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Lowering the Beneluxtunnel

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Abstract. As a result of the persistent increase of container vessel dimensions, future problems regarding navigation draught in the presence of tunnels are becoming more likely to occur. Hence, possible solutions to this problem have been investigated for the Beneluxtunnel. Several design options have been elaborated to determine the technical and economic feasibility of a possible lowering of the tunnel. Important subjects involved are the consequences of increasing the slopes, the cross-sectional concrete capacity, the use of joint rotations, the construction methods and the costs. This initial exploration of the subject shows lowering the Beneluxtunnel seems to be possible and is expected to be economically attractive. However, further research into certain boundary conditions and risky aspects of construction is required to ascertain this statement.

1 Problem

The minimum depth of tunnels crossing waterways is related to the expected maximum draught of navigation during the operational phase of the tunnel. Due to the large and unexpected increase in containership capacity as of 2005, the minimum depth estimates for tunnels built before this period were rather shallow. Consequently, tunnels crossing seaport access channels could become obstacles in the near future.

Rotterdam, Amsterdam, Antwerp and Hamburg are amongst the cities of which port navigation channels are tunnelled and problems regarding the draught of the latest generation of container vessels could occur. Hence, the municipality and the port authorities of Rotterdam have decided to determine a solution strategy to this problem.

2 The Beneluxtunnel

The Beneluxtunnel lies underneath the river Nieuwe Maas on the western side of Rotterdam and therefore crosses the access channel of the so-called "city ports". The connection consists of 2 tubes built in 1967 and in 2002, and houses a 2x4 highway, a 2x1 metro and a passage for bicycles and pedestrians.

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Fig. 1 indicates the draught and the beam of the largest container vessels at the time of construction of the tunnels and now, relative to the depth of the tunnel tubes. It shows the depth related problems if a container ship of the latest generation would attempt to cross the Beneluxtunnel. Currently however, this is only a potential scenario as these types of ships do not (yet) visit the city ports because they are being served elsewhere in the port. But given the ongoing growth of container vessel dimensions and the expected unlikeliness of the port being expanded further into the sea in the coming years, the probability of the Beneluxtunnel becoming an obstacle for navigation is significant and preparing for this scenario by determining solution strategies to this potential problem appears to be sensible.

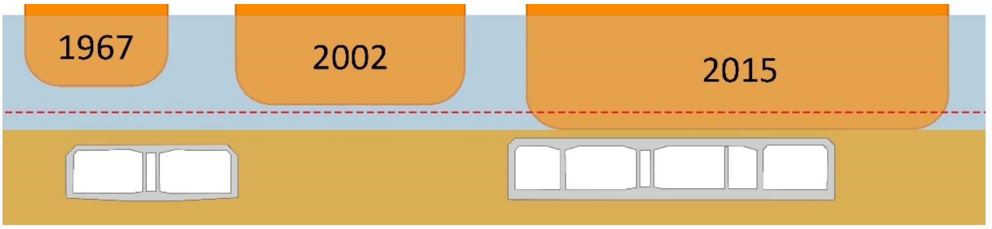

Fig. 1. This image indicates the draught and beam of the largest container vessels at the time of construction of both Beneluxtunnels and now, relative to the depth and width of the tunnel tubes (lowest point roof: NAP - 16.5 m) and the depth of the navigation channel for two-way traffic (red dotted line, NAP - 14.0 m) at low tide (NAP - 0.5 m).

3 Immersed tunnels

Both tubes of the Beneluxtunnel are built using the immersion method. This method for constructing tunnels has originated in the United States in 1910 with the construction of the Michigan Central Railway tunnel, which was built by immersing steel tubes onto the bottom of the waterway and connecting them to each other. This method was further developed in the Netherlands by introducing the reinforced concrete rectangular cross-section, resulting in the construction of the Maastunnel in 1942. Since the 1960's this method has been often applied for the construction of tunnels underneath waterways.

An immersed tunnel consists of two abutments and a number of immersed elements. The abutments are constructed on site and are thoroughly founded with tension-piles/anchors to withstand the upward pressure of the groundwater. The elements are prefabricated elsewhere and are sailed to the construction site when the abutments are finished, where they are immersed into a trench between the abutments, which is then backfilled and covered with bottom protection.

