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Investigation of the remaining life of an immersed tube tunnel in The Netherlands

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ABSTRACT: In this paper we present issues related to the performance of immersed tube tunnels in the Netherlands. A range of issues are experienced for the ageing structures including long-term settlement at tunnel joints and consequent leakage. Because of the age of these structures some important aspects are often unknown thus creating uncertainty regarding remediation measures. Having discussed general issues the paper presents a case study of the Kil Tunnel which has experienced relatively large settlements over the past 40 years. In this case a lack of geotechnical engineering information for the soils below the tunnel was identified. A geophysical survey was undertaken and this provided ley insights into the ground conditions at the tunnel site.

1 INTRODUCTION

Worldwide, renovation of tunnels is becoming a huge challenge. Due to large costs and the need for accessible infrastructure, choices need to be made as to which tunnels will be renovated first or how to divide the renovation in affordable and practical parts, which renovations can be postponed and what should be the scope. Whilst a range of asset management strategies have been developed for road and rail infrastructure, the application of these approaches for tunnels is limited because of lack of data:

(i) From a structural perspective there is uncertainty in assessing the residual life span of the structure due to a lack of information on aging behaviour for joints, transitions and foundations.
(ii) The relationship between changes in the physical environment of the tunnel (soil, groundwater, changing river depths and widths, construction other structures) and the expected residual life span is uncertain.
(iii) Traffic loading is evolving and in conjunction with innovations in vehicle types this provides a further challenge in assessing future loading conditions in tunnels.

In this paper we consider the impacts of ageing on tunnels in soft soils common in the Netherlands. We focus on immersed tube tunnels as this was a very popular form of construction in the Netherlands from the 1960's onwards and a number of tunnels are due for major renovation in the coming years.

2 TUNNELING IN THE NETHERLANDS

2.1 *Background*

The majority of early road and rail tunnels constructed in the Netherlands were located away from urban areas. As a result, immersed tube and cut-and-cover methods were used exclusively from 1941 up to 1999. The need to minimize ground movements in the soft deltaic ground conditions with high water table levels during the development of metros lines in the major cities resulted in bored tunnelling technologies being deployed in approximately 25% of the transport tunnels constructed in the Netherlands since 1999. Given the predominance and relative age of the immersed tube construction form in the Netherlands the performance of these tunnels is the focus of the present paper.

2.2 *Immersed Tube Tunnels*

The first immersed tube tunnel constructed in the Netherlands was the Maas road tunnel in Rotterdam which opened in 1941. The system was a popular solution for Dutch ground conditions and topography with the result that to date almost thirty tunnels have been constructed using this technique, See Table 1. There was a particular boom in tunnel construction in the 1960's and 1970's. Given the design life of these structures many are due to undergo major retrofitting in the coming years. A number of these tunnels have exhibited signs of deterioration including corrosion, uplift of tension piles beneath approach embankments and leakage (Leeuw 2008) and van Montfort (2018). Leakage caused by differential is the largest problem facing tunnel owners and is the focus of the case study in this paper.

Table 1. Details of Immersed Tube Tunnels in the Netherlands.

Number	Name	Year Opened
1	Maas	1941
2	Coen Tunnel	1966
3	Benelux Tunnel	1967
4	Rotterdam Metro Tunnel	1968
5	IJ Tunnel	1969
6	Heinenoord Tunnel	1969
7	Vlake Tunnel	1975
8	Drecht Tunnel	1977
9	Prinses Magriet	1978
10	Kil Tunnel	1978
11	Hemspoor	1980
12	Botlek Tunnel	1980
13	Spijkenisse Metro	1984
14	Coolhaven	1984
15	Zeeburger	1990
16	Willemspoor	1990
17	Noord	1992
18	Grouw	1993
19	Schipol Railway Tunnel	1994
20	Wijker tunnel	1996
21	Willemspoor Tunnel	1996
22	Piet Heintunnel	1997
23	2nd Benelux tunnel	2002
24	Burgemeester Thomastunnel	2004
25	HSL-Zuid Oude Maas	2006
26	HSL-Zuid Dordtsche Kil	2006
27	2nd Coen Tunnel	2013

3 DESCRIPTION OF THE KILTUNNEL

3.1 *Overview*

The Kil tunnel with a length of 405m carries a two-lane highway and bicycle lane (each direction) under the Dordtsche Kil near Rotterdam. In cross-section the tunnel is a double tube concrete structure with a width of 31m and height of 8.75m. The immersed section is primarily composed of three elements, each approximately 113.5m long, with an end (land tunnel) of 35m at each end, See Figure 1. Each element was formed by joining five individual segments in a dry dock. The elements were then transported to site and connected in-situ at immersion joints. The system is sealed at the closure joint.

