Concurrent Segment Lining and TBM Design: A Coordinated Approach for Tunneling Success

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Abstract. The success of a tunnel project relies on many factors, but one of the most important is also the most overlooked: coordination by all parties involved during the design stages. This is particularly true of segment design and TBM design. Tunnel lining with segmental rings is usually designed according to the standards of reinforced concrete construction based on a given GBR. However, for TBM tunneling, the determination of loads during ring erection, advance of the TBM, earth pressure, and bedding of the articulated ring are all part of the tunnel lining design as well. TBM design can be heavily affected by the segment arrangement, dimension, and weight, but these are usually given as a fixed input to the TBM manufacturer—a process that can cause unnecessary complications.

The authors propose that the industry evaluate the process as it stands. In order to find the optimum balance between lining design and TBM cost and operational workflow, both designs should be finalized concurrently. This requires coordination between the TBM manufacturer and segment designer from the early stages. The aim of this paper is to evaluate the influence of the segment lining design on TBM cost and performance, and to provide commentary on existing design guidelines to optimize lining and TBM procurement.

INTRODUCTION

The conventional project setup for tunnel lining design and the design and manufacture of the tunnel boring machine (TBM) should be coordinated in a timelier manner. It is widely acknowledged that the design of segments must consider the forces exerted by TBM rams during tunnel construction, but other inputs are most frequently provided to the TBM manufacturer as fixed parameters to design around. This paper describes other important factors in TBM design that impact not only the interaction with the segments, but also the construction of the tunnel in terms of overall production and even safety. For example, the segment width and tapering have direct influence on shield body length and thrust cylinder size. Furthermore, TBM geometry can also affect the backup (trailing gear) layout and length.

One reason for this lack of coordination is the contractual arrangement on most projects. A design-bid-build set of contract documents does not specify any contractual arrangement for greater coordination between segment design and TBM manufacturer – most frequently leaving these two components disconnected and leaving any coordination arrangements to the contractor. Moreover, the engineer specifies performance requirements of both TBM and segment components of the project. To a greater or lesser degree an attempt is made to design each of these components, but rarely is this attempt made with reference to better coordination between TBM and segment designs.

We will argue here that each of these components and the tunnel construction itself are not optimized unless the segment components and TBM segment handling/erection systems are designed together with good communication and coordination between the two elements. It is the authors' opinion that there are good arguments in favor of making sure that these two elements are well coordinated. Consideration should be given to creating a contractual single point of responsibility for TBM and concrete segment design and manufacture.

To illustrate the discussion, we will discuss an example from Australia where the TBM manufacturer was also contracted to both supply and design the precast concrete segments. It is the authors' opinion that this arrangement worked very well and provided savings during both procurement and construction. We will also provide and discuss example projects where the lack of coordination of TBM and segment design led to compromises in the TBM design that created less than optimal results for the contractor and ultimately for the owner.

HOW SEGMENT DESIGN AFFECTS THE TBM

Segmental rings are nowadays the most commonly used lining method for shield excavated tunnels. There are various competent methods for designing shield tunnel linings; however, they all share the same process sequence, as per the workflow shown in Figure 1 (ITA Working Group 2, 2000).

Reinforced concrete elements are designed according to reinforced concrete standards. In mechanized tunneling, specific circumstances are taken into account as well, such as loads during ring erection, space for installation, pressure of backfill grouting, and segment stock and handling.

Segment arrangement, dimension, and weight are usually given as fixed inputs to the TBM manufacturer; however, these parameters shouldn't be fixed until the TBM manufacturer has been involved because of the effect they have on the TBM design and performance. The main elements determining the shape and dimensions of segments are:

1. Outer diameter of segment ring
2. Segment height (thickness)
3. Segment width and key (K-segment) installation pullback requirement
4. Division of the segmental ring

Outer diameter and segment thickness are strictly related to the tunnel design. The inner section, the thickness of the segments, and the secondary lining requirements are determined by the size of the cross section developed in the design process, mainly in consideration of the loads applied to the lining.

Segment width and division of the segmental ring have a significant influence on the TBM segment handling and installation systems and should be determined considering the purpose of use so that they will be easy to erect and economical.

Segment Width Influence on TBM Design

The segment width is measured in the direction of the tunnel axis. There are arguments on both sides as to segment width. A larger segment width results in a reduction of overall production cost of segments, number of joints, total perimeter of all the segments, and number of bolt holes. A narrower segment width results in ease of transportation and erection, construction of curved sections, and reduction of shield body length. According to past tunnel construction records (Figure 2), the width of segments has tended to become broader over time; however, this could result in inefficient TBM design (Japan Society of Civil Engineers, 2006).