The 1st Beneluxtunnel consists of 8 elements of 8 x 24 x 93 m and the 2nd Beneluxtunnel consists of 6 elements of 8.5 x 45 x 140 m. The abutments are built independent from each other with a spacing of about 30 m and contain amongst others an underwater concrete floor with tension piles and sheet pile sidewalls with anchors.

4 Research

As far as known by researchers the possibility of lowering an existing immersed tunnel has never been investigated. Hence, effort has been made to maintain a broad scope and to use as little fixed variables as possible. By determining the most promising solution strategies as generally as possible, this study can act as a basis for further research in this yet unexplored field of research.

This method is amongst others applied for determining the maximum slope of the road by varying it from the current 4.5 % up to a maximum of 7 %. With a larger slope, the available draught can be increased without having to apply major adjustments to the abutments. To allow fair comparison, the associated lowering of the speed has also been included in the evaluation.

This strategy contributes to objective value determination and therefore to the determination of the economic feasibility. In addition, also certain aspects concerning structural safety and constructability have been examined, aiming to determine the technical feasibility. At this stage, it is presumed that for lowering to be allowed, the structural safety of the tunnel may not be negatively influenced by any of the adjustments.

5 Design options

An initial limited deepening of the navigation channel could be achieved by replacing the bottom protection at the critical points near the edges of the navigation channel with a thinner layer of protection. However, as it turns out this measure has already been applied to allow for the depth of the current channel. Hence, the height of the tunnel roof should be decreased at the critical points to allow for additional lowering, for which possibilities have been examined in this study.

For the additional lowering of the immersed part, mainly method of construction is of importance, for which two main alternatives can be distinguished:

- I_1 The elements can be disconnected and re-floated – which could be interpreted as the inversed immersion process – for them to be re-immersed and re-connected later on a lowered bed.
- I_2 One could also try to lower the elements while they remain connected by using the (limited) freedom of rotation in the joints. To allow lowering, also the soil must be removed from underneath the elements and restored afterwards by underflowing.

For the abutments on the land side of the tunnel, the following design options can be distinguished:

- A_1 One could decide not to adapt the abutments, which would have the lowest impact on the costs but lowering would need to occur in the immersed part only and is therefore limited.
- A_2 The transition points between the abutments and the immersed part could be adapted using the space provided by the presence of dewatering cellars. Consequently, rotation and limited translation of the connecting element could occur without having to alter the water- and soil retaining functions of the abutment.
- A_3 If more depth is required, the abutments will have to be drastically adjusted. The side walls could most likely be reused but the underwater concrete floor and the tension piles will have to be replaced. This is expected to be a very difficult and costly operation but it is not regarded impossible at this stage.

The longitudinal profile of the tunnel is mainly determined by the chosen land part alternative and the maximum allowed slope. An example of possible longitudinal profiles and the associated dimensions of the enlarged navigation channel is shown in Fig. 2. In this example, the transition point has been adapted on one side (A_2) and on the other side the abutment is kept unaltered (A_1).

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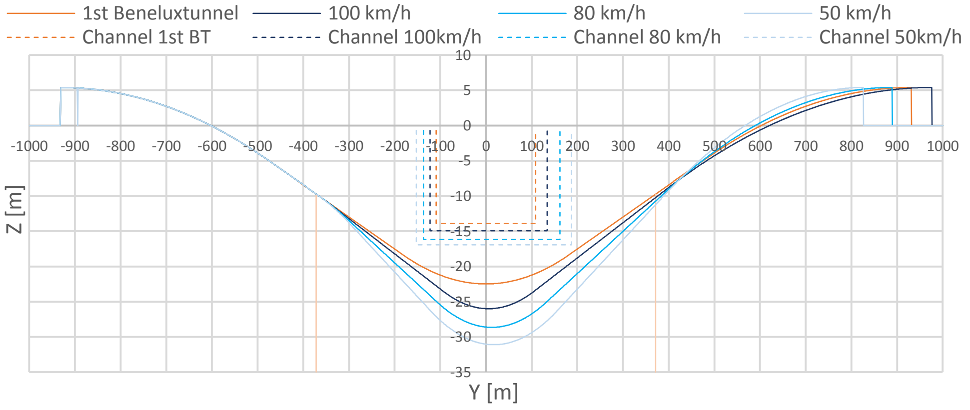

Fig. 2. This graph gives for the 1st Beneluxtunnel, the current and the possible longitudinal profiles for different maximum speeds and the associated maximum slopes, if the transition point has been adapted on one side (A_2) and on the other side the abutment is kept unaltered (A_1). Also, the associated cross-sectional profiles of the navigation channel are displayed.

