Computational model and charts for cut-and-cover tunnels

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Computational Model and Charts for Cut-and-Cover Tunnels

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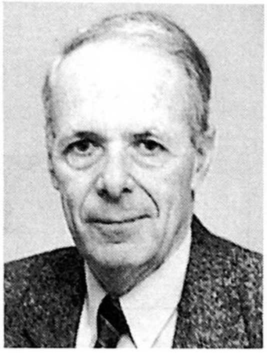


Summary

Arch-shaped concrete linings show even in cut-and-cover situations economical advantages when compared with rectangular profiles. The backfilled soil along the sides of the arch counteracts lateral movements caused by the dead weight of the soil cover above it. Thus, the computational model has to take into account the interaction between the arch and the soil. A comprehensive computational model was developed and validated by field measurements on several types of tunnel profile and at different stages of backfilling. The numerical procedure enabled charts to be developed for the design parameters for different geometrical configurations. Apart from the selection of the cross-section the following factors can be influenced by the engineer: the thickness of the concrete arch, its steel reinforcement and the stiffness of the backfill. The presented curves clearly exhibit the interaction between these factors.

1. Introduction

For environmental reasons roads and railways are being routed more and more through tunnels constructed by the cut-and-cover method. For this purpose a cut is made, the tunnel arch is constructed and then the structure is backfilled in accordance with the landscaping requirements. In Fig. 1 this method is illustrated for the most frequently encountered case of cut. Fig. 2 shows the procedure for an excavation supported by tied-back pile walls and Fig. 3 that of a cut in sloping ground. In this contribution we deal with reinforced concrete arched tunnels of large cross-section that are often met with in traffic tunnels. Rectangular frame structures or thick-walled sewage pipes are not considered. In the case of arched tunnels the deformations of the usually slender concrete construction are sufficient to activate a deformation-dependent interaction between it and the lateral backfill. This does not apply for thick-walled pipes, especially if they are of rectangular shape, since they tend to behave as embedded rigid structures.

The aim of the present work is twofold. Firstly, a computational method is described, whose validity has been confirmed by extensive field measurements in numerous projects under widely

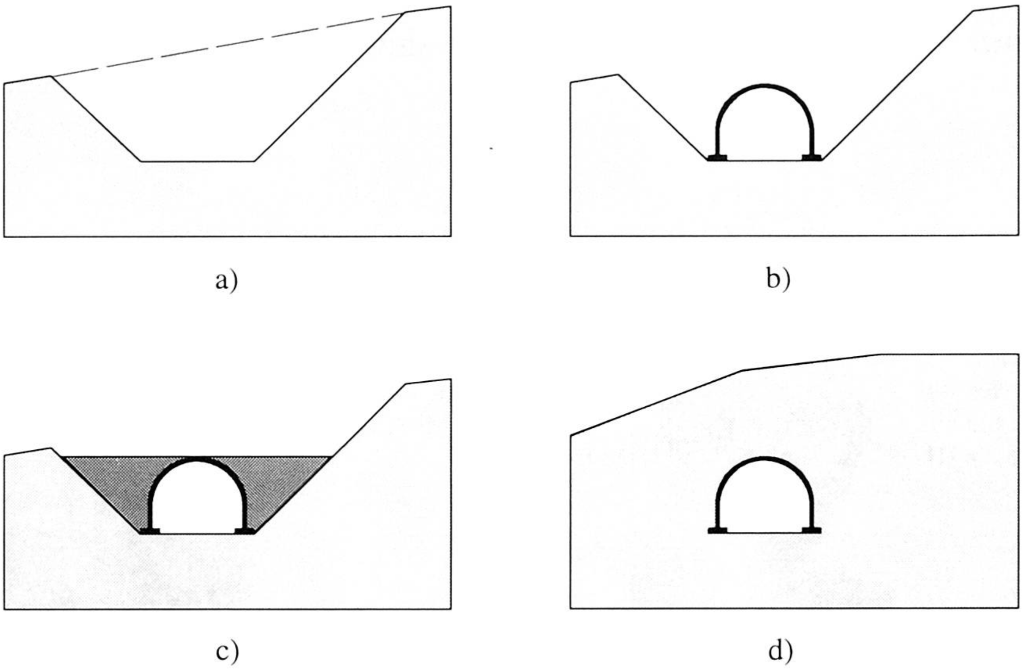


Fig. 1 The different construction stages of a typical cut-and-cover tunnel
a) Excavation *b) Construction of concrete arch*
c) Lateral backfilling *d) Backfilling over tunnel*

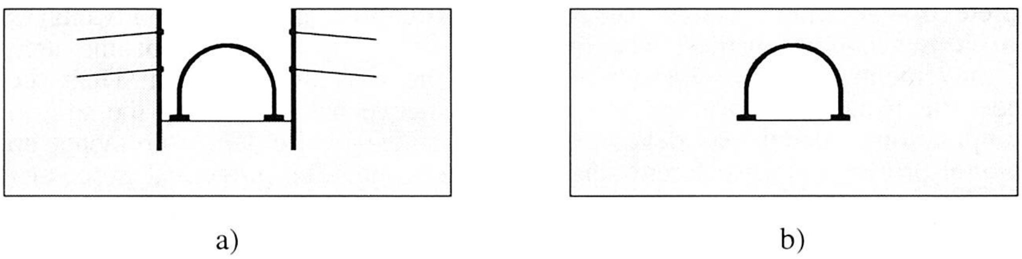


Fig. 2 Cut-and-cover tunnel in an excavation supported by pile walls

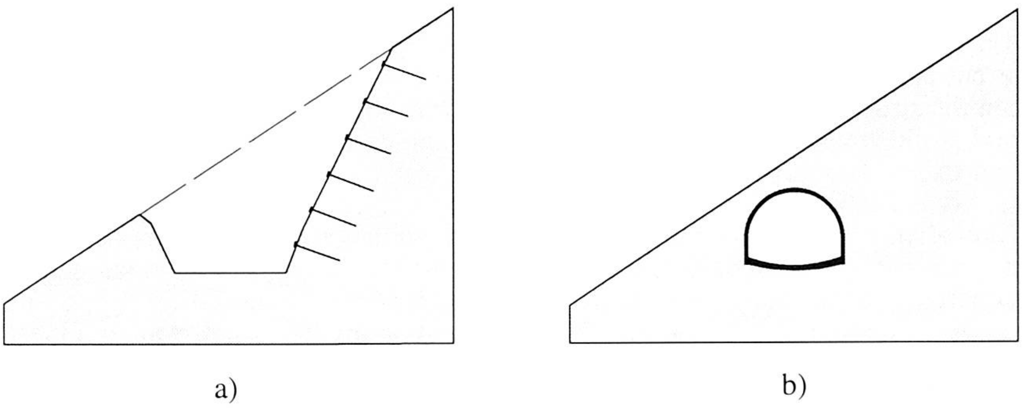


Fig. 3 Cut-and-cover tunnel in sloping ground
a) Excavation and support of slope
b) Construction of tunnel arch and backfilling

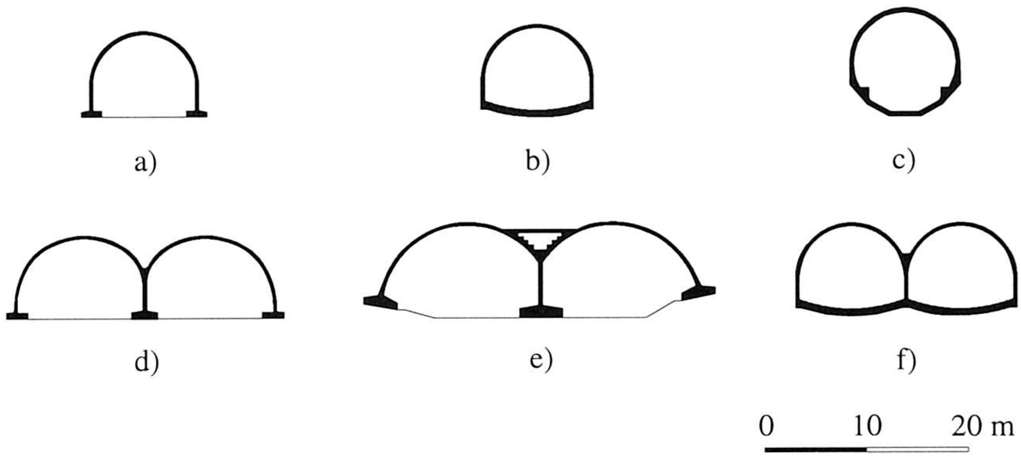


Fig. 4 Typical profiles in traffic tunnels
a) - d) Single and two lane tunnels with open and closed tunnel base
e) - f) Twin tube for two and three lane tunnels

differing conditions. Secondly, the statical behaviour of cut-and-cover tunnels is illustrated with the aid of charts. Ultimately, the economic design of such tunnels depends on a basic understanding of the way the forces act and on a suitable computational method. Several examples of typical tunnel profiles common in traffic structures are shown in Fig. 4.