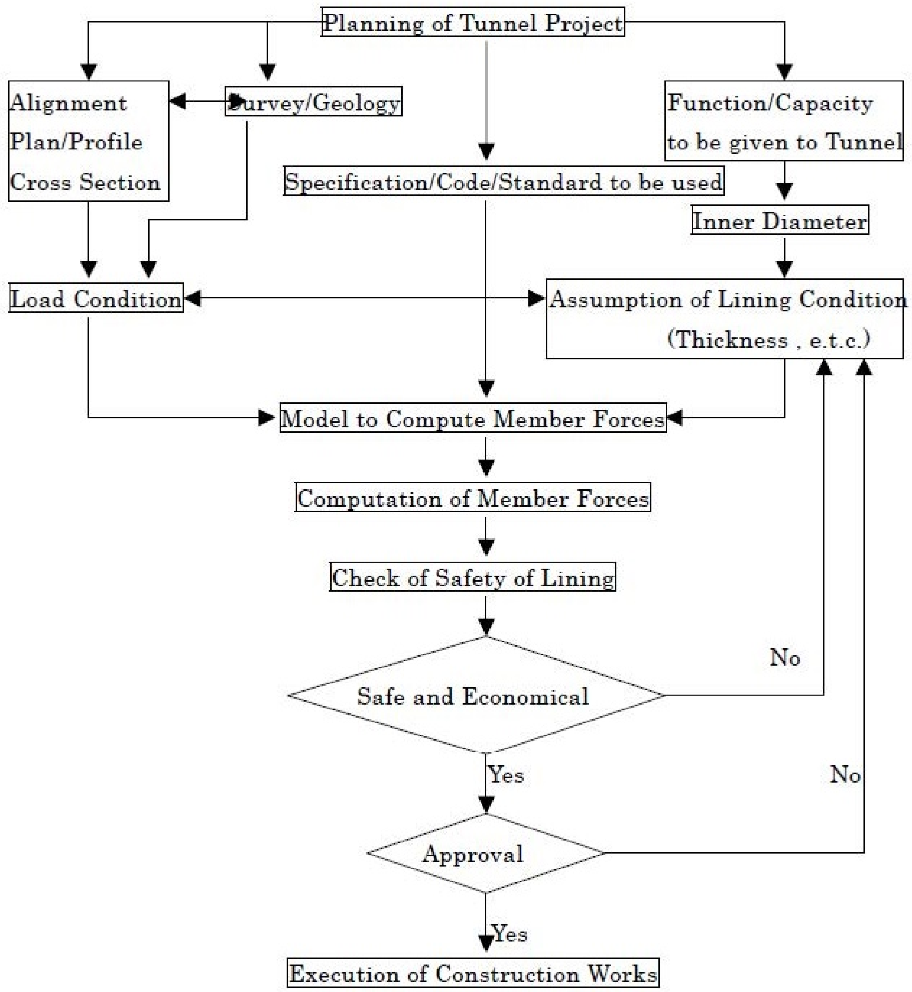

Figure1. Segment design workflow

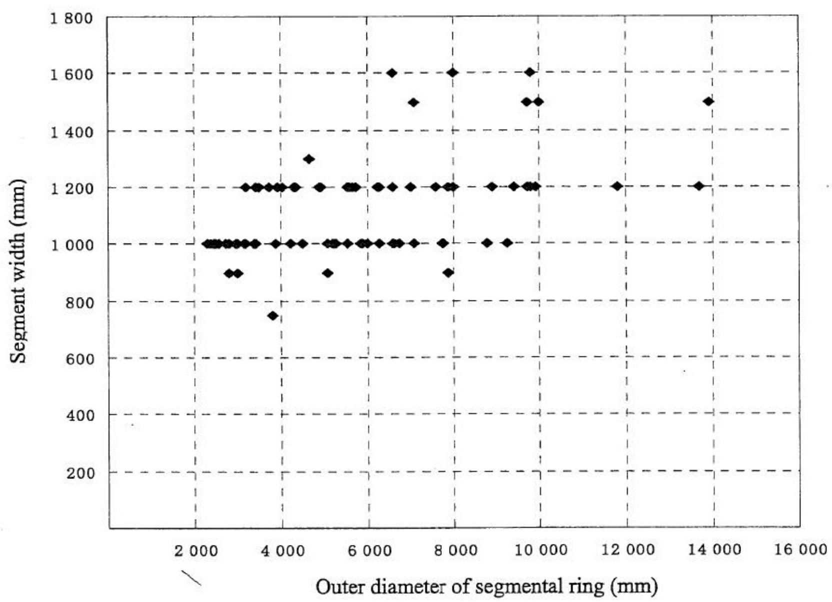

Figure 2. Trend of segment width compared to segment outer diameter

The segment width in fact can be directly related to several aspects of TBM design:

