SEGMENTAL LINING THICKNESS VS. INTERNAL DIAMETER RATIO: A PERSPECTIVE APPROACH FOR LINING DIMENSIONING

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Abstract

One of the most important decisions taken by tunnelling engineers at the beginning of a project, once the internal diameter is selected, is the definition of the concrete lining thickness, which will ultimately determine the TBM diameter and required boring dimensions. In several cases, due to the urgency to define TBM characteristics, a full design is not possible and some general assumption has to be made to establish a reasonable lining thickness. This article through a general approach tries to give an indication on applicable lining thickness as a function of needed tunnel inner diameter. A compilation of data of over two hundred built tunnels has been made and a statistical analysis of the data performed to establish the thickness/internal diameter ratios used in practice. As an example, an accepted closed form solution was applied to estimate the sectional forces for different characteristics of ground conditions and overburden and these values were compared to the interaction diagrams corresponding to the commonly adopted thickness/internal diameter ratios. Although special cases such as squeezing and swelling ground, or presence of high water pressures, which require particular consideration exist, it has been shown that in general, ground conditions do not have a significant influence on the ground loads that will be acting on the lining since they depend mostly on tunnel diameter. In addition, it can be said that as long as the thickness/internal diameter ratio is within certain values used commonly in the practice, it is likely that the structural capacity of the lining will be adequate to resist the imposed ground loads for most geological conditions.

Key words: Segmental lining, thickness diameter ratio, lining dimensioning.

INTRODUCTION

Segmental lining design is usually carried out in several phases, the first being the pre-dimensioning of the lining based on the Designer's experience on similar projects or on bibliographical compilations of lining data used on other projects and second, using closed form solutions or more complex numerical analyses to verify that the lining can resist adequately the expected design loads. This philosophy is reflected in the flowchart included in the ITA "Guidelines for the design of shield tunnel lining" which is reproduced in Figure 1. As the chart shows, after definition of the lining inner diameter, other lining characteristics such as its thickness, concrete strength and steel quantity and segments distribution are defined. After such assumptions have been made, the Designer goes on to compute the sectional forces and check if the proposed lining is structurally safe under the expected loads.

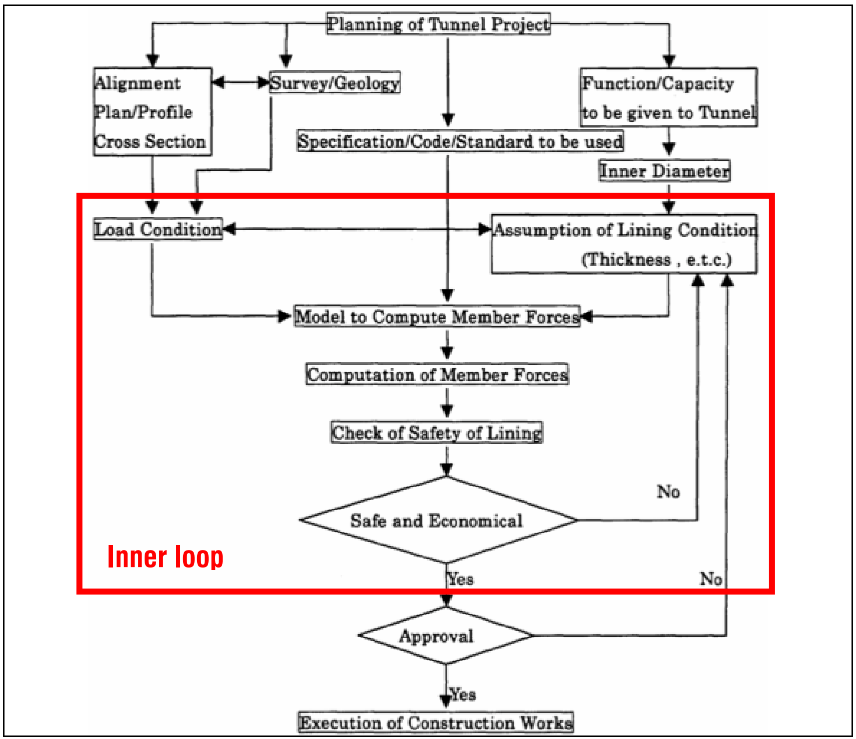

Figure 1. ITA flow chart for segmental lining design. Reproduced from [3].

