Segment Design for a Main Sewer Project under Earthquake Influence and High Exposition Class using Fibre Reinforced Concrete

R. Bishop¹, L. Babendererde², B. Candia³

¹McConnell Dowell Constructors, Auckland, NZ; ²Babendererde Engineers LLC, Vancouver, WA, USA; ³Independent Consultant, La Paz, Bolivia

1. Introduction

The Hobson Bay Orakei Tunnel Project is a part of the general replacement and capacity enhancement program that will adjust water treatment capacities with the increasing demands of the City of Auckland. Local water supplier “Watercare” will replace a 90 year old piled pipeline, which crosses the Hobson Bay above the water level. The new tunnel will be part of a mixed water system. The system will carry rain water as well as sewage from households.

The pipeline replacement will not only improve the view of one of the most toured attractions in Auckland; the Tamaki Drive, it will also enhance recreations possibilities for Hobson Bay. (Fig. 1)

![Fig. 1: Hobson Bay Project Lay-out](image-url)
The design-bid-build project was awarded to the Joint Venture of McConnell Dowell Constructors, Ltd. and Fletcher Construction Company, Ltd. McConnell Dowell was responsible for the tunnel construction and temporary TBM shaft. Fletcher's responsibilities included building an adjacent pump station, the permanent shafts and removal of the existing pipeline. McConnell Dowell utilized the design Joint Venture of Peters & Cheung, Ltd and Babendererde Engineers. Peters & Cheung was the geotechnical engineer and designer for the TBM shafts and conventional tunnels. Babendererde Engineers was responsible for the segment design and TBM related engineering services during tender and construction.

2. Lining Design Process

The lining design process for the Hobson Bay Tunnel project consisted of:
- review and synthesis of geotechnical conditions, (geotechnical data and baseline reports supplied by the Owner);
- establishment of appropriate ground constitutive behaviour and appropriate parameters;
- assessment of seismic influence and liquefaction issues in case of an earthquake;
- development of a practical geometrical arrangement for the segments;
- selection of gasket and lining connection devices;
- assurance of durability of concrete segments for a 100-years service life,
- development and execution of numerical models to establish ground-lining interaction and corresponding lining stresses;
- confirmation of segment thickness and concrete strength,
- structural design and detailing of segment reinforcement, and
- preparation of detailed construction drawings.

3. Geology

The tunnel as planned had a maximum cover of approximately 23 m in the proximity of the Bay. It increased to 80 m close to Coates Avenue in the East of the project alignment. A typical longitudinal section is provided in Fig. 2.

Fig. 2: Typical geological longitudinal section with tunnel alignment
The theoretical water pressure at the tunnel crown was at about 3.0 bar, oscillating to the tidal influences in the Hobson Bay. The tunnel drive was embedded with till and sandstone layers and lied mainly within the “East Coast Bay Formation” (ECBF).

During the first 400 m of the TBM drive the crown consisted of “Recent Alluvium”, which are young deposits consisting of soft to very soft till, locally only mud. Between chainage 1,500 m and 1,700 m the drive cut through “Ash/Tuff” (volcanic sediments) and “Older Alluvium” in the crown. The Older Alluvium consisted of silty clay with moderate stiffness and relatively good water permeability.

In the tunnel direction going East to West, the tunnel alignment rose 1%.

4. Seismic Influence and Liquefaction

New Zealand is located within the earthquake prone zones of the Pacific Rim. Light earthquakes occur frequently, almost on a daily basis. They are usually too weak to be felt by the population, yet earthquakes with strength of 4 to 6 of the Richter scale have a high probability

When compared to surface structures, underground structures are generally less sensitive to seismic effects. Although in adverse circumstances, tunnels could be severely damaged. Seismic effects on underground tunnel structures are divided into two different groups: Ground Shaking and Ground Failure [12].

Ground Shaking addresses seismic waves induced by moving tectonic plates. These waves result in ground movement perpendicular to the wave propagation. Waves acting parallel to the tunnel axis tend to induce a cross deformation into the tunnel structure. Waves acting perpendicular to the tunnel axis tend to move the structure back and forth in longitudinal direction. At transition zones between different ground conditions and at changing structures the uniform waves could suddenly change and induce high loads onto the structure. The main contribution of deformations and corresponding stresses in long linear structures is caused by so-called travelling waves. It is assumed that the tunnel and the surrounding soil are moving together as the seismic waves pass by.

Three types of deformation may be imposed onto the tunnel structure as a result of the Ground Shaking: 1) axial deformation (compression and tension), 2) curvature deformation and 3) ovalization. To simulate these deformations the soil surrounding the Hobson Bay Tunnel was horizontally distorted in the static analysis using the finite difference program FLAC, (i.e. each point of the ground was moved horizontally, starting at the tunnel invert and linearly increased up to the crown). The strains inside the structure, as calculated for the different surrounding soil types, must be below the capacity limits of the concrete.