1. Thrust cylinders (length, dimension and cost)
2. Shield body (length, plate thickness and cost)
3. Backup (layout, length, efficiency and cost)

These are discussed in more detail below.

Thrust cylinders. The segment width regulates the main thrust cylinder stroke necessary for the single boring cycle. The stroke should match the segment width plus a preset margin. For radial insertion of K-segments, the stroke of shield jacks should be the segment width plus 100 to 200 mm (3.9 to 7.9 in.). For axial insertion of K-type segments, the stroke should be further lengthened by a margin of one-third to one-half of the segment width, depending on the arc of the K-segment, the insertion angle, and the segment joint angle (Figure 3).

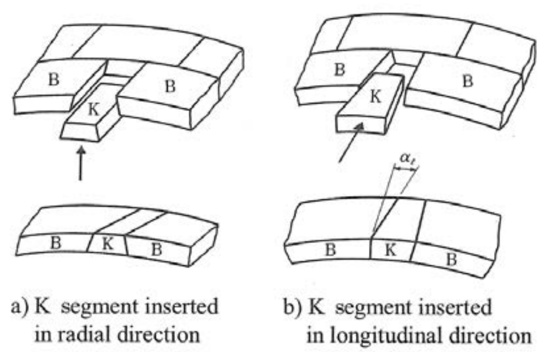

Figure 3. Insertion angle of the K-segment

The longer the stroke of the jacks, the bigger the rod diameter will be (in consideration of the buckling factor under axial loads), and consequently the bigger and more expensive the cylinders. A spreader or pad is attached to the cylinders with a pin or spherical joint so that the thrust is evenly distributed against the edge of the segment ring (Figure 4). The pad height is determined according to the segment height and tail clearance; however, the cylinder body size affects it as well. Consequently, an off- centering rod end might be required, which is more expensive compared to the straight ones.

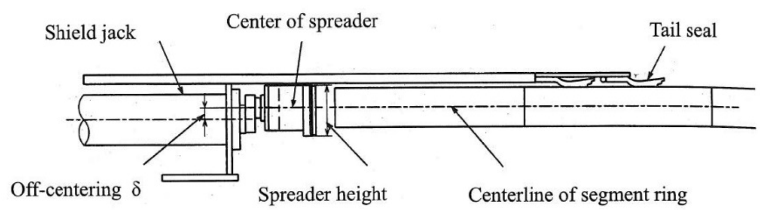

Figure 4. Shield jack with off-centering rod end

Shield body. The segment width regulates the length of the overall shield body, irrespective of the TBM type (soft ground EPB or rock single/double shield) as a direct consequence of the main thrust cylinders stroke and the auxiliary thrust cylinders stroke (for double shield TBMs). As shown in Figure 5, for EPB/single shield TBMs, shields C and D (tail shields) will be affected. In double shielded TBMs, telescopic, gripper and tail shield will be affected (Figure 6).

