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Segmental tunnel lining behaviour in axial direction

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ABSTRACT: A shield tunnel lining is usually conceived and modelled as a bedded ring, loaded by radial and tangential soil stresses. In some cases the mechanical behaviour of the tunnel in axial direction can also be relevant, for instance, when a particular tunnel is situated in multi-layered soil, partly consisting of cohesive soft soil layers in combination with a high ground-water table. Contrary to ring models, models which describe 'girder behaviour' are scarce and relatively simple. In this paper the background of a numerical one-dimensional girder model with an analytical background is described and explained. Unlike existing models, the developed model displays the non-linear behaviour due to opening of circular joints and the mechanical properties of the circular joint material. The developed model can be successfully applied in practice, as is demonstrated by a case study, concerning the North/South line, which is briefly discussed in this paper.

1. INTRODUCTION

Mainly in areas where we have to deal with multi layered soft soil, in combination with a high ground-water level the axial tunnel behaviour (girder behaviour) will be an important aspect of the tunnel lining design. The girder behaviour of a shield tunnel lining results in forces and deformations in the tunnel that occur in combination with forces and deformations due to the ring behaviour of the tunnel. In a well-designed tunnel the forces and stresses in the various lining components should not exceed the capacity of those components. Furthermore the deformations in the tunnel have to be limited in order to preserve the watertightness of the tunnel at the joints. Girder behaviour can be initiated by two phenomena (Figure 1):

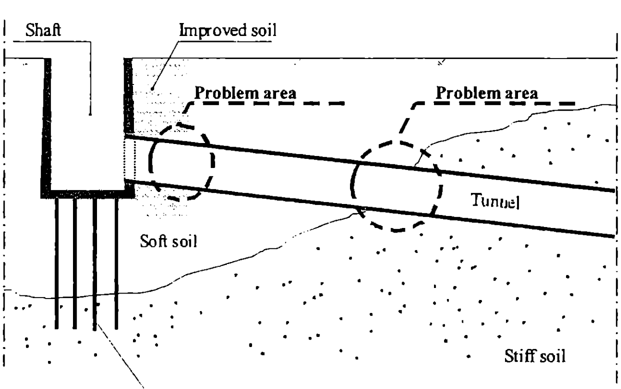

Figure 1 Areas of interest with respect to girder behaviour.

- *Local changes in tunnel loading.* Unequal settlements along the tunnel axis or local loading, for example a local soil raise at the ground surface level, will initiate girder lining behaviour.
- *Locally prevented heave of the tunnel.* After construction the tunnel will reach a new state of equilibrium by translation and elliptical deformation. If the translation of the tunnel is locally prevented by a pile founded shaft or a stiff soil layer, the tunnel will be loaded as a girder.

2. DEFORMATION MECHANISMS

2.1 Bending

In the first place, the tunnel will deform by bending. We are able to distinguish the following extreme cases of bending (Figure 2) :

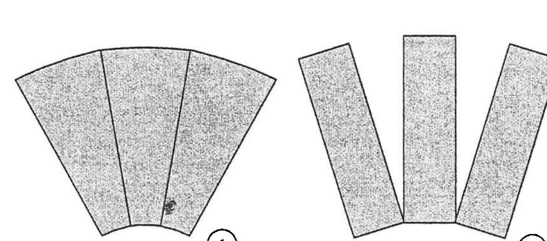

Figure 2 Extreme cases of bending.

❶ Circular joints remain closed so that bending deformation will be continuous along the tunnel axis.
❷ Bending deformation is concentrated in the opened circular joints.

2.2 Shearing

Besides bending the tunnel is also able to deform by shearing. The following extreme cases of shearing can be discerned (Figure 3) :

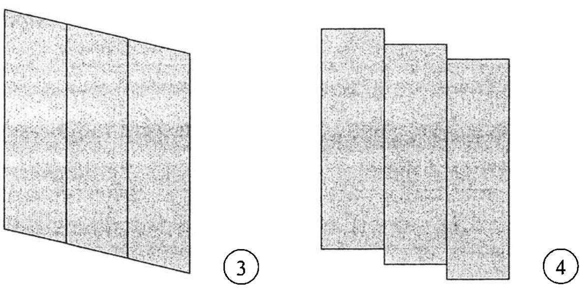

Figure 3 Extreme cases of shearing.

