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Gaussian Random Fields for Modelling the Influence of Soil and Dredging Variation on Shear-Keys of Immersed Tunnels

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Abstract: Immersed tunnels are buoyant structures, which are constructed by immersing elements to the seabed and covering them with sand and rocks to counter the buoyancy and for protection afterwards. From a structural point of view, an immersed tunnel is a flexible system with segments. Between elements the displacement degrees of freedom are coupled, but the rotations are not coupled or restrained. Discontinuous loading in the longitudinal direction or discontinuous bedding conditions will result in a response variation over the length of the flexible tunnel. If the response between two segments is not equal, shear forces are transferred on the segment joints by shear-keys. The foundation of an immersed tunnel is influenced by many factors related to soil but also to construction and dredging tolerances. Because of the geometrical limitation of the tunnel due to immersion and buoyancy requirements, the size and therefore the capacity of these shear-keys is limited. A combination of soil stiffness and dredging depth including their spatial variability is researched in a simple structural model in a systematic and probabilistic approach. For these effects, Gaussian random fields with different covariance lengths are investigated. This research shows that the maximum shear forces are found when the covariance length is in the same order as the segment dimensions.

Keywords: Gaussian random fields; immersed tunnels; covariance length; shear-key

1 Introduction

Immersed tunnels (IMT) are infrastructural crossings through waterways. Different types of IMT as well as their construction methods are discussed by Rasmussen et al. (1997). A description of their development over the years (which continues to date) is given by Glerum (1992). An IMT can be beneficial compared to a bridge, because there are no limitations on ships crossing it besides the depth of the water itself. IMT are positioned in a covered trench, so the water depth can remain the same after construction. Compared to bore-tunnels, the principle is the same, that is, crossing below surface. However, as a construction limitation, the application is limited to the diameter of the circle of the section and for installation a minimum cover over the tunnel-bore machine is needed to ensure stable soil conditions. Therefore, a bore tunnel will have a deeper and longer alignment than an IMT.

Currently, the majority of IMT are constructed using prefabricated elements of 100 to 150m in a dry dock situation. After finalizing the element, it is floated and towed to the tunnel location, immersed into a dredged trench and laterally locked at its horizontal position using a back-fill and a protection layer (see figure 1). A general description of the IMT construction technique and a historical perspective is given by de Wit (2014) and design principles are described by Grantz (1997)

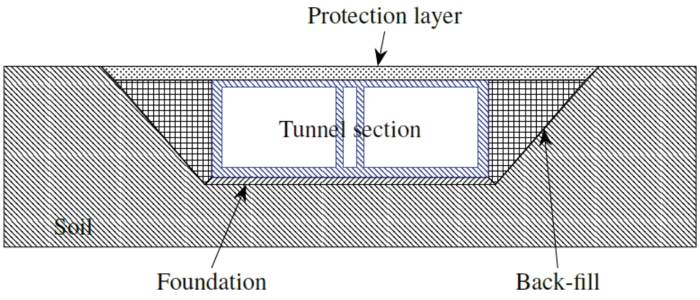

Figure 1. Tunnel cross-section in the final situation, covered and on the foundation

Immersed tunnels have commonly a service lifetime of 100 years. In this period settlements along the alignment will occur due to soil or loading variations. The amount of settlement is specific for each tunnel and the design should accommodate these settlements. During their lifetime, monitoring of settlements will present the current situation, Grantz (2001) gives an overview of settlements for different IMT and more recent research is presented by Hu and Xie (2016)

The tunnel-element is equipped with a longitudinal post-tension system for transportation purposes which is deactivated by cutting the tendons at the joints after final placement on the foundation. A flexible system is created and at the joints shear forces need to be transferred between segments. The magnitude of these shear forces is highly depended on soil conditions, foundation design and settlements. In this paper an approach using Gaussian random fields for soil stiffness as well as for dredging depth is presented which can be used to determine the magnitude of forces in the shear-key. These insights can be used for design optimization of the shear-keys of the IMT.