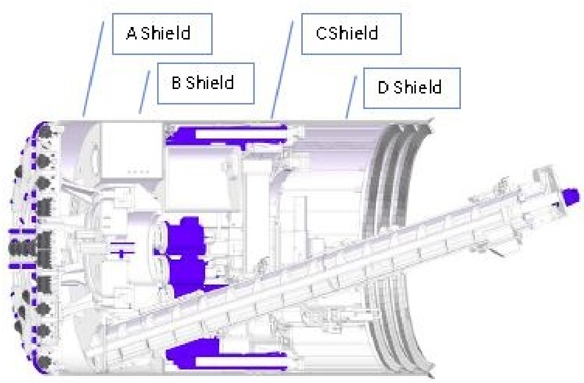

Figure 5. EPB shield configuration

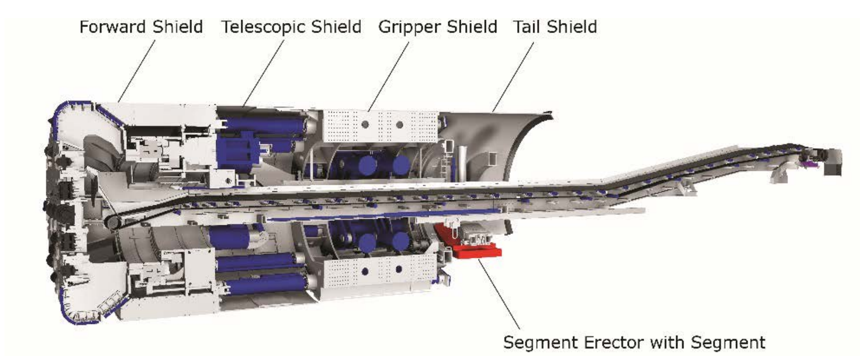

Figure 6. Shield configuration for double shield TBMs

Backup layout. Segments are brought inside the TBM through the trailing gear, longitudinally oriented. Nowadays, the most common backup layout is the so called gantry type (Figure 7). This layout allows for shorter trailing gear and the capacity to allocate the equipment necessary for the TBM operation on both sides of the train track. The segment width and clearance necessary between the structure and the cars regulates the gantry portal opening. However, standards are calling out for a minimum walkway width and working space of the equipment, which reduce the space available for the segment cars (EN 16191, 2014).

If there is not enough space for the segment cars to drive through the gantry portal, the backup layout has to be the so called "deck" type (Figure 8). The resulting structure will be heavier to allow the train to be conveyed on one side of it and longer, as all the equipment will be located on one side only.

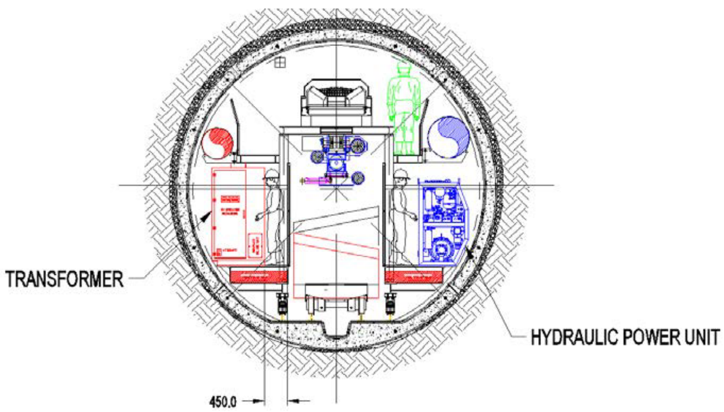

Figure 7. Gantry-type backup system

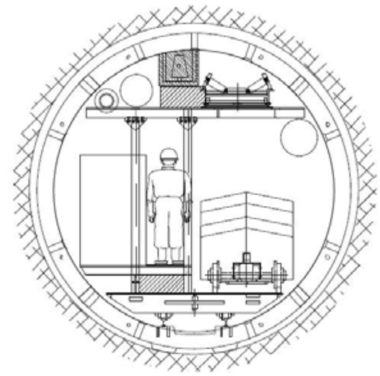

Figure 8. Deck-type backup system

Division of the Segmental Ring and Its Influence on TBM Design

The number of segments constituting the ring affects the design of major components such as the segment hoist and the segment erector. The segment hoist is used to transfer the segments from the train cars to the ring building area. The segment erector is used to assemble segments into the predetermined form within the tail shield. It is necessary for the erector to have the functions of rotation, forward and backward movement, and extension and retraction of the segment grip. All these functions have to be carried out within determined tolerances and required specific clearances.

The operation of these two devices, the segment hoist and the segment erector, determines the ring building time, which is fundamental to determining the production cycle duration.

- In EPB/shield TBMs, ring building takes place after the boring stroke; hence, it directly affects the production cycle duration.
- In double shield TBMs, ring building takes place simultaneously with the boring stroke; hence, it has to be set up based on the predicted advance rate.

The number of segments per ring controls the quantity of handling operations, so the tendency is to reduce this to a minimum. However, the size and weight of the segments will increase accordingly, as will the erector and segment hoist's designed safe working loads, leading to heavier structures. Moreover, the clearance in the building area will be reduced, and this might result in a longer time required for the erection of each single segment, affecting the whole ring building efficiency.

HOW TO OPTIMIZE SEGMENT DESIGN IN TERMS OF TIME, QUALITY AND COST

Several factors affect the segmental lining structural and geometry design. A balance among these factors is needed to produce an overall efficient design. The following paragraphs discuss the main factors affecting the segmental lining design.