For this analysis, the relations between navigation, the navigation channel and the tunnel have been determined using [1]. Because navigation has not only increased in draught but also very strongly in beam – as indicated in Fig. 1 – also the width of the required navigation channel increases very strongly. Consequently, the critical points in the longitudinal profile of the tunnel moves towards the shores if more depth is required.

This analysis gives a first impression of the possible design options. However, the structural safety of the immersed part may impose additional constraints to these design options. Crucial aspects to take into account are the cross-sectional strength of the elements and the consequences of rotations in the joints.

6 Cross-sectional strength

An important condition when lowering a tunnel element is that its strength needs to be sufficient to resist the occurring increase in hydrostatic pressure. To determine the maximum possible amount of lowering, this strength is compared with the forces occurring when the hydrostatic pressure is increased. Only the cross-section of the tunnel has been analysed as al forces are transferred in this direction. Because of available data, only the 1st Beneluxtunnel has been examined.

The results of the analysis are displayed in Fig. 3 as the maximum possible lowering for different load factors. In all scenarios, material factors have been applied as prescribed in the Eurocode. As the situation is based on the maximum possible water level – based on the height of the dikes – increased with an extra 2 meters for waves, a load factor of 1 could be regarded sufficient.

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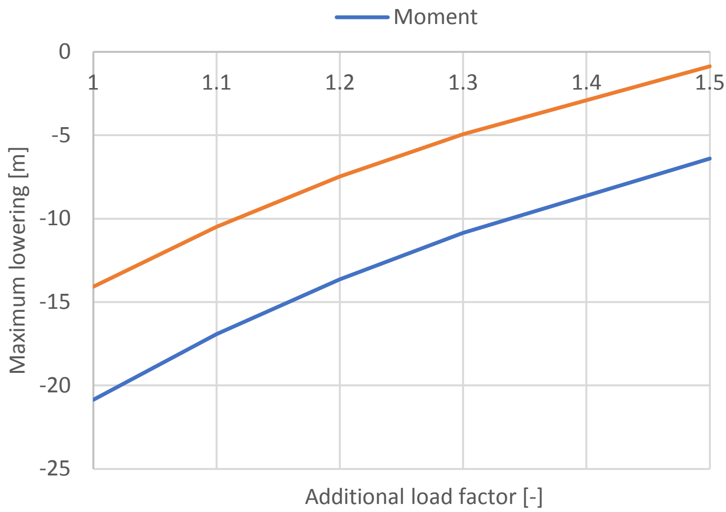

Fig. 3. This graph shows the maximum possible lowering for the deepest elements of the 1st Beneluxtunnel for different load factors, based on the maximum allowed moments and shear forces.

Based on the calculations performed in the study, the cross-section of the 1st Beneluxtunnel has sufficient strength to allow a significant amount of lowering. Depending on the safety philosophy, 5 to 14 meters of lowering would be possible for the deepest elements. The shallower elements are dimensioned less strongly but also require less lowering.

This residual strength is particularly expected to be a consequence of the applied safety philosophy during the design of the elements, when a safety factor of 1.5 has been applied on the maximum considered hydrostatic pressure, resulting in a corresponding water level being much higher than the height of the dikes. In this study however, the design water level has been determined taking the probability of exceedance of the water level into account, resulting in a lower design value of the hydrostatic pressure than based on previous criteria. If a similar residual strength is found for the 2nd Beneluxtunnel is given the 25 years between the construction of the tunnels not certain.