In the design process for cut-and-cover tunnelling a number of decisions have to be taken. They are concerned with the tunnel shape, the thickness of the concrete lining, the amount of reinforcement and the stiffness to be achieved in the lateral backfill. These factors have a big influence on the safety of the structure, its serviceability and costs.

2. The Computational Model

The structure of a cut-and-cover tunnel consists of four elements (Fig. 5):

- the original ground
- the tunnel arch
- the lateral backfill
- the backfill above the tunnel roof.

These structural elements are deformable and interact with one another. The fill over the tunnel roof, however, only acts as a load for small heights and exhibits no real load carrying capacity. It is clear that regarding this fill simply as a vertical load acting on the system backfilled to the crown of the tunnel arch lies on the safe side. But how does the arch interact with the stepwise-backfilled material on the sides of the tunnel? It is clear that as soon as a compacted layer of backfilled earth extends over the whole of the width it becomes a component of the structural system. Thus with progressive backfilling the tunnel arch experiences an increasing embedment implying a step by step change of the structure as a whole.

Assumptions in the computational model (Fig. 5): The original ground ① and the compacted layers of backfill ③ are assumed to be elements acting in plane strain since there is no displacement normal to their plane, while the concrete arch ②, that is structurally connected to them, is assumed to consist of curved beam (i.e. flexurally stiff bar) elements. The vertical and horizontal extents of the ground considered in the analysis depend on the span of the tunnel arch and the depth of backfill. The external boundaries are allowed to have displacements, each in one direction. Fig. 5 shows the final state of the completed structure. The engineer, however, is interested above all in the intermediate stages of placement of the lateral backfill, since the internal forces and moments (M, N) and the deflections due to

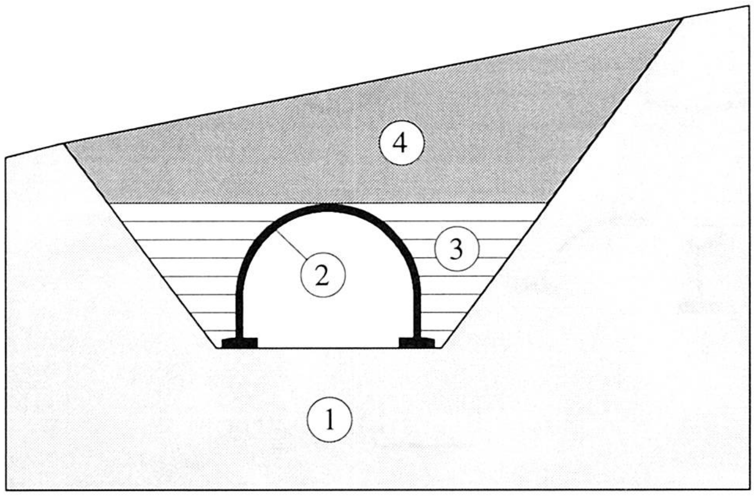


Fig. 5 The structural system for a cut-and-cover tunnel
① the original ground ② the tunnel arch
③ the lateral backfill ④ the backfill above the tunnel roof

bending action change with each new stage of backfilling. The aim is to determine for each point on the tunnel arch the critical values of M and N. Thus only a computational method which is able to take into account the changes in the structure during the stagewise construction process is of interest. The first question to be answered is what is actually the incremental load applied to the structural system. This is given by the unit weight of the layer of backfill in the process of compaction, which has a width of **a**, and the depth of **Δh** of backfill. Since a layer of lateral backfill is side-by-side with the tunnel arch, the earth pressure has to be considered there. Its value lies between the active earth pressure (λ_a) and the earth pressure at rest (λ_0) depending on the lateral movement of the arch. The earth pressure coefficients are a function of the angle of internal friction φ , i.e.

$\lambda_a = \tan^2(45°-\varphi/2)$ and $\lambda_0 = 1-\sin\varphi$.

The formula for λ_0 was proposed originally by Jáky (Jáky, 1944) and then only for cohesive soils. Fig. 6 shows that the load increment components (p_h, p_v) influence the concrete arch ②, the already compacted backfill ③ and the original ground. It is recommended to carry out separate calculations with λ_a and λ_0 and to adopt for design purposes the most unfavourable result for the pair of values (M and N). One can show that with decreasing thickness Δh of a backfill layer in a stage the influence of the difference between the active pressure and the earth pressure at rest decreases. If for any reason the backfilling is carried out asymmetrically, then due to the different heights of the lateral backfill an asymmetrical structure results. In the computational model this is taken into account automatically. Even if in subsequent backfilling the symmetry of the structure is restored in terms of geometry, the distribution of the final deformations and the sectional forces remain asymmetrical. The computational program presented here has a memory capability. An extreme case of asymmetry of final backfilling is obtained for a tunnel in sloping ground (Fig. 3).

After specifying the statical system and the loading quantities the idealisation of the deformational behaviour for the tunnel arch ① and the plane strain regions ② and ③ (Figs. 5 and 6) is discussed. As is usual in the statical analysis of reinforced concrete structures, a linear elastic material behaviour is assumed. Without limiting the validity of the computational model, in the following we exclude the development of plastic hinges. We will not consider this point further, as the structural safety of a backfilled tunnel arch is hardly affected by the presence of a few plastic hinges.

If we consider the plane strain region ① of the original ground (Figs. 5 and 6), then it is reasonable here too to assume linear elastic material properties. Its stiffness is characterised by

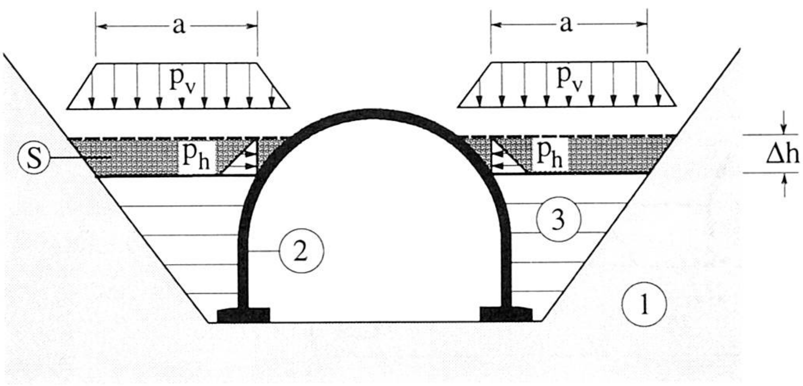


Fig. 6 The layer S during compaction
Consideration as surcharge p_v and earth pressure p_h

the value of the Young's modulus E_0, which is either estimated or determined by field tests. In the case of tunnels comprising twin tubes or a base slab the value of E_0 is of particular importance. If the ground has a low stiffness there is in the case of twin tube profiles a big differential settlement between the middle foundation and those at the sides, which leads to higher bending moments in the concrete arch. There is usually no information available concerning the Poisson's ratio ν_0 of the original ground. It also influences the settlements, however, since a higher value of ν_0 corresponds to stiffer soil. In the following computations an estimated value of $\nu_0 = 0.25$ is employed.

