Monitoring daily and seasonal movement of an immersed tunnel

Broere, Wout; Zhang, Xuehui

DOI
10.1201/9781003348030

Publication date
2023

Document Version
Final published version

Published in
Expanding Underground

Expanding Underground – Knowledge and Passion to Make a Positive Impact on the World

Proceedings of the ITA-AITES World Tunnel Congress 2023 (WTC 2023), 12-18 May, 2023, Athens, Greece

EDITED BY

Georgios Anagnostou
Andreas Benardos
Vassilis P. Marinos

WTC 2023 • ATHENS
ITA - AITES

CRC Press
Taylor & Francis Group

EXPANDING UNDERGROUND - KNOWLEDGE AND PASSION TO MAKE A POSITIVE IMPACT ON THE WORLD

Expanding Underground - Knowledge and Passion to Make a Positive Impact on the World contains the contributions presented at the ITA-AITES World Tunnel Congress 2023 (Athens, Greece, 12 – 18 May, 2023). Tunnels and underground space are a predominant engineering practice that can provide sustainable, cost-efficient and environmentally friendly solutions to the ever-growing needs of modern societies. This underground expansion in more diverse and challenging infrastructure types or to novel underground uses can foster the changes needed. At the same time, the tunnelling and underground space community needs to be better prepared and equipped with knowledge, tools and experience, to deal with the prevailing conditions, to successfully challenge and overcome adversities on this path. The papers in this book aim at contributing to the analysis of challenging conditions, the presentation and dissemination of good practices, the introduction of new concepts, new tools and innovative elements that can help engineers and all stakeholders to reach their end goals.

Expanding Underground - Knowledge and Passion to Make a Positive Impact on the World covers a wide range of aspects and topics related to the whole chain of the underground construction and operation of tunnels of underground structures:

- Knowledge and Passion to Expand Underground for Sustainability and Resilience
- Geological, Geotechnical Site Investigation and Ground Characterization
- Planning and Designing of Tunnels and Underground Structures
- Mechanised Tunnelling and Microtunnelling
- Conventional Tunnelling, Drill-and-Blast Applications
- Tunnelling in Challenging Conditions - Case Histories and Lessons Learned
- Innovation, Robotics and Automation
- BIM, Big Data and Machine Learning Applications in Tunnelling
- Safety, Risk and Operation of Underground Infrastructure, and
- Contractual Practices, Insurance and Project Management

The book is a must-have reference for all professionals and stakeholders involved in tunnelling and underground space development projects.

PROCEEDINGS OF THE ITA-AITES WORLD TUNNEL CONGRESS 2023 (WTC 2023),
12-18 MAY 2023, ATHENS, GREECE

Expanding Underground - Knowledge and Passion to Make a Positive Impact on the World

Edited by

Georgios Anagnostou

ETH Zurich, Switzerland

Andreas Benardos

School of Mining and Metallurgical Engineering at the National Technical University of Athens, Greece

Vassilis P. Marinos

School of Civil Engineering at the National Technical University of Athens, Greece

CRC Press
Taylor & Francis Group
Boca Raton London New York Leiden

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

A BALKEMA BOOK

Front Cover Image:

First published 2023
by CRC Press/Balkema
4 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN
e-mail: enquiries@taylorandfrancis.com
www.routledge.com – www.taylorandfrancis.com

CRC Press/Balkema is an imprint of the Taylor & Francis Group, an informa business

Typeset by Integra Software Services Pvt. Ltd., Pondicherry, India

Library of Congress Cataloging-in-Publication Data

A catalog record has been requested for this book

ISBN: 978-1-003-34803-0 (ebk)
DOI: 10.1201/9781003348030

Expanding Underground. Knowledge and Passion to Make a Positive Impact on the World – Anagnostou, Benardos & Marinos (Eds)

Monitoring daily and seasonal movement of an immersed tunnel

Wout Broere & Xuehui Zhang
GeoEngineering Section, Department of Geoscience & Engineering, Delft University of Technology, Delft, The Netherlands

ABSTRACT: Daily and seasonal deformation behavior of immersed tunnels potentially impacts the structural integrity. In this study, distributed optical fiber sensors (DOFS) are used to instrument both dilation and immersion joints of the Heinenoordtunnel, an immersed tunnel in the Netherlands. This DOFS system proves capable of measuring joint opening and uneven settlement at half-hour intervals. The field monitoring shows the Heinenoordtunnel behaves more like a rigid body and exhibits a cyclic vertical movement under daily tide impacts over a period of 12 hours. Moreover, the joints show a cyclic seasonal opening which is negatively correlation with temperature variations, i.e. the tunnel joints are compressed when the outside temperature rises and vice versa. These monitoring results provide new insights into the daily and seasonal deformation of immersed tunnel structures.