3.2 *Performance to date*

The tunnel in common with many others of this type constructed in the Netherlands has ongoing issues with settlement and leakage. Displacement measurements made throughout the operation of the tunnel are summarized in Figure 2. Linear variable displacement transducers were installed on the tunnel at the junction between segments. Initial movements were small, less than 5 mm and were concentrated in element 2. During maintenance work in 2001 significant quantities of sand was found in the pumping chamber and cracks were noticed in the wall between segments 2C and 2D, See Figure 3. Settlement measurements showed that significant settlements occurred between 1977 and 2001, forming a quite distinct pattern, whereby settlements were concentrated in elements 1 and 2, with element 3 exhibiting relatively small settlements. Unlike other tunnels, the settlements at the Kil tunnel were not concentrated at the immersion joints, rather on segment joints.

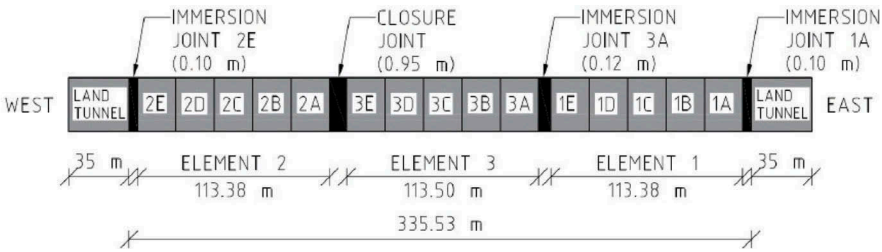

Figure 1. Long section through Kil tunnel showing the element locations, segment numbering and location of joints (from Rijkswaterstaat 1974).

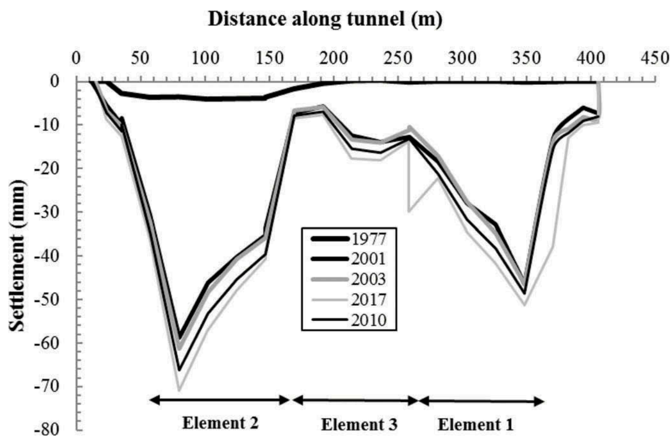

Figure 2. Vertical settlement of Kil Tunnel measured between 1977 and 2017.

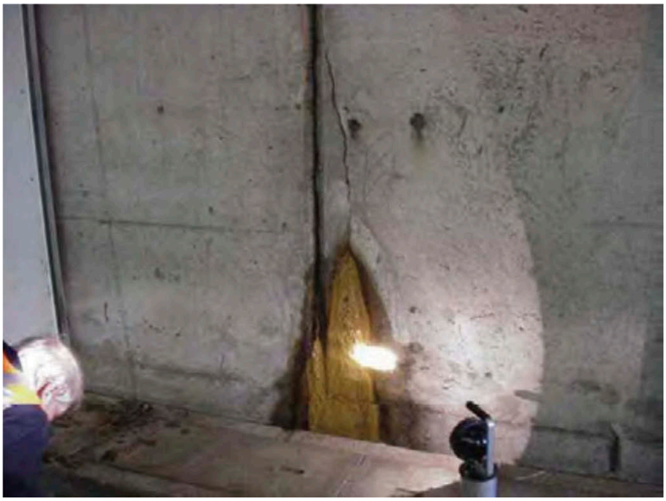

Figure 3. Cracking at segment joint.