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However, the path shown in Figure 1 is not always compatible with project timing, which usually calls for quick TBM purchase and thus an expedite ring geometrical definition. It is often the case that the pre-dimensioning of the lining, or more accurately, the definition of its thickness is done taking as starting point compiled charts of lining internal diameter and thickness, as the one included in the recommendations of the Association Française des Tunnels et de l'Espace Souterrain (AFTES) on "*The Design, Sizing and Construction of Precast Concrete Segments Installed at the Rear of a Tunnel Boring Machine (TBM)*". The graph compiles information on the thickness and internal diameter of tunnels built until 1997 (see Figure 2). As may be observed, the data shows a regular distribution and appears to suggest that the relationship between the two variables is pretty linear. The AFTES graph provides a guide to reasonable but most importantly successfully employed values of lining thickness and herein lays its value. However, it has few data above 9 m diameter and couldn't take into account the undoubted development of tunnelling industry in the last 13 years.

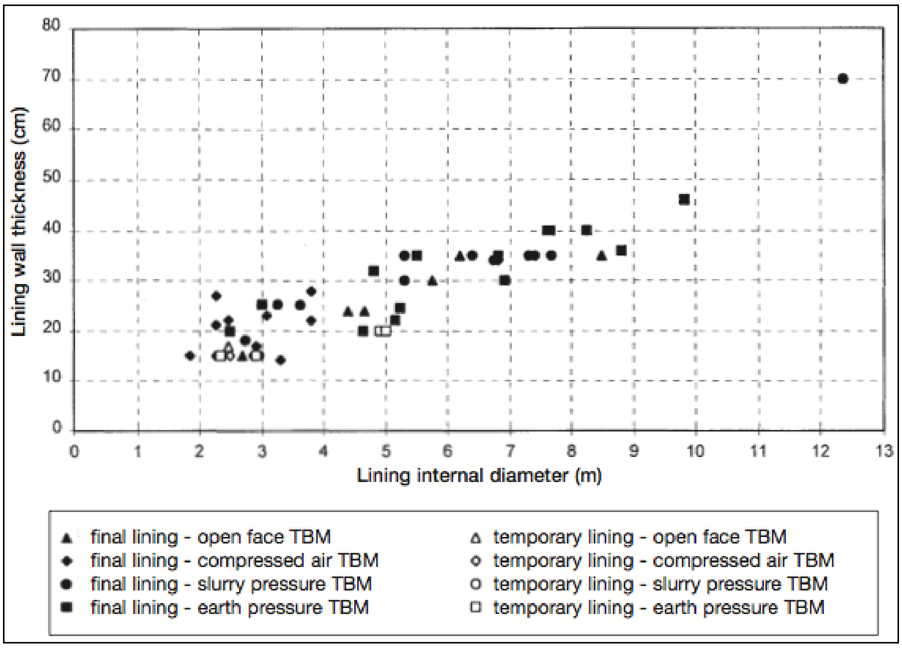

Figure 2. AFTES worldwide data compilation of the ratio between lining wall thickness and tunnel internal diameter. Reproduced from [2].

In any case, the value of this chart is well outstanding, since it clearly indicates that the ratio of lining thickness to lining internal diameter employed in tunnels around the world is fairly constant despite the fact that they are built in materials of widely ranging properties, different tunnel characteristics and as varying overburdens. The answer may well be that, maintaining the usual applied thickness vs. internal diameter ratios, the exerted loads on the lining for a wide range of tunnel cover and ground characteristics are more or less within the same range, or at least, can be taken with similar thickness structural sections. In this article, this hypothesis has been approached and verified using semi-empirical methods and a closed-form solution to calculate the ground loads exerted on the lining for several sets of ground properties and checking them against the lining capacity for sections defined using typical internal diameter vs. thickness ratios. Furthermore, a large database of employed thicknesses vs. internal diameter data for around 200 cases of tunnels built worldwide has been compiled to complement the AFTES table shown in Figure 2. Although the database does not intend to be exhaustive, it should be noted that, in the available technical literature, we were not able to find an equivalent compilation of data making this database a powerful tool for selecting the initial lining thickness for the vast majority of tunnelling projects.