1 INTRODUCTION

Immersed tunnels have been widely constructed as fixed links beneath waterways. Currently, more than 150 immersed tunnels have been built and are in-service worldwide, since the first traffic-use immersed tunnel, the Detroit River Tunnel, was completed and opened in 1910s. About one-third of them have reached an over-50-year service period (Lunniss and Baber, 2013). As more immersed tunnels are reaching half of their designed lifespan, and start to show their age, monitoring the structural health conditions has increasingly become an important aspect in immersed tunnel maintenance.

In conventional deformation monitoring of immersed tunnel, measuring vertical settlement by manual leveling, at yearly or multi-year intervals, is still the dominant monitoring technqiue employed, especially for older immersed tunnels. This method is for example used in most immersed tunnels in the Netherlands. However, there are indications that the seasonal deformation of the tunnel may affect structural safety and watertightness. For example, in some tunnels the seasonal expansion and shrinkage of the tunnel segment changes the concrete crack width and leads to periodical increases in leakage volumes (Limfjord, 2019); at tunnel joints the seasonal deformation may cause decompression of the GINA gasket seal and impose a subsequent leakage risk (Gavin et al. 2019; Van Montfort, 2018), or be related to seal gasket damage (Bai and Lu, 2016; Wang et al., 2020). Moreover, it has been hypothesized that a daily tidal fluctuation in the waterway above the tunnel can cause a cyclic vertical response of the tunnel (Grantz, 2001), but there are very limited studies on this aspects since the (too) low frequency of the conventional monitoring practice can not verify these claims. Therefore, a study into the daily or seasonal deformation behavior of immersed tunnels will firstly require the implementation of a higher-frequency monitoring system, capable to operate with daily or even sub-hourly intervals.

Distributed optical fiber sensing (DOFS) is a type of sensing technology that offers advantages such as distributed strain and temperature sensing, combined with long-distance sensing,

DOI: 10.1201/9781003348030-362

where measuring strain and temperature variation over a hundred kilometers is possible with a single optical fiber loop (López-Higuera et al., 2011; Ohno et al. 2001). DOFS provides a high potential to develop a remote-controlled deformation monitoring system for an in-operation immersed tunnel that can perform at higher frequency measurements than the current settlement monitoring by manual leveling can achieve.

In this study, distributed optical fiber sensors (DOFS) are utilized to develop a joint deformation monitoring system for the First Heinenoordtunnel in the Netherlands, an immersed tunnel opened in 1969. This DOFS monitoring system proves capable of measuring both immersion and dilation joint deformation in two dorections (joint opening and uneven settlement), at half-hour intervals. This field monitoring supports an investigation into the daily behavior of the Heinenoordtunnel under tidal variation, and a data-collection over a one-year period also reveals the seasonal behavior of the immersed tunnel. The findings in this study provide new insights into the behavior of immersed tunnels.

2 FIELD SENSOR INSTALLATION AND MONITORING

2.1 *The distributed optical fiber sensor (DOFS)*

In this study the DOFS based on Brillouin light scattering is used. It has been demonstrated that Brillouin scattering occurs when light propagates along an optical fiber, where the frequency of the Brillouin backscattered light is shifted from that of the original light, and this Brillouin frequency shift (BFS, noted as Δf) is linear to the temperature variation (ΔT) and fiber strain (ε) (Motil et al, 2016), as given in Equation (1):

$$\Delta f = C_{\varepsilon}\varepsilon + C_{t}\Delta T \tag{1}$$

where C_{ε} and C_t are strain and temperature sensitivity coefficients, which are constant properties of the optical fiber. By separately measuring the local temperature, preferably utilizing an unstrained parallel fiber section, the temperature component $C_t\Delta T$ can be deducted and the imposed strain distributed along the fiber axis can be therefore obtained.