Due to the age and total design life of the tunnel a major remediation programme is imminent. Given the significant and ongoing settlement it is important for the tunnel owner to understand the mechanism driving this behaviour and, having established this, to determine if remedial action should be undertaken as part of the tunnel refurbishment. The Geo-Engineering Section at TU Delft and Rijkswaterstaat are lead partners in the EU Horizon 2020 SAFE-10-T investigating ongoing settlements at the nearby Heinenoord tunnel. The Dutch knowledge institute for underground space, Centrum Ondergronds Bouwen (COB) and the owners of the Kil Tunnel requested that this tunnel be included as an additional case study location in the project. Whilst a reasonably comprehensive ground investigation (in terms of number of locations) was conducted for the original construction, a review of the available data that comprised Cone Penetration (CPT) testing revealed that for the immersed tube section of the tunnel (Elements 1 to 3), very limited data was available for the soil immediately below the base of the tunnel. As a result, a geophysical investigation was planned in conjunction with SAFE-10-T partner the University of Zagreb to provide insight into the mechanisms controlling the settlement of Kil Tunnel.

4 GEOPHYSICAL INVESTIGATION

4.1 *Test Method*

The geophysical investigation technique chosen was multichannel analysis of surface waves, MASW. The method introduced by Park et al. (1999) and Xia et al. (1999) uses surface waves for the estimation of shear wave velocity (V_s) profiles. The method is an extension of the Spectral Analysis of Surface Waves (SASW) method (Nazarian and Stokoe, 1984), the most significant difference between the SASW and the MASW techniques, involves the use of multiple receivers with the MASW method (usually more than 12) which enables seismic data to be acquired relatively quickly when compared to the SASW method (Donohue et al 2011). A further advantage of the MASW approach is the ability of the technique to identify and separate fundamental and higher mode surface waves. According to elastic theory the small strain shear modulus, G_0, may be calculated from V_s, using the following equation:

$$G_{max} = \rho . {V_s}^2 \tag{1}$$

Where: G_0 = shear modulus (Pa), V_s = shear wave velocity (m/s) and ρ = density (kg/m^3).

MASW has been used extensively to estimate G_0 profiles when compared to other in-situ techniques such as cross-hole investigation (Donohue et al. 2003), as a quality assurance technique for ground improvement projects (Donohue and Long 2008) and to map changes in soil properties due to climate (Bergamo et al. 2016). The survey was undertaken in the cycle lane of the tunnel with both bike and road traffic remaining open during the survey, See Figure 4a. Due to the presence of large drainage culverts running perpendicular to the tunnel at immersion joint 1a and 2e respectively the survey could only be conducted on the soil beneath the three elements 1 to 3, See Figure 1 over a length of 335m. Four overlapping 100m long MASW profiles were acquired with overlap to ensure complete coverage across the tunnel section.

Whilst some embedment of the geophone in soils is necessary to ensure good contact, on road and concrete surfaces this is not possible and contact was ensured using a steel plates as shown in Figure 4a. A 6 kg sledgehammer was used to generate the surface waves which were in turn detected by 40 No. 10 Hz geophones placed at 2.5m centres, See Figure 4a. The source was located at the mid-point of the geophones, See Figure 4b. Data was recorded with a Smartsystem data logger at a sampling rate of 0.5 msec.

The Software SeisImager was used to obtain a dispersion curve from the phase velocity-frequency spectra, which was generated using a wave-field transformation method (Park et al., 1998). An example of a typical one-dimensional V_s profile measured at the site is shown in Figure 5.

Figure 4. (a) Site test set-up (b) Test underway.

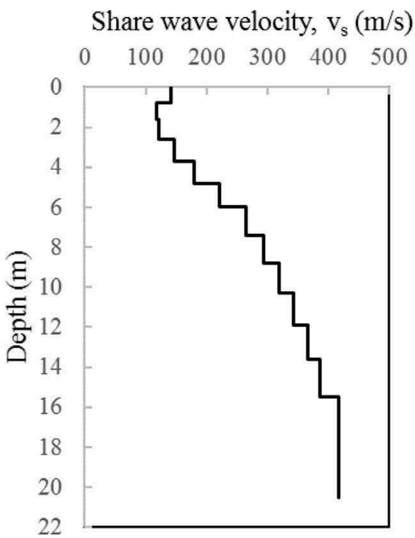

Figure 5. Example of a typical 1D shear wave velocity trace at Kil Tunnel.