As the already compacted backfill forms an essential part of the structure its deformational properties are of particular interest. From the computational viewpoint there would be no difficulty in introducing a non-linear material behaviour by the artifice of assigning higher Young's moduli to the individual layers of backfill with increasing height of the backfill. Such a procedure is not adopted for two reasons. Firstly, one does not generally have detailed information about the stress-strain relationship for the backfill. Secondly, if this information were available, the advantage gained would be outweighed by various uncertainties. Thus a constant, pressure-independent Young's modulus E is used in all calculations. A question of some practical consequence is the choice of the Poisson's ratio ν for the plane strain elements ③ of the already compacted backfill. Here purely theoretical considerations are of little help. To obtain realistic values we resort to back-calculations of the measured deformation of the tunnel arch. Extensive investigations for different profiles (Figs. 4a-d) with different loading stages indicate that the best agreement is obtained with a value of $\nu = 0.5$, i.e. for an incompressible material. If an element of such material is fully restrained laterally then for a vertically applied stress σ_y a horizontal stress σ_x of the same value is induced. For $\nu \leq 0.5$ one obtains the relation:

$$\sigma_x = [\nu/(1-\nu)]\sigma_y$$

The empirical result that the already compacted backfill behaves as an incompressible elastic material whose Poisson's ratio $\nu = 0.5$ is the most important finding of our extensive field measurements.

2.1 The general case of the computational model

The computational model presented here takes into account the geometry of the structure in its various stage of backfilling (Fig. 7), the differing material properties of the original ground and the compacted backfill, as well as the normal and bending stiffnesses of the concrete arch. The shape of the latter- with or without base slab - may be chosen freely. Each stage of lateral backfilling represents a load increment. Fig. 7 shows the factors influencing the results of the computation. They are:
- the geometry (D, d, a_1, a_2, H_1, H_2, α_1, α_2, Δh) and
- the material properties (E_0, ν_0, E, ν, φ, γ).

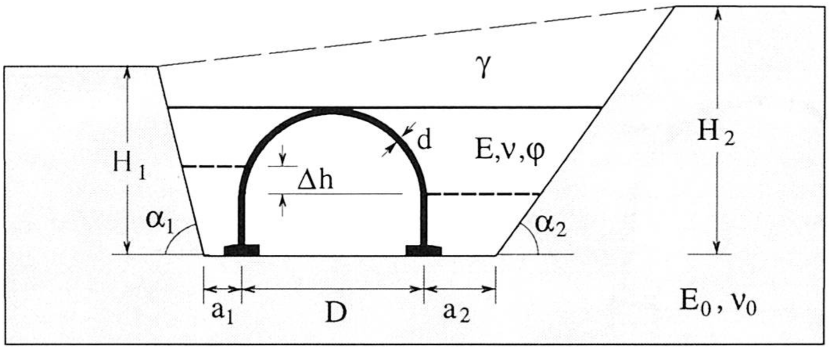


Fig. 7 The general computational model with the computational parameters

3. The Computational Procedure

The computational model consists of plane strain elements and embedded or partially embedded beam elements of the tunnel arch (depending on the stage of construction under consideration) the analysis being carried out by the finite element method. The computer program must be able to store and sum up the results of the individual computations for each stage of backfilling. Between the tunnel arch and the already compacted lateral backfill either a non-slip shear-resistant interface condition or one allowing slip (simulated by special slip elements) can be specified. It should be noted that only normal stresses can be transmitted between the beam elements and the plane strain elements.

The calculation procedure begins with the loading due to the first layer of the lateral backfill. The load quantities are different if there are different thicknesses of backfill right and left of the tunnel arch. After carrying out the calculations the internal forces and moments in the concrete arch together with the displacement components are stored. Fig. 8 shows the results for the stage i of backfilling. If the backfilling up to this point was asymmetric, this is shown by a non-symmetry in the distribution of the calculated quantities (bending moment M_i, normal force N_i, and the displacement components u_i and v_i in the tunnel arch). Here we should not forget that for small layer thicknesses the difference due to differing earth pressure coefficients is also small. This is generally the case for a thickness $\Delta h = 1.00$ m.

After lateral backfilling and over the arch the following internal forces and moments and displacements are obtained on summation:

$$M_n = \sum_1^n M_i, \qquad N_n = \sum_1^n N_i, \qquad u_n = \sum_1^n u_i, \qquad v_n = \sum_1^n v_i.$$

In this way the most unfavourable values of M and N can be determined for each section of the tunnel arch and for a chosen reinforcement content the safety against failure of the concrete arch at each section can be obtained from a corresponding interaction diagram.

It is recommended to represent the internal forces and moments and the displacements graphically as a function of the arch length. Since a translation of the arch as a whole does not produce any internal stressing or deformation it is of little interest. Thus it is advantageous to assume one of the abutments to be fixed and the other to displace only in a horizontal direction. In this way the deformation mechanism, especially in the case of twin tunnel cross-sections, is easily seen and a comparison with field measurements can be easily made.

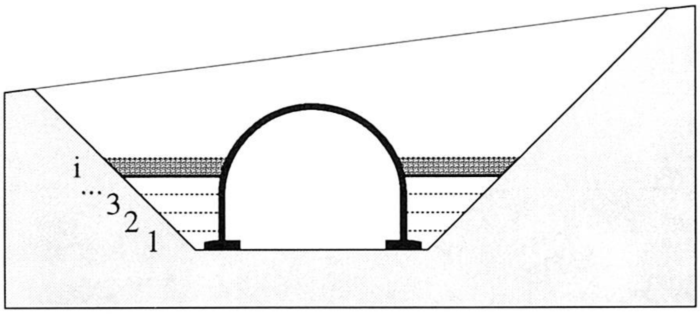


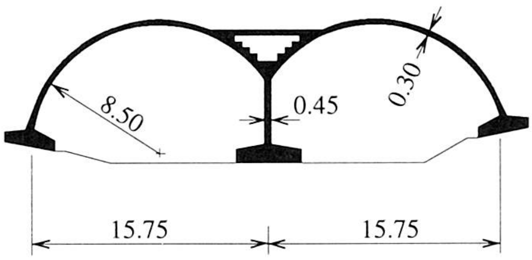
Fig. 8 The simulation of the backfilling stage i

4. Deformation Measurements and Back-calculation

Within the framework of a long-term research project extensive deformation measurements were carried out on 5 different structures with differing profile geometries and sizes of the span (Figs. 4a-d). The results were interpreted with the help of the computational model described above applying the same basic assumptions (Tisa and Kovári, 1993). The agreement between the measured and calculated deflection curves is better for more flexible concrete arches than for stiffer ones. The first would be the case for large spans and relatively small concrete thicknesses. For a particularly instructive example we consider the 550 m long Brünnen Tunnel on the Swiss National Highway N1, which with its twin four lane tunnel tubes (Fig. 9) forms a part of the by-pass around Berne. The spans are each 15.75 m, while the thickness of the concrete arch is only 0.35 m. The middle wall is 0.45 m thick. In three measuring cross-sections roughly 150 m and 250 m apart the deflection curve for the arch was measured for four stages of lateral backfilling. We pick out on the construction stage with the backfilling just to the crown of the arch and consider the displacement vectors in the three measuring cross-sections. From Fig. 9 it is clear that both side foundations experience settlements of about 4-8 mm relative to the middle wall. The three displacement vectors at a point indicate - despite a certain scatter both in their directions and magnitude - a uniform behaviour of the structure. Some deviations - especially in the area of the crown - may be traced back to differences in the procedure for lateral backfilling and compaction. A comparison between the measured and the calculated values can be best made in terms of the distribution of the displacement components u and v as a function of the arc length (i.e. the circumferential length of the arch) S.