A complete DOFS system is generally composed of an optical fiber (as the sensing fiber) plus a signal interrogator. In the monitoring setup, the optical fiber is attached to the structure for a specific sensing task, and either one or both fiber ends are connected to the interrogator. Commercially available interrogator types include Brillouin Optic Time-Domain Reflectometry (BOTDR), Brillouin Optic Time-Domain Analyzer (BOTDA), Brillouin Optic Frequency-Domain Analyzer (BOFDA) (López-Higuera et al., 2011; Motil et al., 2016). In this study a BOFDA interrogator is adopted for data collection, which requires both fiber ends plugged in and a complete fiber loop to be established for higher accuracy and resolution.

2.2 *Instrumentation of the Heinenoordtunnel joints with DOFS*

The First Heinenoordtunnel (hereafter referred as the Heinenoordtunnel) is a rectangular immersed tunnel under the Oude Maas River in the Netherlands. This tunnel was finished and opened to service in 1969. The immersed tube section of the Heinenoordtunnel is about 574m long. Longitudinally it consists of 5 concrete elements, each about 115m long, connected with immersion joints. Every single element is further divided into 6 segments each about 19m long, with dilation joints between, see Figure 1.

Throughout the service period, deformation monitoring of the Heinenoordtunel was mainly limited to vertcal settlement monitoring, measured by manual leveling, at several points along the tunnel axis. Significant uneven settlement has occurred along the immersed tunnel since the reference measurement in 1978. A measurement in 2018 revealed a maximum settlement difference of about 43mm longitudinally along the immersed section. The structural integrity of the tunnel has become an issue and at two dilation joints significant leakage has been observed previously. Observations from similar immersed tunnels and lab experiments show

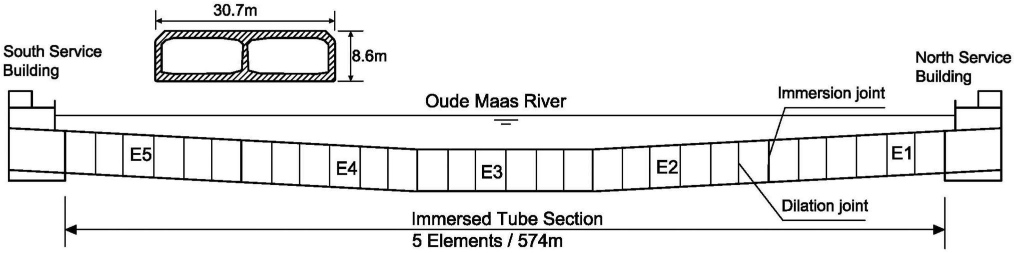

Figure 1. Sideview of the First Heinenoordtunnel.

that seasonal temperature variation may have negative impact on the structural safety, but this could not be validated for the Heinenoordtunnel since monitoring with yearly interval was unable to detect any seasonal behavior (Rahadian et al., 2018). The DOFS is therefore utilized to instrument all joints of the Heinenoordtunnel and form a remote-controlled monitoring system which allows to measure the joint opening and uneven settlement (between both sides of the joint) at a high frequency (in the order of once per hour).

Notably a DOFS only directly obtains the fiber strain (after decoupling the temperature effect) in the direction of the fiber axis. In order to measure the joint deformation (or displacement), the sensing fiber needs to be installed in a special layout so as to effectively sense the anticipated displacements. Here the optical fiber section at the joint is installed to function as two extensometers, with one aligned horizontal and the other inclined, see Figure 2(a). By analyzing the strain changes within the two extensometers, the joint opening and uneven settlement can be derived. During installation, FL1 is oriented horizontally and FP1 and FP3 are aligned on a vertical line (along the Z-axis in Figure 2(a)). If a measurement is made at interval *i*, the relation between BFS and lengths of FL1/FL2 can be established as:

$$l_{1.i} = l_1(1 + \varepsilon_{1.i}) = l_1\left(1 + \frac{\Delta f_{1,i}}{c_\varepsilon}\right) \tag{2}$$

$$l_{2.i} = l_2(1 + \varepsilon_{2.i}) = l_2\left(1 + \frac{\Delta f_{2,i}}{c_\varepsilon}\right) \tag{3}$$