7 Joint rotations

With the existing methods for constructing immersed tunnels it is it is customary to cast the elements in segments with a length of about 15 to 20 meters. This prevents for temperature related cracks to develop during the hardening process and for loads occurring as a result of differential settlements to become unmanageable. Water tightness is provided by mounting rubber-metal profiles (W9ui) in the joints between the segments. Between the elements themselves GINA-profiles are mounted, which provide the primary seal during the immersion process. OMEGA-profiles later provide the final watertight seal. To prevent transverse displacements of the segments relative to each other, both the segment joints and the immersion joints contain a collar structure acting as a shear key.

The rotational capacity of these joints could be used to allow adjustment in the longitudinal profile of the tunnel. Small rotations in many joints can provide significant lowering of the tunnel. This method is especially interesting because the immersion joints in the 1st Beneluxtunnel have been permanently casted meaning the elements are securely fixed against each other. For the 2nd Beneluxtunnel, both joint types could be used. In this article however, only the segment joint will be discussed.

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It is important for the strength and the water tightness of the joints not to be compromised. The segment joints are designed to allow rotation and if one examines the functioning of the collar structure in more detail, it turns out that regarding the strength, there is very little difference between the situations in which an opening of a few millimetres occurs or a few centimetres. The pull-side of this situation is shown in Fig 4. This figure implies that with an enlarged opening, the probability of shear failure of the collar system would increase. However, for openings up to a few centimetres, the functioning of the reinforcement is practically the same. The W9Ui profiles turn out to be governing with a maximum elongation of 22 mm. [2]

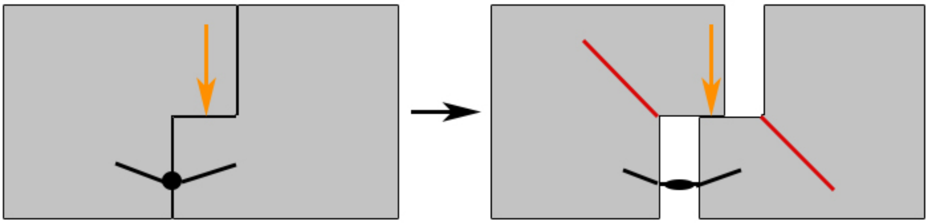

Fig. 4. This figure shows the collar on the pull side of the segment joint, before and after rotation has occurred. The yellow arrow indicates the working line of the shear force. The red lines indicate possible fractures. The horizontal part of the collar has a length of about 25 cm.

To determine the maximum magnitude of the initial rotation, one has to estimate the differential settlements that are expected to occur. This however, is very hard to predict. Partially because limited measuring data is available, but also because after lowering, new foundation is required. Moreover, would the additional joint rotations caused by settlement lead to damage of the profiles, repair is principally possible as is described in [3]. A probabilistic approach could clarify this issue, but for this study it is chosen to estimate the maximum initial rotation as half of the maximum elongation, which is 11 mm or 1.6 x 10-3 rad.

8 Results

Now that the possible profiles like the example in Fig. 2, and the technical boundary conditions are known, the scope of the solutions can be determined. Fig. 5 shows for the 1st Beneluxtunnel, for different combinations regarding the abutments and for different maximum speeds that are related to certain slopes, the maximum possible lowering of the navigation channel. The dotted line indicates the depth of the Maeslantkering its sill, what could presumably be regarded being the maximum required depth increase. Also, a distinction is made between rotation in only the immersion- or the segment joints – providing an almost equal amount of lowering – or in both joint types.

The technically possible lowering is clearly less than if one would only look at the abutments and the slopes, which is mainly caused by the restricted rotation capacity. The maximum depth regarding the strength of the cross section is only reached in case of large lowering of the abutments, as the adjacent elements are dimensioned less strongly and the relative increase of hydrostatic pressure is larger.