❸ Discrete shearing in the circular joint is negligible compared to continuous shearing deformation in the tunnel rings.
❹ Shearing deformation is concentrated in shifted circular joints.

2.3 Axial normal force influence on girder behaviour

The actual tunnel behaviour falls somewhere between these four extremes. A factor which determines the actual behaviour of the tunnel is the axial compressive normal force. When this axial force is relatively large the circular joints will remain closed and local shifting of the tunnel rings at the circular joints will be prevented. In such a case the bending and shear stiffness of the tunnel will be maximal. When the axial compressive normal force is relatively small the circular joints might open and local shifting of the tunnel rings may occur, which results in a relatively flexible behaviour of the tunnel.

2.4 Determination of the axial normal force

During tunnel construction the axial compressive normal force N_{ax} will be equivalent to the total thrust jack force of the shield machine. An important question is what will remain of this initial normal force after a period of time. Phenomena like changes of the tunnel length due to tunnel deformation, relaxation due to the long-term deformation of concrete and circular joint material, temperature changes and long-term behaviour of the grout and soil, will all influence the distribution of the axial normal force along the tunnel axis. At the moment the implications of the above mentioned phenomena are still hard to quantify.

3. CONTINUOUS GIRDER MODEL

3.1 Model philosophy

The tunnel is assumed to be a slender structure. Under this assumption the segmented tunnel can be modelled as a continuous girder, supported by a continuous spring support. In case of linear elastic behaviour of the tunnel and the supporting soil the behaviour of tunnel and supporting soil can simply be described by the following equation (Bouma 1989) :

$$EI_{equi}\frac{d^4w}{dx^4} - GA_{equi}\frac{d^2w}{dx^2} + kw = q(x) \qquad (1)$$

In this equation EI_{equi} and GA_{equi} are representative values for the bending and shear stiffness of the girder. The load on the tunnel and the bedding stiffness are represented by the parameters q(x) and k respectively. In practice the behaviour of the segmented tunnel is highly non-linear. Due to the fact that the circular joints are unable to transfer tensile stresses, opening of circular joints will occur when the local bending moment exceeds a certain value. The value of the bending moment, which causes the circular joint to open, is determined by the axial compressive normal force in the tunnel. When a circular joint opens the bending and shear stiffness will be locally reduced. In fact the bending and shear stiffness of the girder at a certain cross-section of the girder are a non-linear function of the bending moment and the axial compressive normal force at that cross-section. This non-linear behaviour of the girder is not taken into account by the linear differential equation (1) an has to be dealt with in a numerical way by means of a finite element model. The numerical model, used in the case study, is presented in chapter 4.3. In the following paragraphs of this chapter the background of the numerical model is discussed and methods for determination of the model parameters are presented.

3.2 Elementary bending behaviour

3.2.1 Concept of smeared cracking

In this study the effects of circular joint opening are taken into account by assigning a negligible tensile strength to the material of the continuous girder. An opened circular joint is now replaced by a smeared cracking pattern (Figure 4).

If the length of the tunnel ring is relatively small and the bending moment is roughly the same in the entire tunnel ring, the distribution of normal stresses in the entire tunnel ring will not differ very much from the distribution of normal stresses in the circular joint.

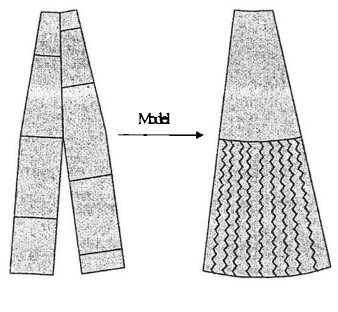

Figure 4 Smeared cracking concept.

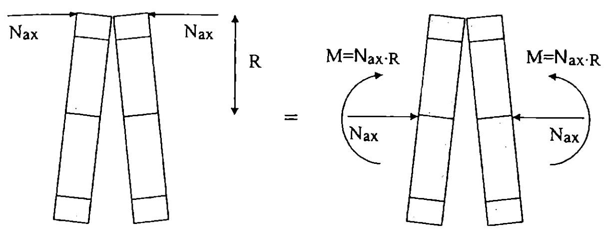

Figure 5 Ultimate bending moment (linear elastic).