and the height difference between FP1 and FP3 is given by:

$$h_i = \sqrt[2]{l_{2,i}^2 - l_{1,i}^2} \tag{4}$$

where $l_{1.i}/l_{2.i}$ are the lengths of FL1/FL2 at interval *i*; $\Delta f_{1,i}/\Delta f_{2,i}$ are the measured BFSs of FL1/FL2 at interval *i* (decoupling temperature component); $\varepsilon_{1.i}/\varepsilon_{2.i}$ are the strains of FL1/FL2 at interval *i*; Δy_i is the joint opening at interval *i*; and h_i is the height difference between FP1 and FP3. Note for another measurement at interval j, the relation of Equations (2) to (4) still holds and the joint opening (relative to interval *i*) can be calculated as the FL1 extension as $\left(l_{1.j} - l_{1.i}\right)$, while the uneven settlement as the change of height difference $\left(h_j - h_i\right)$.

The applicability of the designed sensor block for joint deformation measuring has been validated experimentally by Zhang and Broere (2023). The designed sensor layout can effectively detect two-directional joint deformations with sub-millimeter accuracy. In the subsequent field installation, an optical fiber (type NZS-DSS-C07 manufactured by Nanzee Sensing Company) with a diameter of 2mm was adopted. This type of fiber has a strain sensitivity of 48.55 MHz/0.1% and a maximum working strain of above 1.2% (Zhang and Broere, 2022).

For the convenience of sensor installation in the field, the optical fiber is firstly bonded to small fixing pads at designated points, see Figure 3(b), and in the tunnel these three pads are mounted on the wall at precise distances. Special external cover boards are also prepared to protect the bare sensing fiber from potential impacts. The fiber lengths FL1 and FL2 are

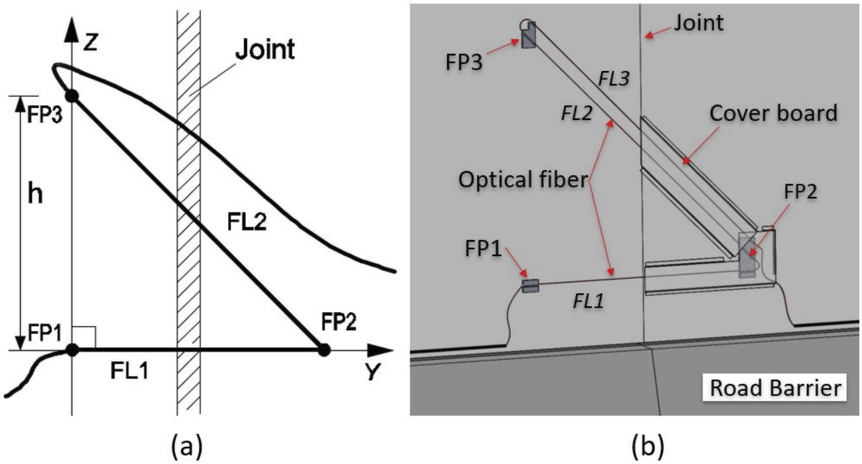

Figure 2. Field sensor design and installation: (a) designed sensor block and (b) field sensor installation.

aligned with a 45-degree angle, and the gauge lengths of FL1 for dilation and immersion joints are 800mm and 1350mm respectively. Note that fiber line 3 (FL3) in Figure 3(b) is unstrained and aligned parallel to FL2 just for the sake of ease for installation of the cover boards.

A BOFDA interrogator, typed fTB2505 manufactured by fibrisTerre Systems GmbH, is used to measure the Brillouin frequency shift. This device has a stated spatial resolution of 0.2m (up to 2km), a spatial accuracy of 0.05m, and strain measuring accuracy of 2 micro-strain, according to fibrisTerre (2021). The BOFDA interrogator directly measures the BFS of FL1 and FL2 within a sensor block, and the BFS is further transferred to joint deformations using Equations (2) to (4). At each joint, the BFS of a short loose fiber length (about 40cm long) adjoining the strained fiber lines is recorded for temperature correction, and thus the temperature effects can be deducted from the total BFS of the tensioned FL1 and FL2.