THICKNESS VS. INTERNAL DIAMETER DATA

An extensive work has been done in compiling information from 205 tunnels built worldwide in the size range between 3.0 and 14.0 meters. The Figure 3 data, as may be observed, shows a much similar behaviour to those previously observed in the AFTES table. The difference of this database vs. the AFTES data relies mainly in the fact that it incorporates information of several tunnels in the larger than 8.0 meters category as well as data from recent projects built in the last decade.

It may also be observed how for tunnels below 9.0 m the scatter in the data is much less than for larger tunnels, suggesting that for the large size tunnels there is not yet an accepted practice regarding the lining wall thickness to be adopted and also that Clients and Designers tend to use higher than necessary thicknesses, probably due to lack of sufficient experience and seeking for increased safety factors and, in few cases only, really demanding soil conditions. Since large tunnels are sometimes adopted for road tunnels, a possible reason might be the thickness increase to satisfy fire resistance requirements. Regarding this issue, it is now widely accepted that the use of polyurethane fibers for increased fire resistance is much more effective than the increase of the steel cover and corresponding lining wall thickness.

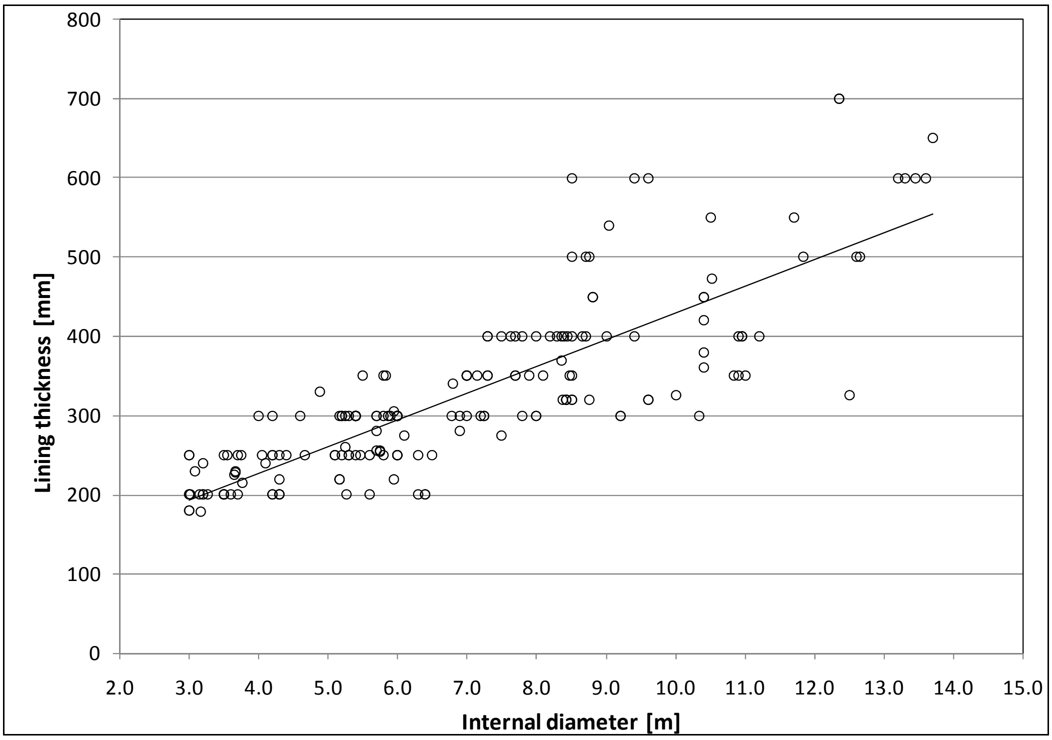

Figure 3. Compilation of lining thickness and internal diameter of tunnel projects around the world.

