Clay/sand mixd layer &gt; 32: Sandstone</td>
<td>0.31</td>
<td>8.0</td>
<td>7.7</td>
</tr>
<tr>
<td>MP8600</td>
<td>20</td>
<td>0 - 13: Sandy soil &gt; 13: Sandstone</td>
<td>-0.11</td>
<td>-4.0</td>
<td>-2.7</td>
</tr>
</tbody>
</table>
Table 3 shows that the maximum settlements predicted using ground loss values estimated from the proposed design charts compare reasonably well with the measured maximum surface settlements above the tunnel centreline. The differences observed in predicted and measured values may be due to the existence of a mixture of interbedded sand and clay layers.

The tunnel was partially excavated through a sandstone layer in sections MP5530, MP6925 and MP8600. The ground loss design charts over-predict the ground loss values for tunnels partially excavated through the sandstone layer and therefore the settlements predicted were slightly higher than the measured settlements.

It may be observed that ground loss values estimated for all six sections were less than 1% due to the slurry shield tunnelling method used in this project. At section MP8600, a negative ground loss, and therefore a heave in the ground surface was observed, due to excessive slurry pressure applied on the tunnel face.

CONCLUSIONS

Excavation of a tunnel provides an opening into which the soil deforms, and gives rise to "ground loss". In this paper, theoretically based design charts have been established to predict the ground loss values prior to the tunnel construction. This design charts were then used to estimate ground loss values for a total of six sections of the Airport link project in Sydney. Surface settlements were predicted using a closed-form solution presented by Loganathan and Poulos (1998). Predicted settlements using the estimated ground loss values compared reasonably well with the measured settlement values, although in some cases, the comparisons were not close due to complex and interbedded overburden soil conditions.

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REFERENCES


CURRICULUM VITAE

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PROFESSIONAL CAREER

1996 Managing Partner of worldwide operating engineering company BabEng GmbH (formerly Babendererde Engineers GmbH), specialised in mechanized tunnelling and underground works; and “tunnelsoft” for specialized software solutions in the tunnelling industry.

1991 Founding partner of engineering consultancy together with Dr. Siegmund Babendererde.


1986 – 1987 Part time representative for German speaking countries for tunnel guidance systems manufacturer ZED.

Court Assigned or Interested Expert Witness / DRB and Insurance Work
- Court assigned expert for court cases in Germany.
- Interested Expert Witness, in court cases and in DRB proceedings, on various projects in Argentina, Canada, Chile, China, Germany, Ireland and USA.
- Expert witness for insurances and loss adjusters on various projects in the Americas, Asia, Australia and Europe.

Panel Work
- Member of the Board of Consultants, PPP Espresso Linha 6, Metro São Paulo, Brazil
- Chairman of the independent Strategic Review Panel, Waterview Tunnel Project, Auckland, NZ
- PoE member for the Sacramento River Delta Habitat Conservation and Conveyance Program Phase 1, USA
- Member of Client’s Panel of Experts during design and construction phase, Metro Barcelona, Spain
- Member of independent Technical Committee during construction phase Railway Tunnel, Hallandsås Project, Sweden
- Member of the Panel of Experts for Client during tender and construction start phase, Metro Thessaloniki, Greece
- Member of the Panel of Experts for Client during design and construction phase, Service Tunnel North Dorchester Bay, Boston, MA, USA
- Assistant to POE member Dr. Siegmund Babendererde, employed by The World Bank, Shanxi Wanjiazhai Yellow River Diversion Project, PR China

Site Experience
- Special troubleshooting assignments in Brazil, Canada, Germany, Italy, Turkey, Peru, Portugal and South Africa.
- Assisting in compressed air work planning, execution and troubleshooting.
- Working as contractor’s staff during the professional career during normal TBM operations on the Philippines.
- Work experience during education in conventional excavated tunnels, pipe-jacking projects and TBM metro tunnels in the ’80s in Frankfurt, Berlin, Mannheim and Karlsruhe (all Germany), Lyon (France) and Edmonton (Canada).
PROFESSIONAL CAREER, CONTINUED

Other Tunnel Related Design Experience

- TBM manufacturers in Schwanau, Kiel and Rostock, all Germany
- TBM guidance system manufacturer ZED-Instruments, London, UK

EDUCATION

1991 Diplom-Ingenieur (FH) in Mechanical Engineering
University for Applied Science Friedberg, Germany

MEMBERSHIPS

ITA Supporting Member of the International Tunnelling Association
2007 – 2016 Animator of Working Group 14 “Mechanized Tunnelling”
Since 2017 Member of the Executive Committee

UCA of SME Underground Construction Association of the Society for Mining, Metallurgy and Exploration, USA

BTS British Tunnelling Society

DAUB Member of the German Tunnelling Committee (Deutscher Ausschuss für Unterirdisches Bauen), an advisory
panel to the legislative bodies, consisting of thirty individuals of the underground construction industry.