The installed DOFS system in the Heinenoordtunnel can simultaneously measure two-directional joint deformation and temperature at designated sampling intervals. The first monitoring period started from December 16, 2020, with 13 joints (from north end, see Figure 1) instrumented; the second monitoring period started from June 11, 2021, with al 30 joints (from tunnel center to south end) monitored. Note that the second dilation joint within the fifth element was not instrumented due to space limitations imposed by tunnel signage.

3 MONITORING RESULT ANALYSIS

3.1 *Daily deformation behavior analysis*

In the joint deformation analysis, the different deformation modes are illustrated in Figure 3. For joint opening, a negative value indicates a joint closure relative to the reference measurement, while a positive value means a joint gap opening. For uneven settlement, if the north side (of the joint) is assumed static, a positive value indicates the south side moves upwards, while a negative value means a downward settlement.

From the start of the second monitoring period from June 11, 2022, measurements of joint opening and uneven settlement for a total of 30 joints are available. As a representative result, the the joint deformation behavior of three successive days (June 14 to 16, 2021, with deformation on June 11 taken as the reference state) are shown here in Figures 4 to 6. The plots explicitly show the general tendency of joint deformation within a daily period, as well as the highly distinctive behaviors of certain joints.

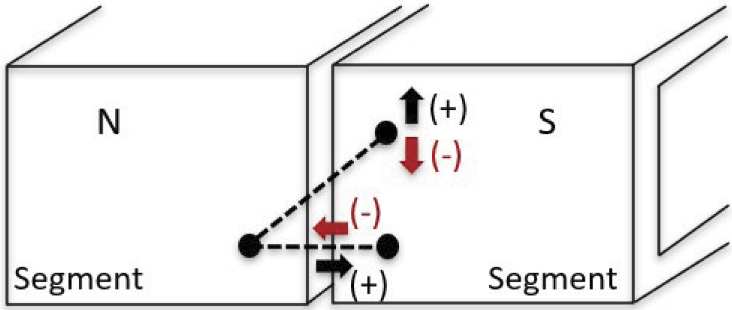

Figure 3. Joint deformation mode analysis (not to scale, viewed from outside tunnel).

The temperature results in Figure 4 depict a high degree of consistency in impact of the temperature fluctuation at all joints, while a small temperature difference (with a maximum of about 5 degrees) exists between the 30 joints. The joint openings, during this time span, lie within a range between -0.15 and 0.35mm, as shown in Figure 5. It can be observed that the joint opening is typically negatively correlated with temperature change, indicating that a decrease in temperature corresponds generally to an increase in joint opening.

The results in Figure 6 indicate that for most joints the uneven settlement does not show a fluctuation as significantly as the joint opening. However, the most distinctive behavior is that of the first and last immersion joints, indicated as Joint-1 and Joint-6 in Figure 6, which show two daily throughs. This daily cyclic pattern of observed uneven settlements indicates the impact of tidal fluctuations in the River Oude Maas above the tunnel. The uneven settlements of the other 28 joints do not exhibit a similar cyclic behavior. As Joint-1 and Joint-6 form the north and south ends of the immersed section (see Figure 1), the regular troughs indicate the entire immersed tunnel section, almost as a rigid body, moves up and down cyclically.

The Heinenoordtunnel is located inside the estuary of the River Maas, which is still impacted by the North Sea's tidal fluctuations. Figure 7 shows the tidal levels plus the uneven settlement at the two end immersion joints. The tidal data is obtained from the Goidschalxoord tidal station, approximately 4 km downriver from the Heinenoordtunnel site. The tidal curve shows a tidal variation between 1.1 to 1.4 m within the expected period of 12 hours and 25 minutes (Rijkswaterstaat, 2022). As seen in Figure 7, it is interesting that the immersed tunnel settles downward when the tide rises and returns upward as the tide falls as in Figure 8. The amplitudes of the daily cyclic deformation (the maximum difference of uneven settlement within a daily period) of Joint-1 and Joint-6 are slightly different. For example, on June 14 the amplitude of this cyclic movement is about 0.30mm at Joint-1 and about 0.23mm at Joint-6. This implies the two ends of immersed section response slightly differently to tidal impacts.