2 Problem description

The longitudinal behavior of an IMT structure can be described by a beam on a bedding. Along the alignment of the tunnel many parameters will vary, such as the external load caused by soil on top of the tunnel and the bedding underneath the tunnel. These variations will cause cross-sectional forces and bending moments in a rigid structure which need to be accommodated.

In earlier days, several monolithic IMT were constructed (Maastunnel Rotterdam, George Massy tunnel, Vancouver) using heavy designs. In the late sixties, flexible joints were introduced as an option. Currently most IMTs are equipped with flexible joints, though in special cases monolithic tunnels are still build such as the Söderstromtunnel in Stockholm. By allowing the tunnel to deform slightly using flexible joints, heavy sectional forces and bending moments and consequently heavy designs are avoided. Leakage of water into tunnels is prevented (or limited) by using rubber gaskets, like GINA gaskets and Omega profiles. The difference in the schematic structural longitudinal system is presented in figure 2.

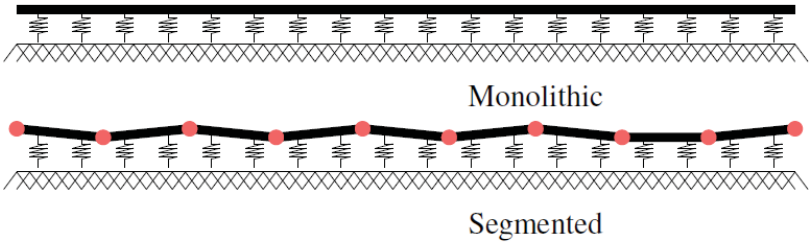

Figure 2. Structural system of longitudinal, monolithic (upper) and segmented (lower)

In these flexible joints, displacements are continuous while rotations are discontinuous. The continuous displacements are facilitated by shear-keys in the structure. A typical joint layout is presented in figure 2. Although larger bending moments are avoided, the shear forces still need to be transferred and that makes the shear-key connection a critical element in the system of the tunnel structure. Failure of a shear-key could introduce leakage and a discontinuous longitudinal alignment. Shear failure in general is a brittle mechanism which does not ”warn“ before failure and should be avoided. The size of a shear-key is limited by the height of the tunnel and consequently the capacity of a shear-key is limited to approximately to 5 MN in a regular situation. Given these limitations, the design in relation to the effect of force on the shear-key is essential for several reasons. See for example the research of Weng et al. (2016) and Hu and Xie (2016) which focuses on shear-key failure originated by differential settlement. So, the soil conditions and the foundation characteristics and their (spatial) variability are important for the design of the shear-key.

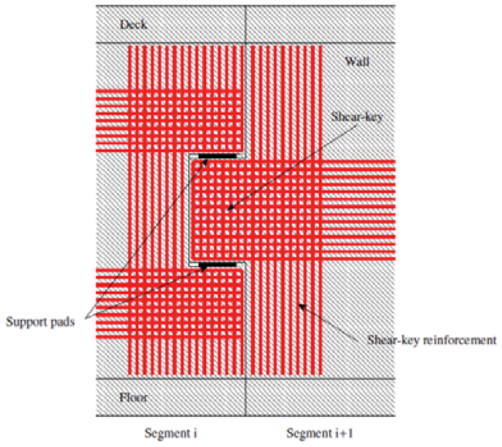

Figure 2. Joint layout including shear-key

3 Model

An IMT is founded on the seabed and various loads act on the tunnel. These loads will result in a bedding reaction underneath the IMT. The IMT is a concrete structure and has a significant higher stiffness than the soil bedding. As a result, the structural behavior of the tunnel segment itself will be insensitive to bedding variations. Flexibility is introduced to the tunnel in the longitudinal direction by the joints between segments and immersion joints. In this research the tunnel is assumed to have a constant vertical displacement over the length of the considered tunnel element.