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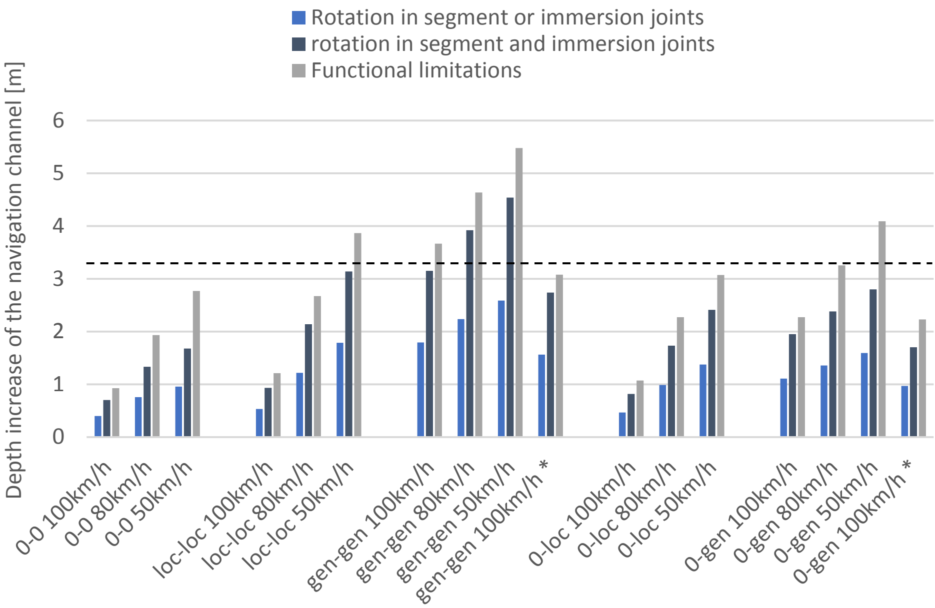

Fig. 5. This graph shows the maximum depth for different combinations of abutment adjustments and for different maximum speeds. 0 = no adjustments (A_1). Loc = locally adapt the transition point (A_2), gen = general lowering of the abutment (A_3). The two options with the * have a slope of 4.5 %, like in the existing tunnel. The dotted line indicates the depth of the Maeslantkering at NAP - 17.0 m.

9 Construction

For all design alternatives, the extent to which problems concerning the constructability are to be expected is examined. On the one hand, this is performed to demonstrate the (technical) feasibility, but it also serves a purpose as a base for cost estimates. The results will be briefly described here:

For the immersed part:

I_1 To be able to re-float the elements, they must be excavated first. Also, the weight of the elements must be reduced by removing some of the ballast and external pre-tensioning must be installed to keep the segments together. Next, the elements must be disconnected. To be able to do so, bulkheads must be placed and the collars and OMEGA-profiles need to be removed from the immersion joints. To remove the elements, also the closure joint must be disconnected, which is expected to be very complicated but we believe it could be accomplished. Instead of re-floating the elements, they could be hoisted up to the surface which would allow for better control during this process. The elements can then be transported to a construction site where they are temporarily stored and revised. When the abutments are adjusted to the increased depth, the elements can be re-immersed.

I_2 Alternatively, the elements could be lowered without re-floating them. To allow this, the soil would have to be removed from underneath the elements with specialized dredging equipment. The axial compression – present in immersed tunnels due to their construction method – will allow limited spans to exist without the occurrence of tensile stress in concrete or rotations in the joints. Consequently, spans of 20-30 meters are expected to be possible. To undermine the entire tunnel however, external pre-tensioning and temporary supports will be required. Both in the pre-tensioning and in the supports, mechanical components must be implemented to allow and control the lowering process. Also, at least one joint must be opened to allow horizontal displacement of the elements when the tunnel is lowered. This joint will later be closed similar to a closure joint. Once the tunnel has reached is desired depth, the elements must be underflown again to restore their foundation.

For the abutments:

A_1 No adjustments requires no constructional effort.

A_2 To locally adjust the transition point, it must be accessible, which requires for the adjacent element to be removed so a water retaining screen can be placed. The space provided by the dewatering cellar could be utilized to reconstruct a new transition point at a lower level, possibly at an increased angle.

A_3 General lowering could be achieved by wet reconstruction. First, additional anchors must be inserted in the side walls. The adjacent element must be removed and a water retaining screen must be placed which will allow for the entire land part can be inundated. The underwater concrete floor and all structures above have to be removed. New tension piles and vertical anchors must be placed. Finally, a new underwater concrete floor can be constructed on the desired depth, the water can be removed and all structures above can be rebuilt.