Under this assumption the bending behaviour of a continuously cracked tunnel will be similar to the bending behaviour of a tunnel, which is discretely cracked at the circular joints.

3.2.2. Analytical background of bending behaviour smeared cracking girder

By considering the horizontal equilibrium of the girder at a certain cross-section the relationships between the quantities related to the bending mechanism, i.e. bending moment M, curvature κ, moment of inertia I and maximum opening of the circular joint u were determined in an analytical way. These quantities can be made dimensionless, introducing the quantities M', κ', I' and u'. The relationships between quantities and dimensionless quantities are dependent on the axial compressive normal force value N_{ax}, tunnel radius R, segment thickness t and modulus of elasticity of the concrete E_c.

Equation (2) shows the relationship between the bending moment M and the dimensionless bending moment M'.

$$M = M' \cdot N_{ax} \cdot R \qquad \text{with } 0<M'<1 \qquad (2)$$

A value of M' equal to 1 represents the situation were the axial normal compressive force is transferred at the extreme compressed fibre of the circular joint. Due to the limited compressive strength of the concrete this singular situation can't occur in reality (see chapter 3.2.4).

The study showed that the relationships between the above-mentioned dimensionless parameters are unambiguous. During the development, testing and evaluation of the numerical model the results of the analytical study played an important role.

3.2.3 Effects of elastic circular joint material on bending behaviour

In order to prevent peak stresses arising from direct contact of the concrete surfaces in the circular joint and in order to introduce the thrust jack forces into the concrete segments in a proper way, flexible plates are often used. These plates are usually made of tar (Kaubit), rubber, or hardwood (triplex). The presence of these elastic plates has a large effect on the bending behaviour of the tunnel.

If the stiffness of the plates is high enough to prevent direct contact between the concrete surfaces the normal stresses will be introduced into the concrete segments in a discrete way. This means that the normal stresses are spread in radial and tangential direction along the segment and only a limited part of the segment is fully loaded, which makes the behaviour of a discretely loaded segment more flexible compared to a continuously loaded segment. Besides discrete load introduction significant flexibility of the circular joint material can also cause a reduction of the bending stiffness of the tunnel.

In this study the effects of Kaubit and triplex plates on the bending behaviour of the tunnel were determined.

Kaubit: If a viscous tar like Kaubit is used in the circular joint it will be almost completely compressed and direct contact between the concrete surfaces in the circular joint will occur (Gijsbers et al. 1997). When fully compressed the Kaubit plates have a negligible axial flexibility and normal stresses are continuously introduced into the segment. Therefore using Kaubit will result in a maximum bending stiffness. When the lining thickness is locally reduced at the circular joints the normal stresses have to spread in radial direction, which causes a small reduction of the bending stiffness.

Plywood: If a more stiff material like plywood is used direct contact between the concrete surface will be prevented. The significant flexibility of the material and the fact that normal stresses are discretely introduced into the segment result in a bending stiffness that is significantly smaller than the bending stiffness of a tunnel, where Kaubit is used in the circular joints.

The effects of the presence of flexible plates in the circular joints are taken into account by reducing the modulus of elasticity of the concrete E_c by a certain factor, which results in an equivalent modulus of elasticity $E_{c,equi}$. For the geometry of the second Heinenoord tunnel in the Netherlands the following equivalent modulus of elasticity were deduced by means of a finite element model of a part of the segment (figure 6)

- 28 Kaubit plates in the circular joint ($E_{c,equi} = 0.9\ E_c$)
- 28 Plywood plates in the circular joint ($E_{c,equi} = 0.3\ E_c$)

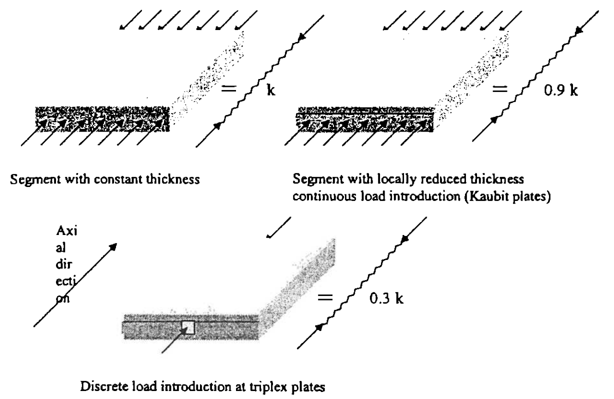

Figure 6 Determination of equivalent E-modulus with FEM.