5 DISCUSSION

The MASW survey described in the previous section resulted in a series a 1D V_s profiles spaced at 2.5 m centres along the immersed tube tunnel. Using linear interpolation, a 2D Vs profile was created See Figure 6a. The dark blue colour indicates low velocity (soft soils) and the red colour is high velocity (stiff soils). The darker shade the blue colour is, the softer the soil. The main results are:

- There are very soft near surface soil zones (dark blue) evident in the profile, beneath element 2, Segments 2b-2E (See Figure 6b) and under element 1, Segment 1b. The location of the soft deposits correlates well with the observed settlement profile of the tunnel, See Figure 2 suggesting these low-stiffness zones are responsible for the unusual profile observed.
- Using Equation 1 to convert to shear wave velocity to soil stiffness suggest that the near surface stiffness of the soil beneath element 1 ($V_s \approx 270$ m/sec) is nine times higher than in these soft zones ($V_s \approx 90$ m/sec) which is generally in keeping with the magnitude of settlement evident in the different elements.

A preliminary interpretation would suggest that these soft zones are potentially old deeper channels of the river that were infilled with soft sediments or perhaps areas of poorly compacted sand that was backfilled into the excavated trench prior to tunnel placement. Given that MASW is a non-intrusive method of investigating the soil it has been recommended to perform addition CPT testing to provide verification of the interpreted ground model.

Considering the settlement pattern with time in Figure 7 and the settlement pattern in Figure 2, the accumulated settlement against time shows ongoing settlements that are highest in the region where the soft zones are evident and much lower where stiff soils exist. Settlements at all locations are continuing with time. Whilst the soft ground is clearly affecting the magnitude of settlement, the mechanism is not known. Two potential causes are considered, cyclic loading and creep. Cyclic loading of the Kil tunnel could arise from a number of sources, differential

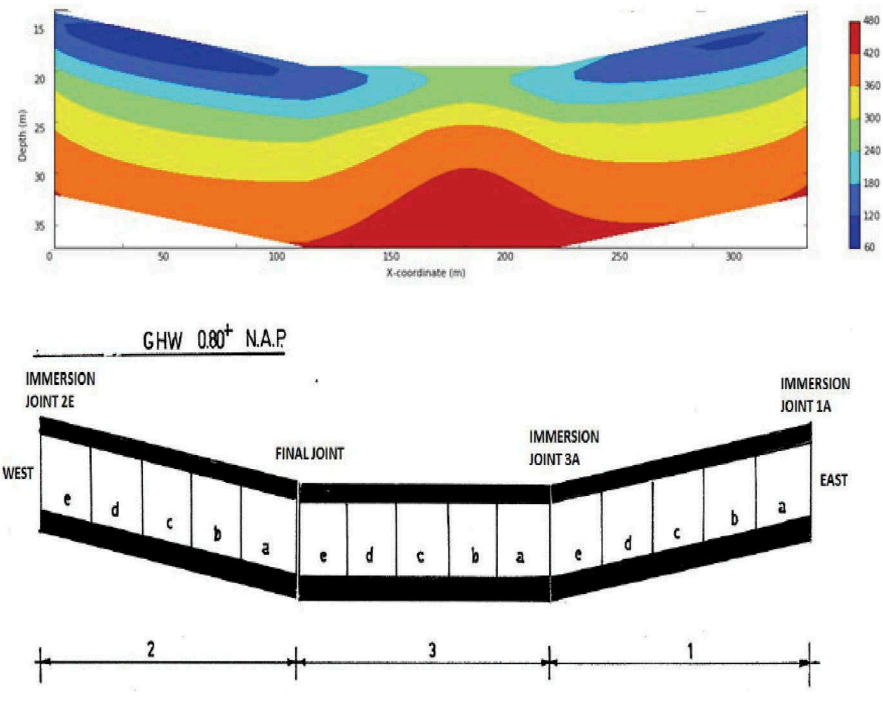

Figure 6. (a) 2D Vs profile at Kil Tunnel (b) location of segments and joints (Rijkswaterstaat 1974).