Structural Design

- Permanent/long term loads: Including earth and groundwater loads, surcharge loads, effect of poor ring build, and internal loads.
  - The number of segments per ring affects the stiffness of the lining and influences the structural design of the lining for permanent loads.
- Temporary and construction loads: Including forces due to stacking, transport, grouting operation loads, and TBM thrust forces.
  - Stacking, transport, grouting operation forces: The structural design is heavily impacted by stacking, transport, and grouting operation loads. These forces sometimes dictate the structural design and impact the size of the segment. The weight and the size of the segment impacts the TBM segment lining erector design and the TBM for required installation space, as discussed below.
  - TBM thrust forces impact the structural design of the segment. The number and arrangement of the thrust cylinders/rams and the force per ram need to be considered in the structural design. Steel reinforcement may be required. This increases cost and labor of the segmental lining production.

Segmental Ring Geometry

- Number of segments per ring: This affects the stiffness of the lining. More segments per ring means a more flexible support system and attracts less ground load, resulting in more efficient structural design in certain cases. It also means lighter segment weight, which directly impacts the TBM erector design. However, more segments per ring requires more labor time to install.
- Width of segmental lining ring: The segmental lining ring width directly impacts TBM design. In particular, the length of the shield and the TBM thrust ram stroke are directly impacted by ring width. A longer ring width requires less labor time.
- Segment ring tapering: The segment ring tapering is a function of tunnel curvature. A tighter tunnel curve requires more tapering, which results in a larger clearance between the segment and the tunnel shield.

It is important to understand the interaction between these factors when designing segmental lining. The interaction is complex and requires in-depth experience to balance the cost. A qualitative assessment should be performed, and a preliminary segmental lining design should be provided for assessment and discussion among the contractor, the TBM manufacturer, and the designer. An interactive design process should be adopted to develop the final segmental lining design.

DISCUSSION

Few projects have been considered to investigate the influence of segment design on the TBM, both for hard rock double shield TBMs and EPB/XRE TBM types with bore diameters between 6 and 8 meters

(19.7 and 26.2 ft). As every project has its specific variables, there might be parameters that would influence the analysis that are not strictly related to segment design. As an example, the Grosvenor Decline Project TBM (XRE265-388), which had to comply with Queensland (Australia) Coal Mine Regulations, was a more expensive type of design. Furthermore, being a crossover-type TBM it was designed for excavating in both rock and soil conditions. Segment geometry, TBM shield body length, TBM weight, and the number and size of cylinders are summarized in Table 1.

With regard to optimization of segment rings, there are many factors to consider when judging the geometry of the ring. Standardizing cost across countries and different economies is extremely difficult, but there are potential differences, particularly with regards to labor cost of building additional rings of shorter width. Nevertheless general considerations can be made looking at these tables.

The segment width affects the overall length of the shield body, as shown in Figure 9. This is more evident on double shield (DS) TBMs than EPBs, being that DS TBMs have a greater number of shields affected. The cost increase for TBM manufacturing needs to be considered as well as the TBM's performance in driving curves or squeezing ground. In these situations, a shorter shield body is more suitable.