Ground Failure relates to many different categories of ground instability. Such forms of ground instability may be faulting, landslides, soil liquefaction, tectonic heaves and subsidence. Each of these can be disastrous for underground structures as the bedding in the ground is in question.

Areas with high liquefaction susceptibility of the soil may cause more damage to underground structures than to those on the surface. Soil liquefaction is the result of heavy vibrations of hydrous, fine, sandy soil during an earthquake. Particularly affected are sandy layers with low water permeability, which tend to lose shear strength under seismic loading. If the soil liquefies, these fine-grained materials behave like a liquid, rather than solid ground. This risk increases with the intensity and duration of the earthquake, as well as with the level of ground water pressure. It increases with the density of the sand [6]. The looser the sand density, the higher the potential for liquefaction. Stiff, geologically biased tone and similar cohesive soils are not prone to liquefaction.
Two (2) further criteria for assessing the liquefaction potential of soil were proposed by the Southern California Earthquake Centre and by the Chinese Criteria. According to the Californian criteria clay like soils may be classified as non-liquefying if the clay content is greater than 15 %, in particle with a diameter of less than 0.005 mm.

Based on the "Chinese Criteria" (Seed and Idriss, 1982) clay like soils should be considered as liquefaction susceptible soils if they have the following characteristics:

- Grain percentage finer than 0.005 mm is less than 15%,
- Yield point of less than 35%, and
- Water content greater than 90% of the yield point

The liquefaction potential for the Hobson Bay Tunnel was assessed on the above mentioned criteria due to missing New Zealand Standards for the assessment of liquefaction hazards in tunnelling,. The probability of soil liquefaction has been identified as unlikely to very low according to the grain size distribution and the Atterberg limits of the soil along the tunnel alignment. Therefore, this risk in the broader planning process was able to be excluded.

5. Tunnel Lining Design Requirements

5.1 Segment and Ring Geometry

The tender documents incorporated a proposal for the segmental lining. Nevertheless, the contractor had to extend the design and detailing to make it compatible with the planned construction works. The lining thickness and the inner tunnel diameter were chosen according to the Client’s preliminary design and later confirmed during the final design process.

To facilitate the ring erection during construction, a universal ring system was selected. It consists of a single ring type and thus ensures that always the correct ring is available on the TBM. It allows further reducing the number of expensive segment moulds and the simplification of the logistics during production and delivery. The segments are rhomboid and trapezoidal. This has the advantage that unfavourable cross joints may be avoided for almost all ring combinations.

The selected 1.20 m long ring has a double taper and consists of six roughly equal size stones with 25 cm thickness, of which two opposite trapezoidal segments can be used as keystones. The remaining four segments have a rhomboidal form (Fig. 3). With this ring system a straight line is achieved by 180° rotation of adjacent rings. This leads to the majority of key positions in the upper half of the segmental ring. The overall taper of 20 mm allows the lining to follow a radius of about 250 m which is well below the theoretically necessary 500 m.

For installation, constructive and structural reasons, the lining segments are provided with 2 bolt positions in the longitudinal joints and with 2 dowels per segment in the ring joints. To allow the requested water tightness of the tunnel lining all segments are equipped with one EPDM gasket frame. The grouting of the ring gap behind the segments is executed through the segments and not through the shield tail due to geometrical limitations.
Durability

One of the most challenging requirements was the 100-year service life of the tunnel lining. Steel fibre reinforcement for the segments was selected after carefully weighing the pros and cons, including the significant benefits for the tunnelling in terms of durability, the facilitating and accelerating of work processes, the strengthening of segment edges from chipping and the improved crack width control.

Pursuant to the German/European requirements of DIN 1045-1 the durability of supporting structures is fulfilled once their performance and sustainability is verified to the same standard structural rules and concrete requirements as stipulated in DIN EN 206-1 and DIN 1045-2 and transferred to the construction according to DIN 1045-3.

The relevant exposure class for the sewage tunnel is selected depending to the surrounding conditions to which it is directly exposed to. According to Table 3 of DIN 1045-1, XA3 was selected for chemically strong attacking environment and associated with a minimum concrete strength class C35/45.

The new DBV-sheet (German Concrete Association) “Steel Fibre Reinforced Concrete”, issue October 2001, recognizes the inclusion of a sacrificial concrete layer for the verification of a cross-section without steel bar reinforcement. According to Table 8.2 of this sheet the sacrificial layer for class XA3 had a thickness of 40 mm. This thickness may be reduced by 5 mm if the actual selected concrete class is at least two classes higher than requested according to Table 3 of the DIN 1045-1. With a selected class of C50/60 the reduction could be applied and resulted in a sacrificial layer to 35 mm.