3.2.4 Bending moment capacity of the tunnel

The ultimate bending moment M_u can be determined by the following equation:

$$M_u = M'_u \cdot N_{ax} \cdot R \quad \text{with } 0<M_u'<1 \qquad (3)$$

In this equation M'_u is a function of tunnel radius R, segment thickness t, the axial compressive normal force N_{ax} and the representative value of the compressive strength of the concrete $f_{c,rep}$.

An important conclusion is that failure of the tunnel due to loss of watertightness at the circular joints is far more critical than failure due to exceeding the ultimate bending moment M_u. In case of the second Heinenoord tunnel and an axial normal compressive force of 11 MN, the maximum opening in the circular joints corresponding to the ultimate bending moment M_u is 160 mm.

3.3 Elementary shearing behaviour

3.3.1 Analytical background of shearing behaviour smeared cracking girder

The elementary shearing behaviour of a smeared cracking beam is characterised by a strong reduction of the shear stiffness GA_d due to opening of the circular joints (non-linear shearing behaviour). By means of the method of complementary energy the shear stiffness $GA_{d,cracked}$ of a cracked girder was related to the dimensionless bending moment M' (see also equation (2)) in an analytical way. This relation can be approximated by the following equation :

$$GA_{d,cracked} = (2.1 - 2.2 \cdot M') \cdot GA_{d,uncracked} \qquad (4)$$

This equation is valid for values of M' between 0.5 (bending moment that initiates cracking) and 1.0 (ultimate bending moment in case of linear elastic concrete behaviour). For values of M' between 0 and 0.5 the shear stiffness of the girder is equal to the monolithic shear stiffness $GA_{d,uncracked}$.

3.3.2 Effects of elastic circular joint material on shearing behaviour

The mechanical properties of the material that is used in the circular joints have a large impact on the shearing behaviour of the tunnel. If the stiffness of the plates is high enough to prevent direct contact between the concrete surfaces shear stresses will be introduced into the concrete segments in a discrete way.

When direct contact between the concrete surfaces in the circular joint exist, the shear force will be transferred from one tunnel ring to the other by tangential oriented shear stresses (Figure 7a). When the shear force is transferred by the plates in the circular joint, the vertically oriented forces at the plates, have a radial component (Figure 7b). In this case the tunnel ring is not only loaded as a beam but also as a ring, which results in a shear stiffness which is just a fraction of the shear stiffness, corresponding to tangentially loaded tunnel ring.

In this study the effects of Kaubit and triplex plates on the shearing behaviour of the tunnel were determined.

Kaubit: When Kaubit plates are used in the circular joint, direct contact between the concrete surfaces in the circular joint will occur and the shear stiffness will have a maximum value, which can be determined by equation (4).

Plywood: If a more stiff material like plywood is used direct contact between the concrete surface will be prevented. The significant flexibility of the material and the fact that shear stresses are discretely introduced into the segment results in a shear stiffness which is a small fraction of the shear stiffness of a tunnel, where Kaubit is used in the circular joints.

The effects of the presence of flexible plates in the circular joints are taken into account by reducing the shear modulus of the concrete G_c by a certain factor, which results in an equivalent shear modulus $G_{c,equi}$.

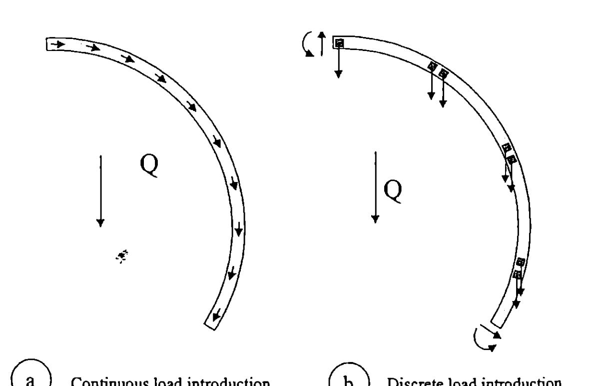

Figure 7 Load introduction at the circular joint.