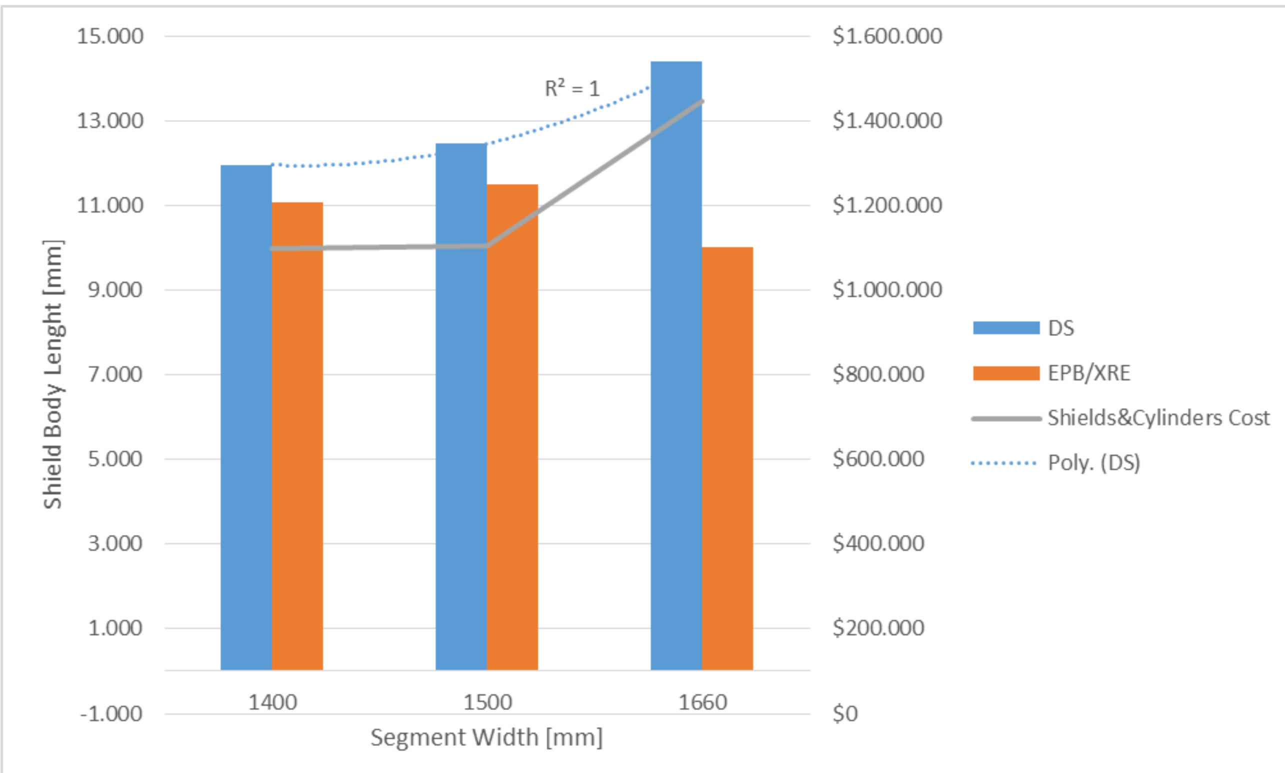

Figure 9. DS segment width compared to shield body length and cost

Table 1. Design parameters for TBMs in the 6- to 8-meter-diameter range

TBM Type	DS		
TBM Number	DS205-277	DS2018-402	Confidential
Project	Yellow River, Water Diversion CHINA	Devoll HEPP - Moglice Headrace Tunnel ALBANIA	Confidential
BORE Ø	6,125	6,22	6,53
Tunnel Length	21.000	6.700	10.000
Ring Width	1400	1500	1660
Pull-back required for Key Assembly	700	400	1200
#Segments/Ring	4 (hex)	5+1	4
Segment OD	5.960	5.900	6.300
Segment ID	5.460	5.400	5.760
Overall Shield Body Length	11.958	12.462	14.395
Shield Body Total Weight	172,0t	182,1t	215,1t
Main Thrust	D70456 (12x) 310Bx200Rx1300S	1092617 (10x) 310Bx200Rx1850S	1086482 (12x) 320Bx250Rx1760S
Aux Thrust	D70455 (8x) 380Bx280Rx2600S	1093315 (22x) 236Bx190Rx2200S	1086536 (16x) 340Bx280Rx3000S

TBM Type	EPB/XRE		
TBM Number	XRE265-388	EPB223-383→386	EPB2111-366-1
Project	Grosvenor Brisbane/Queensland, Australia	Linha 3 Leste Metro de Fortaleza Fortaleza, Brazil	Northgate Link Seattle, USA
BORE Ø	8	6,92	6,64
Tunnel Length	1.000	4.280	7.000
Ring Width	1400	1500	1524
Pull-back required for Key Assembly	720	750	554
#Segments/Ring	5+1	5+1	5+1
Segment OD	7.700	6.600	6.248
Segment ID	7.000	6.000	5.740
Overall Shield Body Length	11.083	11.496	10.021
Shield Body Total Weight	283,2t	130,0t	105,1t
Main Thrust	1052096 (x34) 240Bx180Rx2520S	1053471 (x22) 245Bx190Rx2300S	1072119 (x12) 310Bx250Rx2400S
Aux Thrust	NA	NA	NA

EPB TBMs show an unexpected trend in increase of segment width. This is because of the influence the segment tapering had on the TBM design, as shown in Figure 10.

The K-segment pull-back requirement directly affects the EPB's length and the shield body and cylinder cost, even in the Grosvenor exception shown below.