The best fit line shown in Figure 3 corresponds to a linear regression analysis of the data. It represents varying values of thickness/internal diameter ratio (t/dint). For the smaller tunnels, below 6.0 meters, it indicates values of t/d_{int} higher than 5%; for tunnels over 6.0 meters it tends to represent t/d_{int} values between 4.0 and 4.5%. This difference is due to the fact that small tunnels with internal diameters below 4.5m have t/d_{int} ratios sometimes over 6%. This is most likely due to the minimum thickness of around 200mm that shall be maintained for practical reasons even if the inner diameter of the tunnel calls for less, in fact we deem that producing, transport and installation loads are the driving factors in their structural design. As reference, for a 3.0 meter tunnel a thickness of 200mm represents a t/dint ratio equal to 6.7%.

To better analyse the group of data from a statistical point of view, the histograms of both the complete database and a reduced version excluding the tunnels with internal diameters less than 4.5m have been calculated as shown in Figure 4. The reduced version of the database includes 151 cases while the complete database includes 205 cases. It is evident how after excluding the small tunnels the mean value shifts to the left and the standard deviation is reduced. Excluding the smaller size tunnels, the statistical mean value of the data is of 4.6% with a standard deviation of 0.85.

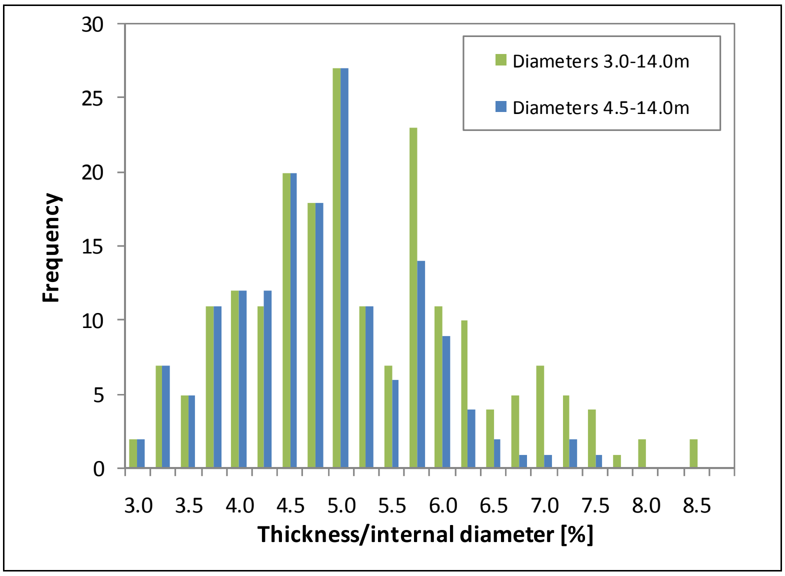

Figure 4. Frequency distribution of thickness/internal diameter data.

The histogram and cumulative percentage curve of the tunnels with internal diameters larger than 4.5m are presented in Figure 5. As shown, around 75% of the tunnels built have a thickness/internal diameter ratio in the range between 3.5 and 5.5% with slightly over half of them between 4.0% and 5.0%.

In order to investigate the structural reasons behind this chart, we have performed a structural verification following the process sequence indicated as inner loop in Figure 1. To carry out such analysis we considered a range of thickness/internal diameter ratios of 3.5%, 4.0% and 4.5%, which account for more than 70% of the tunnels included in the charts.