Under the old DBV-sheet “Design Basis for Fibre Reinforced Concrete in Tunnels”, issue September 1992, the corrosion risk of steel fibre is accounted for by reducing the static thickness by another 20 mm, if the tensile elongation surpasses 0.15 ‰ in the tensile area. This would mean an effective lining thickness of 195 mm at this project.

It is should be highlighted that this further reduction in respect to fibre corrosion is no longer necessary according to the newer DBV-sheet issued in October 2001. Nevertheless, the segment design included this old request in the further steps.
Design Sections

For the segmental lining design, the following critical sections along the tunnel length were taken into consideration:

- CH 2+300 represents the section with the highest overburden, where the tunnel is full face in ECBF rock.
- CH 1+650 represents the section under Hobson Bay with the upper half of the tunnel face in Old Alluvium and the bottom half within ECBF rock.
- CH 0+300 represents the section under Hobson Bay with the upper half face in Recent Alluvium and the remaining half located in ECBF rock.

An additional design section has been analysed, which considers the hypothetical possibility of a full face Recent Alluvium at CH 0+300. This additional and more conservative scenario is unlikely to happen. According to additional geotechnical investigations in the vicinity of CH 0+300, carried out upon the Contractor’s request, the tunnel face is never in a full face Alluvium condition. Nevertheless, design computations confirm that, even in such extreme condition, the tunnel lining maintains its functionality and fulfils all design requirements.

The structural design, carried out using the closed-form analysis model according to Duddeck and Erdmann [6], requires a minimum steel fibre reinforcement of 40 kg/m³ for the entire tunnel alignment. However, for CH 1+650 and CH 0+300 a minimum steel fibre content of 45 kg/m³ was used in order to take into consideration any possible geological uncertainties. After a careful laboratory test program, carried out in a German and an Australian university, on steel fibre types regarding performance, dosages and technical features, Maccaferri WIRAND® FF3 steel fibres were chosen.

6. Construction

Construction started in August, 2007 with site establishment and shaft sinking. In addition to the permanent pump station shaft an access shaft for the tunnel works and TBM assembly and launch was also started.

The TBM access shaft was completed by the end of October and works commenced on the construction of a 45 m long access drive to connect the two shafts together. The access drive was completed in January 2008. Primary support for the access drive was carried out using 3 m long rock bolts and wire mesh, installed as the tunnel advanced. This is the minimum support required in the weak (5-10 MPa) interbedded sandstones and mudstones of the Waitemata series East Coast Bays Formation (ECBF). Following excavation and primary support the access drive was lined with a 300 mm thick cast insitu concrete lining with conventional bar reinforcement.

Whilst the access drive was under construction the TBM was being manufactured and tested by Lovat Canada for delivery in New Zealand in May 2008. The completed access drive allowed the TBM to be fully assembled and commissioned on delivery. Excavation was scheduled to start on the 11 June 2008 and works started as planned on that day after only four full weeks of assembly and commissioning.

The East Coast Bays Formation (ECBF) is predominantly self supporting and the normal operating parameters of the TBM were with an unpressurised plenum chamber. Ground conditioning was used to assist in spoil handling through the TBM since the ECBF breaks down rapidly releasing swelling clays from the matrix which can clog the cutter head and screw conveyor. Trials of ground conditioning products were carried out in the first six weeks of tunnelling to determine the best product for optimal productivity. In full production excavation was completed in less than 20 minutes and ring building took a further 20 minutes, giving an overall cycle time of just under one hour.
Tunnelling was maintained consistently within the original contract programme and the main tunnel works were completed in January 2009, 17 days ahead of the contract programme. Figure 4 shows the construction time chainage programme.

Fig 4: Annotated time chainage programme.

Following the completion of the TBM tunnelling the site was demobilised in early 2009 and the temporary access shaft backfilled and reinstated. Commissioning will be completed in early 2010 with works to demolish the old sewer commencing immediately after acceptance.

7. Conclusions

The project under the Hobson Bay posed challenges to all involved parties. On the one side the application of solely fibre reinforced segments resulted in a highly competitive design. Nevertheless it asked from the client, the designer and the contractor intense studies and discussions during the early project phase to find the optimal solution. The special project requirements caused by the earthquake prone location and by the high durability specifications could all be fulfilled.

The lining geometry itself has already been proven before on a number of sanitation projects. Here, under the Hobson Bay as well, it demonstrated its flexibility and ease to work with.

With the increasing number of steel fibre applications and with the gain of experience in its long term behaviour this technology will become a tunnelling standard for sanitation projects in the future.
References