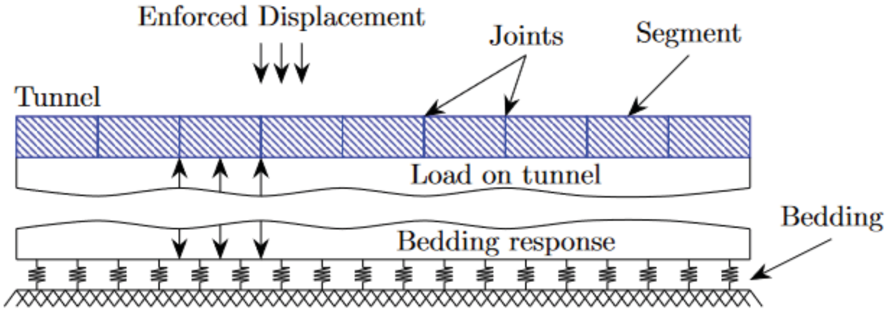

Figure 3. Bedding response of a tunnel as result of enforced displacement

The vertical load on the seabed can be defined with a small tolerance and is 20 to 40% of the structural concrete weight of the tunnel, this load is a combination of the downward forces on the IMT and the upward buoyancy force. The final load on the seabed is usually up to 50 to 60 kN/m^2. This load is the sum of the buoyancy load, the self-weight of the concrete, the ballast load inside the tunnel (concrete), the installations inside the tunnel, the soil cover on the tunnel, and the rock protection on top of the tunnel. Each IMT has specific loading circumstances based on the location, such as a sloping soil cover close to the shore connections. Such variations are not covered in this research.

Commonly, the bedding behavior itself over the lifetime after construction can be considered as linear elastic and is usually derived by a 2D geotechnical cross-sectional finite element analysis. In this analysis the settlement is calculated by externally loading the soil. In these analyses the loading and reloading effects can also be considered. The relation between the external load and the resulting settlements will result in a bedding stiffness which is used as input in the structural analyses in various phases. The analysis in this research considers the final stage only.

Although the global behavior is considered linear elastic, local non-linear effects due to stress redistribution in the soil and bedding material can occur, the effect of this local non-linear behavior is negligible and hence not considered in this research.

The elastic bedding is not constant over the contact area of the tunnel. The linear stiffness derived by the geotechnical analysis is based on the following parameters (see also figure):

- Thickness of the foundation material (h_f in [m])
- Stiffness of the foundation material (k_f in [N/m^2])
- Dredging tolerance (Δt_{dr} in [m])
- Placement tolerance (Δt_{pl} in [m])
- Soil stiffness (k_s [N/m^2])

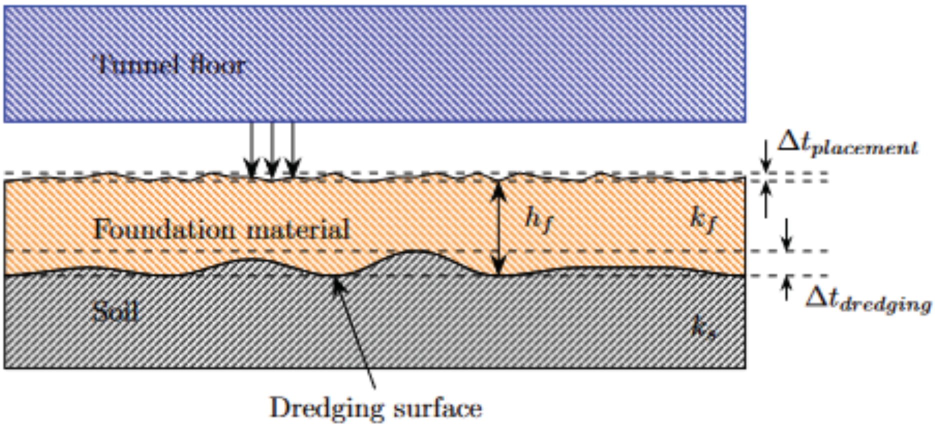

Figure 4. Structural system

The stiffness of the total bedding is defined as in Eq. **Error! Reference source not found.**. However, all parameters will vary over the area below the tunnel. The soil stiffness and the dredging surface will have a spatial correlation. This spatial correlation can be simulated with a Gaussian Random Field (GRF).

$$k_b = \frac{1}{\frac{1}{k_s} + \frac{(h_f + \Delta t_{pl})}{k_f}} \tag{1}$$

The analyses in this research are conducted using a typical tunnel element of 120m length and 30m wide with a section length of 20m (figure).