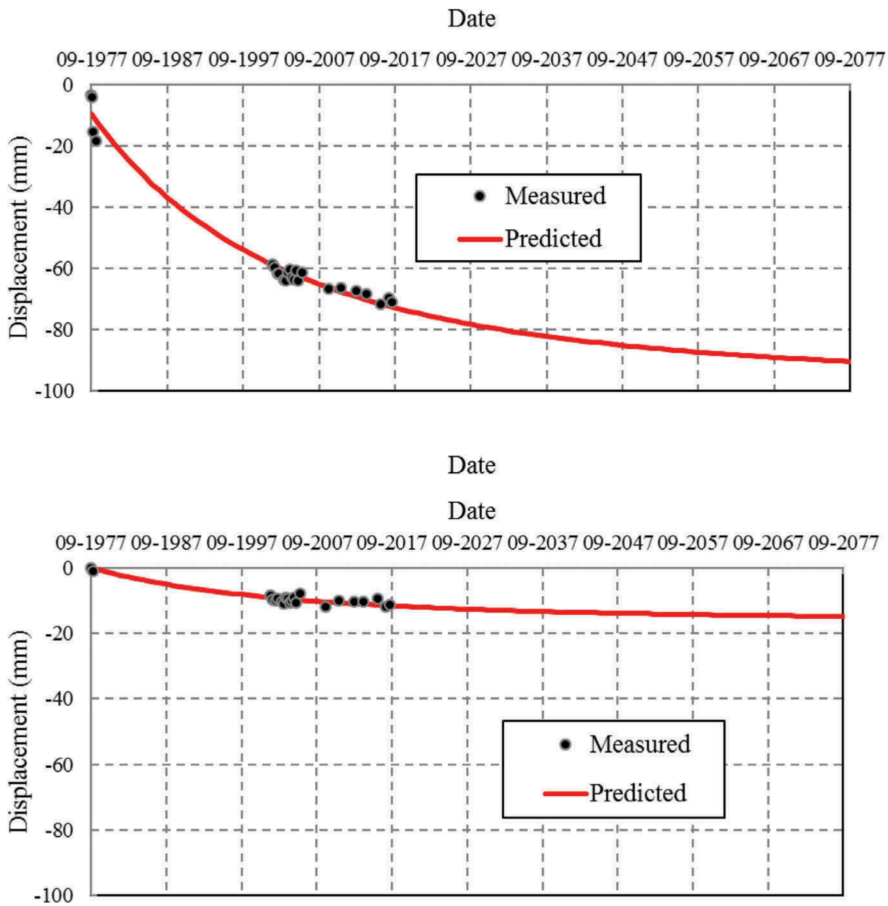

Figure 7. (a) Measured and predicted settlement for segment 2C and (b) segment 2E.

water pressures due to tidal effects, tragic loading, temperature etc. Creep or strain under constant load is a phenomenon affecting most materials, in this case it could arise due to creep of the foundation soil or concrete creep, particularly in the slopes segments 1 and 2 in the Kil Tunnel. For both cyclic loading and creep effects on soils the overall behaviour can be described by simple power-law expressions (Gavin et al. 2009 and Li et al. 2015) shown in Figure 7 assuming either plastic hardening during cyclic loading or time dependent creep reducing settlement with time. For all locations in Kil Tunnel these models suggest maximum total settlements in the range 10mm to 90mm up to the 100-year design life of the structure.

6 CONCLUSION

The paper presents a typical problem with ongoing settlement and leakage of ageing immersed tube tunnels in the Netherlands. MASW testing which is a quick, cost-effective and low-impact (no traffic disruption) technique provided vital information on the soil conditions that affect the displacement pattern observed at the Kil Tunnel. In particular it provided detailed information on the extent of soft soil zones underlying the tunnel and gives fundamental parameters (soil stiffness) for geotechnical engineering calculations. Whilst this is encouraging further work is required to (i) verify the ground model using direct in-situ testing and (ii) understand the mechanism driving the settlement observed at this and similar tunnels in the Netherlands.

ACKNOWLEDGEMENT

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