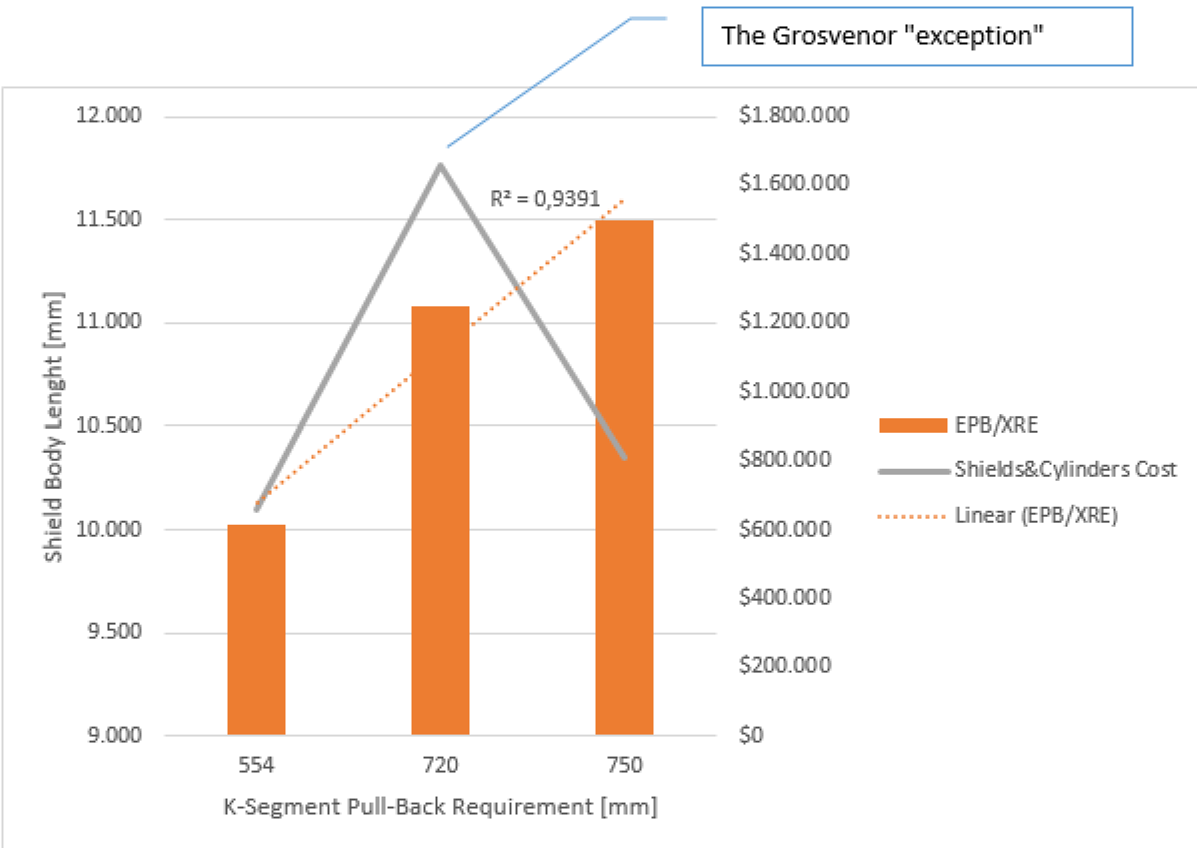

Figure 10. EPB segment width compared to shield body length and cost

The trailing gear of two similar DS TBMs with 7.27 meter (23.85 ft; TBM1) and 6.90 meter (22.64 ft; TBM2) bore diameters with two different backup layouts has been compared as far as length. TBM1 has a gantry-style backup whilst TBM2 has a deck style. TBM1 total length was 140 meters (459 ft) with 12 decks, TBM2 was 223 meters (732 ft) with 24 decks, both with segment width of 1,600 mm (63 in.). Although it is evident that the gantry style backup saves on length and cost, it can be argued that the more difficult access to the equipment could result in less efficient excavation.

Finally, to analyze the impact of lining width and number of segments on schedule, two jobs have been considered: Job A (Grosvenor Decline Tunnel), with segment lining 1.4 meters wide and 6 segments per ring and Job B (confidential) with segment lining 1.66 meters wide and 4 segments per ring, both during the first 200 meters excavation period (which will include the workforce learning curve), see Table 2.

Table 2. Advance time comparison

	Number of rings	Ring Building Time (min)	Meters of Tunnel (m)	Advance Time (min/m)
Job A (Grosvenor)	147	7425	205,8	36,1
Job B (Confidential)	120	7990	199,2	40,1

For a 3.000 meter drive, Job B would theoretically finish 25 days later than Job A, even with the installation of a fewer number of rings (being the width is larger and the rings are made of fewer segments).