For the geometry of the second Heinenoord tunnel the following equivalent shear modulus were derived with the help of a 3-D finite element model of one tunnel ring:

- 28 Kaubit plates in the circular joint ($G_{c,equi} = 1.0G_c$)
- 28 Plywood plates in the circular joint ($G_{c,equi} = 0.03G_c$)

It can be concluded that application of triplex plates in the circular joint significantly reduces the shear stiffness of the tunnel.

3.3.3 Distribution of shear force over triplex plates

An important conclusion emanating from the results of the above-mentioned finite element model is that the shear force is strongly concentrated in the triplex plates that are near the tunnel axis. In the case of the second Heinenoord tunnel about 90 percent of the shear force is transferred by the 12 (out of 28) triplex plates that are situated near the tunnel axis.

3.3.4 Shear force capacity of circular joints

In the case of a circular joint without shearing cams the maximum shear force Q_u that can be transferred at the circular joint depends on the axial normal force N_{ax} and friction factor μ of the circular joint surface and can be determined by the following equation :

$$Q_u = \mu \cdot N_{ax} \quad (5)$$

3.4 Modelling of the soil support

The support of the soil that surrounds the tunnel is modelled by a continuous spring support with a stiffness k. When determining this stiffness one should consider the global deformation mechanism of the tunnel. In case of girder behaviour this deformation mechanism consists of translation of the tunnel through the surrounding soil. Determining the spring stiffness k by integrating radial and tangential bedding stiffness' according to the Duddeck theorem (Duddeck 1980) along the tunnel perimeter is therefore not correct in this case because of the fact that the underlying deformation mechanism of the Duddeck theorem is elliptical deformation instead of translation. A better way of determining the spring stiffness would be using a 2-D numerical continuum model as shown in Figure 8 (Lengkeek 1996).

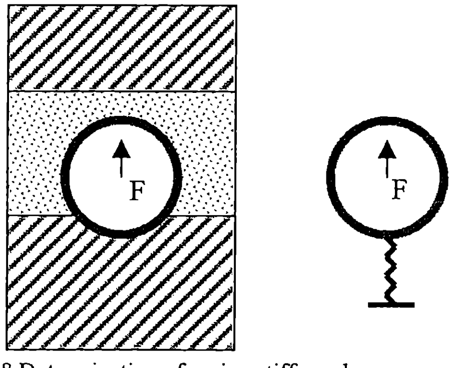

Figure 8 Determination of spring stiffness k..

By using this model the relation between the lifting force F and translation of the tunnel can be determined and the corresponding spring stiffness k_{spring} for drained and, if necessary, undrained soil behaviour can be derived. In many cases the soil behaves in an elastic way and a linear relation between lifting force and translation of the tunnel is found.

3.5 Tunnel loading

The tunnel is basically loaded by a heaving force that is equivalent to the weight of the excavated soil. If relevant additional loads like differential settlements or a local soil raise or excavation have to be superposed.

3.6 Support of the tunnel at the shafts

The tunnel is usually very well supported at the shafts, not only by the connection of the tunnel to the shaft but also by the relatively stiff improved soil that is adjacent to the shaft. Because of the presence of the improved soil a flexible connection between tunnel and shaft will have little effect. Therefore the tunnel must be assumed to be completely supported at the location of the shaft.

4. NORTH/SOUTH METRO LINE AMSTERDAM

4.1 Introduction

In the previous chapter, the background of the smeared-cracking girder model was discussed. The model philosophy can easily be implemented in a finite element model, which consists of a bedded girder with negligible tensile strength, that is loaded by an axial normal force N_{ax} and a load q. As an illustration of the deduced model concept a case study, concerning the North/South metro line in Amsterdam will be presented.

4.2 Situation

The case study deals with the connection of two metro tubes, situated above each other, to the shaft of the metro station Ceintuurbaan in the inner city of Amsterdam (Figure 9). The two shield machines which excavate the two tubes, arrive at the shaft within a time lag of a few months.