In Fig.10 the points represent the measured values in the three measuring cross-sections. The lines represent the back-calculation, which was always carried out assuming the active earth pressure coefficient (λ_a) and the earth pressure coefficient at rest (λ_0). From the good agreement between observation and theory one may conclude that the calculated internal moments and forces, which for technical reasons cannot be measured directly, form a good basis for the design and the determination respectively of the structural safety. In the computational model the following parameters were adopted: $E_0 = 80$ MPa, $\nu_0 = 0.25$, $E = 50$ MPa, $\nu = 0.495$, $\varphi = 30°$, $\gamma = 22$ kN/m^3 and a Young's modulus of 30'000 MPa for the concrete. To experimentally determine the deflection curve the distometer instrument (Kovári and Amstad, 1979) was used, which by means of an invar steel wire is capable of measuring the change in distance between two points of the tunnel arch with an accuracy of around $\pm$ 0.05 mm.

It should be mentioned that with increasing stiffness of the arch the scatter of the measured deflections also increases leading to greater differences between theory and observation.



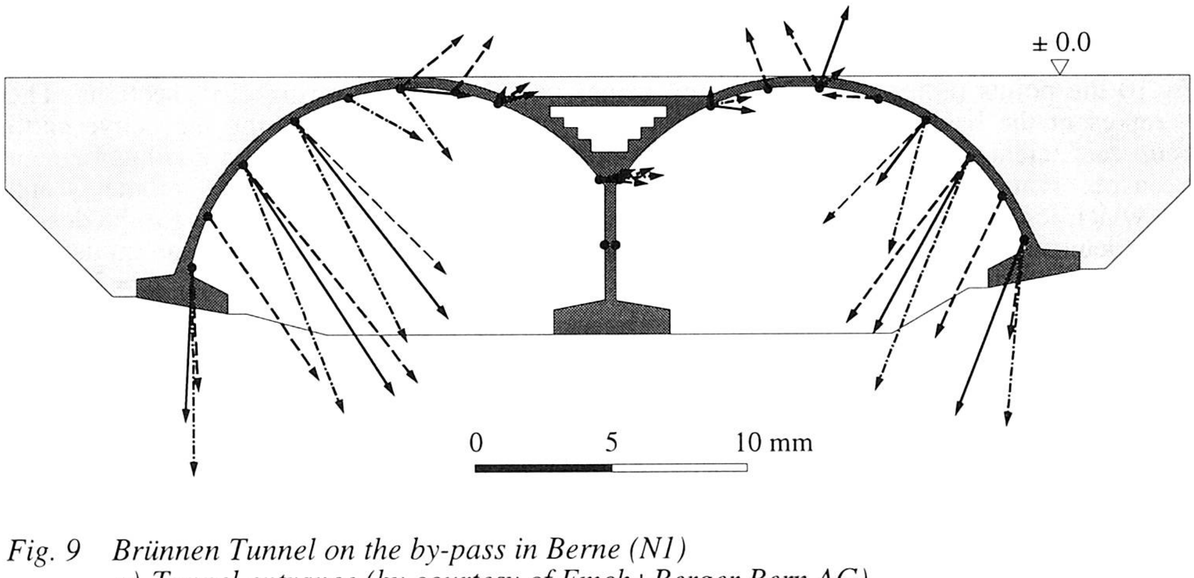


Fig. 9 Brünnen Tunnel on the by-pass in Berne (N1)
a) Tunnel entrance (by courtesy of Emch+Berger Bern AG)
b) Geometry
c) Observed displacement vectors in 3 measuring cross-sections

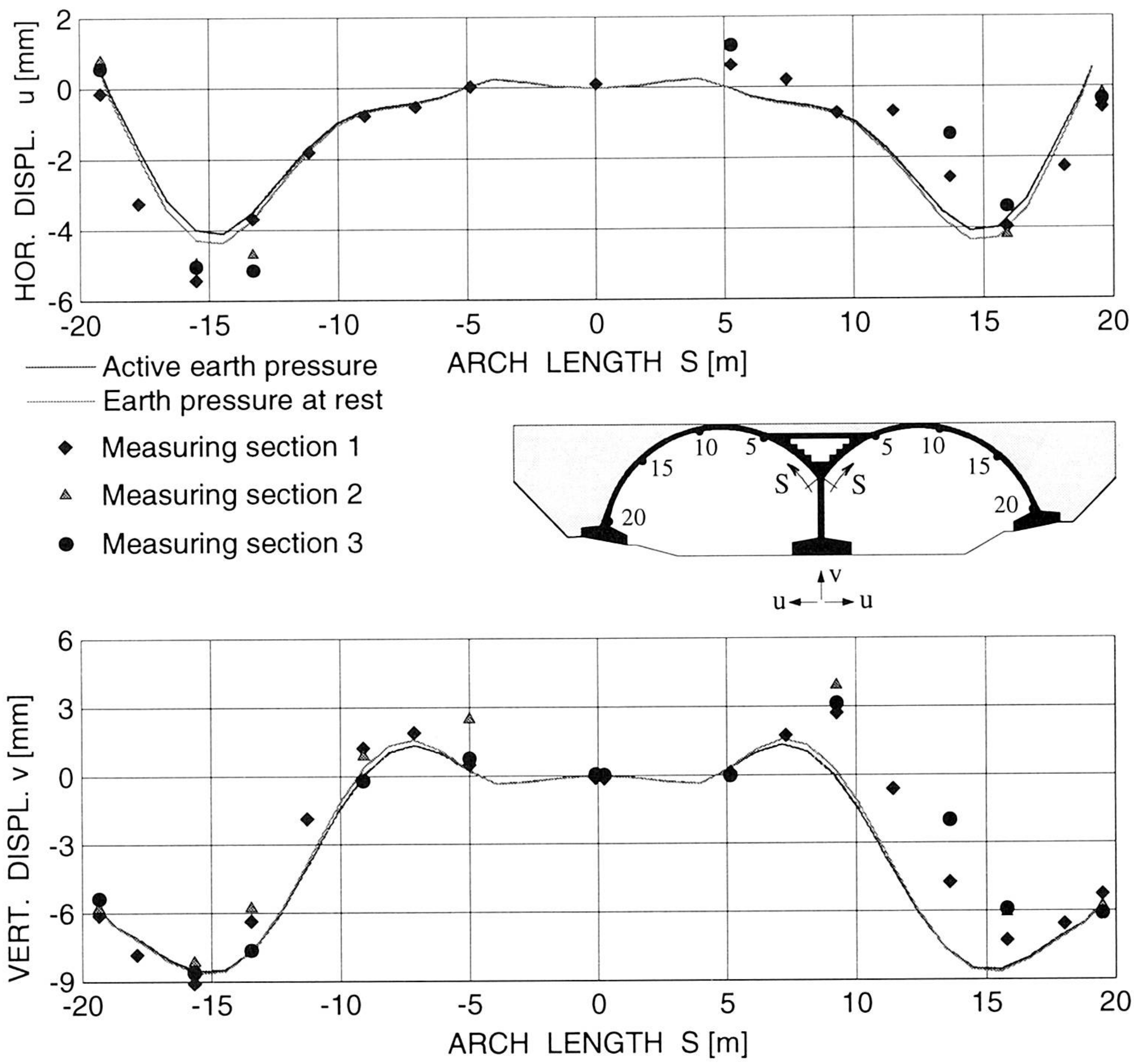


Fig. 10 Brünnen Tunnel: Comparison of measured displacement components (u,v) in discrete points with the calculated bending deflection curve

5. Design Charts

The computational model presented above permits the preparation of design charts for frequently encountered tunnel sections and deepens our understanding of the internal forces acting in cut-and-cover tunnels. In the foreground is the influence of the following factors that the engineer has to determine affecting the forces and moments at the cross-section:

- shape of tunnel section (with or without the invert arch base, etc.)
- the thickness of the concrete arch (d) and the amount of reinforcement (Fe)
- the stiffness of the lateral backfill (E) and
- position and profile of the final backfill above the roof of the tunnel.