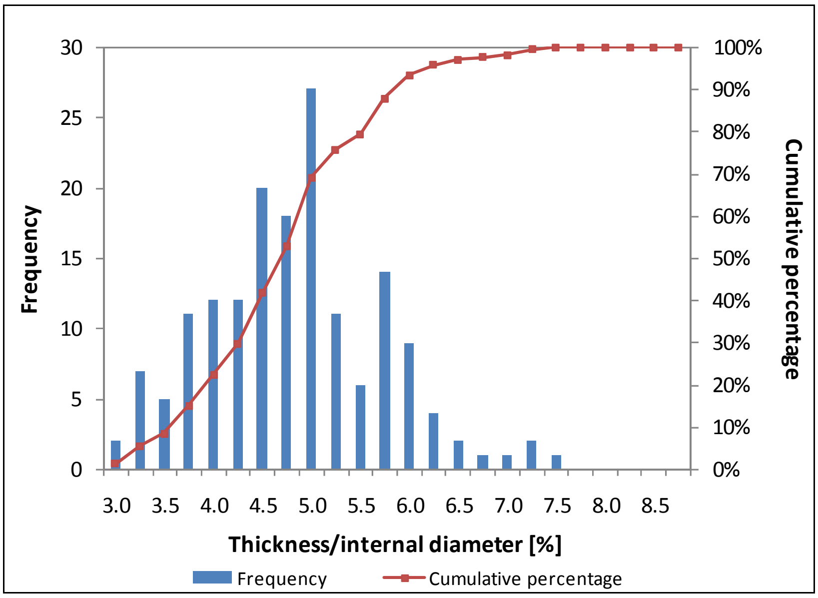

Figure 5. Histogram and cumulative percentage curve of thickness/internal diameter data for tunnels with internal diameters larger than 4.5m.

ON THE VARIABILITY OF SECTIONAL FORCES DUE TO DIFFERENT GROUND CONDITIONS

In order to explore the influence of different soil/rock conditions on the computed sectional forces, three geomaterials have been defined. Each of these materials has been assigned a set of consistent properties. That is, the properties have been selected in such a way to represent actual geologic and geotechnical properties of materials that are expected to be found during tunnel excavations. Ground types A, B, and C represent a soft soil, a stiff soil and a hard soil or soft rock. The assigned properties are summarized in Table 1.

Table 1. Selected materials for ground load analysis.

Ground type	**Friction angle φ [˚]**	**Unit weight γ [kN/m3]**	**Ko**	**Poisson's ratio ν**	**Modulus of elasticity E [MPa]**
A	15	18.0	0.74	0.3	50
B	20	20.0	0.66	0.3	100
C	35	22.0	0.43	0.3	300

In order to have a less favourable approach, cohesion less materials have been considered. To estimate the ground loads acting on the lining the formula proposed by Protodyakonov has been applied as recommended in [3]. It has been assumed that the tunnels' crowns are at depths of more than two diameters and the vertical stress acting on the lining has been calculated as $\sigma_v=\gamma H$. According to Protodyakonov [4},

$$H = \frac{b + 2m\tan(45 - \varphi/2)}{2f} \quad (1)$$

Where
b=m: tunnel diameter
ϕ: ground friction angle
f: ground dependent parameter

For the estimation of the member forces, the closed-form solution for a circular lining in elastic ground proposed in the engineering manual EM 1100-2-2901 of the U.S. Army Corps of Engineering (USACE) [5] has been applied. The formulas for the bending moment and the axial force are as follows.

$$M = \pm\sigma_v(1-K_0)R^2 / \left(4 + \frac{3-2\nu_r}{3(1+\nu_r)^2} \cdot \frac{E_r R^3}{E_c I}\right) \tag{2}$$

$$N = \sigma_v(1+K_0)R / \left(2 + (1-K_0)\frac{2(1-\nu_r)}{(1-2\nu_r)(1+\nu_r)} \cdot \frac{E_r R}{E_c A}\right) \pm \sigma_v(1-K_0)R / \left(2 + \frac{4\nu_r E_r R^3}{(3-4\nu_r)(12(1+\nu_r)E_c I + E_r R^3)}\right) \tag{3}$$

Where

- R : lining axis radius
- E_c: modulus of elasticity of the concrete
- I: lining inertia
- A: lining area
- E_r: modulus of elasticity of the ground
- ν_r: Poisson's ratio of the ground
- K_o: in situ horizontal to vertical stress ratio
- σ_v: vertical stress acting on the lining

No lining inertia reduction has been considered due to joint presence (such as Muir Wood solution) thus providing results that are on the safe side regarding the maximum expected bending moments.

Four different diameters have been selected to encompass the wide range of tunnel sizes today under construction. The following matrix presents the resulting Protodyakonov's heights for each of the three sample materials and the four different chosen diameters. The f parameter in Protodyakonov's formula has been set at 0.5 for vertical pressure maximization.

Table 2. Protodyakonov heights used for sectional forces analyses.

Tunnel Inner Diameter [m]	Protodyakonov's height H [m]		
	Ground type A	Ground type B	Ground type C
4.0	11.0	10.4	8.8
6.0	16.4	15.6	13.2
8.0	21.9	20.7	17.6
11.0	30.1	28.5	24.3

The definition of the structural sections was made taking into account the often used ratios of thickness to internal diameter discussed previously. For each of the four chosen diameters three sections of different thickness were analyzed corresponding to thickness/internal diameter ratios of 3.5%, 4.0% and 4.5%. Uniform length of 1.0 meter was assumed.