The soil at the regarded location is multi-layered and consists of clay and sand layers. The clay layers are sensitive to consolidation. Because of this consolida-

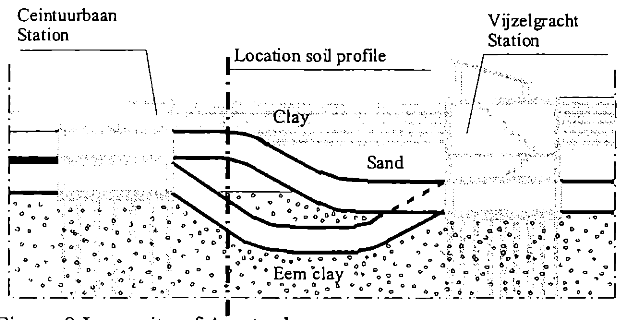

Figure 9 Inner city of Amsterdam.

tion it is expected that the tubes will be subjected to a progressive heave for a certain period after the construction of both tubes. This heave, caused by the missing weight of the excavated soil, is prevented at the shaft so both tubes will be loaded as girders.

4.3 Finite element model

4.3.1 Introduction

The used finite element model is shown in Figure 10. In order to model the embedding effect of the soil and the interaction between both tunnels, three rows of continuous springs are modelled. At the circular joints interface elements with limited shear force capacity are applied.

4.3.2 Determination of soil spring stiffness'

The stiffness of the three rows of soil springs, corresponding to undrained and drained soil behaviour were determined by means of a 2-D finite element model.

4.3.3 Tunnel heave during construction phase

During construction both tunnels are subjected to an initial heave, that does not cause significant forces in the tunnels, because this heave is not prevented during construction. Significant forces in the tunnels due to girder behaviour will arise when the soil support starts decreasing due to consolidation of the clay layers while both tunnels are fixed at the shaft. In order to model the positive effects of initial heave of both tunnels this initial heave is translated into prescribed displacements of both tunnels at the shaft. The values of the prescribed displacement can be determined by means of

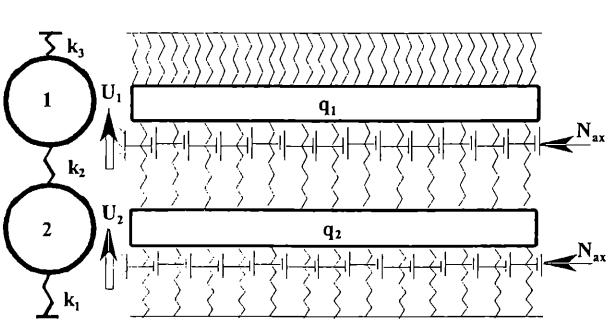

Figure 10 Finite element model.

the spring model as shown in figure 10, applying the spring stiffness' corresponding to undrained soil behaviour. In the girder model the spring stiffness' corresponding to drained soil behaviour are applied.

4.3.4 Parameter study

In order to determine the sensitivity of the model to the various model parameters a parameter study was performed. An important conclusion resulting from the parameter study was that the mechanical properties of the plates in the circular joints have a large impact on the girder behaviour of the tunnels. When using a flexible material like plywood the maximum bending moment, shear force and opening of circular joints in the tunnels are significantly less, compared to a situation where the influence of material in the circular joints is negligible (Kaubit plates).

5. CONCLUSIONS

- Non-linear girder behaviour of shield tunnel lining, potentially subjected to opening of circular joints, can successfully be modelled by a continuous girder with negligible tensile strength, supported by a continuous row of springs.
- The implications of the presence of flexible plates in the circular joint can be taken into account by applying equivalent values for modulus of elasticity $E_{c,equi}$ and shear modulus $G_{c,equi}$ of the girder.
- The stiffness of the continuous spring support is to be determined by means of a 2D numerical continuum model of the regarded soil profile.
- The axial normal compressive force is a determinative factor for the bending and shearing behaviour of the tunnel.
- In general the tunnel will loose it watertightness at the circular joints long before the ultimate bending moment of the tunnel is reached.

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