In the following design charts for a two track tunnel (Fig. 11a) and a twin tube tunnel with four traffic lanes are presented and described (Fig.11b). For a chosen cross-section in the concrete arch (point V) the bending moment M and the normal force N are determined for different values of the above-mentioned factors and these two values are represented as a point in the interaction diagram (Figs. 13 and 14). The most important construction stage (A) corresponds to backfill to the height of the crown of the arch. The subsequent backfill was assumed to be horizontal with

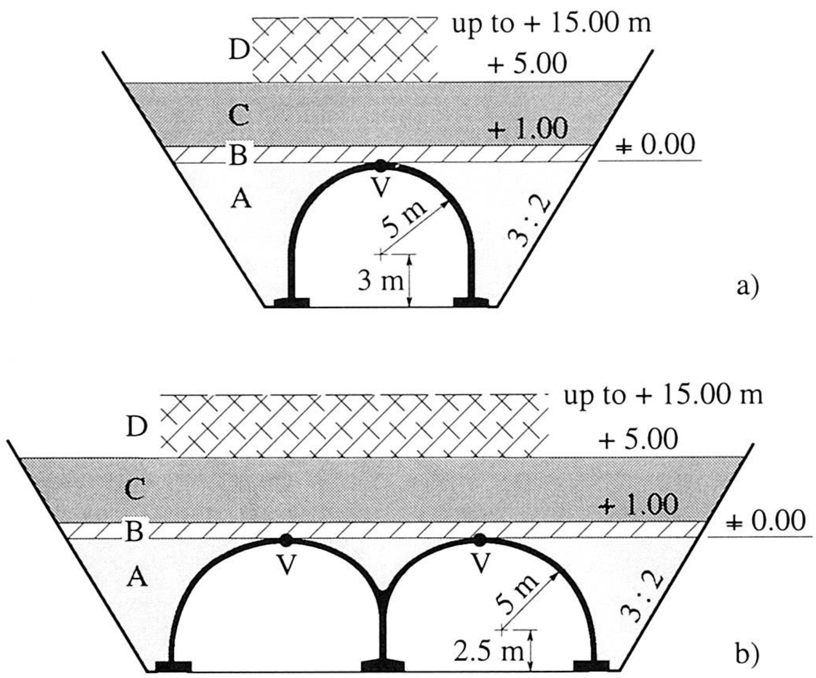


Fig. 11 *Geometry of the profile and the computed backfilling stages A to D. The design charts refer to the cross-section at the crown of the arch (point V).*
a) Two track tunnel b) Twin tube tunnel

steps of 1, 5, 10 and 15 m. The corresponding construction stages are designated by B, C and D in Fig. 11. Each pair of values M/N of the construction stage A is the result of a series of individual computations corresponding to backfill increment of 1.0 m. The earth pressure coefficient at rest (λ_0) was always adopted. The backfilling to B, C and D was each considered as a single loading corresponding to the differential heights.

In view of the large number of parameters that appear in the model it is necessary to restrict the computations to a selected number of thicknesses of concrete arch (0.3, 0.4 and 0.5 m) and values of Young's modulus of the lateral backfill of 10, 20, 40, 60 and 100 MPa. Between the tunnel arch and the lateral backfill non-slip shear resistant interface condition (full friction) was considered. Details of the tunnel profile geometries for the profile types treated here are shown in Fig. 11.

5.1 Interaction diagrams for a two track tunnel

From previous investigations (Kovári and Tisa, 1982) it is known that in this type of profile the crown of the arch (point V) corresponds to the most unfavourable condition of internal stressing (M/N). The interaction diagrams (Figs. 12,13 and 14) relate to this cross-section of the tunnel arch. Each diagram is valid for a given thickness of concrete arch. The approximately horizontal varying series of points correspond to a particular height of backfill over the crown of the tunnel. It may be readily seen that these series of points move in the direction of higher normal force with increasing depth of backfill, i.e. the bending moments remain approximately constant despite the increased loading. Within such a nearly horizontal series of points the influence of the Young's modulus E of the lateral backfill is noticeable. With decreasing values of E a point moves to the right in the direction of greater moments. The permissible region of a pair of values M/N in the interaction diagram is marked for a given amount of reinforcement (0, 0.15, ... 0.60 %). These limit lines apply for a resistance coefficient reduced by the amount $\gamma = 1.2$ (Swiss Code SIA 162).

A look at the charts clearly shows that the construction stage with backfill up to the crown of the arch is the least favourable. Each additional backfill step results in an increase of normal force at an almost constant bending moment. Thus the points on the interaction diagram move away from the corresponding limit lines for varying amounts of reinforcement.

Considering the influence of the thickness of the arch **d** on the bending moment and on the required reinforcement content Figures 12, 13 and 14 clearly show that with increasing value of **d** the bending moment increases and the reinforcement content decreases. These relations are however only pronounced for low values of the Young's modulus E of the backfill (10 and 20 MPa).

Each point for the row 0 m (backfill to crown of the arch) required 8 separate calculations corresponding to the 8 stages of the lateral backfill. For the rows 1m, 5 m, etc. each point required an additional calculation.

In order to show the forces for the critical construction stage A (lateral backfill to crown of arch) in a more explicit way we consider Fig.15. The diagram shows the bending moment M at the crown of the arch (V) and the required amount of reinforcement Fe in % according to SIA 162 for different values of thickness of concrete arch d and different values of Young's modulus in the lateral backfill E. In this figure it may also be clearly seen that with increasing stiffness of the backfill the bending moment and the required amount of reinforcement decrease. Concrete thicknesses induce greater bending moments but require, however, smaller specific reinforcement. The influence of the reinforcement at large values of E is always smaller.

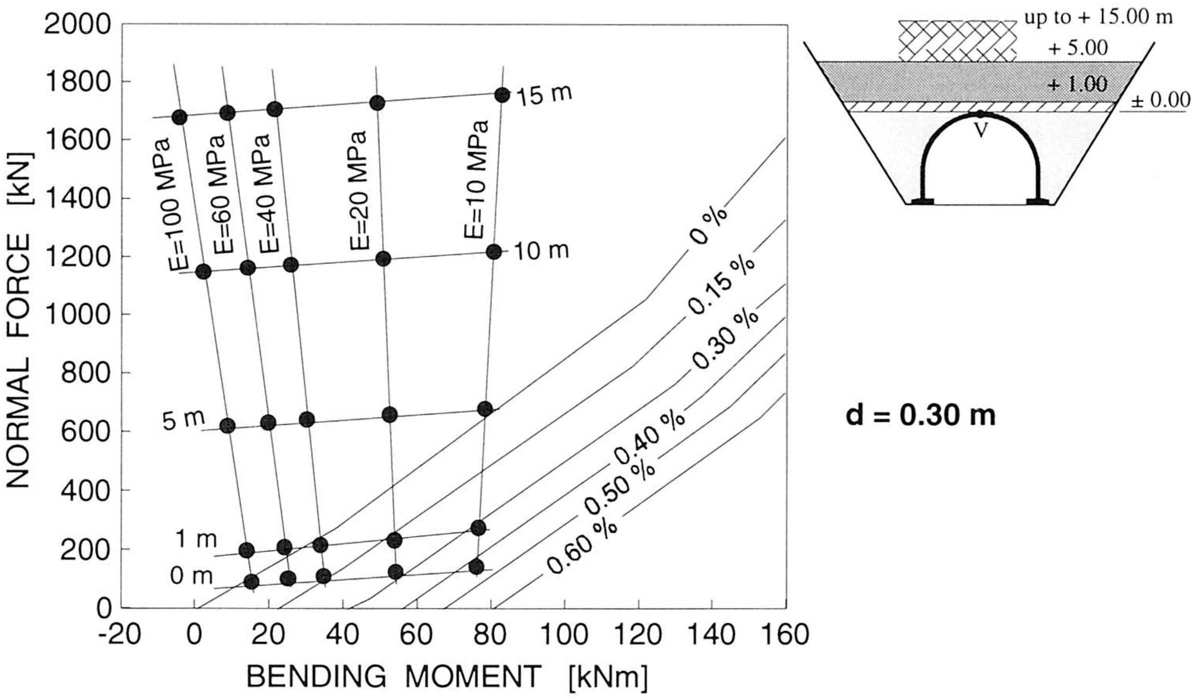


Fig. 12 Interaction diagram M/N for the crown V for the backfilling stage to the crown with backfilling increments of 5, 10 and 15 m Thickness of arch 0.30 m (reinforcement content in %)