Using the solution formulas by the USACE, the following pairs of bending moments and axial forces were calculated for each of the twelve sections analyzed and for each of the three ground types defined previously. The results have been grouped per different thickness to internal diameter ratios used to define the sections.

Table 3. Sectional forces for sections with 3.5% thickness/internal diameter ratio.

		Ground type					
		A		B		C	
Dint [m]	Thickness [cm]	M_{max} [kN-m]	N_{max} [kN]	M_{max} [kN-m]	N_{max} [kN]	M_{max} [kN-m]	N_{max} [kN]
4.0	14.0	7,3	394	5,4	406	2,9	349
6.0	21.0	24,5	887	18,1	913	9,9	784
8.0	28.0	58,1	1578	42,8	1624	23,5	1394
11.0	38.5	151,0	2983	111,3	3071	61,1	2635

Table 4. Sectional forces for sections with 4.0% thickness/internal diameter ratio.

		Ground type					
		A		B		C	
Dint [m]	**Thickness [cm]**	**M_{max} [kN-m]**	**N_{max} [kN]**	**M_{max} [kN-m]**	**N_{max} [kN]**	**M_{max} [kN-m]**	**N_{max} [kN]**
4.0	16.0	10,2	397	7,7	410	4,3	354
6.0	24.0	34,3	894	26,0	921	14,6	795
8.0	32.0	81,3	1590	61,5	1638	34,5	1414
11.0	44.0	211,2	3006	160,0	3097	89,7	2673

Table 5. Sectional forces for sections with 4.5% thickness/internal diameter ratio.

		Ground type					
		A		B		C	
Dint [m]	**Thickness [cm]**	**M_{max} [kN-m]**	**N_{max} [kN]**	**M_{max} [kN-m]**	**N_{max} [kN]**	**M_{max} [kN-m]**	**N_{max} [kN]**
4.0	18.0	13,4	401	10,5	413	6,0	358
6.0	27.0	45,2	901	35,3	929	20,3	806
8.0	36.0	107,2	1602	83,8	1652	48,2	1432
11.0	49.5	278,7	3029	217,9	3123	125,2	2707

As may be observed, the M_{max} - N_{max} pairs calculated for the three different ground types for each of the sets of sections corresponding to the same diameter do not show great variability. This suggests that for a given diameter the corresponding loads and stresses acting on the lining for a wide range of overburden/ground characteristics fall more or less in the same range. Furthermore, it is interesting to compare the obtained values with the structural capacity of the sections. For this purpose, the interaction diagrams following ACI 318 code requirements have been prepared for each of the 12 analyzed sections. Since the USACE solution does not permit to compute the concomitant M and N corresponding to N_{max} and M_{max} , the M_{max} - N_{max} value pairs have been plotted. We consider that the difference between using the actual N and M values corresponding to M_{max} - N_{max} with respect to plotting the M_{max} - N_{max} pairs are not significant when compared to the order of magnitude of the calculated member forces.

To generate the interaction diagrams, a minimum reinforcement for temperature and shrinkage of 0.2% the gross area of the section as per code ACI 318 [1] has been taken into account. Typical strengths used in the fabrication of segmental lining have been assumed for the materials: steel reinforcement with a yielding point f_y = 400 MPa and concrete with a compressive characteristic strength f'c = 40 MPa and an elastic modulus of 35GPa. A 1,4 load factor has been also applied to sectional forces.