STUVA Studiengesellschaft für Tunnel und Verkehrsanlagen (Research Association for Tunnels and Transportation
Facilities, Germany)

LIST OF PROJECTS

Special Projects

- Concept and design of energy storage facilities in shafts; USA and Germany.
- Partial concept for trenching equipment with material transport and ground support by foam; USA.
- Concept, design and construction management for a pedestrian tunnel under railway line by box-jacking in Wolfsburg;
  Germany.
- Concept, design, tender and construction management of underground structures in compressed air to recover tie-back
  anchors in downtown Leipzig; Germany.
- Concept assistance for TBM and extru-concrete lining development in The Netherlands.
- Concept and tender for TBM drive with extru-concrete and slipform for 4.3 m tunnel in Germany.
- Concept and tender for TBM drive o.d. 12 m with extru-concrete lining and segments in Germany.
- Development of a transport system for concrete segments in a tunnel boring machine for a manufacturer in Kiel,
  Germany.
- Development of a remote controlled pipe jacking machine with fully controllable and active, true EPB face support for a
  manufacturer in Rostock, Germany.

Project Development and Design

Participation in early phase planning and design of various projects in diameters starting from small pipe-jacking
applications to XXL diameter excavations for road tunnels.

Assignments for contractor, designer and owners in Europe, the Americas and Australasia. Executed services:

- Pre-calculation and excavation concepts
- Feasibility studies
- Design for civil works
- Mechanical component design
- Special applications
- Software concepts

Consulting

World-wide assignments for contractors, engineers and owners in support for underground projects, involving hand-mining,
soft-ground, hard rock excavation equipment and compressed-air works in horizontal, inclined and vertical applications.

Special assignments for components design or workflow optimizations for trenching, variations in tunnel boring machines
and tunnel linings.
PUBLICATIONS

- “Continuous Face Support with Large Diameter TBMs”, Cutting Edge Conference, Miami FL, USA, 2012
- “Selection Process for Tunnel Boring Machines”, SAT Congress São Paulo, Brazil, 2012
- “TBM vs D&B – a difficult choice in mountain terrain – some geotechnical guidelines”, ISRM Congress Beijing, China, 2011
- “Segment Design for a Main Sewer Project under Earthquake Influence and high Exposition class using Fibre Reinforced Concrete”, article in “Geotechnik”, October 2009.
- “Site Supervision and Quality Assurance of a Project with several TBM drives”, article in magazine „Tunnel“, June 2009.
- “Selection Criteria for the Mechanised Tunnelling Method”, article in Road and Rail Magazine, India 2008
- “TBM with Slurry- or EPB-Face Support, Application and Reliability Analysis”, Geomechanik Kolloquium, Salzburg, Austria, 2003.
- “Problems of TBMs in water bearing ground”, Summerschool, University of Innsbruck, Austria, 2003.
- “Developments in polymer application for soil conditioning in EPB-TBMs“, ITA Conference Tunnels and Metropolises, Sao Paulo, Brasil, April 1998.
- „Auswahl von Tunnelbohrmaschinen für den Vortrieb in nicht standfestem Gebirge“ (Selection of tunnel boring machines in unstable ground conditions), Hamburger Baumaschinen-Seminar, Hamburg, Germany, November 1995.
- “Problems with main bearing seals for large diameter EPB-TBMs”, STUVA / ITA-Congress; Stuttgart, Germany; May 1995.
- “Advanced Techniques for EPB-TBM Operation”, Study day, Association Belge des Techniques et de l’Urbanisme Souterrains; Antwerpen; Belgium, November 1994.
- Lectures in workshops, organized by ITA on tunnel and monitoring related topics in Azerbaijan, Brazil, Canada, Chile, India, Saudi Arabia, Mexico, Vietnam and Thailand.
- Lectures at post-educational programs at the University of São Paulo., Brazil.
- Workshop for customer’s internal training programs.