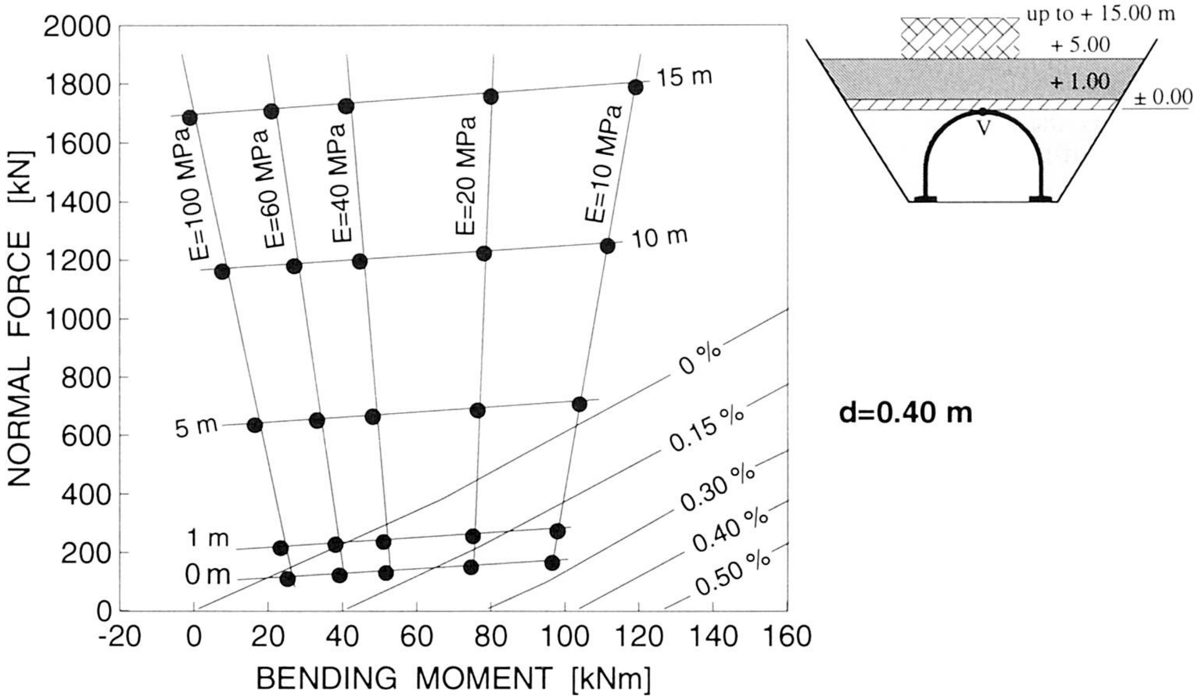


Fig. 13 *Interaction diagram M/N for the crown V for the backfilling stage to the crown with backfilling increments of 5, 10 and 15 m Thickness of arch 0.40 m (reinforcement content in %)*

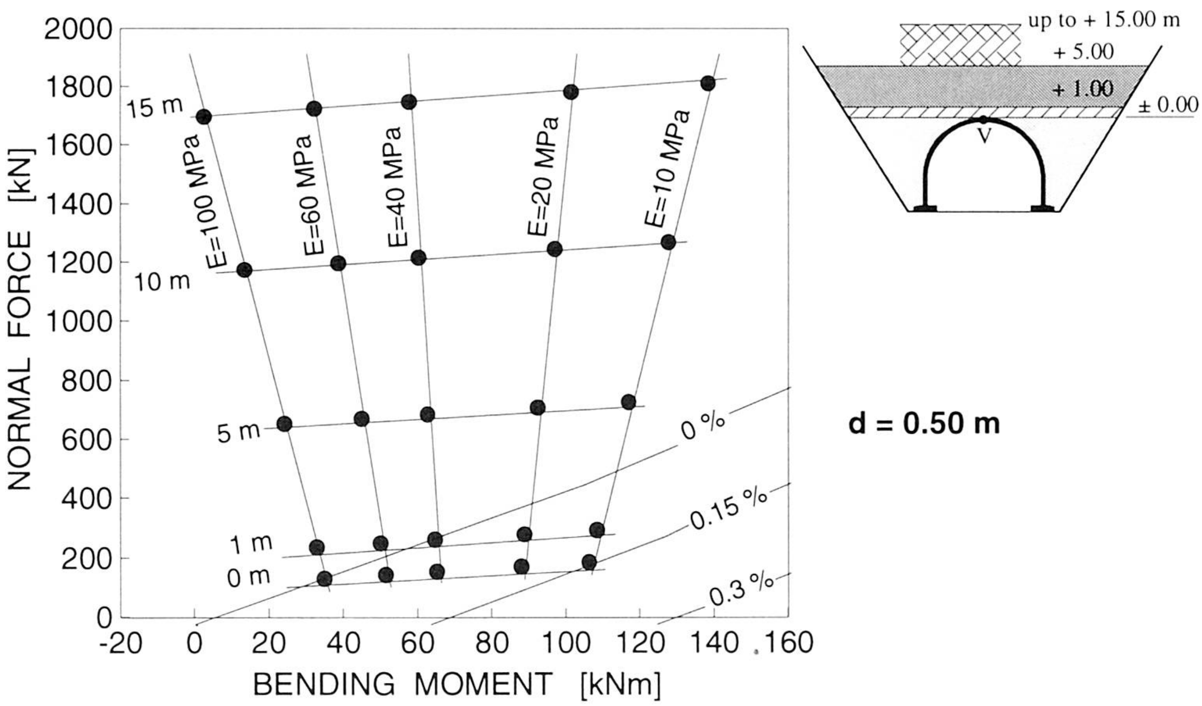


Fig. 14 *Interaction diagram M/N for crown V at the backfilling stage to the crown and backfilling increments of 5, 10 and 15 m. Thickness of arch 0.50 m (reinforcement content in %)*

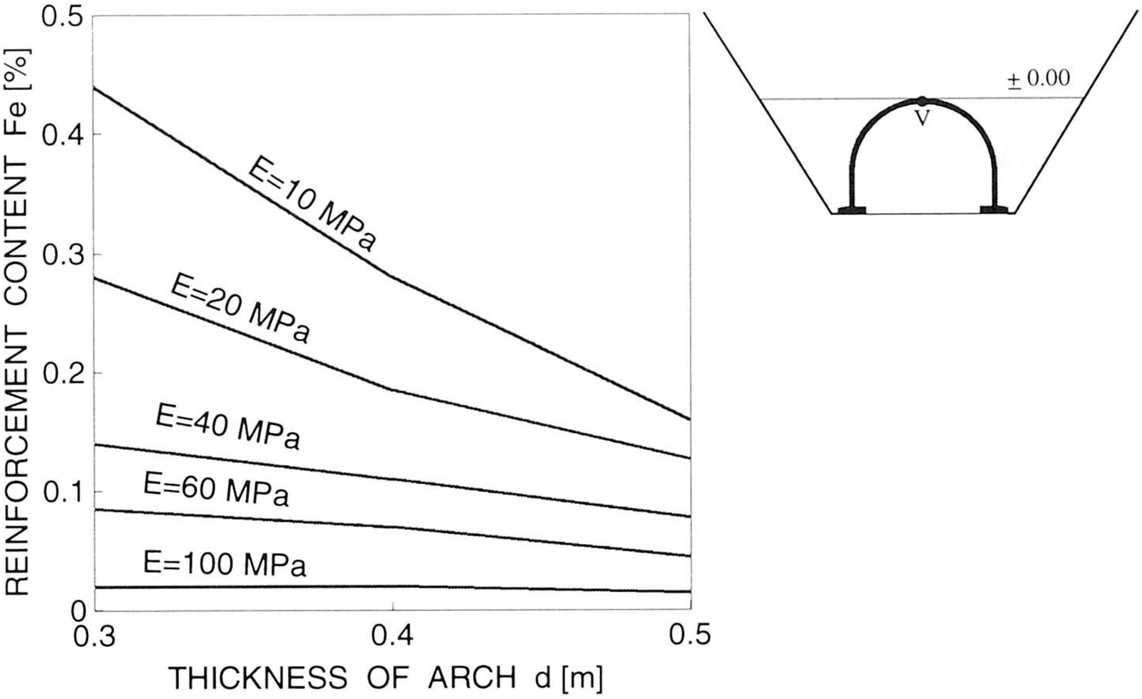


Fig. 15 Lateral backfilling up to the crown. Required reinforcement content (Fe) as a function of chosen values of E and d.