In several recent project cases as mentioned in this paper, The TBM cost and performance could have been optimized if the design of the TBM and segments were closely coordinated. The reasons why this is not done more frequently are unknown but could be due to one or more of the following reasons:

1. Owners and engineers are not aware of the potential for conflicts and inefficiencies between the design of TBM and tunnel lining and apparently innocent specified requirements such as a 5ft (1.5m) segment width can increase cost and slow down the construction process due to unintended consequences for TBM design.
2. Vested interests exist in favor of the status quo of compartmentalized design of segments by owner's engineers (who want to design the lining themselves), and contractors who may find it easier to allocate risk to their subcontractors if the TBM and segment components are kept separate.
3. Contractors are not aware of the many benefits to cost and construction efficiency that exist for their operations by forcing coordination by contractual arrangement among the TBM designer/manufacturer, segment manufacturer, and segment designer.
4. Owners and Engineers are not willing to alter their design parameters to an equivalent but different final lining in order to accommodate a more efficient construction and installation design for the whole system.
5. Owners and engineers are not willing or able to provide purely performance specifications for precast concrete segment linings that would allow the most innovation and still provide the necessary performance in the final lining.

All parties to a contract are interested in making tunnel projects less expensive while also making the tunnel construction more efficient and reliable. It is recommended that the TBM and concrete segments are both designed and manufactured under a single subcontract. This single subcontract should be executed either by a tunnel contractor, or (less frequently) directly with the owner where both the TBM and segments are provided to a contractor to build the tunnel. However the arrangement is made, the important factor remains the single point of responsibility for design, manufacture, and delivery of both TBM and tunnel lining, upon which the TBM depends for thrust, downtime due to lining erection, and trailing gear dimensions.

This contractual arrangement was adopted for the Grosvenor project, a recent successful example of concurrent segment and TBM design. The TBM manufacturer (Robbins), was required to provide segment design, molds, and manufacture for the project, and worked with a segment designer (Aldea Services) and segment manufacturer (Korea Mould) during this process. These components were then supplied to the Contractor (Redpath) for construction. The excavation process used an integrated segmental lining and Crossover (Dual Mode-type) TBM designed for quick removal, and despite difficulties with gaseous tunneling was highly successful. The order for both TBM and lining design was placed on December 2012 and happened concurrently. The TBM was launched to bore two decline access tunnels at grades of 1:6 and 1:8, one for conveyors and another for people and equipment, in December 2013. After completion of the first conveyor tunnel in May 2014, the TBM was successfully retracted and transported to the second tunnel site. The machine was then re-commissioned for the people and equipment tunnel in November 2014 with a new set of shields. The TBM completed its second and final tunnel on February 9, 2015, 44 days ahead of the project overall schedule.

The concurrent design allowed for special parameters to be put into place. The results were improved cycle time and a successful load distribution during the TBM retraction, during which the TBM core had to be hydraulically lifted and pushed up an inclined tunnel, putting a load of 470 tonnes across five to six rings at any one time.

CONCLUSIONS

The following conclusions and recommendations can be made as a result of our argument:

1. Segment geometry affects TBM and back-up layout, increasing their overall cost and possibly leading to inefficient performance. This geometry is directly correlated to equipment access, ring installation time, and quality. The resulting length of the TBM should be evaluated with respect to curves in the alignment and squeezing ground conditions.
2. Better coordination of precast concrete segment tunnel lining design and TBM design would benefit tunnel projects.
3. A contractual arrangement forcing this collaboration would be beneficial to projects.
4. This contractual arrangement is not proprietary and would remain a competitive area with multiple TBM manufacturers and Concrete lining manufacturers interested in this revised arrangement.
5. Contractually requiring the TBM manufacturer to also provide segment design, order molds, and manufacture the segments provides clear lines of contractual responsibility and optimizes the overall system design to the greatest degree possible.

REFERENCES

ITA Working Group 2, 2000. Guidelines for the Design of Shield Tunnel Lining. Tunnelling and Underground Space Technology 15 (3): 303-331.

Japan Society of Civil Engineers, 2006. *Standard Specification for Tunneling: Shield Tunnels*. Tokyo, Japan.

EN16191, 2014. (E) Paragraph 5.2.10.2 “Walkways”. *Tunnelling machinery – Safety requirements*, BSI Group.