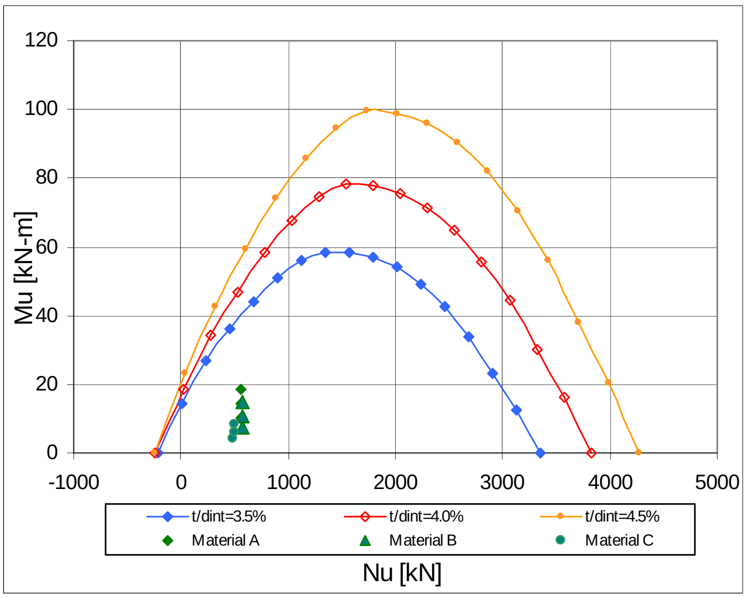

Figure 6. Interaction diagrams for lining with internal diameter of 4.0m.

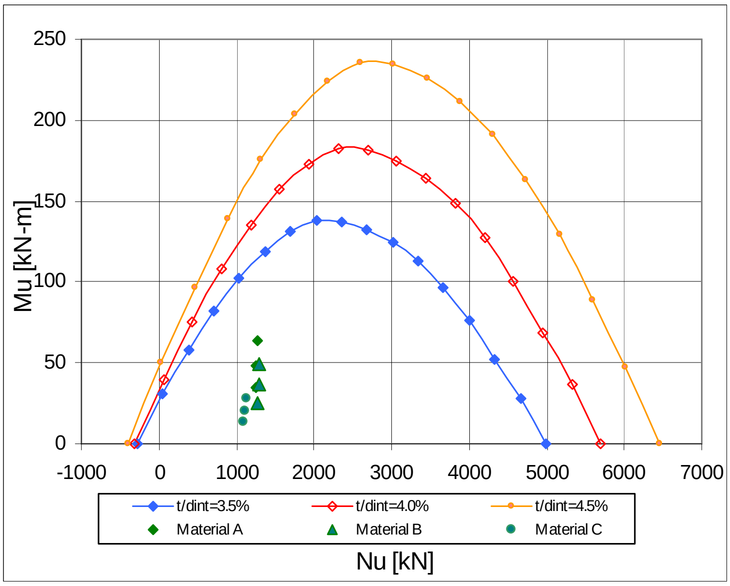

Figure 7. Interaction diagrams for lining with internal diameter of 6.0m.

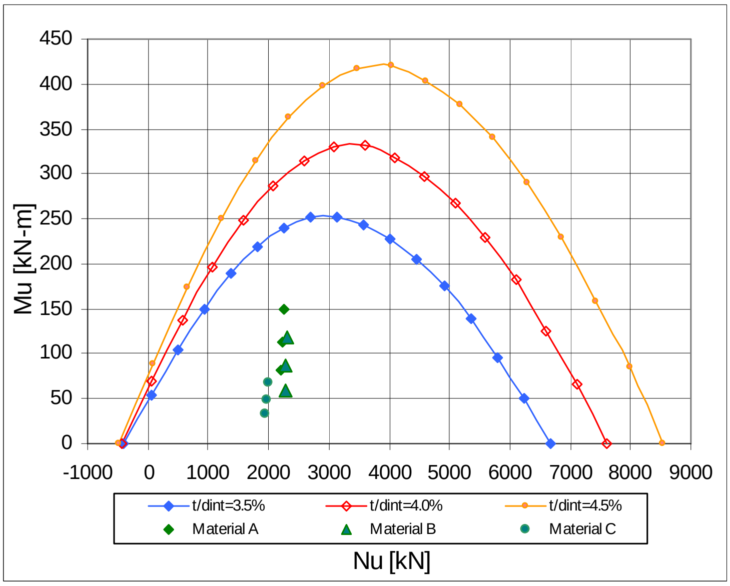

Figure 8. Interaction diagrams for lining with internal diameter of 8.0m.