To further elucidate the way the forces act we refer to the diagrams in Fig. 16. Here too the values of normal force and bending moment are those at the crown of the tunnel V with the lateral backfill level with the crown. One clearly recognises here as well that the stiffness (Young's modulus E) of the backfill only affects the normal force slightly, but the bending moment greatly.

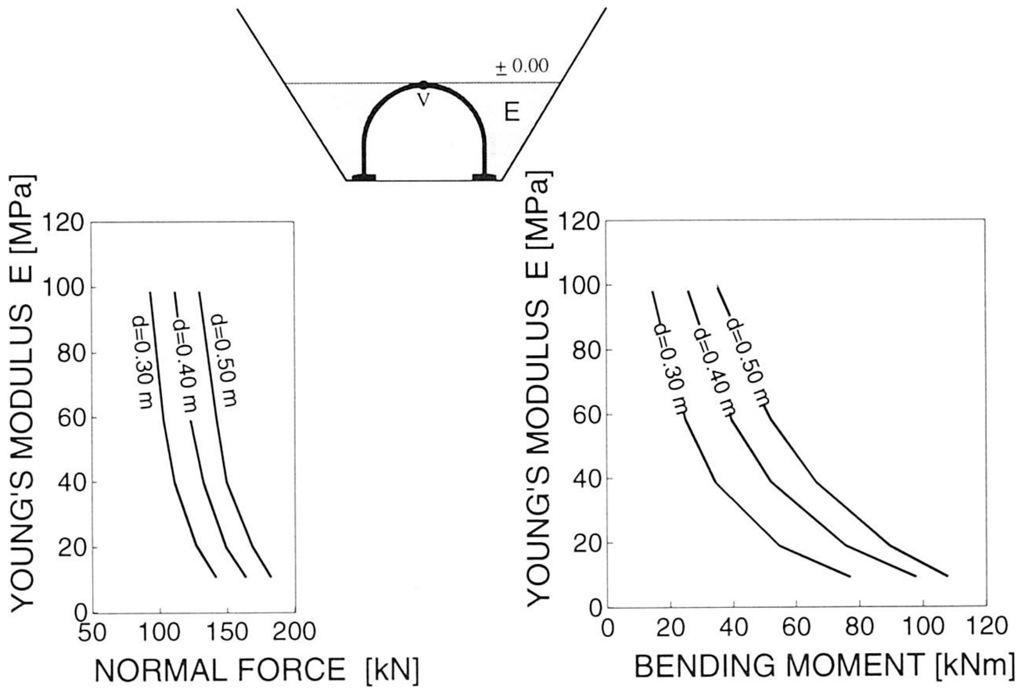


Fig. 16 The internal moments and forces M and N as a function of the Young's modulus E of the backfilling and the thickness of the arch d

5.2 Interaction Diagrams for Twin Tube Tunnels

The exact geometrical details for the tunnel profile may be taken from Fig. 11b. The diagrams in Figs. 17 and 18 apply once again for concrete arch thicknesses of 0.30, 0.40 and 0.50 m. The most striking result in Fig. 17 is the converging of the lines for a constant value of E in a point at d = 0.30 m and a height of backfill of 10 m. This means that at this stage of construction the Young's modulus E of the backfill has neither an influence on the bending moment nor on the normal force at point V. For the thickness d=0.40 m the point of convergence lies at a backfill height well over 15 m (Fig. 18). For d = 0.50 m (Fig. 18) the influence of the Young's modulus E of the backfill becomes for all heights under consideration very pronounced. Fig. 19 shows the same tendency between the crucial factors as Fig. 15.

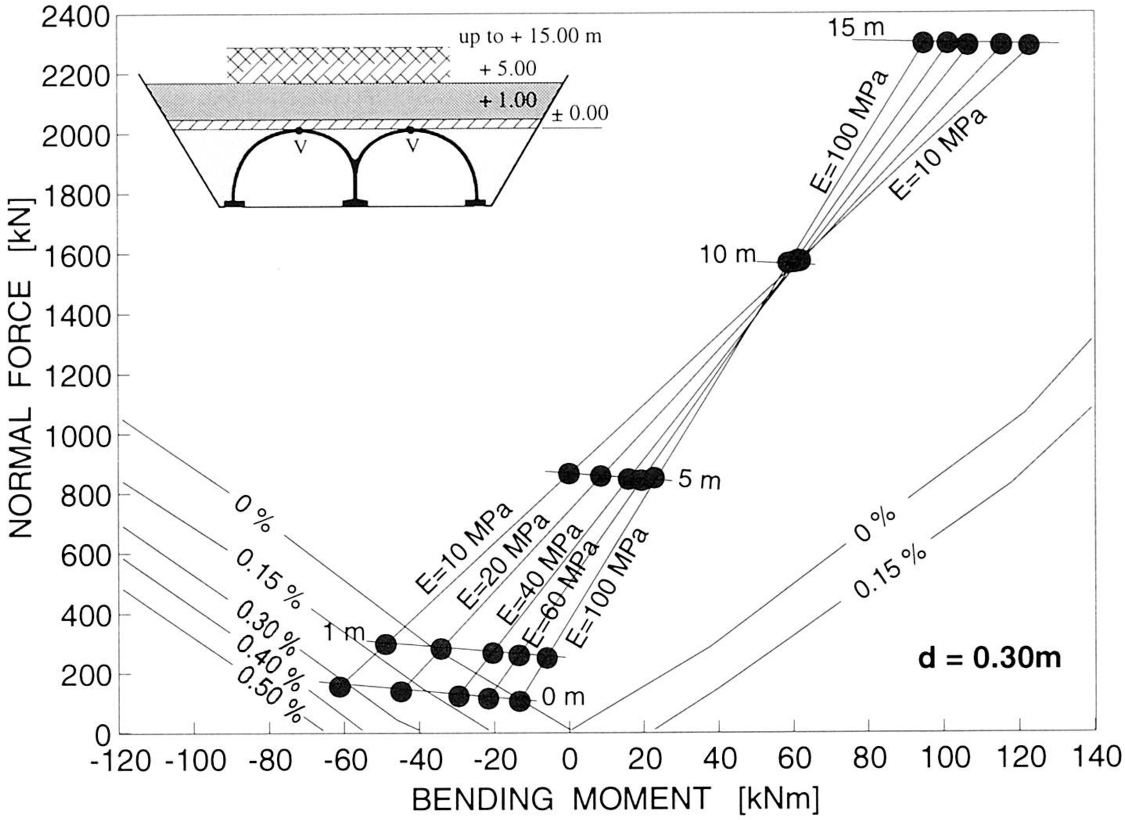
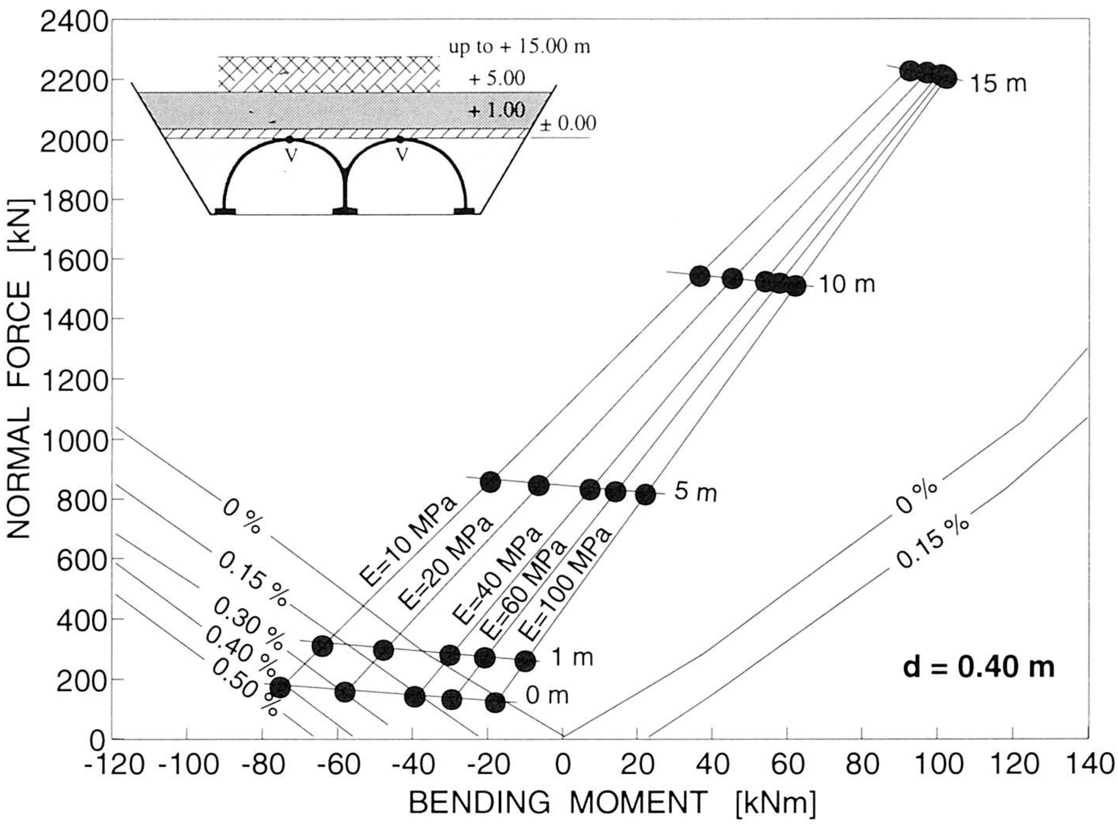