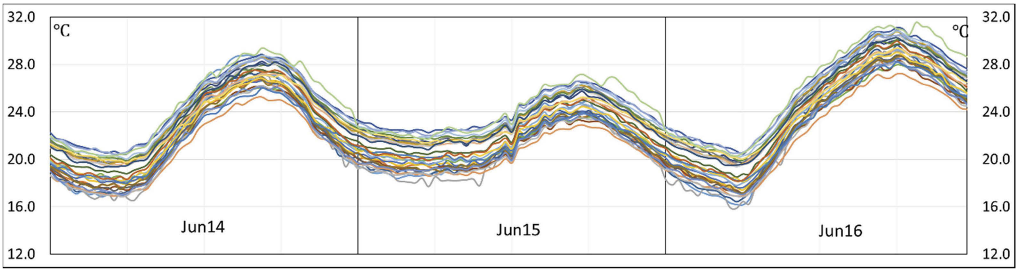

Figure 4. Measured joint temperature.

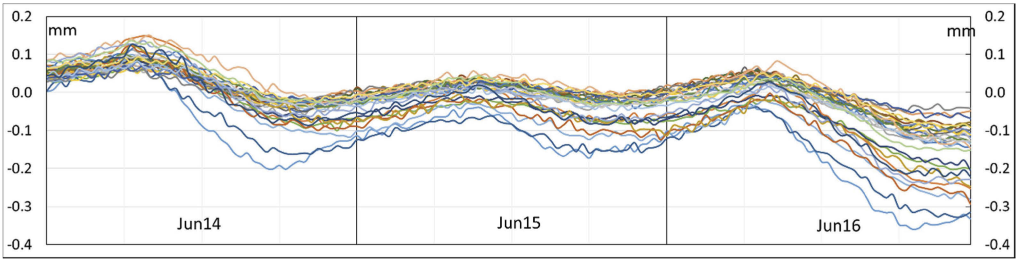

Figure 5. Measured joint opening.

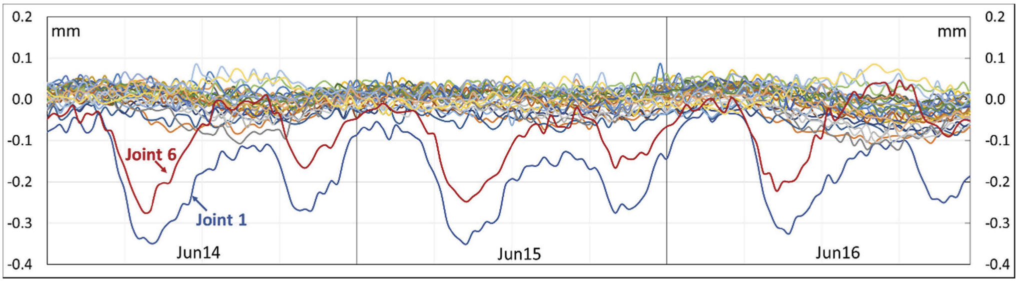

Figure 6. Measured joint uneven settlement (y-values for I6 plotted inverted).

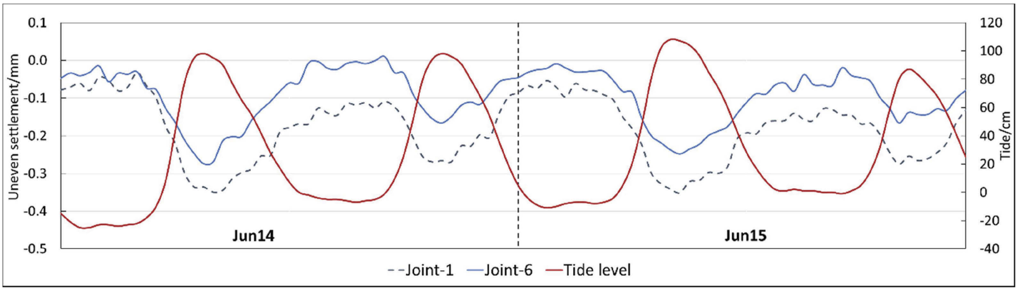

Figure 7. Uneven settlement of joint I1and I6 (y-values inverted) with tide (June 12 to 14).