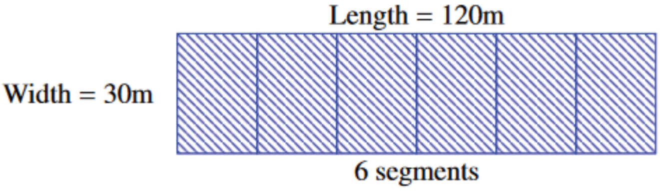

Figure 5. Layout of segmented tunnel model – top view

4 Use of Gaussian random fields for spatial variability

Loosely speaking, a random field is a collection of random variables representing some physical properties in space. A Gaussian random field is one where the dependence between such collection of random variables in space is described through a multivariate Gaussian distribution. In a Gaussian random field, the dependence structure is thus determined through the spatial covariance. The spatial covariance indicates that a local value of a particular parameter is correlated with neighboring values of the same parameter depending on the spatial distance between locations. For our case, the covariance between 2 points is expressed in Eq. **Error! Reference source not found.**. In which x_n and y_n are the coordinates of a location n in the grid and L_{cov} the covariance length. If the distance between 2 points increases, the covariance decreases exponentially as can be seen in figure (left). If a surface is discretized to n_x times n_y in which n_x is the number of points in the longitudinal direction and n_y in the lateral direction, the total number of points n is defined as $n=n_x$ times n_y. The covariance matrix Σ contains all relative correlations between all points within the area. Eq. (2) guarantees that the resulting matrix Σ will indeed be a covariance matrix.

$$\mathrm{cov}\big((x_1, y_1), (x_2, y_2)\big) = e^{-\frac{1}{2}\frac{\sqrt{(x_2-x_1)^2+(y_2-y_1)^2}}{L_{cov}}} \tag{2}$$

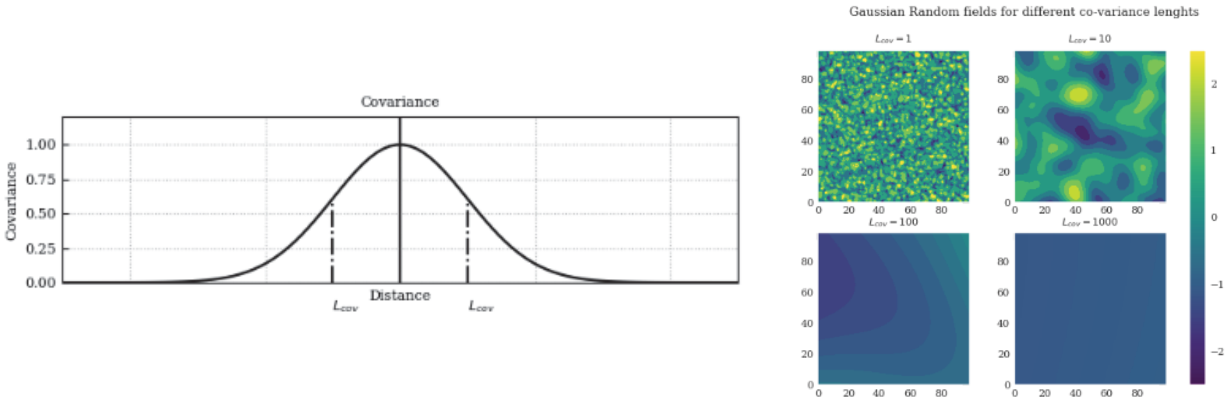

Figure 6. Covariance as function of distance (left) and Gaussian random fields for different co-variance lengths (right)