Fig. 17 Interaction diagram M/N for the crown V for the backfilling stage to the crown with backfilling increments of 5, 10 and 15 m Thickness of arch 0.30 m (reinforcement content in %)



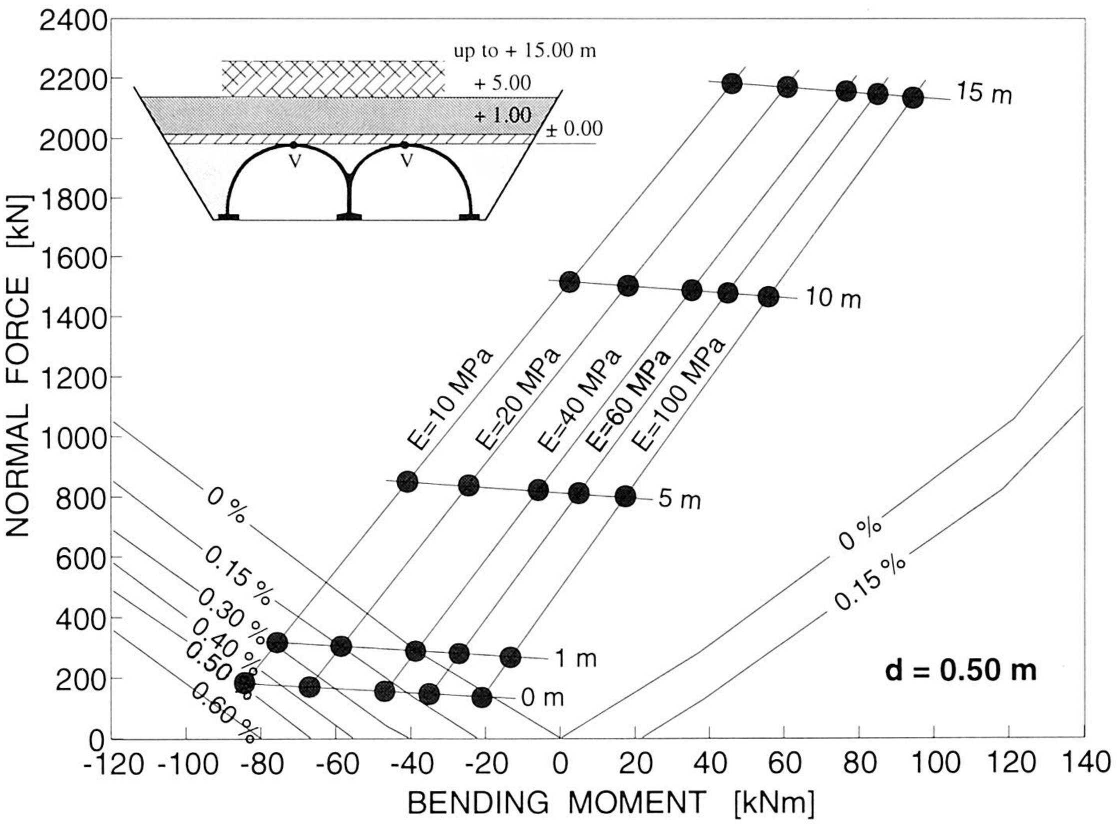
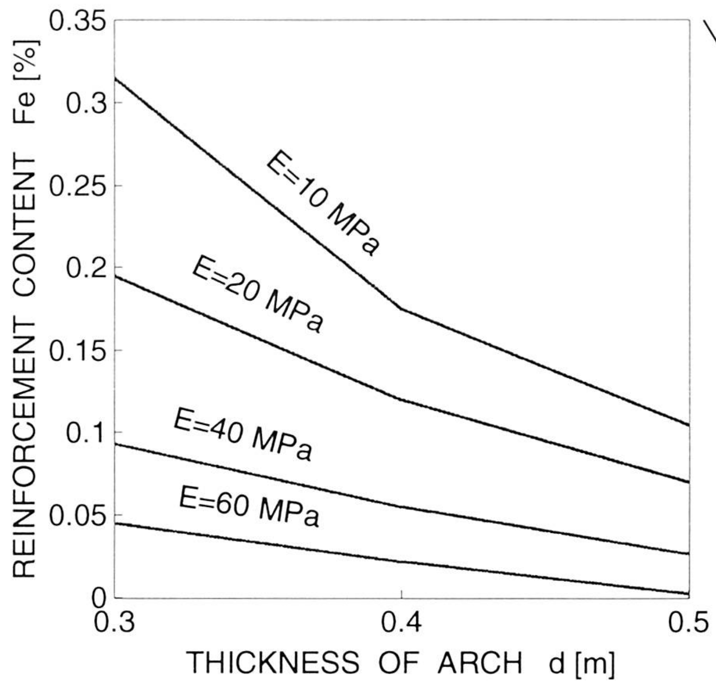


Fig. 18 Interaction diagram M/N for the crown V for the backfilling stage to the crown with backfilling increments of 5, 10 and 15 m Thickness of arch 0.40 m and 0.50 m (reinforcement content in %)



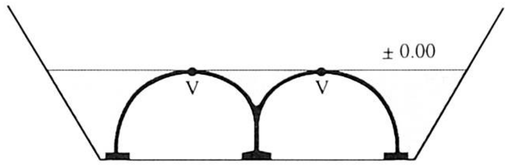


Fig. 19 Lateral backfilling up to the crown. Required reinforcement content (Fe) as a function of chosen values of E and d.

6. Final Remarks

The computational model presented in this paper was validated by measured deflections of various cut-and-cover structures in several stages of backfill. The model gives the possibility to establish a relation between the factors influencing the interaction between the tunnel arch, the backfill and the original ground. The presented charts may serve as a guideline for preliminary designs of tunnels with similar cross-sections as well as a means to understand the structural behaviour of arch-shaped concrete linings in cut-and-cover situations. In case of the final design of a given project such charts may lead to the most economical design. It is recommended to carry out computations for both non-slip resistant interface condition and for one allowing slip between tunnel arch and lateral backfill.

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