Apart from the construction methods of the alternatives themselves, also the consequences of their combinations are important. For instance, to adjust the land part space is required, making it necessary for at least one element to be re-floated in most scenarios. Also access to the elements during construction is an important advantage, making the adjustment of only one of the land parts much more attractive. This will however require for the navigation channel to be moved towards one of the shores.

Also, some differences between the 1st and the 2nd Beneluxtunnel exist. Important is for instance the fact that in for the 1st Beneluxtunnel, the immersion joints are filled with concrete, which highly complicates the re-floating capabilities of this tunnel its elements. Also the foundation is different. Underneath the 1st Beneluxtunnel lie temporary foundation tiles that need to be removed separately. The 2nd Beneluxtunnel is founded directly on gravel which could be removed using the right dredging equipment.

Based on the described methods, constructing the design alternatives is expected to be possible. However, additional research is required to increase the certainty of this statement. To prove constructability, it is required to perform a full safety analysis in which is checked whether the strength, stiffness and stability of all structural components satisfy the limit states during all phases of construction. This was not possible during the limited time of this study. Instead, only the structural components and construction phases that are expected to be most critical are examined. Hence, at this stage a large risk on unexpected setbacks exists.

10 Evaluation

Based on the construction methods, the costs of the different design alternatives are estimated. Also some other aspects are expressed in money for the comparison to be as fair as possible. For instance, the economic damage of traffic hinder during construction and as a consequence of lowering the maximum speed is estimated. The costs of building a new tunnel and demolishing existing one has also been estimated.

This information is used to determine what combination of design alternatives at which desired depth is the most economically attractive lowering method. The results are given in table 1, in which the total costs of the project are shown, including traffic costs. The effects of possible restrictions on combinations and the differences between the 1st and the 2nd Beneluxtunnel have been neglected.

Table 1. This table shows the most economically attractive combinations of design alternatives per for different lowering ranges. The costs include the entire project (reconstructing both tunnels, including traffic costs).

Lowering range	Abutments	Immersed part	Costs (millions)	Slope
0.0 - 0.9 m	Local adjustments on both sides	Remain immersed	€ 295	5 %
0.9 - 1.9 m	General lowering on one side	Remain immersed	€ 415	5 %
1.9 - 3.2 m	General lowering on both sides	Remain immersed	€ 500	5 %
3.2 - 3.6 m	General lowering on both sides	Re-float	€ 665	5 %
> 3.6 m	New immersed tunnel		€ 730	5 %

This cost analysis shows that for all desired depths up to the depth of the Maeslantkering, lowering the existing Beneluxtunnel is economically more attractive than building a new one. Also, increasing the slope with more than 5 % is not desired. The lowered construction costs do not outweigh the economic damage of lowering the speed. However, due to recent changes in design regulations, the slope can be slightly increased from 4.5 % to 5.0 %. [4]

When interpreting these results one should be aware of the large uncertainties in these estimates as they strongly depend on construction methods that are currently not sufficiently detailed to be able to exclude large unforeseen costs.

11 Conclusions

This preliminary study shows that lowering the Beneluxtunnel down to the depth of the Maeslantkering is expected to be technically possible as well as economically attractive. Furthermore, for this depth range can be concluded that:

- The 1st Beneluxtunnel has sufficient excess strength in order to allow lowering.
- Joint rotations can be utilized to adapt the longitudinal profile of the tunnel.
- For the abutments, the preferred solution depends strongly on the desired depth. General lowering is by far the least attractive solution, but is inevitable from a desired depth of more than 1 m.
- For the immersed part, lowering the elements while they remain immersed preferred. To create space however, it is desired to re-float at least one element. Hence, a combination of both methods is preferred.
- The large expected costs of lowering the maximum speed makes this an unattractive option.

It is recommended to perform additional research on certain boundary conditions and construction methods which could only be treated partially during this study and could therefore be defined as large risks during this stage. Important subjects are:

- Determining the excess strength of the 2nd Beneluxtunnel.
- Determining the maximum allowed joint rotations taking into account the effect of deformations.
- The removal of structural components (including the closure joint) and the effects of this on the tunnel.
- The stabilisation of the tunnel elements during excavation and during the lowering process.
- The replacement of the underwater concrete floor and the tension piles of the abutments.

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