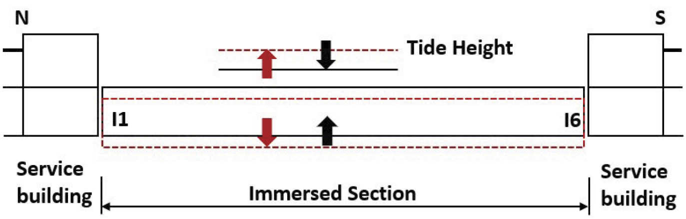

Figure 8. Schematic of cyclic movement of Heinenoordtunnel under tidal impact.

3.2 *Seasonal deformation behavior analysis*

The first 13 joints instrumented from the first monitoring period onward were monitored for a one-year period, from December 16, 2020 to December 10, 2021. Figures 9 shows the joint opening of these joints during the entire period. In general, the three immersion joints exhibit a greater joint opening than the majority of the dilation joints, with the exception of the first dilation joint from the north end of the tunnel, which displays the most significant deformation

(-5.18 to -0.26 mm, see Dilation joint-1 in Figure 9). Compared to the three immersion joints and the first dilation joint, the deformation range of the remaining nine dilation joints (between -2.0mm and +1.0mm) is substantially lower.

Notably, the local jump in joint opening on two of the curves (for the second and third immersion joints) on February 18 occurred as the result of a two-week monitoring gap and was not in all probability not as sudden. It should also be mentioned that the coldest period of the year occurred during these two weeks, with temperatures well below zero. As the temperature recovered to above zero level after February 18, the openings at these two joints decreased dramatically during the days that followed, which indicates that the joint opening deformation exhibits a time delay with respect to the ambient temperature change.

Figure 9 shows that the joint opening exhibits a cyclical behavior through the one-year period. The joint opening decreases (indicating a joint gap closure) from spring to summer, whereas during the summer (June to September), the joint demonstrates the maximum negative opening (namely the largest joint gap closure); after September, the joint opening gradually increases during the colder period from October to December (a joint gap opening). Considering the thermal behavior of concrete segments, the seasonal joint opening deformation is closely connected to the longitudinal thermal expansion of the segment body. In particular, segment expansion narrows the joint gap (causing a joint closure) during the summer, but segment contraction widens the joint gap (a resultant joint opening) during the winter.

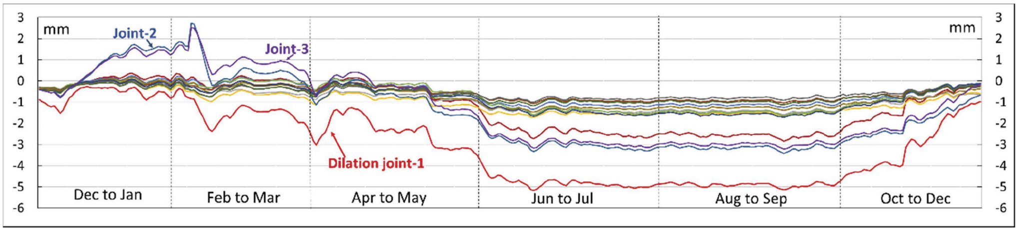

Figure 9. Joint opening of the first 13 joints over one year period.

Figure 10 displays the uneven settlement of the first 13 joints during the entire one-year period. It can be seen that joint uneven settlement is generally small (with an absolute value below 1.5mm). The majority of joints only exhibit a deformation range of -0.3mm to 0.5mm, indicating a much smaller range than that of joint opening at individual joints. Furthermore, joint uneven settlement over a full-year period shows a seasonal variation as well, but this seasonal variation is not as significant as that of joint openings.

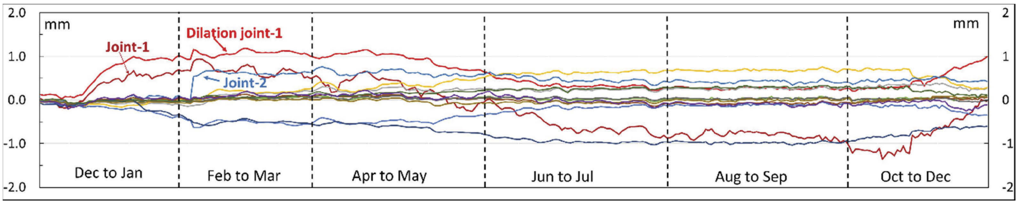

Figure 10. Joint uneven settlement of the first 13 joints over one year period.