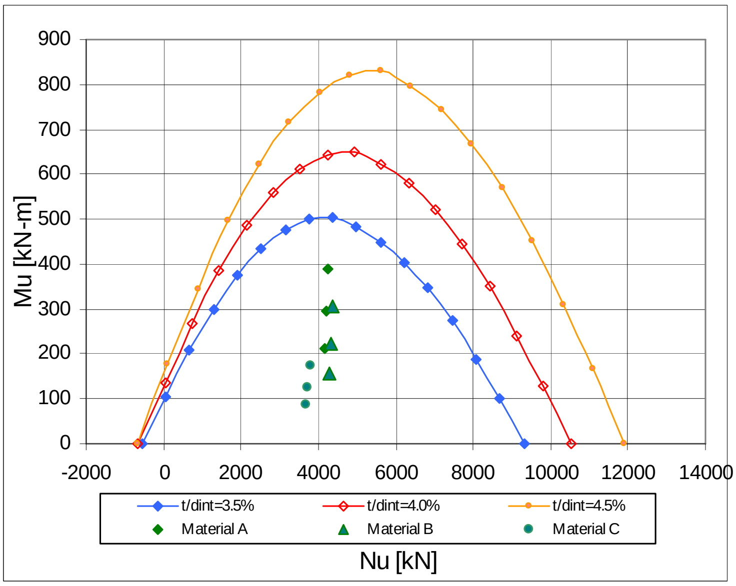

Figure 9. Interaction diagrams for lining with internal diameter of 11.0m.

As shown by the interaction diagrams of Figures 6, 7, 8, and 9, the sectional forces generated by the ground loads for the different ground types are always well within the structural capacity of the sections selected using adopted internal diameter/thickness ratios with large safety factors.

We note that water loads have not been taken into account, since these tends to generate a uniform compression which improve structural capacity against bending moment and, as can be appreciated by the above diagrams, there is a lot of structural capacity left for axial forces induced by water loads.

CONCLUSIONS

A time consuming effort has been made to compile data on the lining thickness and internal diameter of more than 200 tunnels built around the world. The database is of extreme value for designers and contractors alike since it puts in their hands the experience gained through tenths of successfully built tunnels. The data shows how a strong linear relationship exists between the lining wall thickness and the tunnel's internal diameter, almost irrespectively of ground and boring technology.

According to performed statistical analysis, it can be inferred that around 75% of the tunnels with diameters larger than 4.5m have a thickness/internal diameter ratio between 3.5 and 5.5% with slightly over half of them between 4.0 and 5.0%. For tunnels of internal diameters below 4.5m, the applied ratios are higher, situation that is the result of the need of a minimum thickness due to design and constructive reasons. It is also evident how for tunnels with internal diameters between 3.0 and 9.0 meters the dispersion of the data is small indicating that the adopted thickness vs. internal diameter values adopted in the practice are within a narrow range.

An accepted closed form solution was applied to calculate the sectional forces induced by different combinations of ground characteristics and overburden. They were then verified structurally and as shown by the interaction diagrams of Figures 6, 7, 8 and 9, the pairs of bending moment and axial force generated by the ground loads for the different ground types are always well within the structural capacity of the sections selected using common internal diameter/thickness ratios with large safety factors. The analysis that has been performed, although simple, serves to compare the effect of the choice of lining thickness on the structural capacity of the lining with respect to sets of ground loads that correspond to real life situations. As mentioned before, the soil parameters used for determining the ground loads are consistent with ground conditions frequently found in nature.

It must be stated of course, that the full structural verification of a lining [2] & [3] is always recommended and that hydraulic, seismic and grout loads shall also be taken into account. However, one of the prime conclusions of our work is that ground conditions do not have a significant influence on the ground loads that will be acting on the lining, which will mostly depend on tunnel diameter. Another valid conclusion is that as long as the thickness/internal diameter ratio used is within certain values already applied in tunnelling practice, the structural capacity of the section is likely to be proper to adequately resist the imposed ground loads for most geological conditions.

That said, special ground conditions might always exist, like squeezing and swelling ground, high water pressures, asymmetrical loads,…, which will require accurate consideration. In any case, we believe that the solution is not always to increase lining thickness, but an equilibrium between excavation conditions (boring overcut, shield conicity, annular gap backfilling,…) and lining structural capacity.

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