A sample of a field, considering the covariance matrix Σ, can be found by using a multivariate distribution with the density as expressed in Eq. **Error! Reference source not found.**. This is the multivariate Gaussian distribution. As an example, 4 samples of a Gaussian random field are presented in **Error! Reference source not found.** (right). In this sample a grid of 100x100 points with a covariance length of 1, 10, 100 and 1000 points are used. For a covariance length of 1, which is equal to the sample size, an independent distribution is visible. If the covariance length is increased, the variation of the samples reduces. The variation runs to zero in case the covariance length is 10 times as large as the grid size.

The variation of the bedding, based on the covariance lengths of the soil bedding and the dredging depth, will lead to variations in the shear forces in the shear-key.

5 Results

The covariance lengths for both the soil stiffness as well as for the trench dredging are considered to be equal. For each covariance length 1000 samples are considered and the distribution for F_{key} is derived. The distribution of the maximum shear-key forces found from the model are presented in **figure** (left). If the covariance length is larger than 40m or smaller than 15m the distribution is slender and the shear force with maximum density is smaller than the distributions within the interval 15m to 40m. This is more illustrated when the 95th quantile of each distribution of F_{key} and plotted as function of L_{cov} (**Error! Reference source not found.** and the maximum value is found at 15m which is close to the segment length of the structure. In relation to **Error! Reference source not found.** (right), this is explained by selection of a covariance length close to the segment length, a segment with a lower foundation stiffness will span between two adjacent segments and load will be transferred using the shear-keys. If a smaller covariance is used, the bedding difference is averaged out within a segment and all segments will behave equally. On the other hand, in case the covariance length is larger than a segment, the bedding stiffness is equalized more over the whole structure and all segments will behave also equally. In both situations, the forces on the shear-key will be smaller than when a covariance length corresponds or is close to the segment size.

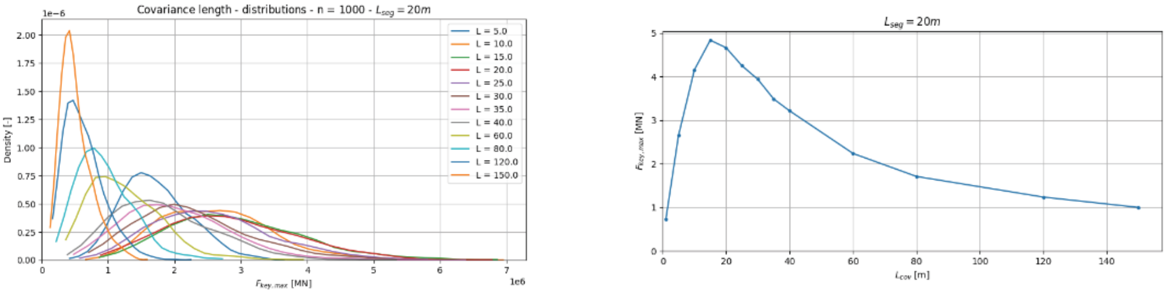

Figure 7. Distribution of maximum shear forces for different covariance lengths (left) and 95% quantile of the shear force distribution (right)

6 Conclusions

If the covariance length is 15m, the maximum shear force is found. This length is in the same order as the segment length of the tunnel. If the covariance length is smaller than 50% of the segment length, the shear-key forces decrease to less than 50% of the maximum shear-key. The shear-key force and the covariance length have a negative relation for covariance lengths significantly larger than the segment length. The influence of the covariance length, which characterizes the variation of physical properties over the area, is clear. For soil, the spatial variability cannot be influenced. However good understanding of the local circumstances can lead to design optimization. If the variability is small and the covariance length is large, the soil stiffness will be close to a constant value. The thickness of the foundation material is based on the dredging tolerance. Using quality measures to improve the dredging accuracy will lead to a more constant thickness and stiffness, which will in turn lead to smaller shear-key forces and smaller measures for accommodating these forces.

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