4 CONCLUSION

The main conclusion is that the distributed optical fiber sensor (DOFS) is an effective sensing tool to build a monitoring system for immersed tunnel joint deformations, which is also resilient enough to operate in field conditions. It has been demonstrated in this study to be capable of data-taking at half-hour intervals, highlighting its potential in immersed tunnel monitoring.

Secondly, monitoring results reveal the daily behavior of the Heinenoordtunnel under the influence of tidal variations in the river above the tunnel. The whole immersed section behaves more or less like a rigid body and moves upwards and downwards cyclically with tidal variations, with a sub-millimeter movement amplitude.

Thirdly, the field monitoring validates the hypothesis that seasonal periodic joint opening occurs at the tunnel joints, and this joint opening shows a negative correlation with temperature, indicating that the joint gap tends to close during summer and open during winter. The amplitudes of seasonal joint opening at immersion joints are generally larger than those of most dilation joints, but at a few dilation joints the amplitude of joint opening is comparable to that of the immersion joints. Moreover, at most joints the uneven settlement is within a range of less than 1 mm, and this uneven settlement also exhibits a seasonal variation but not as significant as that of joint opening. These findings presents new insights into behavior of immersed tunnel structure.

REFERENCES

Bai Y. and Lu H., 2016. Damage Analysis and Repair Technology of OMEGA Gasket in Immersed Tube Tunnel. JOURNAL OF RAILWAY ENGINEERING SOCIETY, No 9, 87–92. (In Chinese)

Fibristerre (2021), Information of BOFDA interrogator see https://www.fibristerre.de/files/fibrisTerre_flyer.pdf (latest accessed in June 2021)

Grantz, W.C., 2001. Immersed tunnel settlements: Part 2: case histories. Tunnelling and Underground Space Technology, *16*(3), 203–210.

Gavin, K.G., Broere, W., Kovačević, M.S. and de Haas, K., 2019. Investigation of the remaining life of an immersed tube tunnel in The Netherlands. In *Proceedings of the WTC 2019 ITA-AITES World Tunnel Congress*, p. 4831.

Horiguchi, T., Shimizu, K., Kurashima, T., Tateda, M. and Koyamada, Y., 1995. Development of a distributed sensing technique using Brillouin scattering, Journal of Lightwave Technology, vol.13, 1296. DOI: 10.1109/50.400684

Limfjord Tunnel report, 2019. Limfjord Tunnel Assessment and Retrofitting Technical Summary Report, Version 1.0.

Lunniss, R. and J. Baber (2013). Immersed tunnels, CRC Press.

López-Higuera, José Miguel, Luis Rodriguez Cobo, Antonio Quintela Incera, and Adolfo Cobo, 2011. Fiber optic sensors in structural health monitoring. *Journal of lightwave technology*, 29, no. 4, 587–608.

Motil, A., Bergman, A. and Tur, M., 2016. State of the Art of Brillouin Fiber-Optic Distributed Sensing. *Optics & Laser Technology*, 78, 81–103.

Ohno, H., Naruse, H., Kihara, M., and Shimada, A., 2001. Industrial Applications of the BOTDR Optical Fiber Strain Sensor. OPTICAL FIBER TECHNOLOGY 7, no.1, 45–64.

Rijkswatart, 2022. Tide level information, see https://waterinfo.rws.nl/

Rahadian R., van der Woude S., Wilschut D., Blom C.B., Broere W., 2018. A new test setup for studying sand behaviour inside an immersed tunnel joint gap. In Physical Modelling in Geotechnics. p. 443–448. CRC Press.

Van Montfort, R., 2018. Insufficiency of immersion joints in existing immersed tunnels: Case study on functioning of Gina-seal and Omega-seal in the Kil Tunnel. MSc Thesis, Delft University of Technology, Delft, The Netherlands.

Wang S., Zhang X., Bai Y., 2020. Comparative study on foundation treatment methods of immersed tunnels in China. Frontiers of Structural and Civil Engineering, 14(1):82–93.

Zhang, X. and Broere, W., 2022. Sensing fiber selection for point displacement measuring with distributed optic fiber sensor. *Measurement*, *197*, p.111275.

Zhang, X. and Broere, W., 2023. Design of a distributed optical fiber sensor system for measuring immersed tunnel joint deformations. *Tunnelling and Underground Space Technology*, *131*, p.104770.